Scientia

FROM CLIMATE CHANGE TO THE COSMIC WEB

EXCLUSIVES:

- The European Geosciences Union
- American Geophysical Union – Space Physics and Aeronomy
- The Square Kilometre Array

HIGHLIGHTS:

- Observing and Projecting Global Sea-Level Change
- A Fair Approach to Flooding
- From THEMIS to ELFIN: Exploring Near Earth Space
- Using the Hubble Telescope to Investigate the Universe's Hidden Baryons

Issue: #112

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WELCOME...

I am delighted to present this enticing new edition of Scientia, which covers a range of important research areas, from geology to climatology, and from aeronomy to astronomy.

Mitigating disaster is one pressing theme that pervades this edition, and we start off by featuring research devoted to predicting devastating seismic events. Here, we showcase the work of two scientists, who are developing creative ways to forecast volcanic eruptions and earthquakes.

The lion's share of this edition is dedicated to perhaps the greatest disaster humanity will ever experience – anthropogenic climate change. Thousands of scientists across the globe are working to accurately quantify the impact of climate change, so that we can predict and hopefully mitigate its most damaging effects, such as sea-level rise, extreme weather events, droughts, flooding and crop failure. Because of widespread denial in the face of this global disaster, this type of research is extremely important, in order to further highlight that our greenhouse gas emissions are the cause of global temperature rises. In this edition, we feature the work of many research teams, each striving to predict or mitigate the severity of this imminent global disaster. Predicting future sea-level rise, managing flood risks, quantifying the effects of vegetation on the climate and mining graphene for the renewable energy sector, are just a few of the many research projects showcased here.

Next, we focus on another danger, which lurks beyond Earth's atmosphere – space weather. Space weather disturbances, caused by fluctuations in the solar wind, can cause a huge array of problems here on Earth, such as widespread electricity blackouts and satellite damage. Because of our heavy reliance on satellites for communication, GPS and air traffic control, many scientists are dedicating their research efforts to devising ways to forecast space weather events. In this section of the edition, we showcase the latest research in this area, and feature an exclusive interview with last year's president of the AGU's Space Physics and Aeronomy section.

From near-Earth space, we venture deeper into the cosmos, with our last section dedicated to the mind-blowing field of astronomy. First, we meet Professor Philip Diamond, Director General of the Square Kilometre Array – set to become the world's largest and most sensitive radio telescope. Next, we introduce Kimberly Arcand, Visualisation Lead for NASA's Chandra X-Ray Observatory, who makes science more accessible to the public by improving the ways we visualise astronomical objects. To close the edition, we introduce Dr Bart Wakker, who uses the famous Hubble Telescope to find the Universe's hidden matter, which resides outside galaxies and forms the filamentary structures of the Cosmic Web.

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Meet The Team...

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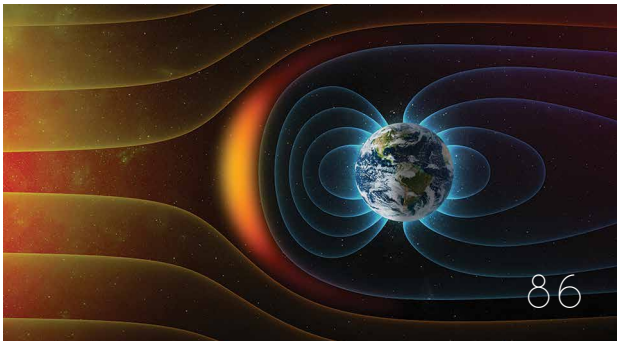

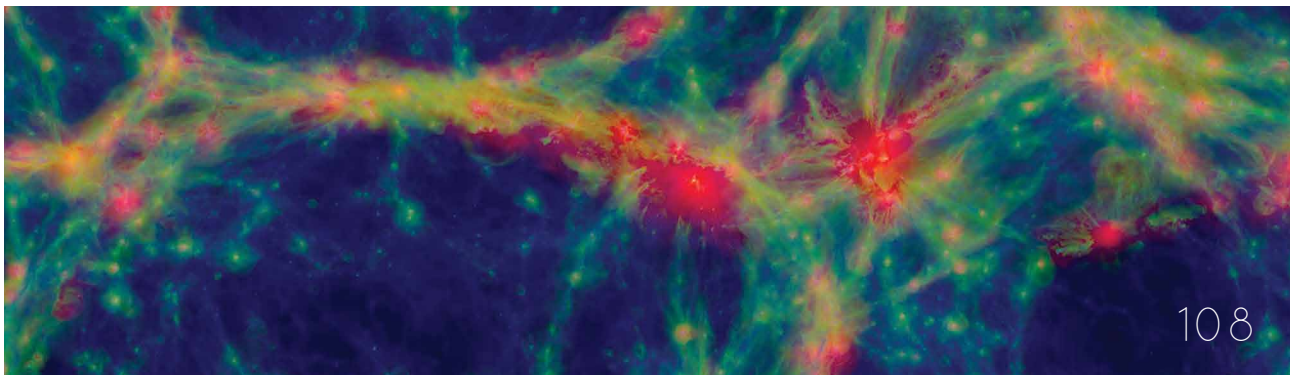

GEOLOGY – MITIGATING DISASTER AND FUELLING RENEWABLE ENERGY

In our first section of the edition, we start with our feet on solid ground, where we deep-dive into the dynamic field of geological science. Geology has given our human race enormous insight into the history of our home planet, by unveiling plate tectonics, mapping out life's evolutionary history and offering an understanding of ancient climates, to name just a few. Indeed, investigating past climates and their influence on Earth can help us to predict and adapt to the effects of human-induced climate change. Aside from the perils of climate change, geology also helps us to understand other hazards, such as earthquakes and volcanic eruptions, both of which we will address over the next few pages.

To open this section of the edition, we have had the opportunity to speak with Bárbara Ferreira, the Media and Communications Manager of the European Geosciences Union (EGU) – Europe's largest geoscience union. In this exclusive interview, Bárbara tells us about the EGU's dedication to pursuing excellence in the Earth, planetary and space sciences, for the benefit of humanity.

Next, we highlight the remarkable research of Dr Taka'aki Taira, a seismologist at the University of California at Berkeley. Alongside his colleagues, Dr Taira develops new ways to listen to and interpret ambient seismic noise, in order to investigate changes in Earth's interior related to earthquake rupture and volcanic activity. By studying patterns in seismic noise, and relating them to actual earthquakes and eruptions, the team are uncovering what signals may be possible indicators of stress in tectonic plates.

Also working hard to advance our ability to predict geological hazards is Professor Ken Sims, a geologist and volcanologist at the University of Wyoming. As a testament to his dedication, Professor Sims and his team climb up some of the world's most highly active volcanoes, in order to obtain volcanic samples. By analysing the isotopes in these samples to estimate their age, he intends to map out the chronology of extensive flows and eruptions around volcanoes. His team hope that by gaining a better understanding of the past activity of these dramatic geologic phenomena, eruptions will be easier to predict, helping to protect the lives of people living nearby.

Isotope geochemistry is an interest also shared by Dr Andrew Conly, a mineralogist and geologist at Lakehead University. Rather than employing isotope dating to predict natural disasters, Dr Conly uses it to investigate materials for the renewable energy sector, thus helping in the mitigation of anthropogenic climate change. Recently, Dr Conly has teamed up with Zenyatta Ventures Ltd., a mineral development company, offering his geological expertise to identify and characterise a newly discovered graphite deposit. Zenyatta and Dr Conly hope that this high-purity graphite will be used in the manufacture of lithium-ion batteries, fuel cells and pebble-bed nuclear reactors, all used to either store or provide renewable energy, thereby reducing our reliance on fossil fuels.

THE EUROPEAN GEOSCIENCES UNION

Credit: EGU/Foto Pflueg!


Credit: EGU

Founded in 2002, the European Geosciences Union (EGU) is Europe's largest geoscience union, dedicated to the pursuit of excellence in the Earth, planetary, and space sciences for the benefit of humanity, worldwide. Based in Munich, this non-profit international association of scientists boasts over 12,500 members from all over the world. Membership of the EGU is open to individuals who are professionally engaged in or associated with Earth, planetary or related studies, including students and retired seniors.

The EGU facilitates the advancement of research in these fields by offering various platforms for the scientific community to present and discuss their work. Here, we have had the pleasure of speaking with **Bárbara Ferreira,** the EGU's Media and Communications Manager, who discusses the Union's role in promoting research in Europe and further afield.


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Describe some of the many ways that the EGU promotes the advancement of earth, planetary, and space sciences in Europe?

The EGU provides platforms for the scientific community to present and discuss their research work, thereby promoting the advancement of the Earth, planetary and space sciences.

One of the most important ways in which we do this is through the organisation of our annual General Assembly, a scientific conference that brings together some 13,000 Earth, planetary and space scientists from around the world. The General Assembly is a forum where scientists, especially early career researchers, can present their work and discuss their ideas with experts in all fields of the broad geosciences.

We also publish, through Copernicus Publications, 17 peer-reviewed open access journals covering various topics of the Earth, planetary and space sciences. Most of these publications are two-stage journals with public peer-review and interactive public discussions, providing a transparent way to discuss science and promoting its advance.

Another way in which we promote the advancement of these fields is through our awards and medals programme. EGU awards and medals recognise, on an annual basis, eminent scientists for their outstanding research contribution in the Earth, planetary and space sciences, and identify the awardees as role models for the next generation of early career scientists to foster geosciences research.

Finally, we also sponsor scientific meetings in all areas of the Earth, planetary and space sciences. These include the EGU Galileo conferences, which address well-focused cutting-edge topics at the frontier of geosciences research, as well as various co-sponsored meetings.

Who are the EGU's main collaborators, and in what ways do you work together?

The EGU collaborates with various geoscience organisations around the world. We have signed memoranda of understanding or memoranda of cooperation with the American Geophysical Union (AGU), the Asia Oceania Geosciences Society (AOGS), the Geological Society of America (GSA), the International Union of Forest Research Organizations (IUFRO) and the Japan Geoscience Union (JpGU). These collaborations aim to foster international exchange in scientific research and promote opportunities for the memberships of the different organisations. For example, in the case of the AGU, our members get a discounted registration at their annual meeting and vice-versa, and the EGU has an exhibition booth at a discounted rate at their meeting and vice-versa. The leadership of both organisations meets on a regular basis to discuss further joint initiatives, and recently we have started organising common-themed great debates and the AGU and EGU annual meetings.

In what way does the EGU help early career scientists to become established in their field?

The EGU offers a platform for early career scientists to become involved in interdisciplinary research in the Earth, planetary and space sciences, through sessions, networking events and short courses at the annual General Assembly. We provide financial support to early career scientists who wish to attend the meeting and present their research, to encourage participation of more junior researchers at the conference.


Credit: Bernhard Aichner (distributed via imagegeo.egu.eu)

For students, we also have the Outstanding Student Poster and PICO (OSPP) Awards to further improve the overall quality of poster and PICO (Presenting Interactive COntent) presentations and most importantly, to foster the excitement of younger colleagues in presenting their work in the form of a poster or a PICO.

In addition the EGU has awards and medals specifically for early career scientists: these include the Arne Richter Award for Outstanding Early Career Scientists, which is Union wide, as well as field-specific Division Outstanding Early Career Scientists Awards.

Finally, I should mention that early career scientists have a voice in the EGU, since they have representative in the EGU Council as well as in some of the Union's committees. This means they can play an active role in developing activities targeted specifically at early career scientists, namely initiatives that help younger researchers become more established in their fields.

You mentioned that The EGU publishes several academic journals, please give our readers a brief overview of these.

Yes, the EGU publishes 17 scientific journals, through Copernicus Publications. These cover a number of areas within the broad geosciences, namely atmospheric science, biogeosciences, climate sciences, geomorphology, hydrology, natural hazards, ocean sciences, soil sciences, cryospheric sciences, to mention a few. We also have specific journals dedicated to geoscientific instrumentation and model development. All journals are open access and the articles published in them are free to read for all.

The most innovative aspect of EGU journals is their review and publication process, which (in the majority of EGU journals) happens in two stages. The discussion and peer-review of submitted papers are handled in the open access discussion forums (e.g., Atmospheric Chemistry and Physics Discussions) while final papers, upon acceptance, appear in the corresponding peer-review journals (e.g. Atmospheric Chemistry and Physics).

Like in traditional journals, papers submitted to EGU journals are peer-reviewed by two or more referees (researchers working in the broad area of the article). The difference is that the referees' comments, which can be attributed or anonymous, are published alongside comments by other members of the scientific community (attributed) in an open-access, public discussion forum, where the authors publish their replies as well.

This open, public peer review system aims to make the publishing process more interactive, efficient and transparent, while assuring the quality of the scientific research that is published after peer review.

Please also tell us a bit about the EGU's position on public outreach and education, and about some of the events you have organised in the past for both the scientific community and the public.

The EGU has an Outreach Committee and a Committee on Education, both of which are dedicated to overseeing and organising EGU's public-engagement activities, many of which are coordinated by EGU's permanent staff at the EGU office in Munich.

EGU's main educational initiative is GIFT (Geosciences Information for Teachers): two and a half days of teacher-enhancement workshops, which are held in conjunction with EGU's annual General Assembly. There, selected top-level scientists working in the Earth sciences offer the invited teachers talks centred on a different theme every year. The main objective of the GIFT workshops is to spread first-hand scientific information to science teachers of primary and secondary schools, significantly shortening the time between discovery and textbook, and to provide the teachers with material that can be directly transported to the classroom. In addition to GIFT at the General Assembly, the EGU usually organises another similar workshop during the year, which is generally hosted in a developing country. Another educational activity we have is Planet Press: bitesize press releases for kids, parents and educators to get to grips with the latest geoscientific research going on across the world.

For EGU members and the scientific community, we produce a monthly EGU newsletter to inform researchers about EGU events and activities, maintain a database of geoscience pictures (also useful for the broader public and educators), and run a public-engagement grant scheme. For the scientific community, as well as the broader public, we have a number of blogs where accurate information about geoscientific research is shared on a regular basis. We also have an established

presence on social media channels, such as Twitter and Facebook, where we share current news in the Earth, planetary and space sciences, as well as updates on EGU activities and publications.

For the media, as well as the broader public, we issue press releases about new and exciting scientific research published in EGU open access journals. We also organise press conferences at our annual General Assembly to showcase some of the inspiring science presented at the conference.

Does the EGU engage with European policy makers?

Recently, the EGU started developing its engagement with science for policy activities on the European scale. These initiatives aim not only to inform policy workers about science-related issues within the EGU's scientific remit, but also to help EGU members and other geoscientists communicate with policy workers more effectively. This work was only initiated about a year ago, when we hired a science policy fellow to work at the EGU office. As such, we are not yet in a position where we can influence policy decisions, though we have had success providing our members with tools to allow them to give evidence to policy makers. For example, in a session on 'Working at the science policy interface', one of the most popular short courses at the 2016 General Assembly, each panellist provided useful background and tips on communicating science to policy officials. The EGU policy fellow also maintains a regular column on the EGU blog aimed at informing the scientific community on European policy, the scientists contributing to this process, and how other researchers could play a role in influencing policy making.

Finally, climate change and dwindling natural resources are two of the biggest challenges facing our generation; please tell us about the EGU's plans to address these challenges, in working towards a sustainable future.

One of EGU's aims is to identify and draw attention to social and environmental problems that could be addressed by the scientific work of its members and communication with the public.

There are various ways in which the EGU does this. Our publications and annual conference are ideal platforms to develop interdisciplinary and international collaborations, which are crucial to develop solutions to the world's most pressing issues relating to the geosciences. These activities, together with our co-sponsored meetings programme, can help catalyse new research and develop solutions to key challenges.


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More specifically, at the EGU General Assembly we have held Great Debates targeted precisely at stimulating discussion and finding solutions to pressing environmental issues. For example, at our 2016 conference, two of the debates we held were 'Plan it Earth: is there enough resource for all? Is it just a matter of planning for the future?' and 'Is global economic growth compatible with a habitable climate?', while in 2015 we discussed 'Global Freshwater Use - The thirsty 10 billion: Are we managing?' and 'Negotiating climate policy - resigning to resilience?'. Through these debates, we aim to raise awareness of these issues, as well as stimulate our members and conference attendees to shape their research agendas in a direction that addresses these challenges. More broadly, our outreach and education activities also inform and engage the public with these challenges. To give an example, the EGU 2014 GIFT workshop was on the theme of 'Our changing planet', focusing on climate change and its consequences. In 2015, the workshop was dedicated to 'Mineral resources', with a few lectures focusing on the use the depletion of raw minerals. By educating the next generation, we hope to ensure tomorrow's policy makers, researchers, and other members of society are prepared to address the world's environmental challenges.serve.

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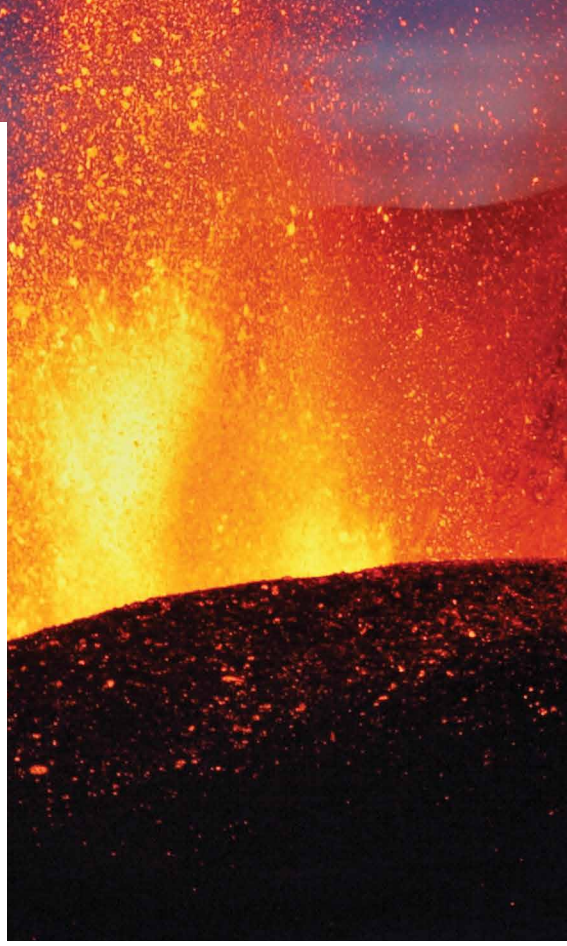
TAKING THE EARTH'S PULSE – LISTENING TO SEISMIC NOISE

Research Seismologist **Dr Taka'aki Taira** at the University of California at Berkeley and his colleagues investigate changes in Earth's structures related to earthquake rupture and volcanic eruption by exploring ways to listen to and interpret ambient seismic noise.



The Earth Not Only Shouts at Us – It Also Whispers

Earthquakes are scary things. Just the shaking and rolling of the normally stable ground in a mild temblor is enough to frighten people and animals. And the damage large earthquakes cause – including the human death toll – seems to make the news on a regular basis. For example, recently a violent earthquake struck Gorkha, Nepal, killing 9,000 people and injuring 22,000. A century ago it was the historic 1906 San Francisco earthquake – one of the largest natural disasters in the history of the United States resulting in the destruction of 80% of the city of San Francisco and the loss of over 3,000 lives – that resulted in a veritable eruption of scientific interest in earthquakes, seismic motions and methods to observe and forecast these kinds of disasters. For the last century, scientists the world over have studied the creaking and cracking of the Earth's crust in an effort to warn us of impending catastrophes. But the big sounds that accompany such phenomena as earthquakes and volcanic eruptions are not all that you can detect with a seismograph. You can also hear background whispering of the Earth's crust – the so-called 'seismic noise.'

Seismic noise is the rather nonspecific term for the fairly persistent, low frequency vibration of the Earth's crust from any number of causes. Also known as ambient vibrations, it is referred to as 'noise' because it is ordinarily an unwanted part of the signals recorded by seismometers. Other disciplines besides seismology also term it 'noise' because it is a nuisance for things that are sensitive to vibrations, like precision telescopes or the commercial growing of crystals. On the other hand, measuring ambient vibrations can be helpful in engineering, where projects such as the building of bridges and high-rise buildings require calculations of the elastic properties of the soil to determine whether the structures will be susceptible to shifting due to earthquakes and other seismic events. In other words, seismic noise may indicate whether the ground is firm enough or not. This is where Dr Taka'aki Taira and his colleagues concentrate much of their recent professional attention – studying seismic noise in relation to actual earthquakes for determining whether noise is not noise at all, but a possible indicator of stress in the tectonic plates near earthquake prone areas.

The Science of Seismic Fault Dynamics is Itself a Dynamic Science

Since the 1950s and 1960s, scientific understanding has been that the Earth's rigid outer layer – the lithosphere – is broken up into seven or eight major tectonic plates, along with a number of smaller plates, that essentially float on the fluid inner layers of the Earth. These tectonic plates are always slowly moving, separating in some places and colliding in others. But the important thing is when they collide their edges grind together causing massive friction. Where plates collide – called a fault – the friction of that collision can cause energy to accumulate over time, which can suddenly release when the amount of built up energy overcomes the force of friction between the two edges. According to this model, an earthquake results from a sudden slip on a fault. This slip causes the edges move against each other, releasing energy in waves that travel through the Earth's crust and causing vibrations and movement that can lead to damage and destruction. Simply speaking, the tension builds up over time until the edges of the fault can't hold it anymore and an earthquake results. Thus scientists have been focusing on observing the deformation at the Earth's surface to measure the total strain accumulation by this tectonic plate model. But this is not enough. We need to know when the Earth can't endure the accumulated strain anymore, i.e., the strength of the crust. Moreover, scientists recognise the strength might vary over time. When the crust is weakened, earthquakes would occur more frequently even though the accumulated stain is smaller. This would lead to a more complex pattern of earthquake cycles. Without knowing the crustal strength, it is extremely difficult to forecast earthquakes. Therefore, observing the temporal variations of the fault strength has been a long-sought goal of the earthquake science community over the last few decades.

Together with Paul Silver of Carnegie Institution for Science, Dr Taira and his team developed a new means to monitor fault strength by analysing seismic waveforms and microearthquake activities, and published their findings in Nature. The team found the first field evidence showing the fault strength was temporally weakened, and this temporal weakening was responsible for clusters of earthquakes in Central California. More importantly, the reduction of the fault strength they found in California was induced by dynamic stress changes from a distant 2004 magnitude 9.1 Sumatra earthquake that had occurred on the other side of the world.

The implication of their finding is that distant large earthquakes may increase the risk of subsequent earthquakes around the globe. More recently, Dr Taira has concentrated on recording ambient vibrations – generally considered nonspecific background noise – and correlating them with specific volcanic and earthquake activity.

'Noise' Can Be Considered a Heartbeat of Seismic Activity

In the American Pacific Northwest, Pacific Oceanic tectonic plates have slid below the North American Plate for millions of years. Heat from this tectonic subduction has given rise to numerous volcanoes from California all the way up to British Columbia over the recent geologic past – say, the last 30 million years. It is also responsible for seismic activity in the Lassen volcanic area, located at the southern edge of the Cascade Mountain Range. Here, at the Lassen Volcanic Center, is where Dr Taira and his colleagues have their seismology listening post. The Center sits above a hydrothermal system that is feared might be the site of hydrothermal explosions at some time in the future. Dr Taira monitors this area, aiming to develop a new way of forecasting volcanic phenomena by using seismic noise correlated with actual seismic and geologic activity.

Dr Taira and his colleague Florent Brenguier, of the Université Grenoble Alpes, analysed ambient vibrations at six stations in the Northern California Seismic Network around Lassen Peak, a mountain in the Lassen volcanic area. The data from these stations was electronically processed to show changes in the speed of seismic waves traveling through this area. Variations in seismic wave speed are indicative of changes in tectonic stress in the area. Essentially, they established a quasi-real-time velocity monitoring system through the use seismic interferometry with ambient vibrations. Their monitoring system showed the variability of seismic velocity over time in response to stress changes from earthquakes and from seasonal environmental changes.

Interestingly, dynamic stress changes from an actual magnitude 5.7 local earthquake produced a measurable velocity reduction 1 km below the surface. Calculations from the changes surrounding this earthquake indicated that the Lassen hydrothermal system contained highly-pressurised hydrothermal fluid deep beneath the surface. Dr Taira's measurements also show that the long-term seismic velocity changes closely follow snow-induced vertical pressure almost immediately. That is, winter snow accumulation on the surface actually pushes down with enough force to cause changes in the seismic velocities in the subsurface hydrothermal fluid. Dr Taira feels that this is most consistent with a hydrological load model, where surface loading presses the hydrothermal fluid out, leading to an increase in the opening of cracks in the crust. The weight of snow forces fluid already below the surface to cause cracks in the various subsurface rocks and sediment. At any rate, this effect of the hydrothermal fluid movement is correlated with reductions of seismic velocity. This allowed Dr Taira and his team to deduce that heated hydrothermal fluid is responsible for the long-term changes in seismic velocity, and those changes in velocity can be used to understand – basically in real time – what is going on with the subsurface fluids. This is exciting news, giving hope that monitoring of the ambient vibrations can tell us what the fluids and rocks kilometres deep are doing. This in turn might give an early warning of volcanic or earthquake activity.

Is This an Isolated Finding?

Dr Taira's results from the Lassen monitoring are very exciting, but they aren't the first time he's used ambient vibration monitoring to listen to earthquakes. Recently, in the journal Geophysical Research Letters, Dr

Taira and his group published their studies of ambient vibration-based monitoring they used to look at the temporal variations of crustal seismic velocities before, during, and after the 2014 magnitude 6.0 earthquake in the South Napa area. This South Napa earthquake is the largest earthquake in the San Francisco Bay Area, since the 1989 magnitude 6.9 Loma Prieta earthquake. They saw a velocity drop immediately after the South Napa earthquake. The spatial variability of the velocity reduction correlated best with the pattern of the peak ground velocity of the South Napa mainshock. This told them that fracture damage in rocks induced by the dynamic strain is likely responsible for this velocity change. About half of the velocity reduction was recovered at the first 50 days after the South Napa mainshock.

This velocity recovery is a fascinating observation. Dr Taira believes that these findings after the earthquake may actually indicate a healing process of damaged rocks. This implies that fault lines can 'heal' themselves very rapidly to some extent after they have released energy in an earthquake. Again, what some folks consider noise – these ambient vibrations – is giving Dr Taira and his colleagues an important new technique to monitor seismic activity.

Future Needs and Directions?

What else can we find out about earthquakes and volcanoes by eavesdropping on them? With the advancements of computer resources and instrumentation, Dr Taira and his colleagues are pushing the limits to uncover more of these secrets. Their efforts spent watching and listening to 'noise' will hopefully yield more information on the genesis of earthquakes and allow us more precision in our ability to understand the underlying mechanisms of earthquakes and volcanic eruptions. However, their monitoring system is not complete. Their present system puts out a daily velocity change of the ambient vibration pattern. If they had more computing power, however, they could perform massive cross-correlation computations and perhaps give an hourly update, even streaming it in real-time online. This would enable researchers around the world to detect changes in the velocity of 'noise' that accompany and perhaps precede a volcanic eruption or an earthquake.

In addition, Dr Taira tells Scientia that he recently obtained a grant from National Science Foundation with Rice University and Lawrence Berkeley National Laboratory to perform an active source experiment at Parkfield, central California. Recent advancement of the instrumentation allows the team to generate and detect the seismic waves in high precision. Previous experiments carried out by another researcher team found velocity changes that preceded small earthquakes. This measurement could lead to a sort of 'stress meter' at greater depth to better understand how fault-zone stress is related to earthquakes. Dr Taira has recently joined this active source experiment project as a co-Principal Investigator and is planning to go into the field soon to begin monitoring. This is important research on an important subject – not noise at all.

Meet the researcher

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Dr Taka'ai Taira did his undergraduate studies in Japan, receiving his BS in Earth Sciences in 1999 from Yamagata University and his MS in Geophysics in 2001 from Hokkaido University. He then received his PhD in Geophysics from the University of Hokkaido. After receiving his doctorate, Dr Taira did postdoctoral work at the Institute of Seismology and Volcanology of Hokkaido University, the Department of Terrestrial Magnetism of the Carnegie Institution for Science and the Department of Geology and Geophysics of the University of Utah. He then started a role as an Assistant Research Seismologist at the Berkeley Seismological Laboratory, where he is now Associate Research Seismologist.

Dr Taira's research interests include earthquake and observational seismology, transient stress changes at seismogenic depth, subsurface hydrothermal fluid migration, source mechanism of fluid-induced earthquakes, developing seismic array methodologies, seismic imaging of crustal structure, seismic wave propagation, and modeling of conduit flow dynamics. He has authored or co-authored nearly 30 articles published in peer-reviewed journals and other professional proceedings, as well as multiple oral presentations, media releases and interviews. Dr Taira is heavily involved in the operation of the Northern California Earthquake Data Center. Dr Taira's research has been recognised by the Young Scientist Award from the Seismological Society of Japan in 2011 and the Best Young Scientist Poster Award at the 2013 International Continental Scientific Drilling Program science conference at Potsdam, Germany. He also received the nation's top scientific honour – the Young Scientists' Prize from the government of Japan in 2016.

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Berkeley Seismology Lab

Northern California Earthquake Data Center

Nyiragongo Lava Lake in 2007. Photo by John Catto.

UNDERSTANDING VOLCANOES TO HELP PROTECT PEOPLE

Geologist and volcanologist **Professor Ken Sims** and his colleagues from across the globe want to improve our understanding of active volcanoes in an effort to advance the science of volcanology. But they also want to protect the lives of people living near these dramatic geologic phenomena.

Magnificence and Deadliness All in One Spectacular Mountain

Volcanoes have fascinated humans since prehistoric times. Primitive peoples feared them as deities, such as the fire goddess Pele, who lives – according to Hawaiian mythology – in the active Kilauea volcano on the island of Hawaii. Volcanoes are fearsome to us moderns as well, enough to be memorialised in modern culture. For example, the 1968 epic adventure movie Krakatoa: East of Java is set against the backdrop of the catastrophic 1883 eruption of Krakatoa in the Dutch East Indies. Notwithstanding the fact that Krakatoa is actually west of Java, the explosion and eruption of that volcano, along with the tsunamis it generated, killed an estimated 40,000 people and had global impact. More recently, the movie Pompeii dramatised ill-fated lovers caught in the eruption of Mount Vesuvius, just north of Naples, Italy, that totally obliterated the Roman city of Pompeii and several neighbouring villages in 79 AD. It is estimated from excavation of the ruins that well over 1,000 people died, many almost instantly from the heat of at least 250°C. It is the height of understatement to say that it is dangerous to live near a volcano.

Human beings are stubborn, however, and live where they will. Visitors to the city of Catania in Sicily can see evidence for themselves that people do not like to move, even after repeated destruction by a volcano. Catania lies on the sunny slopes of the Mount Etna, the tallest active volcano in Europe. Modern construction excavations reveal layer upon layer of destroyed ancient buildings, then lava, then destroyed buildings, then more lava. Over the centuries Catania and the towns around it repeatedly have been totally or partially covered with lava. Yet the inhabitants return to rebuild in the same spot, perhaps due to the fertile soils that result from volcanic activity. Not that the people do not try to defend themselves. In the deadly eruption of 1669 resulting in over 20,000 deaths, the people refused to evacuate, trying instead to divert the flow of lava. Their efforts were in vain. But these unfortunates were trying to play catch up – the lava was already on the move. What if they had advance warning? Couldn't the people in Pompeii, for example, have evacuated well in advance of the eruption if they had sufficient warning? Forewarned is forearmed, and that is just what Professor Ken Sims is trying to do with his research of volcanic activity – predict volcanic activity with enough lead time to prevent loss of human life. An important focus of one of his current studies is the African volcano, Mount Nyiragongo.

‘This research addresses both basic science, as magma genesis is a fundamental dynamic process; but it is also societally relevant, as a volcanic crisis on Nyirangongo would create a humanitarian crisis in this war-torn region of the world’

Volcanologist Jacques Durieux (1949–2009) and Ken Sims on the summit of Nyiragongo looking down into the crater before descending in 2007. Photo by John Catto.

A Million Souls Living Near a Time Bomb

Professor Sims has always loved being outdoors and challenging himself. Early on he became a climbing and mountaineering guide in Peru, Alaska and Antarctica. ‘I eventually tired of guiding as I saw a bigger picture when guiding so many interesting people up big mountains,’ he tells us. ‘My work as an isotope geologist and volcanologist enables me to pursue both the intellectual and physical challenges of our natural world.’ But learning about volcanoes means learning about the human toll volcanoes can exact on those living near them. According to Professor Sims, ‘One aspect of how my work inspires me is the knowledge that the research my volcanologist colleagues and I are pursuing has the potential to save many people’s lives.’

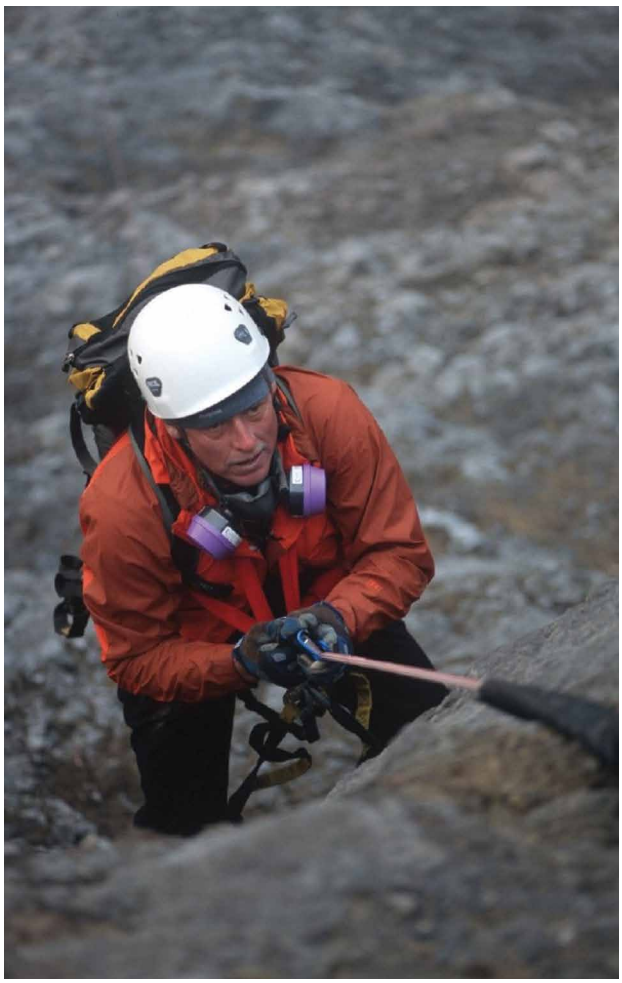
Professor Sims has taken a special interest in the volcanoes of the East African Rift system, an area in Eastern Africa where two tectonic plates – the Nubian Plate and the Somali Plate – are diverging. The rift has produced a number of volcanic mountains, including the legendary Mount Kilimanjaro. He is particularly interested in a spectacular volcano in the Democratic Republic of the Congo, Mount Nyiragongo. Mount Nyiragongo is a stratovolcano – a steep, conical volcano made of layers, or strata, of lava, pumice, ash and other material – that reaches almost 3,500 feet high. Notably, Mount Nyiragongo boasts perhaps the world’s largest lava lake. Professor Sims claims it was one of his favourite field experiences, ‘descending into the volcano Nyiragongo and climbing 15 meters up the vertical spatter cone to see the world’s largest lava lake from just a few feet away.’

Mount Nyiragongo lies a mere 20 kilometres north of the city of Goma, as well as nearby Gisenyi, Rwanda, with an area population of at least a million. In spite of destructive eruptions in 1977 and 2002 in which more than 400 people died and tens of thousands were left homeless, there is little scientific knowledge addressing magmatic cyclicity at this volcano. In other words, nobody knows when the next calamitous eruption could occur. However, just as did the people in Catania, Sicily, the people of Goma have since rebuilt on both the 1977 and 2002 lava flows.

The Nyiragongo volcano is particularly dangerous because the lava it releases is unusually low in silicon dioxide. This makes the lava very fluid and results in lava flows that can reach speeds of up to tens of kilometres per hour. It is imperative that eruptions be predicted, rather than for the residents to try to outrun the lava. Professor Sims intends to provide the concrete scientific framework for hazard assessment and risk mitigation. In his words, his work is ‘both basic science, as magma genesis is a fundamental dynamic process; but it is also societally relevant, as a volcanic crisis on Nyirangongo would create a humanitarian crisis in this war torn region of the world.’ For one thing, Goma is the centre for the UN peacekeeping mission in this area and houses more than a million residents and refugees from civil war in the Eastern Congo and genocide in Rwanda. How does Professor Sims plan to analyse this volcano? By taking samples.

Investigating Volcanoes… By Climbing into Them

Recently, in 2015 Professor Sims, mountaineer that he is, along with one of his similarly trained colleagues, John Catto, and his graduate student, Erin Phillips, took an expedition to Mount Nyiragongo. There they collected rock samples from Nyiragongo’s lava flows and parasitic cones. Parasitic cones are those cone-shaped accumulations of volcanic material, separate from the central vent of a volcano, formed from eruptions through fractures on the sides or flanks of a volcano. Funded by the National Science Foundation, that research expedition was primarily designed to sample the parasitic cones that surround Nyiragongo, both in the city and in the surrounding countryside. These samples were not taken in isolation, however. On two previous expeditions supported by the National Geographic Society, one in 2007 and one in 2010, Professor Sims collected numerous samples from the vertical walls in the summit crater, the outer flanks of the volcano, and even samples from the lava lake. This last daring exercise, descending within feet of the molten lake, was reported in National Geographic magazine. This earlier data gave Sims and his team a leg up on understanding the volcano’s long-term and short-term eruptive history as evidenced by material in



Ken Sims coming out of Nyiragongo's crater while collecting lavas along the crater wall and from the lava lake. Photo by John Catto.

the crater walls.

Professor Sims' most recent expedition, in August 2016, was capped off with yet another descent to the lava lake for sampling. However, this time Professor Sims saw a marked difference in the lake from his 2010 visit. This time the lake was smaller and has sunken deep into the crater – in 2010 it was perched perhaps 100 feet higher. In this most recent 2016 expedition, it was completely impossible to get right to the edge of the lake to get a fresh sample like in 2010. The bottom crater, or third terrace had a new vent that started erupting while Professor Sims was camping down there. It started with a Strombolian type of eruption sending lava bombs near to their camp on the second terrace in the crater and culminated with massive lava flows that poured back into the sunken lava lake. Fortunately for Professor Sims these lava bombs provided another fresh lava for his research. He wasn't surprised, however. As he perceives it, 'It is after all a volcano: one of Earth's "crucibles of change".'

Analysis Will Be the Key to Predicting Future Catastrophes

The city of Goma is actually built on a lava flow that was laid down sometime between 1208 AD and 1374 AD, as closely as can be told by Carbon-14 dating technology. Because these lavas are extremely fluid, this flow is speculated to have quickly covered the area where today's Goma is built. If this type of lava flow happened today, hundreds of thousands of people could be killed. But since the modern city of Goma was founded around 1941, there have been the two deadly eruptions and, like in Catania, Sicily, Goma has been rebuilt after each of these eruptions. It looks like the people of Goma want to stay where they are. They need some help – some warning about the volcano in whose shadow they are living.

Besides these early known lava flows, hundreds of parasitic cones of unknown age surround Nyiragongo's main cone. Some of Nyiragongo's cones have erupted within the actual city of Goma. The Goma Volcano Observatory is actually located directly on one of them. Many very large flows on the flanks of Nyiragongo seem to be relatively young based on morphology, but their age has not yet been determined. This is where Professor Sims and his team are trying to make some headway. By analysing their samples with mass spectrometry, to determine the chemical and isotopic composition of these samples, and radioisotope dating, using proportions of radioactive decay products to estimate age, they intend to map out the chronology of the extensive flows and eruptions around Nyiragongo's neighbourhood. This can greatly improve the predictive power of any predictions of Nyiragongo's future activity. 'Essentially, the past is the key to the future in understanding this volcano,' Professor Sims tells us.

Up until now, current hazard maps for this region are based only on data taken from the 1977 and 2002 Nyiragongo eruptions. But this assumes that no other lava flows were produced in the last few hundred years. Professor Sims knows that this is an inaccurate assumption and a limitation in the present hazard evaluation. Assuming that future venting will follow patterns observed in the 1977 and 2002 eruptions – without taking into account older eruptions – is not scientifically reasonable. Without knowing Nyiragongo's magma cycles and the ages of the flows and parasitic cones in the Goma region, scientists cannot make accurate estimates as to possible future flows. Professor Sims' research recognises the urgent need to provide a concrete scientific framework for hazard assessment of Nyiragongo and to plan ways to mitigate its risk for Goma and Gisenyi. When the analysis and calculations are complete, the team can hopefully give some security to the inhabitants of Goma and surrounding environs. A better and more accurate hazard map could literally save lives.

What Are the Plans for the Future?

Professor Sims and his colleagues hope to get the samples from their project analysed and correlated to better understand and predict the Nyiragongo volcano. But looking to the future, Professor Sims says he 'wants to expand the toolbox of isotope systems' that he is applying to his studies. Volcanoes produce a variety of materials when the lava cools. A myriad of crystals and compounds results from the cooling of magma and lava, many of which lend themselves to isotopic analysis. Professor Sims wants to branch out from his current set of isotopic by-products and find others that can be used to further expand his analytic repertoire. He is also starting to collaborate with microbiologists in the hopes of collectively better understanding the nexus between geology and life. After all, evolutionists theorise that life arose on this planet in the caldron of a volcanic Earth. And now life – including human life – can be snuffed out by volcanic activity. It behoves scientists to put their heads together and put all their energies into finding ways to avoid that possibility.

Meet the researcher

Professor Ken Sims
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Professor Ken Sims did his undergraduate studies at Colorado College where he received his B.A. with Honours in Geology in 1986. He then received a M.Sc. from the Institute of Meteoritics, Earth and Planetary Sciences, from the University of New Mexico in 1989. In 1995 he received his Ph.D. in Earth and Planetary Sciences from the University of California at Berkeley, where his thesis was entitled Magma Genesis in the Earth's Mantle. From UC Berkeley Professor Sims was awarded a Woods Hole Oceanographic Institution Post Doctoral Scholar fellowship and was subsequently taken on as a research scientist. After spending 12 years as a tenured scientist at the Woods Hole Oceanographic Institution, he joined the faculty of the Department of Geology and Geophysics of the University of Wyoming in 2009, where he is currently Professor at the Department of Geology and Geophysics.

Professor Sims' research interests include the application of Uranium-series disequilibria, radiogenic isotope geochemistry, major- and trace-element geochemistry and the principles of physics and chemistry to a variety of fundamental problems in Earth and planetary sciences. He has authored or co-authored over 70 articles published in peer-reviewed journals. His field research has covered the globe and spanned a wide range of elevations including diving to the bottom of the ocean to sample the East Pacific Rise (4k meters beneath sea level) to climbing and sampling the world's highest active volcanoes (6k meters above sea level) in Ecuador. Professor Sims has also been a mountain climbing guide and instructor, a wilderness instructor and has received numerous academic awards, including the Fulbright US Scholar Award in 2016–2017.

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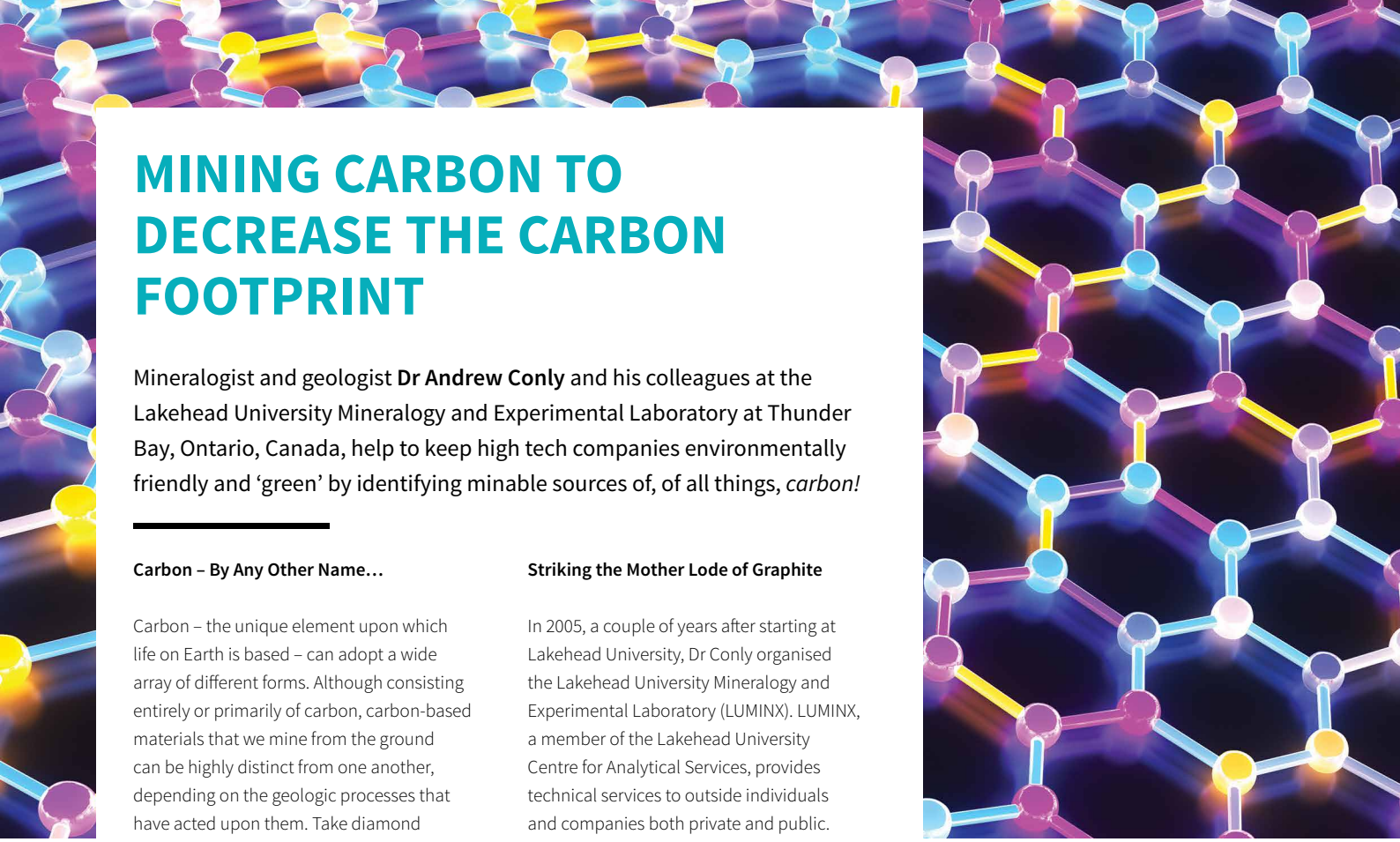


MINING CARBON TO DECREASE THE CARBON FOOTPRINT

Mineralogist and geologist **Dr Andrew Conly** and his colleagues at the Lakehead University Mineralogy and Experimental Laboratory at Thunder Bay, Ontario, Canada, help to keep high tech companies environmentally friendly and 'green' by identifying minable sources of, of all things, *carbon!*

Carbon – By Any Other Name…

Carbon – the unique element upon which life on Earth is based – can adopt a wide array of different forms. Although consisting entirely or primarily of carbon, carbon-based materials that we mine from the ground can be highly distinct from one another, depending on the geologic processes that have acted upon them. Take diamond for example – this pure, crystalline (and of course valuable) form of carbon is almost incomparable to coal – an impure, combustible sedimentary rock. If the right temperatures and pressures act upon carbon sediments over the centuries, another crystalline form can emerge, known as graphite. Unlike the 3-dimensional structure of diamond, this mineral possesses a layered, planar structure – the individual layers of which are called graphene. In each graphene layer, the carbon atoms are arranged in a two-dimensional honeycomb lattice.

When talking about graphite, most people will say it's the stuff in pencils. In fact, the name graphite comes from the Greek word *graphein*, which means to write or draw. But graphite and graphene sheets have a myriad of uses in our modern technology, such as in steel production, batteries, semiconductors, brake linings, lubricants, motors, plastics and electrodes. In fact, natural graphite is usually too impure to satisfy some of the more high-tech applications, so synthetic graphite has become quite valuable for use in scientific research and other highly technical endeavours. However, production of synthetic graphite requires the thermal transformation of petroleum coke, a by-product of oil production, which has many unfavourable environmental impacts. This is where Dr Conly and his collaboration with the Zenyatta Ventures Ltd. (Zenyatta) team are making their mark.

Striking the Mother Lode of Graphite

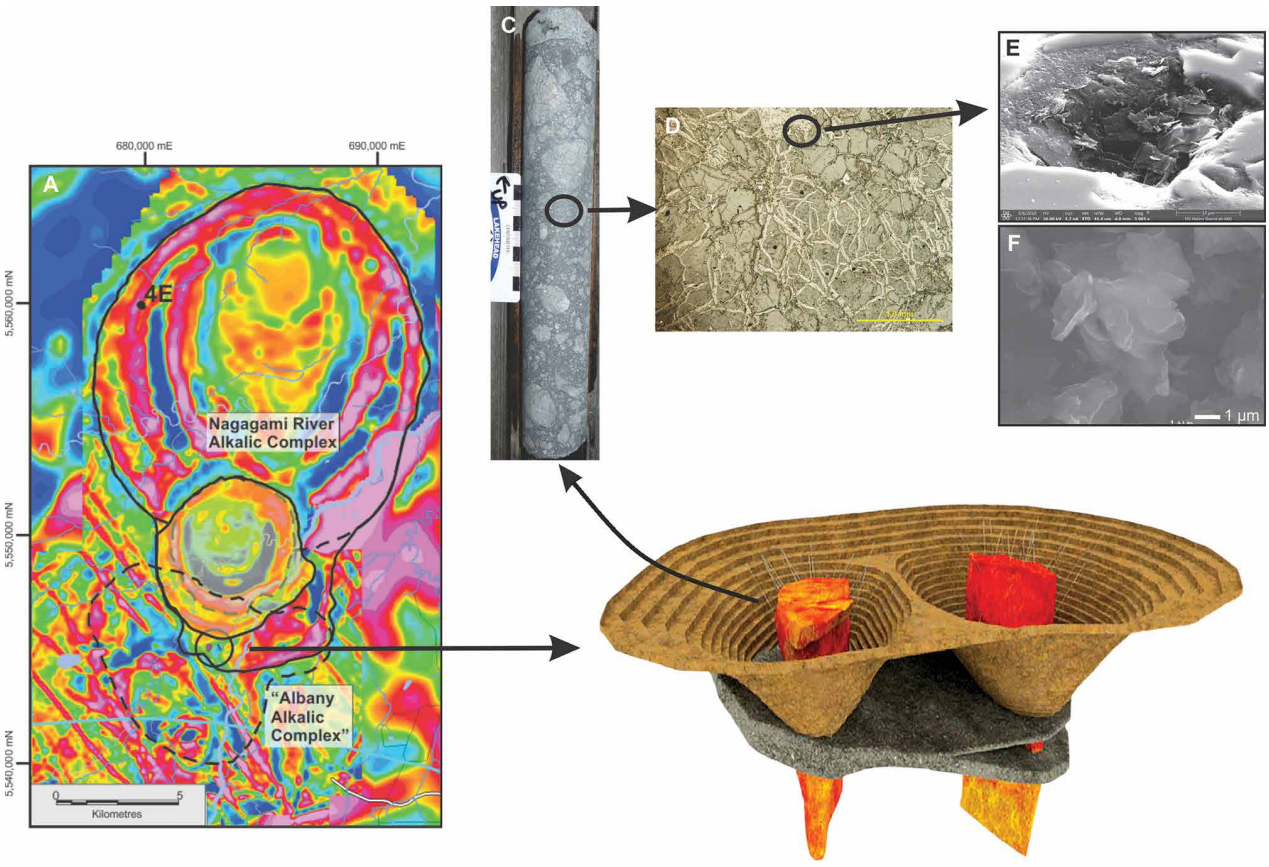
In 2005, a couple of years after starting at Lakehead University, Dr Conly organised the Lakehead University Mineralogy and Experimental Laboratory (LUMINX). LUMINX, a member of the Lakehead University Centre for Analytical Services, provides technical services to outside individuals and companies both private and public. The laboratories also provide interested students the necessary training and hands-on access to modern technologies with the goal of letting them develop essential skills to ultimately benefit the economic future of northern Ontario.

As far as LUMINX, Dr Conly says its main focus is 'to provide advanced mineralogical and geochemical technical services and expertise that are not readily available from commercial service providers.' Many LUMINX clients are either individuals or small junior exploration companies that are in the initial stages of exploration and have specific mineralogical and geochemical questions that might not meet the scope of larger service providers, or that may require more of a research approach to their scientific questions. While LUMINX largely provides services for the exploration sector, Dr Conly's lab also provides environmental services such as static and kinetic acid-base accounting tests. LUMINX has worked with individuals, small companies, international companies, as well as provincial, state and federal government agencies. 'It is always the goal of LUMINX to evolve a technical service contract into a full-scale, multi-year research project,' Dr Conly tells us. And in 2011, he connected with Zenyatta.

In late December of 2011, the CEO and President of Zenyatta, Aubrey Eveleigh, contacted Dr Conly about some interesting attributes of their drill core from a property that they were exploring in northeastern Ontario, Canada. Dr Conly and his research associate Lindsay Moore visited Zenyatta's office in Thunder Bay to sample what was immediately evident upon inspection of the core – Zenyatta's exploration efforts had uncovered a very unusual graphite deposit. This marked that start of what has become an unbelievable and completely unplanned research opportunity. Dr Conly found that Zenyatta had uncovered graphite deposits that exist as breccia pipes in igneous rocks – something globally rare. 'These types of graphite deposits have the potential to produce high-purity graphite required to compete with the $8 billion per year synthetic graphite market,' he explains.

Graphite for Green Technologies

High-purity graphite – perhaps purer than 99.9% graphitic carbon – is required to support Canada's emerging *green technology* sector. High-purity *graphite* is required for the manufacturing of lithium-ion batteries, fuel cells, graphene-based applications, and pebble-bed nuclear reactors, all used to store or provide renewable energy. In fact, Canada is on the verge of potentially developing the world's first fluid-derived, igneous-hosted graphite deposit because of Zenyatta's discovery. The Albany graphite deposit was



(A) Geophysical map showing the location of the Albany graphitic breccia pipes within the Nagagami River Alkalic Complex. (B) 3D block model showing the graphite grade distribution within the two breccia pipes that comprise the Albany graphite deposit (courtesy of Zenyatta Ventures Ltd.). (C) Drill core sample from the West pipe displaying the typical breccia texture of the graphite-hosting syenites. (D) Photo of the graphite mineralisation (light grey mineral). (E) SEM image of in situ µm to nm sized graphite. (F) SEM image of µm to nm after liberation by caustic leach.

formed by the separation of water vapour rich in carbon dioxide and methane from magma chambers deep in the earth. Dr Conly says that mining and processing costs for this natural graphite would come at much lower production and environmental costs over synthetic graphite.

In fact, synthetic graphite is a petroleum by-product, since it results from the refining process of oil. But Dr Conly says that 'only about 5% of the global supply of petroleum coke can be thermally transformed into synthetic graphite, a transformation process that requires substantial energy input since temperatures exceeding 3000°C over 30–60 days are required.' Thus, graphite that is produced by expensive (upwards of US$6,000 per tonne) and energy demanding refinement of petroleum coke has a very large carbon footprint. Zenyatta is now developing a metallurgical process to purify the graphite from this discovery, achieving a carbon purity of over 99.9% using a proprietary and more environmentally friendly purification process.

To generate such high-purity graphite usually requires some form of mechanical, chemical and/or thermal treatment. Zenyatta is working on improving the mechanical–chemical process. Depending on the host rock to the graphite, the chemical methods vary, but they typically involve either hydrofluoric acid or a caustic bake/leach process. Zenyatta is currently working on optimising a caustic purification process for Albany graphite so that much less caustic soda is used in the process while still achieving a high-purity product. This makes Zenyatta's process environmentally friendlier than the hydrofluoric acid digestion used for many other graphite deposits in the world. Dr Conly tells us that 'this process does not remove the need for environmental monitoring and potential remediation, but it lessens the environmental impact'. All this potentially makes this graphite economically competitive with synthetic graphite used for high technology processes and is produced in a much more environmentally friendly way. Canada's potential benefit from this discovery is its own supply of high-purity graphite for its emerging green technology sector. Beyond that, Dr Conly is interested in this graphite discovery not simply because the potential economic benefits are significant, but also because the geological understanding of igneous-related graphite deposits is limited, owing to very few known global discoveries and the resulting paucity of data on these formations. The scientific knowledge to be gained is significant and exciting.

Consequently, a research partnership between Zenyatta and Lakehead University has been established. 'This research will involve the integration of field and laboratory techniques, including core logging, microscopic studies, whole-rock geochemistry, spectroscopic investigations,

radiogenic isotope geochemistry, geochronology and stable isotope geochemistry,' Dr Conly explains. In addition to the potential long-term economic benefits, Canada will benefit in the short-term through student training and research. This will lead to the development of more robust mineral deposit models, which can be applied by exploration industries in Canada and by Canadian companies working abroad to aid in future discoveries. The university's partnership with private industry benefits all parties and stimulates the advancement of science and science education, as well as the advancement of environmentally friendly technologies. Interestingly, the genesis of the deposit has resulted in the formation fine graphite crystallites that have been found to easily convert to graphene and associated derivatives with higher yields when compared to other natural graphite. This has been confirmed by other researchers at Lakehead and also by academics in Israel, Japan and the UK. Zenyatta, realising the potential upside of the cleantech sector, is now actively involved in graphene research and application development and has been making significant progress.

New Vistas in Geology

These days, graphite is Dr Conly's main research focus – he has also worked with several other companies at the service contract level. But the study of igneous-hosted, fluid-derived deposits like the Zenyatta graphite find fits very well with his overall research goals and interests. For one thing, Dr Conly admits: 'I have a general interest in studying the genesis of what one may call unique, rare, one-off or oddball deposits.' While one can argue that every mineral deposit is unique in its own right, Dr Conly is more interested in working on deposits that cannot be readily classified within well-established ore deposit types or models and that are not the study of large and multiple research groups. His doctoral work on a specific Copper-Cobalt-Zinc-Manganese deposit in Baja Mexico was the first foray into such deposit oddities. For the Zenyatta deposit, he saw the potential to conduct ground-breaking research on a previously unrecognised sub-type of graphite deposit. He could be the first researcher to characterise a new sub-type and establish its origin and formation.

Dr Conly readily admits that 'a unique opportunity like this does play to one's ego', as it is not often that one has the opportunity to be the first to characterise a previously unrecognised style of mineralisation. Second, his work on the Zenyatta deposit falls within his overarching research program where he is interested in using an integrated approach involving field, analytical and experimental techniques to understanding the complex interaction among magmatic, hydrothermal and meteoric fluids.

What intrigues him about graphite is that it is somewhat of an unknown commodity within the geological community. In the past, the discovery of graphite by an exploration company could often have been viewed as the death knell for a program, as most economic geologists and geophysicists are familiar with graphite as a nuisance in geophysical exploration due to its excellent conductivity that produces a similar geophysical response to that of targeted massive sulphide mineralisation. However, the current and growing demand for graphite, both in its traditional market sectors and technology sectors, has resulted in some amusing situations. 'It is not unheard of these days to see a company promote what in the not so distance past would have been considered a failed exploration play and now portray it as the latest graphite discovery, though often with questionable economic potential. However, this "jumping on the band wagon" approach has also highlighted some of the challenges associated with the graphite sector – challenges that are invigorating as well as frustrating,' Dr Conly tells us.

Unlike precious and base metals that have variable, but pre-set market prices, graphite has more economic parallels to commodities such as rare earth elements and diamonds. The valuation for any graphite producer comes down to grade-tonnage and a host of other attributes that ultimately dictate its market use, including but not limited to: purity, the percentage of carbon that can be achieved through processing; crystal size and shape; and, the physical-chemical properties, like conductivity and crystallographic properties. The challenge is that the specific attributes are dictated by the often-proprietary requirements of the end-users and, therefore, often the performance of a producer's graphite is not always fully disclosed. This then also results in graphite's market price not being pre-set, but rather negotiated with individual end users. However, Dr Conly sees that the general lack of understanding and market complexities have provided him and his colleagues with ample research opportunities and challenges that were non-existent just a few years ago.

Finally, Dr Conly likes the fact that the graphite geological 'community' is small. The overall scientific community investigating graphite may be relatively large and growing, especially considering the research being carried out by material scientists, chemical engineers and nano-chemists on developing new technological uses for graphite and graphene – a special form of graphite. But the participation of geologists like him remains minimal. Again, this reflects some of the market-exploration challenges and uncertainties discussed above. But it also reflects the fact that while graphite mineralisation in general is not geologically uncommon, the number of known deposits that are of any significant size to be economically viable, or at least potentially so, is small. This will change as applications employing natural graphite will grow with the help of companies like Zenyatta and their purification process. This should replace the demand for synthetic graphite to some degree, thus increasing the demand for new discoveries of graphite – particularly igneous-hosted deposits. In the meantime, the small number of players in the graphite geosphere makes it much easier for newcomers like Dr Conly to join in and, as he says, 'have a seat at the table.'

What Does the Future Hold?

This marks the last year of Dr Conly's grant from Natural Sciences and Engineering Research Council supporting his project with Zenyatta. However, Dr Conly tells us that the grant was just recently extended by NSERC into 2018, as there have been some delays encountered due to some analytical challenges. So, the next steps are to ensure that all the milestones of the existing research project are met and of course all the results are published. Of the outstanding research goals, the main one that Dr Conly and his group are focusing on is constraining the age of the graphite deposit through Uranium-Lead isotope dating of the igneous host rocks and other related igneous rocks. Dr Conly thinks this 'is a critical gap in our data and will ultimately be a key finding of the research.' The age data will also enable him and his team to chronologically relate the formation of the deposit to specific regional geological events related to the Superior geological province.

Meet the researcher

Dr Andrew G. Conly
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Dr Andrew Conly took his studies at Carleton University in Ottawa, Canada, receiving a BSc in Geology and MSc in Earth Science. He then received his PhD in Geology from the University of Toronto. In 2003, Dr Conly joined the faculty of Lakehead University Department of Geology. Then, in 2005, he started the Lakehead University Mineralogy and Experimental Laboratory (LUMINX), which is a member laboratory of the Lakehead University Centre for Analytical Services (LUCAS). The role of LUCAS laboratories is to provide technical services to outside researchers and companies.

Dr Conly's research interests include the fields of applied mineralogy, trace element geochemistry and isotope geochemistry. He is interested in the application of these disciplines to investigate the origins of metals and fluids responsible for the formation of magmatic-hydrothermal metal deposits and to aid in mine site remediation.

Dr Conly's research encompasses a wide variety of analytical instrumentation and methodologies, including optical microscopy, XRD, SEM-EDX, EMPA, FTIR and Raman spectroscopy, XRF, ICP-AES/MS, stable isotopes, radiogenic isotopes and geochronology. His research has resulted in collaborative projects ranging from Canada and the United States to Mexico and France with university researchers, government, and mining and exploration companies.

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CLIMATE CHANGE – HUMANITY'S GREATEST CHALLENGE

Forget economic recession, unemployment, war and terrorism – climate change represents a vastly greater danger that threatens the very survival of our species and countless others on Earth.

Since the Industrial Revolution, humans have been pumping ever increasing quantities of carbon dioxide into the atmosphere, along with other greenhouse gases such as methane and nitrous oxides. Before this, the concentration of carbon dioxide in the atmosphere was about 280 parts per million (ppm), or 280 carbon dioxide molecules for every million molecules in the air. This value has since risen by around 45% due to human activity, up to its current value of 406 ppm (April 2017). The Earth releases some of the heat energy derived from the sun as infrared radiation, which is readily absorbed by carbon dioxide, and other greenhouse gases. With increasing levels of greenhouse gases in the atmosphere, more of this infrared becomes absorbed, trapping heat and disturbing the planet's delicate equilibrium. In fact, 16 of the 17 hottest years on record have occurred since just 2001, undeniably due to this enormous increase in anthropogenic greenhouse gases. This continued warming of the Earth will lead to a myriad of disastrous consequences, many of which have already begun, such as melting sea- and land-ice, flooding, droughts, severe weather events, species decline and decreased crop yields.

Despite the confusing and unbalanced coverage that climate change receives in the media, scientists can now declare with absolute certainty that human activity is the cause behind this increase in greenhouse gases, and the resulting rise in global temperatures. Rather than continuing with a futile debate as to whether or not humans are the cause, we must now focus our efforts on measuring the speed and magnitude of present and future changes, and their potential consequences.

This is exactly the approach adopted by many of the scientists featured in this section of the edition. Their efforts will help us to prepare for – and hopefully mitigate – this imminent global disaster, by informing government bodies and corporations, so that we can more rapidly change the way our society currently operates.

In the first article of this section we meet Dr Joyce Penner and her team at the University of Michigan, who employ mathematical tools to investigate how aeroplane aerosols affect ice and cirrus cloud formation in the atmosphere. Scientists have believed for several years that aircraft contrails contribute to climate change by spreading and actually transforming into cirrus-like clouds. This aviation-induced cloudiness warms the earth by trapping heat; however, many of the mechanisms that lead to cirrus cloud formation are not well understood. A greater understanding of this process allows us to much more accurately to quantify the impact of human activity on cloud formation and how this affects climate change.

Also investigating how human activity is changing our atmosphere and climate systems is Dr Darryn Waugh and his team at Johns Hopkins University, who have a particular interest in polar vortices. They explore how greenhouse gases and ozone can influence polar vortices, and the ways in which they interact with the atmosphere and impact our weather. This research into large-scale atmospheric dynamics provides an important connection between the warming of the Earth's atmosphere and its effects on the weather at a specific place, so Dr Waugh's research offers a clearer picture of what specific weather events are driven by anthropogenic climate change.

Next, we introduce Dr Michael Notaro, and his dedicated team of climate scientists at the Nelson Institute Center for Climatic Research, University of Wisconsin–Madison. By studying climate variability and change, these researchers can deduce how weather

events such as monsoons can be influenced by variations in vegetation in certain regions of the world. Dr Notaro and his colleagues conclude that vegetation dynamics are highly important elements of the climate system, and need to be accounted for in climate models to more accurately predict the effects of climate change.

Perhaps one of the most terrifying consequences of climate change is sea-level rise, caused by thermal expansion of the ocean and melting ice caps, and expected to wipe many low-lying cities and towns off the map. However, the timescale and magnitude of future sea-level rises are extremely difficult to predict, even if we make assumptions about the concentration of greenhouse gases in the atmosphere over the next few decades. One way to gain information on how our quickly sea level will rise in the future is by studying past changes in sea level, to infer how Earth's oceans and ice sheets responded to ancient climates. This is the approach taken by geologist Dr Ken Ferrier and his team at Georgia Institute of Technology. They have found evidence that rivers carrying vast amounts of sediment may have altered the sea level in the past. Just like Dr Notaro's conclusion that we must account for vegetation dynamics in our climate models, Dr Ferrier's results imply that when investigating the relationship between past climates and sea level, we must account for the action of rivers.

Also looking into the past to help us predict and prepare for the future are two scientists – Dr David Pollard at Penn State University and Dr Robert DeConto at the University of Massachusetts – who develop computer models to simulate how ice sheets have grown and retreated in response to climatic change over past epochs. Their models are now being used to predict Antarctic ice sheet melt and corresponding sea-level rise over the next few centuries. In fact, if current trends in greenhouse emissions continue, the team's model predicts that the retreat of the Antarctic ice sheet and other factors, such as melting from the Greenland ice sheet and the thermal expansion of seawater, we could experience a sea level rise of up to 2 metres by the end of this century.

Meanwhile at New York University, Dr David Holland, Denise Holland and their research team are also working hard to better understand the impact of disappearing ice sheets on global sea level. In the next article of this section, we discuss the clever measurement techniques employed during their polar expeditions, and how they combine these measurements with climate models in order to improve their predictive power. One of their unique data collection methods involves catching seals and tagging them with devices that collect and transmit data on the local water conditions. Because seals often swim in regions that are inaccessible to scientists, the tags often provide more useful information than the conventional salinity, temperature, and depth probes.

Another way to probe these inaccessible environments is by using robots. This is Dr Jekan Thanga's area of expertise, whose research team at Arizona State University is developing new and sustainable solutions for extreme environment exploration. In addition to space exploration applications, Dr Thanga and his colleagues design robots and sensor-networks for quantifying the effects of global warming on the world's ice sheets. In particular, they are developing devices to accurately measure and predict the density of the Greenland ice sheet, to accurately measure its present and future contributions to sea-level rise.

As well as causing the melting and breakage of sea ice, rising global temperatures can also cause mountain snowpacks to decline. Since snow is the primary source of freshwater in many mountainous locations, understanding how its loss will impact water supply for people, plants and wildlife is crucial. Adopting innovative approaches, Dr Stephanie Kampf and her team at Colorado State University identify regions that are most vulnerable to losing winter snow, and determine how this affects soil moisture and streamflow.

This reduction in sea and land ice, rising sea levels, and an increased prevalence of extreme weather events, will all contribute towards

serious flooding in many regions across the globe. Mindful of this fact, many researchers are now channelling their efforts into devising ways to manage and mitigate flooding risks. Around the world, it is typically the poor who suffer most due to the effects of climate change, such as flooding. In the next article of this section, we introduce Dr Neelke Doorn at Delft University of Technology, who is working to improve policies related to water, with the aim of achieving a fairer distribution of flood-related risks between different countries and individuals, while limiting adverse environmental consequences.

Next, we showcase the work of Dr Iris Möller and her colleagues at Cambridge University's Coastal Research Unit, who look for ways to protect our coastal areas from flooding by investigating the natural protection offered by the coastal geography itself. She and her team constructed a full-scale salt marsh, and through a series of experiments, showed how these ecosystems can dampen waves and resist wave erosion during a simulated storm surge. This research suggests that planting and nurturing marshland to help protect against storm surges and flooding may offer hope for a more sustainable future.

From here, we move on to uncover the relationship between regions of high salinity in the oceans due to evaporation, and severe rainfall on land, which can cause flooding. Here we introduce the research of Dr Raymond Schmitt and his colleagues at the Woods Hole Oceanographic Institution in Massachusetts, who analysed records spanning 60 years to show, for the first time, that salinity levels in the ocean's surface can be used as a predictor of rainfall on land. The team has successfully correlated salinity levels in two different areas of the North Atlantic with rainfall in Africa and North America, and they're now on the hunt for other similar 'teleconnections'.
This enlightened understanding of how our oceans work can be used to help us anticipate flooding, and indeed other effects of climate change, such as sea-level rise, severe storms, droughts and ocean acidification.

Dr William Lau and his colleagues at the Earth System Science Interdisciplinary Center are also interested in atmospheric water vapour. In particular, Dr Lau's team investigate how rising global temperatures are causing a worldwide increase in atmospheric water vapour, and explore whether these humid conditions are paradoxically leading to an increased prevalence of wildfires. Dr Lau's team has shown that despite this increase in global water vapour levels, the world is actually becoming relatively drier, and their research efforts are now focusing on whether the increasing severity and frequency of wildfires can be predicted.

Indeed, the burning of vegetation poses an enormous threat to the environment. First, there is an initial release of carbon dioxide and other harmful gases, and second, there are then fewer trees to remove excess carbon dioxide from the atmosphere. This is one important research focus of Dr Merritt Deeter and his team at the National Center for Atmospheric Research, who monitor pollutants produced during the burning of vegetation in the Amazon Rainforest. In addition to wildfires, the Amazon is commonly burnt intentionally, in order to clear land for agricultural use. Using a NASA satellite called Terra, the team map the distribution of atmospheric carbon monoxide – a toxic gas which can also be converted into carbon dioxide, thus contributing to climate change.

Also hoping to enhance our understanding of the distribution of pollutant compounds is Dr Albert Presto at Carnegie Mellon University's Center for Atmospheric Particle Studies. In our final article in this section, we introduce his team of dedicated researchers, who employ atmospheric measurements, laboratory studies, and mathematical methods advance our understanding of the geographic distribution of pollutants released from our modern technology, in the hope of developing ways to reduce them.

CLIMATE CHANGE FACTS

280 ppm

Pre-industrial concentration of atmospheric CO_2

406 ppm

Current concentration of atmospheric CO_2 (April 2017, NASA)

36 billion gigatons

CO_2 released into the atmosphere in 2016; this number has stabilised from 2013-2016, but must be rapidly reduced if the most dangerous effects of climate change are to be avoided

1.1°C

Rise in Earth's average surface temperature since 1880

30%

Increase in ocean acidification since beginning of the Industrial Revolution

13.7 million hectares

Forested land lost due to deforestation each year, comparable to the size of Greece

2016

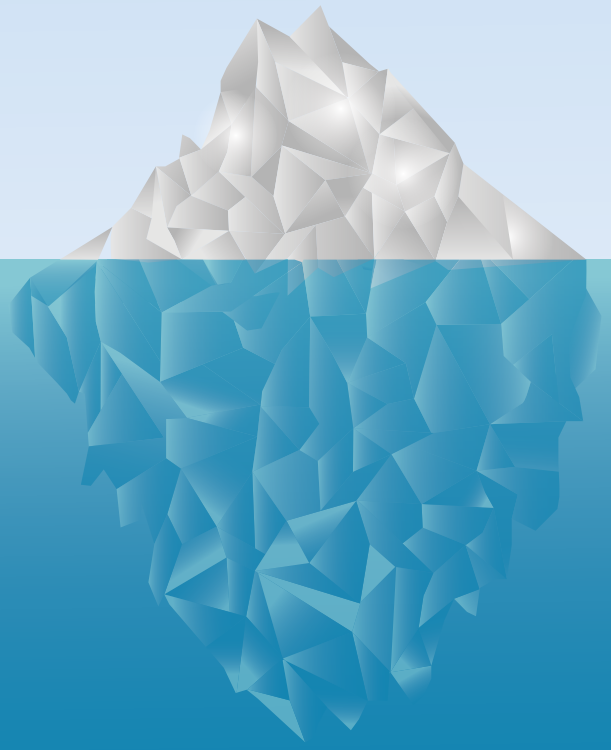
Warmest year on record to date; in fact, 16 out of the 17 warmest years on record have occurred since 2001

0.2 m

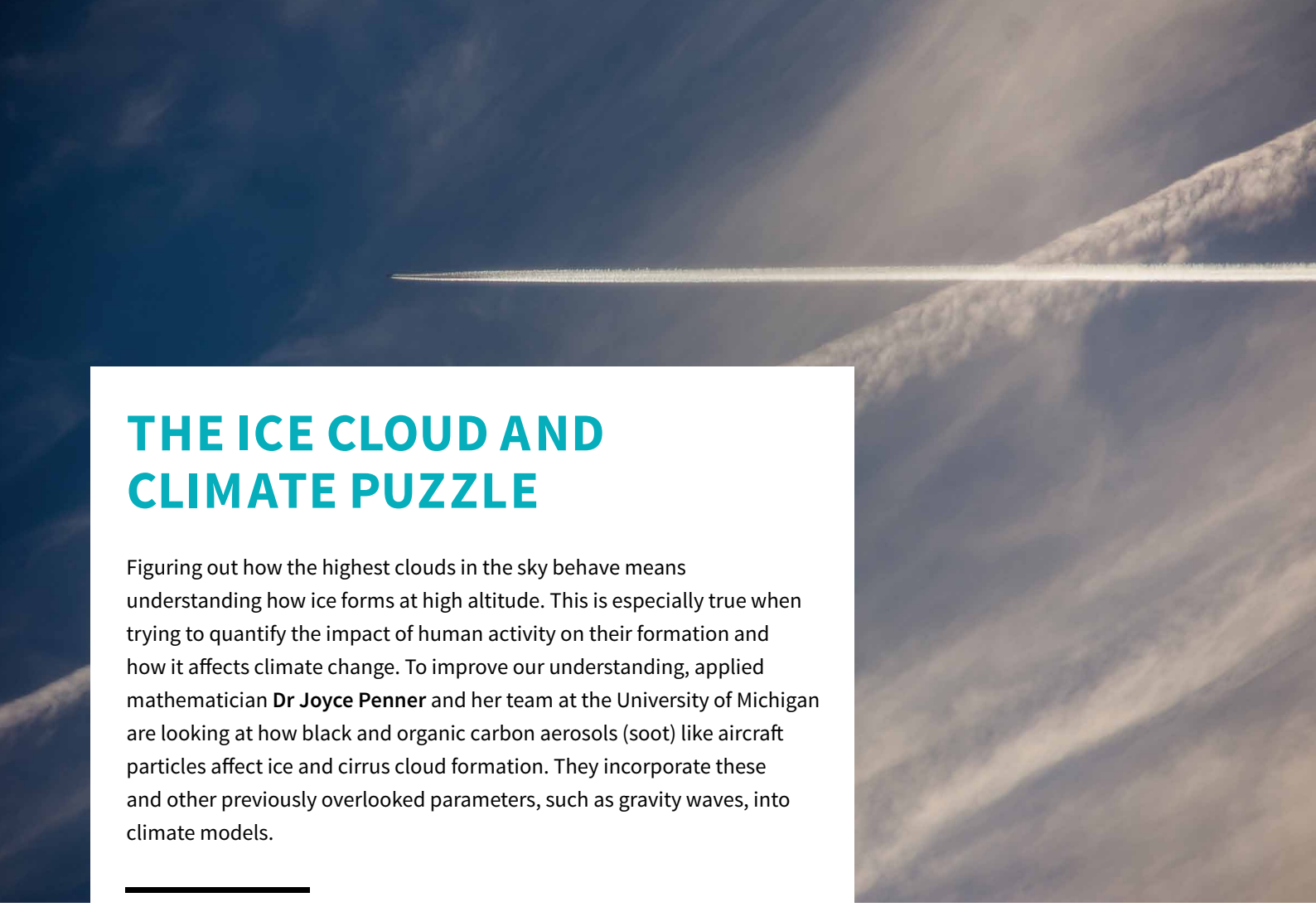
Sea-level rise in the last century

0.3–2.5 m

Expected range of further sea-level rise above present level by 2100 (NOAA, 2017)



Sources: IPCC, NASA, NOAA



THE ICE CLOUD AND CLIMATE PUZZLE

Figuring out how the highest clouds in the sky behave means understanding how ice forms at high altitude. This is especially true when trying to quantify the impact of human activity on their formation and how it affects climate change. To improve our understanding, applied mathematician **Dr Joyce Penner** and her team at the University of Michigan are looking at how black and organic carbon aerosols (soot) like aircraft particles affect ice and cirrus cloud formation. They incorporate these and other previously overlooked parameters, such as gravity waves, into climate models.

On Cirrus Clouds and Contrails

There are probably few people on Earth who haven't seen those familiar vapour trails left by airplanes cruising high in the blue sky. Soon after their emission, these contrails (short for condensation trails) break up and dissipate, and it can be hard to distinguish them from wispy and filamentous clouds known as cirrus clouds.

Cirrus clouds are the highest clouds in the sky, occurring at altitudes of 5 to 12 kilometres or even higher in the tropics. The name cirrus is appropriate, since 'cirri' in Latin means hair or wisp. Cirrus clouds actually consist of thin featherlike bands of ice crystals that form from water droplets or vapour in super-cold temperatures below −30°C. At any given time, cirrus clouds cover up to 30% of the Earth, but their occurrence frequency can be even higher in the tropics.

In nature, cirrus clouds are formed when moist rising air cools sufficiently to allow ice to form. This can occur in large-scale clouds formed as gravity waves travel through the atmosphere or as a result of rising air in thunderstorms, which then spread out in the form of anvils.

The formation of ice may result from freezing of haze particles (particles that are mainly composed of liquid water) or from solid aerosol particles (or 'ice nuclei') that promote crystal formation due to their special surface properties. In today's modern world, as a result of both increasing haze particles and increasing ice nuclei, cirrus cloud formation is increasingly being impacted by human activity.

Scientists have believed for several years that contrails contribute to climate change by causing the earth to warm. Those long contrails in the blue sky can eventually spread and actually transform into cirrus-like clouds. Both the contrails and the cirrus clouds that subsequently form can cover large areas and last for up to 17 hours. This aviation-induced cloudiness warms the earth by trapping heat.

But not all the mechanisms by which cirrus clouds form are well understood. In particular, the prevalence of the formation of ice crystals on either haze particles or ice nuclei is unknown. If ice nuclei are added to a region dominated by ice formation on haze particles, the number concentration of ice crystals in a cloud can decrease, causing the

‘When I first got into modelling of cirrus clouds, the formation of ice crystals was not physically based, i.e. it did not depend on aerosol particles and their characteristics, and supersaturation in the upper troposphere was poorly observed, and not included in models at all. We had to add this feature, and make assumptions about which aerosol particles acted as heterogeneous ice nuclei.’

cloud to trap less heat, thereby cooling the earth. However, if added to a region where ice formation on existing ice nuclei dominates, then the number concentration of ice crystals will increase, and the trapping of heat (and warming of the earth) increases. The soot particles emitted by aircraft will likely act as a catalyst for ice formation via the ice nuclei path once they have already formed ice in contrails, since their surface characteristics may already be similar to ice.

The quandary of whether tiny particles such as aircraft aerosols are actually contributing to a warming or cooling earth is what Dr Joyce Penner and her research team at the University of Michigan have set out to investigate. ‘In general, I am attracted to problems that are not well understood or well represented in models,’ explains Dr Penner.

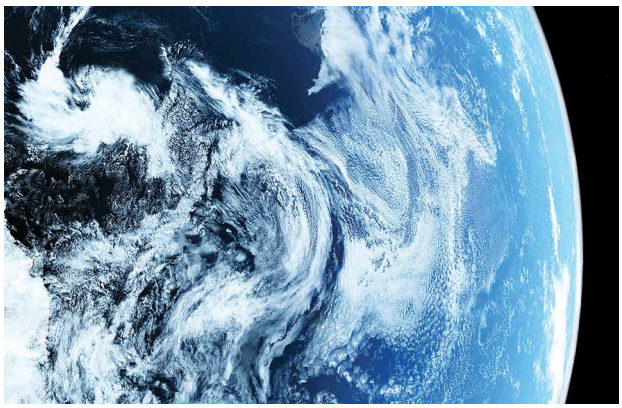
Ice Nucleation – What Causes It?

The formation of ice crystals in air is known as ice nucleation. At high altitudes, ice nucleation can occur either upon a surface such as a particle of aircraft soot, or through the freezing of haze particles. Scientists refer to these events as heterogeneous or homogeneous nucleation. For ice crystals to form in a homogeneous way (i.e. from a haze), the air has to be highly concentrated, or super saturated, with water. As Dr Penner explains: ‘Heterogeneous nucleation takes place when a solid particle “seeds” the freezing of water. Homogeneous nucleation takes place when liquid haze particles freeze. The latter process requires a much higher supersaturation than the former.’

It turns out that previous models of high cloud formation did not take into consideration the effect of solid particles on ice nucleation, and it was generally accepted that haze particles dominated ice crystal formation. Also, little was known about the moisture content and characteristics in general of the upper troposphere – the layer (7–20 kilometres) of the atmosphere where most cirrus clouds form.

‘When I first got into modelling of cirrus clouds, the formation of ice crystals in models was not physically based, i.e. it did not depend on aerosol particles and their characteristics, and supersaturation in the upper troposphere was poorly observed, and not included in models at all,’ says Dr Penner. ‘We had to add this feature, and make assumptions about which aerosol particles acted as heterogeneous ice nuclei.’

In a 2014 study, Dr Penner and her colleague Dr Cheng Zhou used models to predict whether aircraft soot was indirectly causing



a warming (positive) or cooling (negative) effect on the global climate. They assumed that aircraft-emitted particles such as soot could act as seeds for ice formation, or so-called heterogeneous ice nuclei, if previously incorporated within contrails. If that were the case, ice would form on these particles first and presumably remove water vapour from the high-altitude air. In turn, this should prevent homogeneous nucleation that produces more abundant ice particles, thereby causing lower ice number concentrations.

They already knew from previous studies, however, that the amount of ice nucleation on aviation-emitted particles depended on many factors, such as the size and temperature of particles and even the type of fuel used by the aircraft. Also, studies using global climate models were demonstrating varying degrees of uncertainty, depending on what type of particles were present in the background atmosphere.

To keep the variables constant, Drs Zhou and Penner assumed that aircraft soot would freeze heterogeneously after being incorporated into a contrail. They used both established and in-house models to then adjust other variables such as the number of haze droplets and background dust that act as homogeneous and heterogeneous nuclei. Their aim was to estimate how sensitive climate change, or forcing, was to aircraft soot.

They combined a model known as the Community Atmosphere Model version 5.2 (CAM5) with the University of Michigan's IMPACT aerosol model. The IMPACT model developed by them simulates up to 16 different aerosol mixes, allowing them to tweak variables such as fossil soot type, amount of sulphate on the soot or even dust size. They were able to test how the climate would react to aircraft soot acting as heterogeneous ice nuclei.

It turns out that simulations showed different results, depending on the nature of the existing background atmosphere. In some atmospheres, ice formation is dominated by homogeneous nucleation, i.e. ice mainly forms in haze and not on surfaces of dust or other particles. These types of atmospheres are observed in the tropical Indian Ocean, Central America and the North Atlantic Ocean. In these regions, the model showed that aircraft-emitted particles acting as heterogeneous nuclei actually *reduces* the number concentration of ice crystals, causing less trapping of heat and thereby more cooling.

On the other hand, in regions with atmosphere backgrounds that had predominantly heterogeneous ice nucleation – such as regions found over Africa and the Middle East to Central Asia – the net effect was positive (warming). The model showed that aircraft soot *increases* ice formation and subsequent ice crystal number concentrations.

In 2015, Dr Penner and her colleagues from the University of Michigan teamed with Dr Ulrich Schumann from the Institut für Physik der Atmosphäre in Germany to look at other effects that contrails might be having in the troposphere. They used a similar model combination (CAM3+-IMPACT) that allowed them to study the exchange of water between contrails and ambient air. This allowed them to study the changes in the atmosphere, including cloudiness and hydrological cycle, over a 30-year period.

Their modelling demonstrated, among other things, that the amount of water found in contrails was much greater than the amount of water emitted from the aircraft. Therefore, the contrails freeze up much of the water around them and effectively dehydrate the ambient air. Eventually, the ice falls to lower levels and sublimates. Because dehydration reduces the amount of liquid and ice, cloud cover is also reduced. The entire hydrological system is affected.

Both the 2014 and 2015 studies illustrate the puzzle of predicting net cooling or warming effects of man-made activity like contrails on the earth. As Dr Penner highlights: 'Once ice crystals start to form, supersaturation will be lowered as water vapour deposits on the crystals. So adding a small number of heterogeneous ice nuclei to a parcel can cause supersaturation to remain too small for homogeneous ice crystal formation to take place. So the addition of heterogeneous ice nuclei can actually lower ice number concentrations. This is the opposite of what takes place when warm clouds form, and can cause a net cooling. Therefore, it is critical to find out how many homogeneous and heterogeneous ice nuclei are present in the atmosphere and how these numbers have changed.'

Gravity Waves are the Future

Dr Penner's research has shown ways in which aviation activity – such as aerosol particles and dehydrating contrails – can impact ice and cloud formation in the upper troposphere. Now her team is turning to investigate what other factors could be at play. 'We are still working on that aspect, but have also expanded to trying to understand in detail the influence of gravity waves on ice crystal formation,' she tells us.

Gravity waves are the focus of Dr Penner's future research. Gravity waves cause the upward and downward movement of air, which can affect how water vapour behaves. 'In addition to the general effect of aerosol particles on ice number concentrations, the rates at which ice crystals form and the number that form depend on vertical movement in the upper troposphere. Fast upward movement, carries water vapour upward, and cools the air, thereby forming higher supersaturations, while slower movement allows the water vapour to more readily deposit onto crystals,' explains Dr Penner.

In a recent study, Dr Cheng Zhou and Dr Penner and colleagues from the University of Wyoming and Nanjing University in China were able to use updraft velocity models to explain how the upper troposphere had such low concentrations of ice crystals. Low updraft velocities were consistent with low ice number concentrations because of the speed in which water vapour rose and cooled. 'Treating this process within a global model requires treating a spectrum of gravity waves (gravity waves carry parcels both upward and downward at different speeds). This is one aspect we are still working to implement in our model,' says Dr Penner.

Meet the researcher

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Dr Joyce Penner is the Ralph J. Cicerone Distinguished University Professor of Atmospheric Science at the University of Michigan, where she is also Associate Chair of the Department of Climate and Spaces Sciences and Engineering. Dr Penner received her MSc in 1972 and PhD in 1977 in Applied Mathematics from Harvard University. She has served on many committees related to atmospheric science and climate change, including the NRC Committee on Earth Science and Applications from Space, which oversees NASA's program on earth science. She has been the lead editor and author for several reports relating to aviation, aerosols and the global atmosphere for the Intergovernmental Panel on Climate Change (IPCC). She teaches and advises several undergraduates and graduates in earth science modelling and atmosphere sciences.

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UNIVERSITY OF MICHIGAN

THE POLAR VORTEX: MESHING AND STRIPPING THE GEARS OF THE ATMOSPHERE

Earth's atmosphere is composed of multiple interlocked rotating parcels of air. At the poles, rotating vortices form an important part of this system. Climate scientist **Professor Darryn Waugh** of Johns Hopkins University investigates how polar vortices interact with the rest of the atmosphere, and the ways in which they can impact our weather.

Understanding Polar Vortices

Until recently, most people had never heard of polar vortices. It was only during the extremely cold winter of 2014 that the term became popular in the United States media. Now when you hear it mentioned in the news, the *polar vortex* is often shorthand for 'bad winter weather', which is quite misleading. One researcher seeking to better understand polar vortices and to reduce misconceptions surrounding them is Professor Darryn Waugh, of Johns Hopkins University in Maryland.

The term polar vortex is commonly used to describe the circumpolar vortices that cause severe or unusual weather at high latitudes. However, circumpolar vortices can have many different characteristics and influences on the weather. Also, far from being unusual or rare, they are actually a fairly common feature of the Earth's atmosphere, and occur on other planets. When extreme cold events occur, this is not because of the existence of a polar vortex (which was always there) but rather because the edge of the vortex has shifted or a piece has been stripped off and moved south.

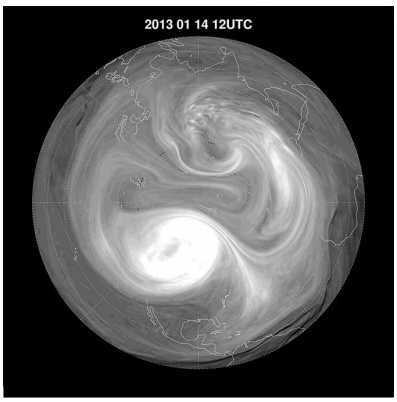
Polar vortices occur in two layers of the atmosphere: the troposphere (the lowest layer, up to 5 miles high at the poles) and the stratosphere (up to 30 miles high). In both cases, they refer to the flow of air from west to east, circling the pole. These two types of polar vortex occur separately from one another, and occupy different latitudes as well as height ranges.

The stratospheric polar vortex is a seasonal feature of the polar atmosphere, forming in late autumn and disappearing in spring. However, the tropospheric polar vortex exists all year round, and occurs at lower latitudes in addition to being lower in the Earth's atmosphere.

So what causes them, and what keeps them going once they have started? Polar vortices form when a strong temperature gradient forms between low and high latitudes. This happens particularly in winter when the pole gets much less sunlight than areas closer to the equator. The temperature gradient and the Coriolis Force, caused by the Earth's rotation, produces the prevailing 'westerlies' in the mid-latitudes, which are stronger in winter because of the stronger temperature gradients. At the North Pole, greater variability in land and sea surface temperatures and elevations result in more waves propagating into the stratosphere, and a weaker and less stable stratospheric polar vortex than at the South Pole.

Vortex Stripping

In characterising polar vortices, the concept of 'vorticity' is important. This is a measure of the rate of rotation of air parcels. Another important term is stratification, which occurs when layers of stable air form, mixing less than in unstratified air. Both of these terms are used in the determination of Potential Vorticity – a similar concept to angular momentum which can be used to describe how a polar vortex behaves. A polar vortex is usually defined as a region of high Potential Vorticity (PV), where the air is rotating as a parcel and is relatively highly stratified.



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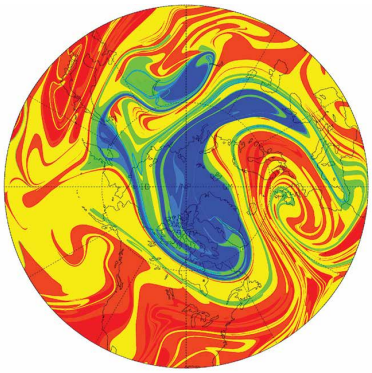
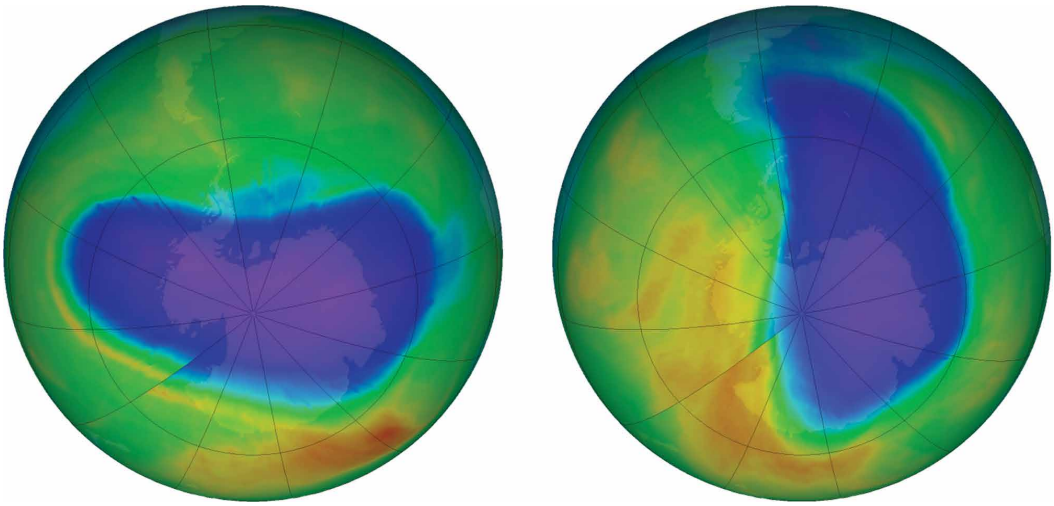


Professor Waugh and his colleagues examined the 'surf zone' at the edge of stratospheric polar vortices, where a steep gradient exists in the PV and acts as a barrier to mixing. Using a simulation that considers the atmosphere to be a shallow layer of fluid

CREDIT: NASA OZONEWATCH



on the surface of a sphere, they were able to describe the dynamics of this system. This enabled them to investigate the effects of surface elevation (mountain chains and high-altitude zones such as Tibet), solar radiation and the Earth's rotation on polar vortices.

In particular, Professor Waugh's simulations allowed him to examine the characteristics of Rossby waves – north-south meanders in the polar vortex caused by variations in topography, oceanic heating and other factors. When these Rossby waves 'break', they can result in vortex stripping, where a long filament of air separates from the main body of the vortex, moves south and mixes with the warmer air.

The team showed a strong agreement between their observations and simulations of vortex stripping, and published their findings in the *Journal of Geophysical Research* in 1994. In this work, the simulations were matched with NASA high-altitude observation flights, where stripped vortex filaments were found. These filaments were detected using equipment that measured temperature variations and the concentrations of multiple chemical 'tracers' occurring naturally in the atmosphere. These tracer compounds are present in different concentrations inside and outside polar vortex air, and provide a signature of vortex filaments.

Polar Vortices and the Climate

The stratospheric polar vortex exerts an important influence on the Earth's climate. One of the most obvious effects is ozone depletion. This is caused by chemical destruction by chlorine and bromine from CFCs and other manmade compounds. Polar ozone depletion is linked to chemical reactions taking place within polar stratospheric clouds, which occur in the stratosphere when the temperature drops below a threshold value. This effect is particularly strong in the southern hemisphere, where the polar vortex is colder and more stable than northern counterpart. The lower temperatures lead to more chemical destruction while a stable polar vortex means that ozone-depleted air is not dispersed into middle latitudes. 'The formation of the ozone hole leads to an even colder, stronger polar vortex,' Professor Waugh explains. This happens because ozone absorbs ultraviolet radiation and warms the stratosphere, so less ozone means lower temperatures, strengthening the vortex and further driving the creation of polar stratospheric clouds.

As modelling of climate change predicts warming in the lower atmosphere but cooling in the stratosphere, there is a further risk of more polar stratospheric clouds forming and a resulting increase in ozone depletion – just as our reduced use of ozone-depleting chemicals seems to be recovering stratospheric ozone levels.

In work published in 2011 in the *Journal of Climate*, Professor Waugh and his colleagues demonstrated that the Antarctic ozone hole has a much stronger influence on tropospheric (lower-atmosphere) circulation in the southern hemisphere than greenhouse gases. This highlights a strong link between the southern polar vortex and weather patterns throughout the southern hemisphere.

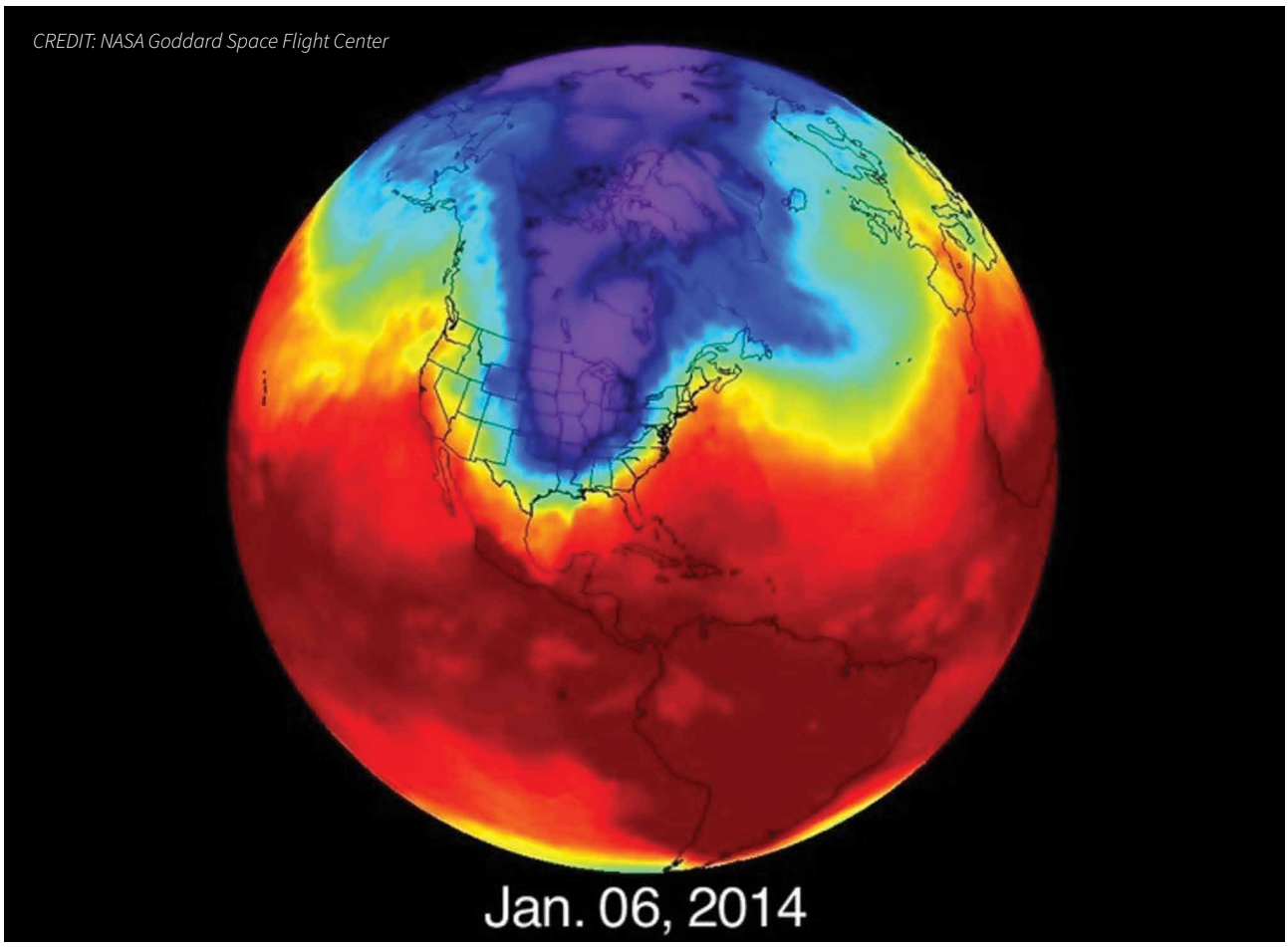
In the north, one of the most noticeable features of the Arctic weather is the sudden warming or cooling that can take place. These sudden changes in temperature are strongly related to the Arctic polar vortex structure. Recent work by the team has identified links between upper-atmosphere polar vortices and lower-atmosphere activity such as this sudden warming and cooling, and also to atmospheric activity further from the poles.

These links have a range of time scales, from weeks to years, and the processes behind them are still relatively unknown. Professor Waugh is continuing to work on a number of problems relating to stratosphere-troposphere coupling, including the effects of polar vortices on surface weather and ocean circulation. His team is also continuing to make progress on understanding the behaviour and movement of polar vortices, and the complex relationships that exist between vortices and stratospheric ozone.

This research into large-scale atmospheric dynamics provides an important connection between greenhouse gas warming of the Earth's atmosphere and the effects of this warming on the weather at a specific place and time. While climate scientists are always cautious in stating that climate change is the cause behind any one extreme weather event, research like Professor Waugh's is giving us a clearer idea of what weather events are driven by human-induced climate change.

Martian Polar Vortices: Undeniable Differences, Significant Similarities

Polar vortices also form in other planetary



CREDIT: NASA Goddard Space Flight Center

atmospheres, through similar processes as those on Earth. Professor Waugh and his colleagues have studied their formation in the winter hemisphere of Mars, where instead of an increase in the potential vorticity (PV) towards the pole as is seen on Earth, the maximum PV values are seen in a ring around the pole. In 2016, the team published an article in the *Journal of Geophysical Research* detailing similarities between the Martian polar vortex and the Earth's tropospheric polar vortex, which forms an approximate annulus shape.

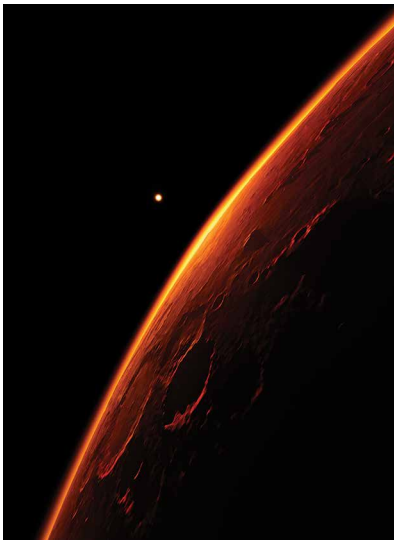
Professor Waugh and his team set out to thoroughly investigate the reasons behind this differently-shaped polar vortex on Mars. Using a simulation of the Martian atmosphere, they showed a connection with the existence of the Martian CO_2 polar icecaps. These icecaps form when the temperature drops sufficiently for carbon dioxide to condense out of the air and form a solid. When a substance freezes, it releases what's known as the latent energy of condensation. This energy is given out because the molecules have transformed into a more stable configuration, thus releasing much of their kinetic energy. In the case of Mars' atmosphere, where approximately one-quarter of the atmosphere freezes out during the winter, this is sufficient to weaken the potential vorticity directly over the pole, resulting in maximum PV values in an annulus surrounding the pole but not directly over it.

Even with the presence of a CO_2 polar icecap to explain the formation of an annular polar vortex, this feature should not persist due to natural instabilities. However, Professor Waugh's team has shown that a combination of the relatively flat topography and the rapidly-cooling Martian atmosphere explains the relative stability of the Martian polar vortex. This work is to be published in the *Journal of Atmospheric Science* in 2017.

Looking Deeper into the Vortex

The team's future plans include investigating the effects of polar vortices on the Earth's weather systems and on extreme weather events. He also intends to investigate Martian polar vortices and the ways in which trace atmospheric components such as dust and water vapour are transported into and out of that planet's distinctive polar vortex system.

They also plan to look at polar vortices on



Titan, one of Saturn's moons. 'There are polar vortices in Titan's stratosphere, and there are questions – similar to those for Earth and Mars – regarding the structure and seasonal evolution of these vortices and their impact on trace gases,' Professor Waugh explains. The formation, structure and behaviour of Titan's vortices under conditions very different to those on Earth may reveal new insights into fundamental vortex processes.

Meet the researcher

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After obtaining a BSc in Mathematics at the University of Waikato in New Zealand in 1986, Professor Darryn Waugh went on to receive his MSc at Waikato in Mathematics in 1988. He was then awarded his PhD at the University of Cambridge in the UK in 1992, after which he pursued postdoctoral work at MIT in the USA and Monash University in Australia. Since 1998, he has worked at Johns Hopkins University, where he became Professor at the Department of Earth and Planetary Sciences in 2004. Professor Waugh has received three Group Achievement Awards from NASA for projects he has been involved in. He also received the Francois N Frenkiel award for Fluid Mechanics for a 1993 paper and the Stanley Jackson Award from the South African Society of Atmospheric Sciences in 2012.

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JOHNS HOPKINS
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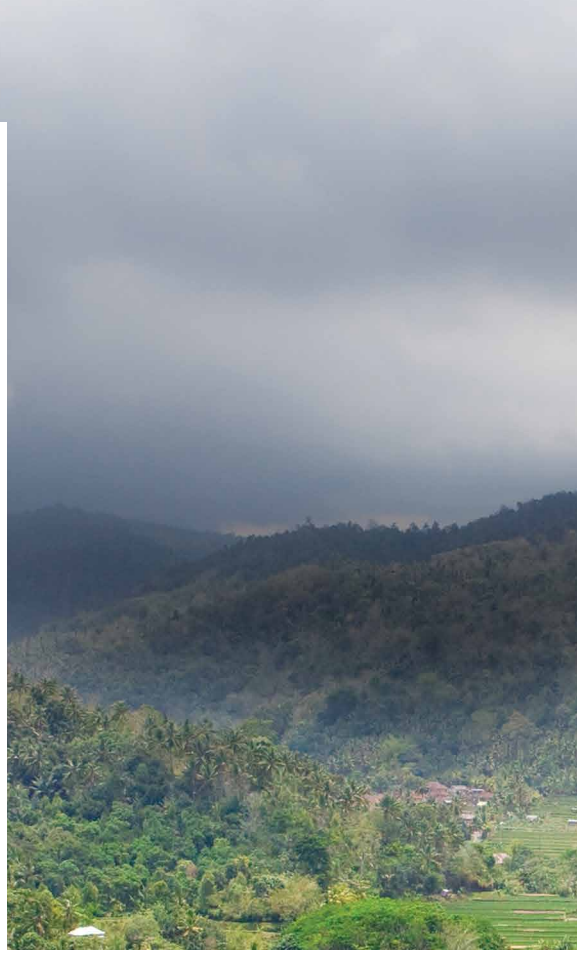
DOES CLIMATE AFFECT THE WORLD'S VEGETATION – OR IS IT THE OTHER WAY AROUND?

Climate scientist, **Dr Michael Notaro,** and his colleagues at the Nelson Institute Center for Climatic Research, University of Wisconsin–Madison, study climate variability and change, including how the weather, including monsoons, can be influenced by variations in vegetation in a given region of the world.



You've heard the slogan made popular by the World Wildlife Federation: 'Plant a tree, save a planet.' Or perhaps it's the conservationists' slogan, 'Plant a tree, save a life'. Whatever the phrase, it's clear that the benefits attributed to vegetation are multiple and well known. Trees absorb carbon dioxide and release oxygen; trees absorb groundwater and release moisture into the atmosphere; trees absorb impurities – or pollution – from the air; trees provide shelter for birds and other animals; trees provide raw materials for human civilisation. In short, trees are miraculous creations in nature that we should save, preserve and cherish for our benefit and the benefit of our planet.

However, some individuals and groups are concerned that climate change, or various extreme weather events that occur as natural variability in the Earth system, are causing adverse conditions that negatively affect the Earth's vegetation. After all, the poor trees are sitting there innocently saving humanity while being set upon by storms, tornadoes, and tropical cyclones that damage them and cause disruption to their beneficial activities. But is this image correct? Are trees simply innocent 'victims' of climate change? Or do trees and other vegetation actually, in a sense, fight back? Scientists like Dr Michael Notaro are intensely interested in the latter picture – the power vegetation has to modify the climate around it, even to the point of affecting such massive meteorological phenomena as monsoons. Rather than passively allowing weather to push it around, our planet's vegetation actually participates in the production of the climate that we experience.

Studying the Interaction Between Land and Climate

Vegetation generally can influence the climate in a number of ways. Vegetation can directly influence the climate through biophysical feedbacks via the momentum, energy, and moisture transfer that vegetation has with the atmosphere. Vegetation generally has greater roughness than the ground, thereby reducing wind speeds, increasing low-level atmospheric convergence of winds, supporting rising atmospheric motion, and therefore favoring more precipitation. Plants have a lower albedo (the amount of sunlight reflected by a surface) than dry desert soil or snow cover, so they can absorb more solar radiation, but the excess heat is at least partly offset by evaporative cooling from transpiration. Plants transpire soil moisture into the atmosphere, perhaps enhancing atmospheric moisture and rainfall. Plants basically control the 'micro-climate' around their leaves by absorption and release of heat and moisture. Furthermore, vegetation can indirectly affect the climate through biogeochemical processes that alter the atmospheric carbon dioxide concentration. Greater vegetation cover allows for more absorption of carbon dioxide, used for photosynthesis. This results in a lower concentration of carbon dioxide in the atmosphere, and thus, a reduction in the greenhouse effect. But until now, most studies on biophysical vegetation feedback have been restricted to running and analysing computer model simulations based on theoretical considerations. This doesn't satisfy Dr Notaro, however.

‘In the real world, it is not feasible to perform large-scale vegetation perturbation experiments to dynamically assess feedbacks to the atmosphere, so a statistical method is necessary’

Since theoretical inputs that researchers feed into a climate model vary, climate computer models can differ dramatically in terms of simulated land-atmosphere interactions. In an article published a few years ago in the journal *Climate Dynamics*, Dr Notaro explained that many model experiments are based on radical baseline assumptions – such as total destruction of a massive forest, versus a more real-life scenario of patchy or partial deforestation. Very few studies have attempted to actually validate simulated vegetation feedback against actual vegetation and climate observations and give credibility to the model findings. For this reason and others, land-atmosphere interactions have been great sources of uncertainty in climate scenarios and simulations.

Generally speaking, the atmosphere’s effects on vegetation are stronger than vegetation’s effects on the atmosphere. This makes it quite challenging to extract the influence of vegetation fluctuations on atmospheric conditions using observational data. Furthermore, regional climate is affected by variability in both the ocean and vegetation, making it difficult to clearly separate their individual roles. ‘In the real world, it is not feasible to perform large-scale vegetation perturbation experiments to dynamically assess feedbacks to the atmosphere, so a statistical method is necessary,’ Dr Notaro tells Scientia. In other words, you can’t destroy a large forest – or magically produce one where it didn’t exist before – to obtain data to verify your computer model. But new techniques have arisen to help the situation.

Evaluating Models with Actual Physical Data

Climate scientists recently developed a multivariate statistical method, known as the Generalized Equilibrium Feedback Assessment (GEFA), and began using it for quantifying local and non-local feedbacks from a slowly-changing variable that can actually be measured in the climate system, such as sea-surface temperatures (SSTs) or leaf area index (LAI), to the atmosphere. Statistical estimates of oceanic and vegetation effects on the atmosphere across North America have already been validated dynamically with an ensemble of experiments in a fully coupled global climate model (GCM), that shows the reliability of this statistical approach. Since then, GEFA has been applied to observational and remote-sensing data to separate the influences of individual oceanic and terrestrial effects on the atmosphere and to establish an observed benchmark against which models can be evaluated. Now models can be tested against measured variables to make sure the model is correctly designed and trustworthy for climate change projections. What Dr Notaro and his group were interested in, among other things, were monsoons.

In a report published in the *Journal of Climate,* Dr Notaro and his research group explored the way vegetation interacts with monsoons in different areas around the world, from China to Australia to the U.S. Southwest and Northern Mexico. They looked at vegetation’s effects on climate, on a sub-annual time scale, across six separate monsoon regions.

He and his colleagues used a fully coupled atmosphere–ocean–ice–land computer model that allows the atmosphere to interact with dynamic vegetation changes. They ran their initial calculations where the total vegetation cover fraction across the six global monsoon regions was reduced and the climatic response was assessed. Responses among the regions that were consistent included reductions in LAI, moisture and heat fluxes from the land to the atmosphere, and atmospheric moisture; enhanced atmospheric subsidence; and increases in ground and surface air temperature. The most distinct changes in vertical motion, precipitable water, and precipitation occurred along the edges of the monsoon season, with small changes in mid-monsoon rainfall. Unique responses to lower levels of vegetation cover were noted among the monsoon regions and some surprising results jumped out at the scientists. While the monsoon is delayed and weaker over northern Australia owing to diminished leaf area, it actually occurs earlier over China. The study suggested that the subtropical monsoon regions – cooler areas further from the equator – are characterised by a larger response in sensible heat than latent heat flux, while the opposite is true for tropical monsoon regions closer to the equator. Sensible heat describes the heat that's absorbed or released by any substance while it changes temperature, while latent heat is the heat absorbed or released by a substance changing phase, e.g. solid to liquid or liquid to gas. Northern Australia experienced the most substantial decline in both moisture flux convergence – the concentration of moisture that precedes convection events like thunderstorms – and precipitation in response to reduced vegetation abundance.

What We Do to Our Vegetation Affects Our Climate

Dr Notaro concludes from this research that vegetation dynamics are most definitely important elements of the climate system, in particular over northern Australia. He agrees that climate models need to include better representations of observed vegetation and to be evaluated in terms of their simulated land-atmosphere interactions compared to observations. It is apparent that heat stress could reduce vegetation cover in certain regions, which could enhance surface warming. In the case of northern Australia, drought events can lead to loss of vegetation, which could amplify the drought intensity through positive vegetation–precipitation feedbacks. Ongoing farming practices in China and India and grazing in North America and northern Australia likely reduce the total leaf area and could lead to surface heating and a dampened water cycle. He and his colleagues are closing in on some of the specific answers to this phenomenon.

Dr Notaro investigated the hypothesis that subtropical and tropical monsoon regions showed unique responses to vegetation anomalies. He and his co-workers used a coarse global climate model, the Community Climate System Model (CCSM), and saw that reduced vegetation cover led to an earlier subtropical Chinese monsoon and delayed, weaker tropical Australian monsoon. However, significant climate and LAI biases in the coarse global climate model clouded the reliability of these findings. To fix this problem, the team used observed boundary conditions and applied them across China and Australia in the high-resolution Regional Climate Model Version Four (RegCM4). The model matched the observed dominance of crops, grass, and evergreen trees in southern China and grass and shrubs in northern Australia.

The team then ran a regional climate model for the period of 1960 to

2013. The Australian and Chinese monsoon regions' LAI was modified in such a way as to look at contrasting vegetation effects between tropical and subtropical regions. He found that a greater leaf area supports reductions in albedo, air temperature, wind speed, atmospheric boundary layer height, and ascending motion and increases in diurnal temperature range, wind stress, evapotranspiration, and specific humidity. This leads to enhanced rainfall during Australia's pre-mid monsoon season, but this was not found to be the case for China. Modified leaf area was found to cause dramatic changes in the temporal distribution and intensity of Australian rainfall events. Enhanced North Australian LAI supports a reduction in the frequency of dry periods, a greater frequency of drizzle or light-moderate rainfall periods, and decline in occurrence of extremely wet periods. In other words, the increase in LAI in northern Australia spreads the rainfall out over time so there are fewer dry spells and fewer heavy rain intervals. Inconsistencies between China's monsoon response in RegCM4 and the one that Dr Notaro published a few years ago using CCSM are attributed to CCSM's excessive forest cover and leaf area, exaggerated roughness mechanism, and deficient evaporation and transpiration response. Basically, that model ignored crops, so China was unrealistically represented as being covered with trees. Essentially though, the more forest you have, the greater effect you can have on even a significant climate phenomenon such as a monsoon. The implications are pretty impressive. Certainly, Dr Notaro aims to continue this line of investigation. But it's more than just scientific curiosity that motivates him.

Why is All of This Important?

The timing and intensity of the summer monsoons has critical effects on, for example, the flooding in the Yangtze River Basin of China, drought in northern China and associated Yellow River flow and crop production both in China and Australia. It can also affect grazing stock and cattle productivity in Australia, along with the duration of fire-season across the Australian savannahs. A better understanding of the monsoon's controls could help with seasonal predictions and agricultural planning. Moreover, validation of the computer model applied by Dr Notaro over the tropical Australian monsoon and subtropical Chinese monsoon will allow its successful application to other regions. This will potentially lead to the development of powerful climate prediction tools that can save lives and money. And perhaps we can try to plant appropriate trees and vegetation to actually help make a difference.

Meet the researcher

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Dr Michael Notaro received his PhD from the State University of New York at Albany in 2002, with a dissertation entitled 'Model and observational analysis of the Northeast's regional winter climate and its relationship to the PNA pattern'. He then joined the Center for Climatic Research at the University of Wisconsin–Madison as a Research Associate, where he is now a Senior Scientist and Associate Director of the Nelson Institute Center for Climatic Research. Dr Notaro's research interests include the interactions between land, ocean and atmosphere; the impact of climate change on ecosystems; dynamical downscaling; the hydrology of the Great Lakes Basin; the study of lake-effect snow; monsoon dynamics; and mechanisms of dust storms in the Middle East. He has authored and co-authored 65 articles published in peer-reviewed journals and has given 115 oral presentations in the field of atmospheric science.

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INTERPRETING ANCIENT SHORELINES

One way to understand Earth's climate is to study past changes in sea level, which leave tell-tale signatures in the geological record. Scientists often look at ancient shorelines to infer how Earth's oceans and ice sheets responded to previous climates. Geologist **Dr Ken Ferrier** has found evidence that rivers carrying vast amounts of sediment may have deformed these geological features and altered sea level near them. This implies that using paleoshorelines to infer the sensitivity of sea level to climate change requires accounting for the action of rivers.

Understanding Ice and Sediment Loading

Scientists agree that mean global sea level is rising. Measurements over the last century indicate that air and ocean temperatures are rising and ice caps and glaciers are shrinking as atmospheric carbon dioxide is increasing. The addition of new water into the ocean, along with the expansion of the seawater as it warms, have led to a rise of mean global sea level that has accelerated to more than 3 mm per year in the past two decades.

Most of the present-day rise in sea level is driven by recent increases in temperature. A portion of the changes in sea level, however, is driven by ongoing responses to things that happened thousands of years ago. The classic example of this is the most recent ice age, in which ice sheets reached their maximum extent about 26,000 years ago before gradually retreating to their current state. As they melted, their enormous weight vanished, and the parts of Earth's crust that had been pushed down under the ice sheets began to rise up. This so-called crustal uplift continues today, and is highly variable from place to place. The most dramatic uplift is found in places that were once covered by the thickest ice sheets, like Hudson Bay and Scandinavia, but it has also been observed in the European Alps. There, scientists have conjectured that the 1–2 mm annual growth in elevation is mostly due to land 'rebounding' from the weight of former ice masses.

Evidence of this process, known as glacial isostasy, is seen around the world. Sometimes, the effect of the weight of ice is so large that it causes sea level to change over a relatively short geological time period. An example of this is found in the eastern United States, where ancient ice cover is thought to have shifted the so-called paleo-sea level by as much as 20 metres.

Distortions such as these thwart scientists who look for climate clues in ancient seashores. They often use these paleoshorelines to estimate the amount of ice and ocean that covered the earth at various points in the past. Some scientists like Dr Ken Ferrier, however, don't think that ice is the only phenomena moving paleoshorelines around. He wonders if huge sediment loads being carried by rivers into the ocean are also involved.

Already, Dr Ferrier and his team, the Surface Processes Group at the Georgia Institute of Technology in Atlanta, have demonstrated that sediments carried by water into the ocean can perturb sea level just like large ice masses do. The team has found that erosion and deposition of sediment, which are especially rapid near large rivers, have been significant enough to deform and change paleo-sea-level markers near large rivers.

'In many places, local sea-level changes are strongly influenced by sediment that is transferred from continents to the ocean. In Earth's largest rivers, the Amazon and the Ganges-Brahmaputra, sediment fluxes exceed 1 billion tons per year. These fluxes are so large that they perturb sea level,' claims Dr Ferrier.

Indus River – Arabian Sea

One of Dr Ferrier's studies that support this claim involves the modelling of the Indus River. The Indus originates in the Himalayas and flows into the Arabian Sea, and has a large delta at its mouth. The Indus is notable for its length (3,200 kilometres) and the amount of water it discharges (approximately 243 cubic kilometres a year), but what really makes it stand out is the amount of sediment it carries. Before massive dams built in the 20th century trapped most of the sediment in reservoirs, the Indus River moved some 250 million tons of stones, sand and silt into the ocean per year, making it one of the top ten sediment-producing rivers in the world.

This feature of the Indus – referred to as fluvial sediment load – is the prime reason that Dr Ferrier and his colleagues chose it for their modelling study. If sediment loading was indeed capable of influencing sea level, they'd be sure to see it there.

In their study, they set out to construct a history of sediment loading between the present and 120,000 years ago, when Earth's most recent glacial cycle began. The team reckoned that this amount of time is also long enough for Earth's thick crust and viscoelastic mantle to respond to weighty sediment loads.

They used a 'gravitationally self-consistent global model', which assumes that Earth is symmetrical, rotating, and has a viscoelastic mantle under an elastic lithosphere, and which accounts for changes in Earth's gravity field as water moves across the Earth's surface. Changes in ice loading as well as sediment loading for the last 120,000 years were incorporated into the model. Using a widely-used reconstruction of global ice history and distribution, known as ICE-5G, the team could input changes in ice mass. For sediment loading, however, they themselves pieced together a history from published data on erosion and deposition rates, including data from sediment cores.

In their 2015 publication in *Earth and Planetary Science Letters,* Dr Ferrier and his colleagues conclude that the Indus River produced such large sediment fluxes that they were capable of changing sea level near its delta. They explain that the dominant way that sediment induces sea-level rise is through subsidence of the ocean floor.

‘Understanding how sea level will change in the future requires quantifying how much present-day sea-level changes are affected by ongoing responses to ice and sediment loading in the past’

The group also found that sediment produces different sea-level ‘signals’ compared with those of ice sheets. Over the past few million years, as Earth’s ice sheets have cyclically grown and shrunk, sea level has responded by oscillating up and down dozens of times. By contrast, sea-level responses to sediment loading have continued growing larger over time, because the sediment redistribution is largely a one-way street – sediment moves from the continents to the oceans, but rarely in reverse. At the Indus delta, the team estimate that the gradually growing sediment loads may have caused sea level to rise by as much as 30 metres in the last 120,000 years.

According to Dr Ferrier, scientists using paleoshorelines to estimate global ice volumes in the past have to correct for this effect of sediment loading in places with large sediment fluxes. Otherwise, they could misinterpret the sensitivity of sea level to changes in climate, especially in sites near large rivers such as the Indus.

Three-Million-Year-Old Shorelines

Dr Ferrier’s Indus models demonstrated that in over a relatively short period of 120,000 years, sediment loads significantly perturbed sea level around the Indus delta. Now his team is taking a bigger step back in time – to approximately 3 million years ago – to a period known as the Mid-Pliocene Climate Optimum (MPCO).

Scientists view this period as relevant to today’s climate for many reasons. For one, it is the most recent time in Earth’s history with atmospheric carbon dioxide concentrations as high as those Earth is projected to experience soon, which suggests that its climate may be similar to the climate Earth may soon have. Estimates of mean global sea level during the Mid-Pliocene Optimum range from 10 to 40 metres higher than they are today, which imply a wide range of possibilities for what’s ahead for modern civilisation. Finally, the planet’s continents and oceans were arranged around the planet much like they are today.

As such, the Mid-Pliocene Optimum is ideal for understanding rising sea level in the future. ‘One way to predict sea-level changes is to look forward in time and use numerical models that predict sea-level changes in the future,’ says Dr Ferrier. ‘Another way is to look into the past and examine the geologic record of past sea-level at moments that had climates similar to those we are about to experience.’

To examine sea-levels from the Mid-Pliocene, Dr Ferrier’s team has chosen three ancient shorelines: the Orangeburg Scarp in the eastern United States, the De Hoop plain in South Africa, and the Roe Plain in Australia. These so-called paleoshorelines, which today appear as terraces well above modern sea level, all formed at sea level around the same time.

‘These past sea-level changes are recorded as relatively smooth, planar features that used to be at sea level but no longer are,’ Dr Ferrier explains. ‘These are useful for studying past sea-level changes because, if the time

of their formation is known, they mark sea level at a given location at a given moment in time – in other words, the local paleo-sea level.'

Today, Dr Ferrier's study sites are all found at different elevations, even though they formed at the same time. For example, the remnant shoreline known as the Orangeburg Scarp extends from Florida to northern Virginia. During the MPCO, an ancient ocean would have existed around 100 to 200 kilometres further inland. Over on the tip of South Africa, the De Hoop coastal plain would have been forming around the same time. Today, the Orangeburg Scarp ranges in elevation from 35 to 80 metres while the De Hoop coastal plain doesn't rise above 30 metres. Why the difference?

The answer is that geological forces have warped these paleoshorelines by different amounts over the last 3 million years. Dr Ferrier thinks sediment loading is a major player, but it remains an open question how much the warping of the shorelines is due to sediment and how much is due to other geological processes, like convection of the underlying mantle. In a proposal with Professor Jerry Mitrovica (Harvard University) for the US National Science Foundation, Dr Ferrier builds his case for quantifying this. Previous studies have focused mostly on ice sheets and flow in the earth's mantle, but few on how sediment loads might have twisted and shaped these paleoshorelines.

As with the Indus River in his previous modelling efforts, Dr Ferrier believes this effect can't be ignored, especially when trying to understand ancient oceans and climate. 'We propose to take steps toward closing this knowledge gap by constructing histories of sediment erosion and deposition in the regions around these paleoshorelines, and by modelling the effects that those sediment loading histories had on sea level,' he states.

Paleoshorelines are Key to the Future

Dr Ferrier tells *Scientia* that he enjoys studying this topic because of the environmental challenges posed by future sea-level changes. He strongly believes that to plan for the future you have to look to the past, like he's doing with paleoshorelines.

He says, 'Because sea level changes at different rates in different places, interpreting local sea-level changes based on paleoshorelines requires modelling how the Earth's shape and gravity field have deformed since the time the paleoshorelines formed. That's what our models do. They help us compute how much sea level should have changed everywhere on Earth, which helps us interpret past sea-level changes and in turn helps us predict how sea level is likely to change in the future.'

Dr Ferrier also thinks his sea-level work will improve our understanding of how Earth's topographic features, such as mountains and canyons, are formed and carved over time. 'One of the strongest controls on the evolution of continental topography is changes in sea level, which set the boundary condition for landscape evolution, so that provides further motivation,' he explains. 'To understand how mountain ranges evolve, you need to understand how sea level changes over time too.'

Meet the researcher

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Since 2014, Dr Ken L. Ferrier has been an Assistant Professor at the Georgia Institute of Technology, where he heads up the Surface Processes Group that focuses on the evolution of the Earth's surface and sea level dynamics. After obtaining his AB in Physics at Cornell University in New York in 2000, Ferrier went on to receive a PhD in Earth and Planetary Science at University of California in Berkeley, California, in 2009. From 2010–2012, Dr Ferrier was a postdoctoral associate at MIT in Cambridge, Massachusetts. In 2012, he received a CIFAR (Canadian Institute for Advanced Research) postdoctoral fellowship at Harvard University in Cambridge. He is currently a member of the executive committee of the Earth and Planetary Surface Processes Focus Group in the American Geophysical Union (AGU).

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THE BIRTH AND DEATH OF ICE SHEETS: UNDERSTANDING THE PAST AND PREDICTING THE FUTURE

Drs David Pollard and Rob DeConto have developed computer models that simulate how the world's ice sheets have grown and retreated in response to climatic change over past epochs. Their models are now being used to predict Antarctic ice sheet melt and sea level rise over the next few hundred years.

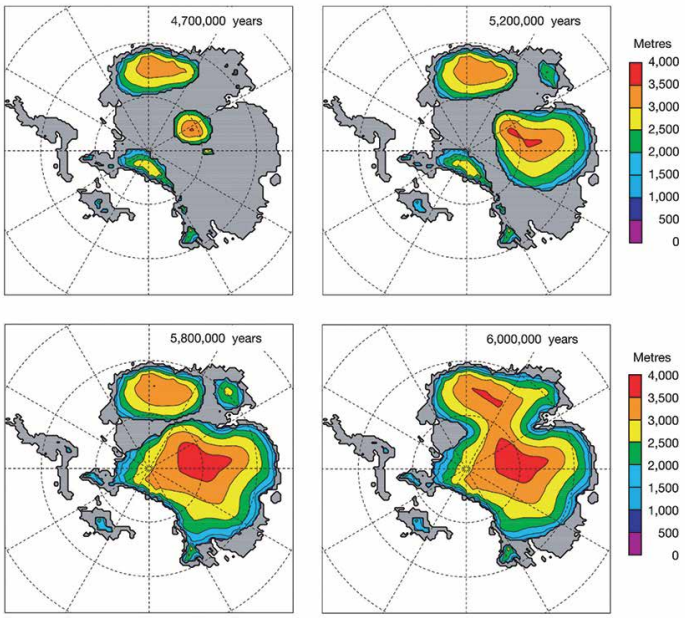
Building Models of Antarctica's Past

The Earth's climatic conditions have changed dramatically over geological time periods, with considerable shifts in global temperatures, atmospheric carbon dioxide (CO_2) and sea levels. These changes caused the formation, and repeated cycles of growth and retreat, of the world's ice sheets. The largest ice sheet on today's Earth, the Antarctic ice sheet, was first created during the cooling climate transition that occurred between the Eocene and Oligocene epochs, around 34 million years ago.

'Ice sheets are huge masses of ice several kilometres thick, today covering Greenland and Antarctica, and in the past, they have repeatedly covered Canada and much of Eurasia,' Dr David Pollard tells Scientia. 'These ice sheets flow slowly under their own weight, and have grown and melted in the past due to climate variations.' He explains his work as: 'testing climate and ice sheet models against the geological data of the past, and applying them to future melting and sea rise in our warming world.'

'From the start, I have liked writing computer code that solves equations describing geophysical variations in the natural world. To me it's like building an actual model, like a model airplane,' says Dr Pollard. 'I originally got into ice sheet and climate modelling in graduate school, after a Woods Hole Oceanographic Institution summer course in 1976, with lectures by leading professors in paleoclimate and ice sheet modelling. I now develop computer codes solving for the slow variations of large ice sheets over hundreds to millions of years.'

'These ice sheets flow slowly under their own weight, and have grown and melted in the past due to climate variations' – Dr Pollard



Ice-surface elevations during the transition from 'Greenhouse' to 'Icehouse' conditions around 34 million years ago, at particular times during a 10 Myr-long simulation. From: RM DeConto and D Pollard, Rapid Cenozoic glaciation of Antarctica induced by declining atmospheric CO_2, Nature, 421, 245–249.

Dr Robert DeConto has a background in geology, as well as climate science and ice-sheet modelling. During his acceptance lecture, on receiving the 'Tinker-Muse Prize for Science and Policy in Antarctica' in 2016, he spoke of the people and events that shaped his worldview. In 2001 he attended his first SCAR (The Scientific Committee on Antarctic Research) meeting and was inspired by scientists from many disciplines and nationalities coming together to study Antarctica. Later he co-founded the SCAR-ACE (Antarctic Climate Evolution) and then the SCAR-PAIS (Past Antarctic Ice Sheet dynamics) programmes. Dr DeConto also spoke about the thrill of being in the field for the first time, and now encourages his students to take any opportunity to visit Antarctica 'to get on the ice and do work.'

In 2003 and 2008, Drs Pollard and DeConto published two papers in the journal Nature describing the results of modelling studies of Antarctic and northern hemisphere ice sheets. The models showed that the most important factor explaining the onset of glaciation was a drop in atmospheric CO_2 concentrations. The long-term goal of these modelling studies is to define threshold values of temperature and CO_2 that trigger the birth and death of ice sheets.

Ice cliff at the marine terminus of Helheim Glacier, East Greenland. Glacier ice flows from the right, terminating at the ocean in a ~700 m cliff, nearly 100 m of which is visible above the water line. To the left of the cliff is a jumble of floating ice pieces called mélange. Structural failure of slightly larger cliffs anticipated around Antarctica is a key component of the model's projected future retreat. CREDIT: Dr Knut Christianson, University of Washington.

Combining Models with Drilling Data

Computer models are at their most powerful when validated by real-world data. In terms of the Antarctic ice sheet, the start of the multinational ANDRILL (ANtarctic geological DRILLing) programme in 2006 was therefore of great importance. The main aim of ANDRILL is to drill down into the sediments surrounding the Antarctic ice sheet, and so back in time, to reveal the scale and frequency of glacial and interglacial change in the Antarctica.

'We wrote an integrated proposal from the start, showing how the modelling and the geological data from ANDRILL wove together,' says Dr DeConto. At the same time, they were improving their ice-sheet model. 'Suddenly we had a way to parameterise the amount of ice going out through the grounding line into the floating ice shelf. This was a big step forward for us.' The grounding line is the point where the ice sheet leaves the land mass and starts to float on the ocean. The models show that declining CO_2 leads firstly to the growth of land ice. If the ice sheet becomes big enough to reach the ocean, this results in the expansion of floating ice shelves and the advance of grounding lines across the ocean floor.

In a 2009 publication in Nature, entitled 'Modelling West Antarctic ice sheet growth and collapse through the past five million years', Drs Pollard and DeConto included coupled ice sheet and ice shelf dynamics in their model for the first time. The repeated surges in glacial extent and occasional collapses in the ice sheet simulated by the model were consistent with the new data from ANDRILL.

Floating ice shelves are important because they hold back and slow down the flow of land ice into the oceans. If the ice shelf is suddenly lost, the ice sheet at the grounding line is exposed and ice loss is accelerated. Although the loss of an ice shelf does not significantly raise sea levels because it is already floating, the ensuing loss of land ice can considerably raise sea levels.

After a series of studies focusing on how an ice-free world changed into one containing extensive ice sheets, the team turned their attention to past global warming events. 'We began the first part, of at least my career, trying to grow the ice sheet, and the next 12 years trying to destroy it with the models,' explains Dr DeConto.

Ice Fracturing and Cliff Failure

Studies of ice retreat in the past have shown that the Antarctic ice sheet is sensitive to climate change. It was a primary contributor to sea level rise, for example, during the relative warmth of the Pliocene epoch (around 3 million years ago) and in the last interglacial period (130,000–115,000 years ago) when the geological record suggests the oceans were 10–30 metres and 6–9 metres higher than present, respectively.

When climate and ice sheet models do not agree with the geological data (e.g. sea level height or isotope data for atmospheric conditions), then refinements are made to the models. A study published in 2015 by Drs Pollard and DeConto, along with their colleague Richard Alley describes the addition of ice retreat mechanisms – hydrofracturing and ice cliff failure – to the Antarctica ice sheet numerical model. This resulted in the model being able to much better simulate high sea-level stands in past epochs characterised by climate conditions warmer than today.

Hydrofracture occurs when pools of meltwater or rain drain through cracks, causing fissures in the ice shelf. This escalates until the floating ice breaks up. The destabilisation and loss of ice shelves in turn leads to ice cliff failure, in which newly-exposed sheer ice cliffs, rising 100 metres or more above the sea surface, become unstable and repeatedly crash down under their own weight. Both processes speed the loss of ice from ice sheets. This type of ice shelf collapse has been observed recently in

both the northern and southern hemispheres due to unusually warm conditions, for example, on Antarctica's Larson B ice shelf in 2002.

In effect, these ice retreat mechanisms enable computer models to take into account the warmer air, caused by high levels of CO_2 and other greenhouses gases in the atmosphere, which accelerates hydrofracture and ice cliff collapse. Previous models had largely focused on the warming of the sea and its effect underneath the floating ice shelf.

Predicting Ice Retreat and Sea Level Rise

Around 65% of the Earth's freshwater is held in the Antarctic ice sheet (equivalent to about 58 metres of sea-level rise). Even a small percentage of ice sheet melt off the land could result in dangerous levels of sea level rise. Previous estimates of sea level rise, for example from the UN Intergovernmental Panel on Climate Change (ICPP), have incorporated only a minimal contribution from the Antarctic ice sheet, but this may have to change.

From their experience of looking at the values for CO_2 and temperature that have triggered ice retreat episodes in the past, Drs Pollard and DeConto are now working out the thresholds for a catastrophic collapse of the Antarctic ice sheet in the future. Their paper, entitled 'Contribution of Antarctica to past and future sea-level rise', in which hydrofracture and ice cliff failure were incorporated into the model, predicted sea level rises well beyond those in reports by the IPCC.

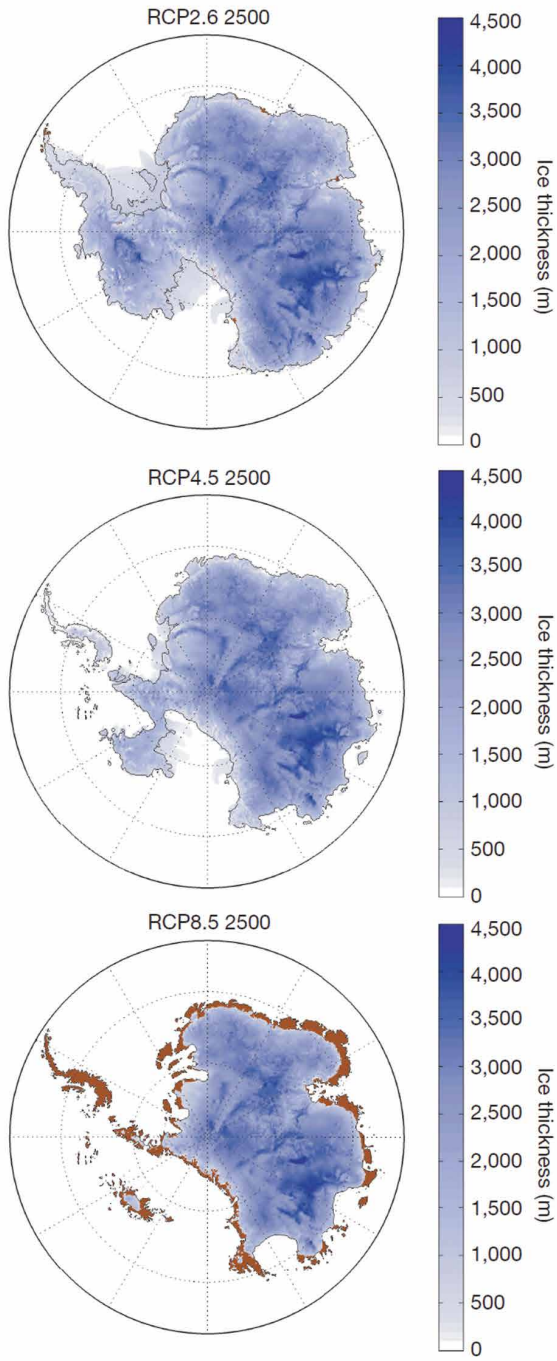
The good news is that if greenhouse gas emissions are reduced quickly enough to limit average global temperature rise to no more than 2°C above pre-industrial levels, then the model shows that there will be little or no sea level rise from Antarctic ice sheet melt. This requires aggressive mitigation strategies (such as the IPCC's RCP 2.6 emissions reduction scenario). However, with a continued and unabated ('business as usual') growth in greenhouse gas emissions, the model predicts that the retreat of the Antarctic ice sheet alone could result in sea level rises of 1 metre by 2100 and more than 15 metres by 2500. Taking into account other factors, such as melting from the Greenland ice sheet and the thermal expansion of seawater, coastal cities could be threatened with sea level rise of up to 2 metres by the end of the century.

The model confirms that over time atmospheric warming becomes the main driver of floating ice sheet loss, rather than the impacts of ocean warming. It also suggests that once started, ice shelf collapse will be essentially irreversible, because ice formation will not be possible until the oceans cool down again, and this could take thousands of years.

'We simulate as much as one metre of sea level rise coming from Antarctica in the course of a century, which is more than other models. This is where we are going: to continue to refine the modelling tools and to try to determine the validity of the results,' says Dr DeConto.

Dr Pollard also has clear ideas where the research is heading: 'We will collaborate with colleagues to produce local sea-rise impact analysis tools using our future Antarctic projections as inputs, develop more physically-based models of drastic ice retreat mechanisms, and apply our ice sheet model to past ice ages in the northern hemisphere.'

'We simulate as much as one metre of sea level rise coming from Antarctica in the course of a century, which is more than other models' – Dr DeConto



Future ice-sheet simulations using a high-resolution atmospheric model and 1° NCAR CCSM4 ocean temperatures. Ice-sheet snapshots at 2500 in the RCP2.6, RCP4.5 and RCP8.5 scenarios. From: RM DeConto and D Pollard, Contribution of Antarctica to past and future sea-level rise, Nature, 2016, 531, 591–597.

Meet the researchers

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Dr David Pollard is a Senior Scientist in the Earth and Environmental Systems Institute at Pennsylvania State University. He obtained a degree in Mathematics from Cambridge University in 1973, and a master's in Aeronautics in 1974 and a PhD in planetary meteorology in 1979 from the California Institute of Technology. Following postdoctoral work at Caltech and Oregon State University in Corvallis, he worked from 1983 to 1988 as a commercial software developer. He then re-joined academia, working on global climate models at NCAR in Boulder, Colorado. In 1997 he moved to the Pennsylvania State University, where he continues research in climate and ice sheet modelling.

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OBSERVING AND PROJECTING GLOBAL SEA-LEVEL CHANGE

Professor David Holland, Denise Holland and their colleagues at New York University in New York and Abu Dhabi combine field measurements in the polar regions with climate models, in order to better understand how disappearing ice sheets will influence sea level worldwide.

The great ice sheets of Greenland and Antarctica are currently undergoing change, and are losing ice through melt at an accelerating rate. With a significant amount of ocean water being trapped in land ice sheets, diminishing ice sheets mean a greater overall volume of water in the oceans. This could lead to a substantial rise in sea level, thus posing a serious threat to many low-lying coastal cities. The complexity and far-reaching nature of the problem of observing, understanding, and projecting changes in sea level means that scientists need to take an interdisciplinary and international cooperative approach, to a problem of high societal relevance. Professor David Holland, Denise Holland and their research teams at New York University in New York and Abu Dhabi combine field observations in the polar regions with state-of-the-art global climate models to better understand the impact of the disappearing ice sheets on global sea level.

They have established the Environmental Fluids Dynamics Laboratory (EFDL) at New York University in New York and the Center for Global Sea Level Change (CLSC) at New York University in Abu Dhabi in an effort to accelerate the pace of observing and projecting sea-level change. Although the hot desert climate of Abu Dhabi may seem like an unusual location for studying ice melting in Greenland and Antarctica, the fact that this city lies so close to sea level makes it particularly vulnerable to even a small rise in global sea level, as is also the case for New York.

Bringing Together Experts

The EFDL and CSLC bring together global experts to understand past, and project future sea-level change, using a combination of observational data and computer models. As well as Professor David Holland's roles as Director of the EFDL and CSLC, both David and Denise are involved in educational outreach activities, ranging from graduate level to high school to the public. The EFDL group annually participates in the World-Science Festival in New York, and the CLSC hosts conferences and summer schools in Abu Dhabi, educating the next generation of young researchers in this field of environmental science.

Denise is also responsible for overseeing organisation of expeditions for members of their research teams to Greenland and Antarctic coastal waters aboard icebreakers such as the MV Adolf Jensen in Greenland and the RV Araon in Antarctica. Data acquired by team members, in collaboration with international collaborators, is invaluable in understanding the change occurring in these regions and in refining the accuracy of computer models of sea-level change.

Understanding Calving Events

Often during these expeditions, the team needs to find creative ways to make observations in the hostile environments of the North and South polar regions. A great deal of the most interesting data is to be found at the edge of the ice sheet where it meets the ocean, a hazardous place where icebergs break off from the glacier front, dramatically falling into the ocean.

Ice sheets are formed by snow accumulating on land, a process that lowers global sea level. They flow toward the ocean under the action of gravity, where they can in places become floating ice shelves, yet still attached to the land ice from which they formed. It is the transition from being grounded on land to going afloat on the ocean that causes global sea level to rise. These ice shelves can then undergo fracturing events (known as calving) to form

icebergs – free-floating masses of ice that vary wildly in size. Professor David Holland is particularly interested in the physical processes that occur during calving events, a normal and natural mechanism for ice sheet mass loss to the ocean. However, the recently observed collapse of entire ice shelves in both Greenland and Antarctica through accelerated calving is possibly a consequence of global warming, and perhaps a warning of more, similar events to come.

The Hollands and their teams use a variety of techniques to monitor ice loss and formation in various regions in Greenland and Antarctica. Expeditions by icebreaking ships are usually conducted during the summer, when light sea-ice coverage make such regions easier to access. The teams have been collaborating with residents in Greenland so that if weather and sea-ice conditions present an opportunity to investigate a certain area, the researchers can mobilise quickly, deploying probes and instruments to collect valuable data in short order.

Typical instruments used during these expeditions include ocean sea floor moorings and ocean gliders to record ocean temperature and salinity throughout the water column, yearlong. However, these devices are often challenging to deploy and recover due to icebergs in these areas or heavy sea-ice cover, or both, posing a serious risk to safe ship operation. An additional complication in instrument deployment or recovery is that these regions are virtually inaccessible during the colder parts of the year, leaving relatively narrow time windows in summer in which to operate.

Activity at the glacier fronts are monitored using diverse instrumentation, ranging from seismic arrays to ground-based radars located on nearby rock outcroppings. Collectively, these devices can detect when and where any calving events in the glaciers have occurred, and provide information on the behaviour of the glacier at that time. At present, the mechanism by which these calving events occur is largely unknown, and this is one of the uncertainties in a global climate model's ability to project sea-level change. Consequently, it is imperative to accurately track the occurrence of calving and understand the underlying mechanism of fracture formation at the glacier front.

Science's Little Helpers

An unusual and surprising way to circumvent the dangers associated with investigating these unpredictable ice-choked areas is to recruit help from the local wildlife. In collaboration with the Greenland Institute of Natural Resources, the researchers catch and tag members of the local ringed-seal population with devices that can collect and transmit data on the local water conditions. Each time a seal dives down through the water column, and then returns to the surface, it immediately transmits data via satellite relay back to a computer server at New York University. The transmitted data provides a detailed vertical profile of the ocean's temperature and salinity state. Being completely harmless, these tags have no impact on the seals' quality of life and simply drop off when they undergo their yearly moult.

Because seals swim year-round in ice-covered ocean areas, often very close to the dangerous calving front, they provide observations that are unattainable by traditional ship or helicopter-based survey methods. These unique observations provide important information on water composition, for example, the amount of freshwater from

glacial melt can be measured, as meltwater is fresh and thus has much lower salinity than ocean water. This data allows the researchers to build up an understanding of water composition and transport near the glacier, which have a strong influence on the overall melting of the ice sheets.

In combination with remotely-sensed data from international space agencies, the team's various instruments are continually generating a wealth of data on the environmental conditions in the region. The team are confident that the quality and quantity of observational data being collected as part of their sustained monitoring strategy will lead to significant improvements in the accuracy of global sea-level projections coming from global climate models.

Improving Sea-Level Models

The observational data being collected in regions such as Greenland and Antarctica is key in developing accurate models to project future change in global sea level. Such climate models currently account for the interaction between various parts of the climate system such as the atmosphere, continental land, oceans, sea ice, and ice sheets, and thus reflect the complex interconnectivity of the global climate system. To date, however, they have an inadequate representation of the physical process near the glacier fronts. This is a consequence of the lack of observations in these places upon which such representation could be based and put into updated and improved climate models.

By having access to new, extensive observational data sets, the output simulations from climate models can now be compared to these data sets to see if the models accurately reproduce observed past change. If a model simulation is successful in such a hindcast mode, this improves confidence that the model is likely to be reliable in projecting future change, in a forecast mode. Such hindcasting can also highlight any deficiencies in the model, prompting the researchers to improve the mathematical description of the physical processes at work or to include additional physical factors that may be needed to reproduce the observed data.

David and Denise and their team have collected ocean data showing that warming waters unequivocally forced the collapse of a large ice shelf in Greenland. Based on that data, they have been working to more accurately model land ice interactions with warming ocean waters and to better understand how this affects the melting and stability of ice shelves.

A Changing World

Land ice in both hemispheres is undergoing large change, as is clear from observations. This change could continue given the projected rising global temperatures due to greenhouse gas emissions further exacerbating global sea-level rise. If sea-level rise mitigation is to be effective, it is necessary to have accurate projections about which coastal regions are likely to be most affected, by when and by how much.

The team will continue to search for innovative ways to collect important observational data from such harsh and remote environments, an activity that is key to pushing forward the accuracy of sea-level projections from global climate models. Accurate projections are vital for coastal planners and policy makers in a world where significant sea-level rise is a looming possibility.

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Denise Holland is the Field & Logistics Manager of the Environmental Fluid Dynamics Lab (EFDL) at New York University New York and for the Centre of Global Sea Level Change (CSLC) at New York University Abu Dhabi, coordinating David Holland's research teams at both facilities. Her main role is organising and participating in Greenland and Antarctic expeditions, as well as organising summer field schools for undergraduate and graduate students. At both EFDL and CSLC she is also responsible for supporting research infrastructure capabilities and educational outreach activities in environmental science, particularly in the area of ice-sheet–ocean interactions.

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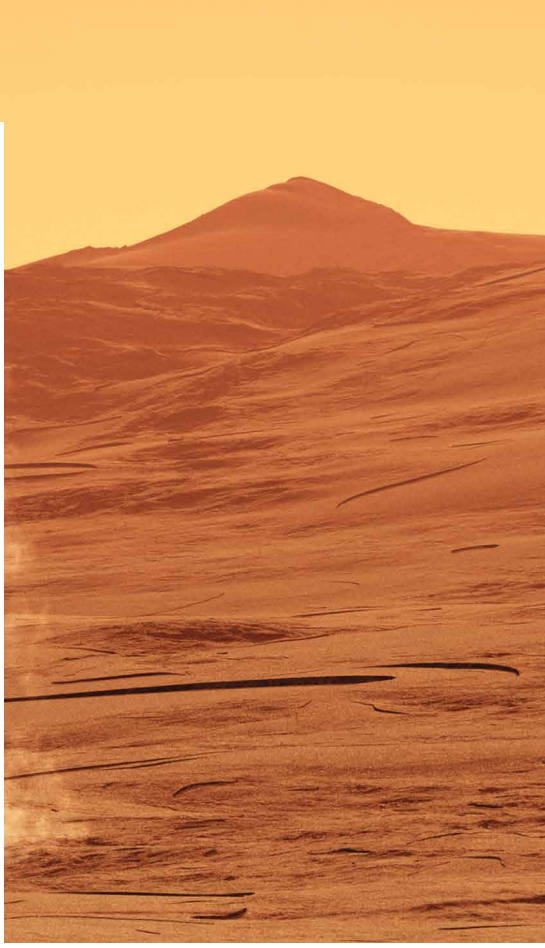
DESIGNING DEVICES FOR EXPLORING SPACE AND INVESTIGATING CLIMATE CHANGE

Dr Jekan Thanga and his team at Arizona State University are developing new and sustainable solutions for low-cost space and extreme environment exploration. His team operates robots and sensor-networks for quantifying the effects of global warming on the Greenland ice sheet.



Planetary scientists and geologists are looking towards robotic exploration of hard to reach and extreme environments on Earth and beyond, including caves, canyons, craters and cliffs. These robots are typically battery powered. Batteries are self-contained chemical power packs that have high and variable power, but for only a limited amount of time. Hence, they possess low energy densities.

The ability to recharge conventional batteries is limited especially when there is no access to solar insolation. A relatively new technology is emerging as a preferable alternative to batteries for sustainable power generation: proton exchange membrane (PEM) fuel cells. Also known as polymer electrolyte membrane fuel cells, PEM fuel cells produce electrical energy using hydrogen gas (H_2) and oxygen gas (O_2) input sources. The general structure of a PEM fuel cell consists of two platinum metal electrodes, the cathode and anode, which are surrounded by gas diffusion layers. In between the electrodes is an acidic polymer membrane that is used as an electrolyte *i.e.* a material or solution that can carry charge. The electrodes and electrolyte form the main body of the fuel cell with an external electric circuit connecting the two metal electrodes.

The mechanism for generating power and electricity with a PEM cell is chemically rather simple and does not require complex mechanical systems. The hydrogen fuel input is pumped into the fuel cell through a gas diffusion layer, where it comes into contact with the anode. At the anode, the platinum surface coating acts as a catalyst, allowing the hydrogen to react and separate into protons and free electrons. The protons then travel through the polymer electrolyte towards the cathode, whilst the free electrons generated travel through the external circuit, thus generating electric charge as power. At the cathode side of the cell, oxygen (O_2) fuel is pumped in through a gas diffusion layer, where it reacts with the travelling protons and electrons to produce the only waste product, water.

PEM fuel cells operate *via* chemical reactions with high operating efficiencies of 50 to 65% and high energy densities, making them more suitable for applications that require low power and long operating times such as sensors for robotics in space exploration.

The use of sustainable sources of energy are becoming ever more prevalent in modern technology, including technology used for extra-terrestrial missions. One reason for the increased use of sustainable technologies is due to an understanding of the environmental consequences of extracting and burning fossil fuels. A second reason is that the PEM fuel cells are highly efficient and can enable mobile devices in the field to operate for long duration, with minimal environmental footprint.

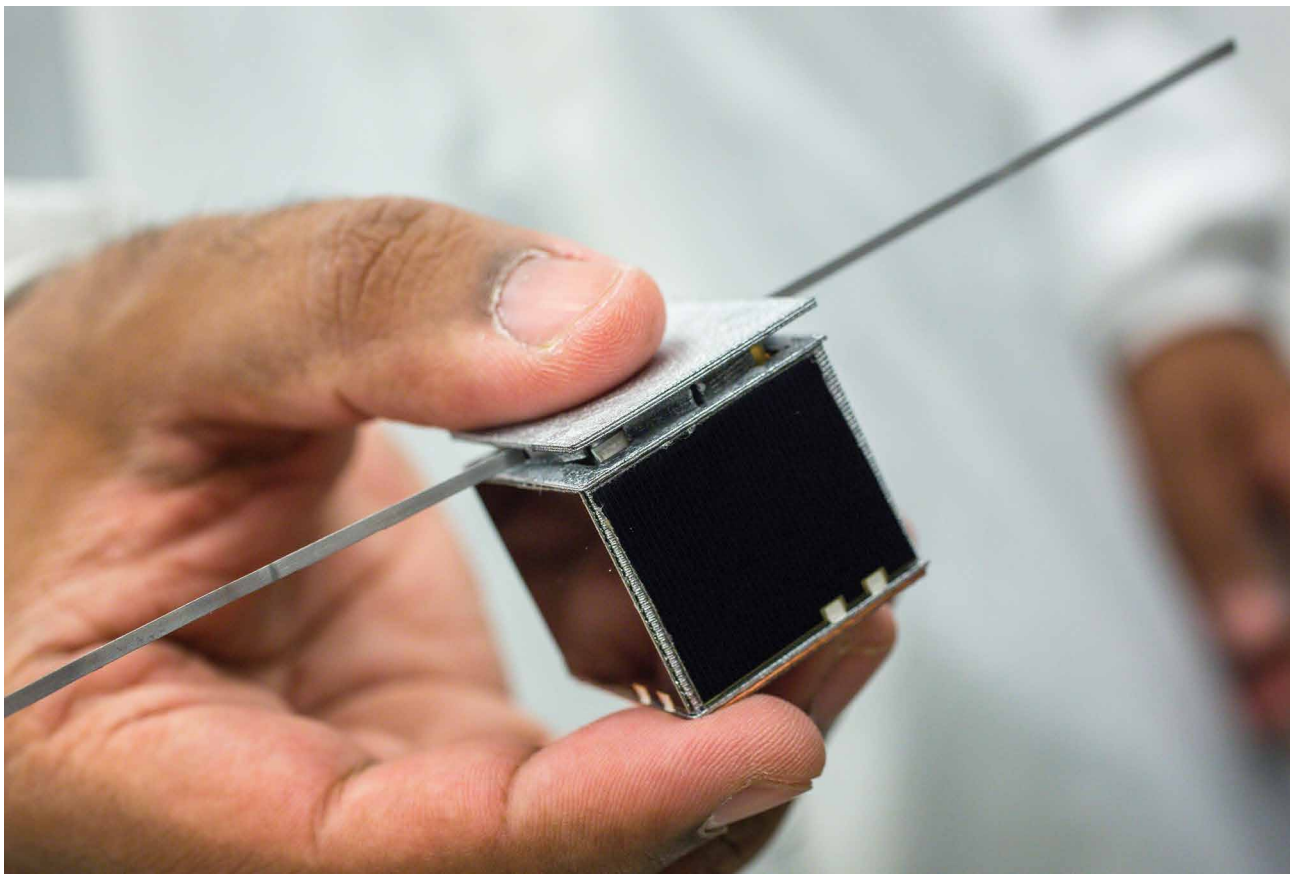
Accurately Predicting the Lifetime of PEM Fuel Cells

Predicting the device lifetime of PEM cells is critical in reporting accurate device stabilities and suitability for a proposed application. There are several components within a PEM cell that experience degradation with use, thus limiting the operation lifetime of the fuel cell. The catalyst layers of the anode

and cathode experience some of the most significant degradation within fuel cells.

In addition to the dissolution of catalyst particles, as was previously considered in existing models, Dr Thanga and his team recognised the problems associated with the catalyst leaching into the polymer electrolyte membrane at the cathode, and becoming an impurity. Impurities cause local structure disruption and act as nucleation sites for further impurity precipitation. These local regions of disorder lead to additional gas mobility and diffusion pathways being created through the device layers, which in turn reduces the operating efficiency of the fuel cell.

Dr Thanga and his research team incorporated several unique features into a new analytical model to more accurately predict the lifetimes of PEM fuel cells. The additional features they incorporated include the conductivity of the electrolyte membrane



and the effects of catalyst dissolution and impurity formation in the electrolyte membrane. Predicted device lifetimes with varying temperature, humidity and voltage were shown to accurately reproduce experimentally measured efficiencies of PEM fuel cells. Such accurate prediction of device lifetime is crucial for understanding and improving device stability.

Hydrogen Storage: A Hot Topic for PEM Fuel Cells

The term hydrogen storage often sparks great debates in the scientific community. Currently, hydrogen storage in PEM devices severely limits the economical and practical use of PEM fuels cells. As an alternative to storing significant amounts of hydrogen as a liquid or gas, solid-state minerals such as Lithium Hydride (LiH), which contain a large amount of hydrogen, can serve as an efficient alternative, enabling hydrogen production on demand.

LiH undergoes a hydrolysis reaction in the presence of water to produce hydrogen gas and lithium hydroxide (LiOH). Dr Thanga's team showed that LiH could efficiently produce hydrogen gas under humid conditions at room temperature. They also demonstrated that the build-up of LiOH prevents water from being efficiently transported to the LiH mineral surface. The surface area of LiH samples, the concentration of water that the material is exposed to and the pressure applied to the system all control the volume and rate at which hydrogen is produced.

Dr Thanga's research has resulted in the construction of a PEM fuel cell using LiH as the hydrogen fuel source. This device was the first of its kind to be constructed with the capability to control both the applied pressure on the cell and the flow of water to the LiH surface. Following a series of device measurements, Dr Thanga developed a semi-empirical model to accurately report the operational lifetime of the PEM fuel cell as a function of voltage, pressure and humidity, which incorporates the slow-down effects due to the production of LiOH. The waste product LiOH can scrub CO_2 from the atmosphere to form lithium carbonate, an environmentally friendly substance.

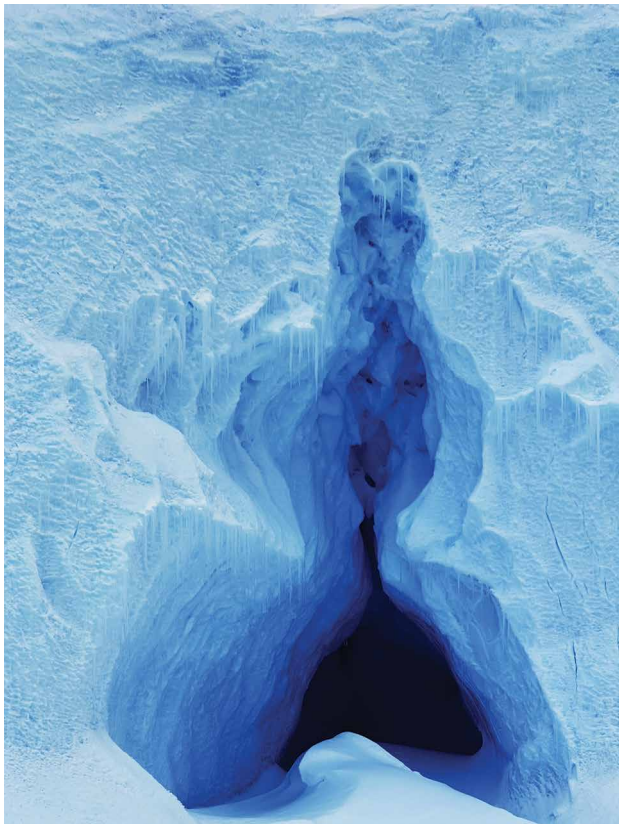
The combination of Dr Thanga's model for predicting PEM device lifetimes and using LiH as a hydrogen fuel source has allowed his team to accurately predict optimum operating conditions. Understanding the operating lifetime and efficiency of a PEM fuel cell as a function of applied voltage, humidity and temperature, has enabled the team to design a PEM fuel cell with an operating lifetime of 5 years. Furthermore, because LiH was used as a hydrogen fuel source for this reported cell, the system has a theoretical energy density of 5000 Wh/kg – nearly 40 times that of lithium ion batteries.

Producing Heat to Prevent Robots Freezing in Space

A common problem facing robots in space exploration is that the extreme temperatures of space can cause robotic components, in particular sensor modules, to freeze.

PEM fuel cells produce a clean waste product that offers a route to the thermochemical production of heat: water. Dr Thanga and his team have developed a thermochemical device that allows chemicals to dispense heat on demand, such as under eclipse conditions. Thermochemical devices do not require valuable electrical energy to operate, and are mainly formed of an absorbent chemical that has high-energy storage capabilities such as lithium chloride (LiCl).

Dr Thanga and his team reported the structure of a thermochemical device containing LiCl absorbent that allows the controlled release of heat at a given



temperature, using the waste product produced by PEM fuel cells. Additionally, the researchers altered the standard design of a terrestrial thermochemical cell to incorporate the control of water flow to the absorbent. After building the thermochemical device, and demonstrating its successful operation, Dr Thanga derived a mathematical model to reproduce device efficiency as a function of operating time and temperature. Fabricated thermochemical devices were shown to produce heat for 3 hours after activation.

Flying Robots in Space? Hopping Mad!

Flying and hopping robots in space sounds like a concept from a Hollywood movie, however work of Dr Thanga is bringing this futuristic technology into reality. Dr Thanga and his team recognised the difficulties in maintaining and extending battery lifetimes in large robots for space exploration. An alternative solution is to deploy smaller robots to process and image the local terrain and extra-terrestrial environment. Dr Thanga's team has designed small robots called pit-bots for this very purpose.

The pit-bots are formed of electronics comparable to current smartphones and contains a propulsion system utilising hydrogen peroxide fuel and lithium thionyl chloride batteries. The spherical device design is also fitted with micro-thrusters to allow the robots to hover and fly. For accurate distance measurements, the pit-bots are fitted with laser range finders and bright lights and move as a trio in a triangular formation. The pit-bots offer a low mass, low energy solution to battery restrictions in robotics in space, and are capable of taking high resolution images and distance measurements.

Other more efficient robots designed by Dr Thanga for space exploration include the SphereX M. Weighing just 2 kg, the SphereX M robot has a spherical design with inbuilt hopping mechanism for navigation of difficult terrains and holonomic chassis. Owing to the design of the hopping mechanism and additional energy store to drive the hopping mechanism, the SphereX M robot is able to hop to a height of 16–20 cm in the low gravitational environment of the Moon. Incorporated into the design of both the pit-bot and SphereX are sophisticated guidance, navigation and control systems. These systems have led to robots being able to navigate climbing steep terrain and descend deep crevices, roll, summersault and rest literally on cliff edges.

Measuring the Density of Greenland's Ice Sheet

Alongside his research on designing robotics for space exploration, Dr Thanga has also been awarded a grant from NASA for a project named Compaction Reconnaissance Artic Glacial Snow (CRAGS). The CRAGS project involves the fabrication of devices and derivation of models that can accurately measure and predict the density of the Greenland ice sheet. The purpose of the project is to remove the errors associated with current altimetry methods, to accurately measure the ice sheet's present and future contributions to sea level rise due to global warming.

Altimetry is simply the measurement of altitude or height, and is used to estimate the size of the Greenland ice sheet to predict what the rise in sea level would be if the ice sheet were to melt. During altimetry measurements, the density of different layers in the ice, such as snow firn layers and surface snow coverage, are fixed with constant values, leading to substantial measurement errors. Dr Thanga and his team have designed sensor packages to measure the change in surface snow accumulation in different regions and at different altitudes of the ice sheet. Currently three CRAGS stations have been deployed in Greenland to start making these surface coverage measurements. When measurements using CRAGS stations over a long period of time have been made, a more accurate measurement of the density changes with altitude of the ice sheet can be made.

To sum-up, the research conducted by Dr Thanga and his team is extensive, covering many important applications including climate solutions, space robotics and sustainable energy.

Meet the researcher

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Dr Jekan Thanga received a BaSc in engineering science (aerospace) in 2002 from the University of Toronto, and obtained his PhD in Space Robotics in 2008. He then pursued a career path in academia, spending four years as a postdoctoral researcher in the mechanical engineering department at MIT, where he worked in the field of robotics. In 2013, Dr Thanga was promoted to assistant professor within the School of Earth and space exploration at Arizona State University. Throughout his research and academic career, Dr Thanga has published over 50 articles in peer-reviewed academic journals and conferences and has had 2 patents awarded for his inventions. He is being funded by NASA, JPL, the US Airforce and NSF. Dr Thanga is an emerging researcher in the fields of extreme environment robotics and engineering. His work has garnered wide media coverage from the BBC, CNN, Smithsonian, Nature, FastCompany, Wired, Popular Science and Popular Mechanics. His team of students and postdoctoral researchers are developing cutting-edge technology for space exploration and to probe the effects of climate change.

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Arizona State University

TRACKING THE SOURCE OF MOUNTAIN STREAMFLOW

Warmer temperatures can cause mountain snowpacks to decline, especially at lower elevations and in dry climates. Since snow is the number one source of fresh water in many mountainous regions, it is important to understand how its loss will impact water supply for people, plants, and wildlife. Using innovative approaches, **Dr Stephanie Kampf** and her team at Colorado State University are identifying areas most vulnerable to losing persistent winter snow and how this affects soil moisture and streamflow.

The Problem of Predicting Streamflow

Water managers, particularly those in dry parts of the world such as the western United States, are constantly vexed by threatened water supplies. For this reason, Dr Kampf was naturally drawn to the subject. 'I am a native of Colorado, a dry state in the Rocky Mountains where water availability is always a concern, so I have long been interested in improving our understanding of water processes in arid mountain regions,' she explains.

Predicting river flow is challenging on its own, and it depends on understanding which snowpack regions are most vulnerable to warming. Traditionally, water managers and users have relied on data from snow monitoring stations to estimate streamflow in any given year, but found their predictions weren't always accurate. Dr Kampf elaborates: 'When I began working at Colorado State University, water users wanted to know why streamflow forecasts were not always accurate from year to year. Here in the Rockies, most of our streamflow comes from snowmelt, and water managers use snow monitoring stations high in the mountains to predict how much water will flow through rivers each year.'
The problem with high mountain stations is they are located far from river gauging stations, missing the middle elevations that cover more of the surface area of mountain watersheds. An important example for the research team is the Cache la Poudre, a Colorado river that originates from snowmelt in the Rocky Mountains. When Eric Richer, a former graduate student, developed models of streamflow in the Cache la Poudre, it became clear that most of the water in the river originated above a transition between intermittent and persistent winter snow. The high mountain snow stations were not low enough to document snow patterns near this transition area, so the team began to explore how they could identify where the snow transition is located.

The group used satellite remote sensing to develop a snow cover index that reveals patterns in snow coverage. Richer used the index to examine how snow patterns related to variables such as elevation, slope, solar radiation, precipitation, temperature and vegetation cover. He found that elevation was a dominant influence on snow patterns because it affected both temperature and precipitation. The index allowed Richer and others to identify three distinct snow zones: persistent, transitional and intermittent. Results from this also confirmed that the transitional zone, or the middle elevation, was an area in need of more monitoring, as it was the most sensitive to losing winter snowpack due to climate warming.

Dr Kampf points to both the Cache la Poudre and modelling studies as the reasons they are now homed in on their current research: 'My research group started mapping snow patterns with satellite data, and we realised that we had no idea how much streamflow was coming from middle elevations, where there are no snow monitoring stations. Since climate projections suggest that snow elevations will rise, we set out to understand how loss of snow at middle (transitional) elevations affects streamflow.'

‘Mountain snowpack is a primary source of water supply for mountain regions throughout the world. In a warmer climate, snowpacks are expected to decline, affecting both water supply and freshwater habitat.’

These unmonitored middle elevations are critical to understand because they are likely to lose their persistent winter snow in a warmer climate. Not only that, the group’s current research indicates that arid climates are more vulnerable to loss of permanent snowpack and resulting loss of freshwater flow.

Understanding Snow Transitions

With funding from the National Science Foundation, Dr Kampf is driving her team towards a better understanding of these middle elevations and their snow patterns, especially in semi-arid climates. Specifically, they are looking at the ‘snow transition’, or the boundary between the persistent and intermittent snow zone, and how it affects regional hydrology.

Their project aims to see whether the loss of persistent snowpacks (and resulting loss of runoff) has a greater impact on arid than on wetter climates. They want to know how changes in the persistence of winter snowpacks will impact water supplies, so they are looking at connections between snow, streamflow and soil moisture in both wet coastal and dry interior mountain ranges of the western U.S.

Their first goal is to document the distribution of snow transitions in different areas of their study region. To do this, they are using point recordings from automated snowpack and climate sensors, collectively known as SNOTEL (snow telemetry), located in their study area. They’re also using spatial snow maps generated from satellite imagery known as MODIS (moderate resolution imaging spectroradiometer). Cara Moore, a former graduate student, used MODIS to map areas across the Western US. She identified areas where snow falls and melts several times over the winter (intermittent snow zone), areas where snow lasts until late spring or summer (persistent snow zone), and the area between intermittent and persistent snow called the transitional snow zone. She published her techniques and findings for a ten-year period from 2000 to 2010, and the research team has been continuing to update the maps since then.

The second goal of their research is to examine how snow transitions affect streamflow and soil moisture. They are compiling discharge data from gauging stations and soil moisture data from SNOTEL sites, which they compare to snow indices and measurements to see how they are changing across the snow transitional zones. They’ll use established HYDRUS-1D software models to simulate changes in soil moisture for the SNOTEL sites in two different regions.

The team’s studies already suggest that in these snow transition zones, there is a steep drop in streamflow compared to the higher elevation persistent snow areas. Areas with more persistent snow don’t seem to suffer as great of a loss of streamflow because the amount of moisture stored in the soil is high. In intermittent snow zones seen in more arid climates, however, the connectivity of water flow is often broken. As Dr Kampf explains: ‘Our findings suggest that persistent winter snow is particularly important for producing streamflow in dry regions because the concentrated snowmelt in the spring fills up the soil and allows more water to flow into streams and rivers.’

So, in a warming climate, this implies that already arid regions will be further troubled as permanent snow disappears and water yield declines. Snowpacks in dry places, it would appear, are on the frontline of susceptibility.

Lessons from a Flood and Other Applications

The snow zone maps that the team developed using MODIS satellite imagery have proven useful in other scenarios. For example, Moore's snow maps were helpful in explaining how the peak flows in the devastating Colorado Front Range floods in 2013 related to prior peak flows in the region. In September that year, more than 200 mm of rain fell in a week after a slow moving cold front met up with warm humid air from the south. The storm runoff from this eastern Rocky Mountain range, which rises from 1,500 to over 4,000 meters in elevation, caused extensive flooding. This storm created the highest peak flows at many streams that usually peak during snowmelt.

While the 2013 storm itself was highly unusual, in a 2016 publication, Dr Kampf and her colleague Dr Michael Lefsky identified a regional trend of declining snowmelt contributions to peak river flow. It further reinforced that the snow transition zone was the area most sensitive to loss of snow.

Identifying sensitive snow transition zones with MODIS was also useful in another part of the world – the Andes Mountains. There, the countries of Peru, Bolivia, Chile and Argentina heavily depend on snow and glacier-melt for their water supplies but on-the-ground climate data are sparse. Using MODIS, Freddy Saavedra, a recent PhD graduate, defined snow climate regions throughout the Andes. His approach provided more information on regional differences than previous interpretations, which relied on temperature and precipitation data. Saavedra identified areas with declining snowpack and rising snow lines in central Chile and Argentina, and he is examining how changing snow patterns can be used to predict water supply in these areas. The researchers suggest that tracking these snow zones over time will help identify which are regions are more susceptible to climate change.

Next Steps

Understanding this relationship between persistent snow and streamflow in semi-arid climates such as those in the southern Andes Mountains and western United States could help water and resource managers deal with the challenges of a changing climate. This is particularly important for areas with few or no physical monitoring stations.

Dr Kampf explains that after analysing connections between snow, soil moisture and streamflow, they are moving towards a better understanding the processes involved. PhD student John Hammond will be working with Dr Adrian Harpold of the University of Nevada in Reno to evaluate how soil moisture is affected by rain and snow. Other collaborators are examining related topics such as quality of snow data, persistence and connectivity of streamflow in different snow zones, and how soil water nitrogen is affected by snowmelt patterns.

The team plans to make their datasets public as well as develop maps of snow and streamflow patterns for both researchers and resource managers. Hammond and Saavedra are finalising their updated snow maps for the western U.S. and releasing the processing code to enable others to develop these maps in different regions. In related research, Hammond, Kampf, and collaborators at Colorado Mesa University have established field monitoring sites for the mapped snow zones in eastern and western Colorado.

The team hopes that their map products, streamflow and soil moisture analyses for the western U.S., and field measurements will provide insights for water resource management in a changing climate.

Meet the researcher

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Dr Stephanie Kampf received her PhD from the University of Washington in 2006, after obtaining her MSc in Hydrogeology in 2002 at the University of Nevada in Reno. She is currently an Associate Professor at Colorado State University in Fort Collins, Colorado, where she teaches hydrology and watershed science. Dr Kampf's research focuses on how hydrology is affected by climate and landscape. She has authored or co-authored more than 30 articles and served on over 90 graduate committees.

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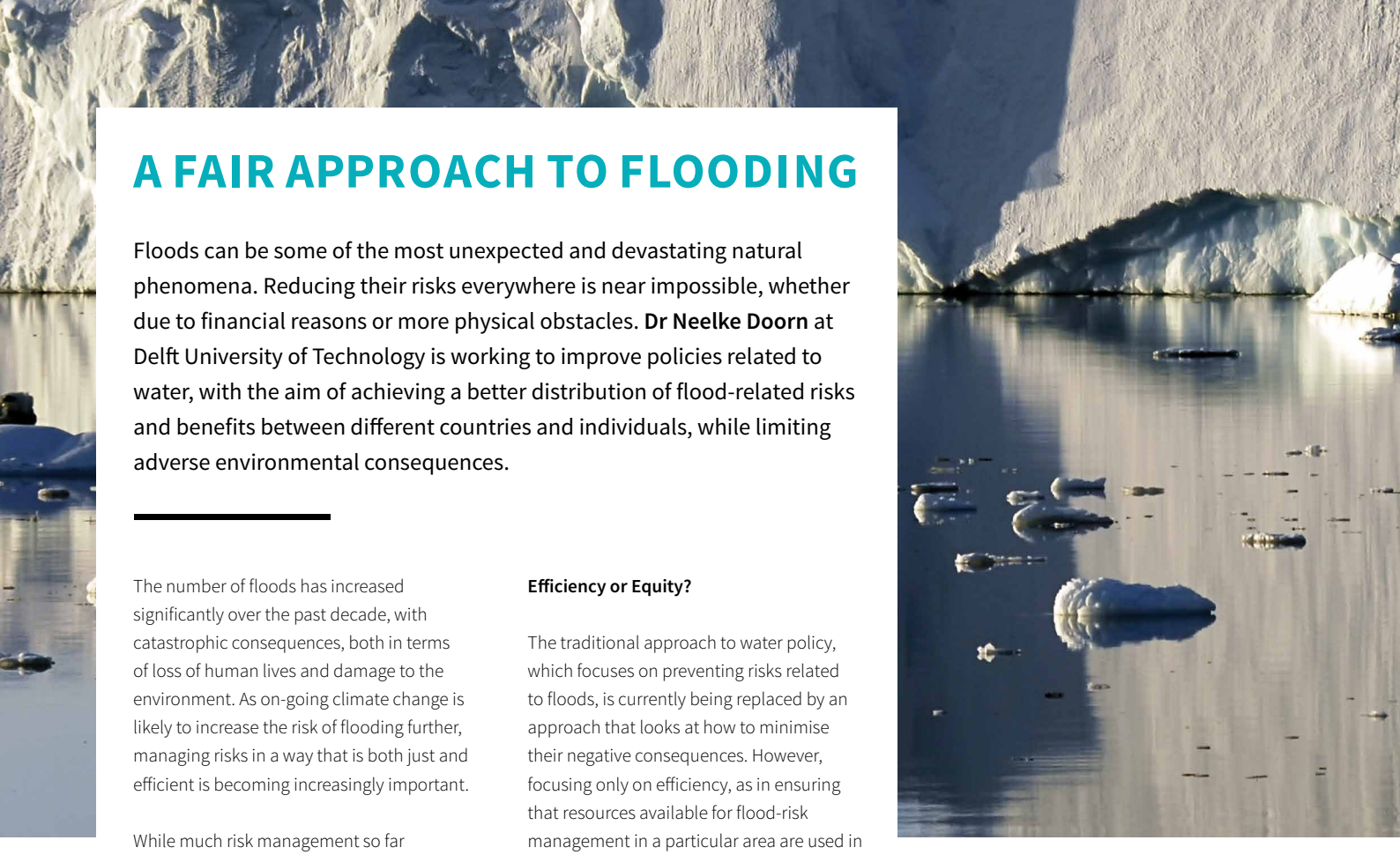

A FAIR APPROACH TO FLOODING

Floods can be some of the most unexpected and devastating natural phenomena. Reducing their risks everywhere is near impossible, whether due to financial reasons or more physical obstacles. **Dr Neelke Doorn** at Delft University of Technology is working to improve policies related to water, with the aim of achieving a better distribution of flood-related risks and benefits between different countries and individuals, while limiting adverse environmental consequences.

The number of floods has increased significantly over the past decade, with catastrophic consequences, both in terms of loss of human lives and damage to the environment. As on-going climate change is likely to increase the risk of flooding further, managing risks in a way that is both just and efficient is becoming increasingly important.

While much risk management so far has focused on optimising costs, the development of efficient solutions also comes with important ethical dilemmas. Managing flood risks also involves questions such as how to fairly distribute safety and predict adverse consequences that can arise from the application of safety measures.

Dr Neelke Doorn has been involved in developing frameworks for flood risk management for more than two decades. Her interest in water governance dates back to her teenage years. 'When I finished high school, I wanted to save the world from flooding, so I started my studies in civil engineering,' she tells us. 'When I finished, I realised that technology is only part of the answer and that we also have to look at how technology is embedded in our society and how it impacts people.'

Due to her varied and extensive academic background, Dr Doorn's research merges ideas from the fields of engineering, philosophy and law, with the aim of developing new models that can be used to ensure more ethical and efficient flood risk management. 'In my work, I try to improve water policy in such a way that risks and benefits are distributed more equally, not only between the people that are currently alive, but also between us and future generations. By avoiding irreversible harm, we can try to leave a liveable planet for future generations as well.'

Efficiency or Equity?

The traditional approach to water policy, which focuses on preventing risks related to floods, is currently being replaced by an approach that looks at how to minimise their negative consequences. However, focusing only on efficiency, as in ensuring that resources available for flood-risk management in a particular area are used in the most effective way possible, could cause inequalities between areas that are better supported economically and those that have less financial resources. In addition to this, technical applications such as dams and dykes can sometimes provide protection in the place in which they are implemented, but adversely affect safety somewhere else.

'The underlying idea in my research is that flooding poses a distribution problem: flood risks cannot be reduced everywhere, either because that is physically impossible or because we lack the financial resources, so improving safety at some point often reduces the safety at some other points,' Dr Doorn explains. The issue, therefore, becomes how to best use available resources so that optimal solutions are implemented, while also taking into account how these solutions impact on social justice.

Having pursued both engineering and philosophy degrees, when it comes to managing flood risks Dr Doorn is well acquainted with both those frameworks prioritising the efficiency of measures and those emphasising their equity. 'If we need to distribute something, we ideally take both considerations of fairness or justice into account and considerations of efficiency and efficacy,' she says. 'Engineers tend to focus on the latter, philosophers tend to focus on the former. Being both a philosopher and an engineer by training, I wanted to develop ideas or frameworks in which we can include both considerations of fairness and efficiency.'

The Ethics of Water

Over the years, Dr Doorn has developed a particular interest in what she refers to as 'water ethics' and 'water justice'. 'To me, water ethics is about the values involved in water management – values like safety, solidarity, health, sustainability, etc. Water justice refers to the distributive aspects involved in water management.'

Water justice relates to how we best distribute water-related risks, as well as the responsibility for preventing these risks. This also includes a number of procedural aspects, such as who is involved in decision-making processes related to flood related threats.

Irreversible Loss

Sometimes applying measures to reduce the risks of flooding in one particular place can also affect the safety in another place or at a future point in time. This is why Dr Doorn believes that it is important to distinguish between reversible and irreversible measures and consequences.

‘In my work, I try to improve water policy in such a way that risks and benefits are distributed more equally, not only between the people that are currently alive, but also between us and future generations. By avoiding irreversible harm, we can try to leave a liveable planet for future generations as well.’

For instance, choosing to strengthen dykes or implement ‘harsh’ technological solutions can be irreversible and can eventually lead to regretful consequences such as ecological damage. This is why, sometimes, reversible measures are preferable, as is the prevention of irreversible damage to people and the environment.

Although many policy makers might prefer cost-benefit analyses (CBA), meaning a process of decision-making that takes into account the costs and benefits of a particular measure, these analyses do not always take into consideration environmentalist concerns related to irreversible loss. In this context, irreversible loss refers to the damage that could be done to the environment or eco-system that, unlike financial loss, cannot be repaired at a later stage.

Dr Doorn believes that policy-making should be done taking possible irreversible adverse consequences into account, in order to minimise these and preserve living conditions for present and future generations. Implementing protective measures against irreversible loss could help limit the damage done by a natural disaster, even if they come with reversible losses, such as financial ones. In her own words: ‘irreversible losses should be avoided first, even if this comes at the expense of reversible losses.’

Resilience

In her work, Dr Doorn often concentrates on the idea of resilience, which she believes to be of crucial importance for flood risk management. In the context of natural disasters, resilience refers to the ability of a system or society to return to its normal functioning after disruption.

Academics have different interpretations of resilience, but it nonetheless refers to how well society, the ecosystem and individuals involved in a natural disaster are able to recover promptly after natural disasters, such as floods. While some researchers see it as an outcome, or the ability to ‘bounce back’, some see it as the process of adapting to changing circumstances and transforming accordingly. This way, resilience could be seen as the ability to ‘bounce’ to a ‘better position’.

For Dr Doorn, operationalising the idea of resilience in terms of the ability to ‘bounce to a better position’ is of extreme importance, as it can lead to the development of more effective measures for flood risk management that also contribute to fairness.

Shared Responsibility

If operationalised and made applicable to real life situations, resilience also involves a shift in the distribution of responsibility in the management of water-related risks. According to the resilience paradigm, flood risk management is a responsibility shared by central governments, private parties and citizens. However, citizens may not always be equipped to assume these responsibilities.

Dr Doorn's research suggests that fairness is an important factor when it comes to distributing responsibility in flood risk management. If repairing damage done after a flood relies on private insurance, this could increase inequality among citizens, as not everyone will be able to afford it. This will in turn have an impact on the distribution of risk levels, making it uneven among members of society. In other words, citizens without private flood insurance would be disadvantaged and would be exposed to greater risks compared to those who can afford it.

According to Dr Doorn, the state should provide basic protection against flooding. The conditions under which citizens can be given a share of responsibilities related to flood risk management are of great interest to her, and she is currently working on a follow-up project that explores this further.

A Moral Framework

In 2013, Dr Doorn was awarded a prestigious Veni-grant for outstanding researchers from the Netherlands Organization for Scientific Research (NWO). Her project, The Ethics of Flood Risk Management, explored different moral views on how optimal solutions for the society at large should be balanced against the rights of individuals to be safeguarded against flooding.

Her project's aim was to develop a moral framework that could help judge whether differences in safety level for flood risk management are acceptable, both in terms of equity and efficiency. Dr Doorn highlighted that to do this, both the notion of equity and efficiency should be clearly delineated, so they can be effectively taken into consideration within the context of flood risk management.

Ultimately, Dr Doorn hopes that this new framework, which combines ideas of equity and efficiency that she acquired through the pursuit of her different academic backgrounds, will prove to be a useful tool for future policy-making.

A Glance at the Future

Dr Doorn is currently working with colleagues in Adaptive Delta Management to develop her ideas and operationalise them, so they can become applicable to policy making. Her future work will provide further insight into how citizens can be more involved in decisions related to flood risk management. 'We currently see a trend that the government expects citizens to take a larger responsibility, whether in flood risk policy or in other fields,' she explains. 'My future research will focus on what people actually need to take this responsibility. In other words, under what conditions it is fair to give citizens a larger responsibility.'

Over the next decades, climate change could have serious consequences on the environment, causing greater water scarcity and floods. Even the way water is used in one place could have serious effects on another. The work of researchers such as Dr Doorn will be of crucial importance to developing new ways of counteracting floods and water-related disasters. 'We have to look beyond the local impact here and now and see what we owe to other areas and future generations,' says Dr Doorn. 'I would advise policy makers in the water sector to involve local stakeholders in water management plans. For distributive justice, I would urge water managers to look beyond traditional cost-benefit analyses and see whether no irreversible harm is done by certain measures, either to human beings or the eco-system at large.'

Meet the researcher

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Dr Neelke Doorn's academic background has roots in Civil Engineering (Delft 1997, BSc and MSc), Philosophy (Leiden 2005, BA and MA) and Law (OU 2016, LLB and LLM). From 1998 to 2007, Dr Doorn worked as a research engineer at the hydraulic research institute WL I Delft Hydraulics (now Deltares). After obtaining her PhD in 2011, with a thesis entitled 'Moral Responsibility in R&D networks', she became assistant professor at Delft University of Technology, where she is now an associate professor. Dr Doorn's research primarily focuses on water, with a particular interest in moral and environmental issues involved in technological risks and water governance. She looks at water-related issues from the angle of resilience, which she considers to be a very important paradigm for flood risk management. In 2013, she was awarded a prestigious Veni-grant for outstanding researchers from the Netherlands Organization for Scientific Research (NWO).

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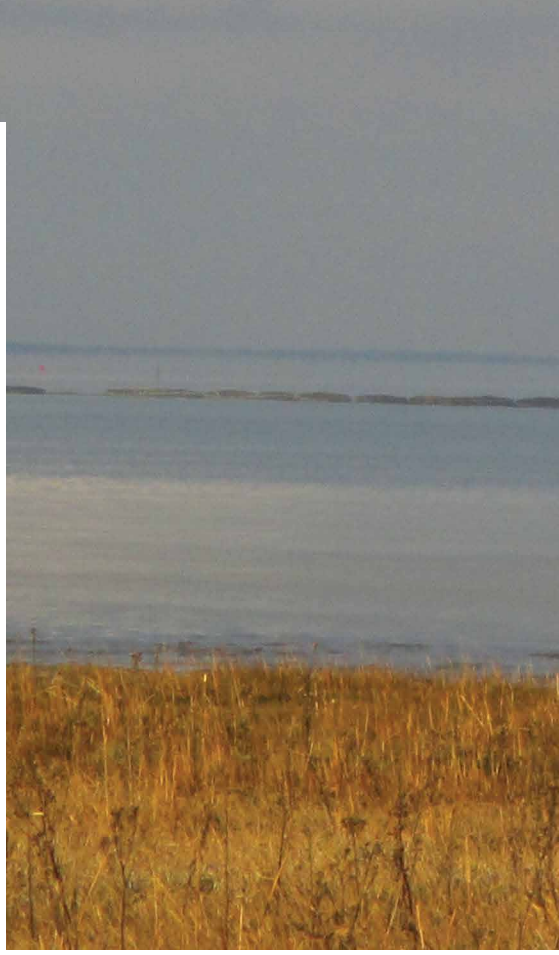
USING NATURE TO PROTECT US FROM… NATURE

Environmental geographer **Dr Iris Möller** and her colleagues at Cambridge University's Coastal Research Unit look for ways to protect our coastal areas from flooding by studying the natural protections provided by the coastal geography itself.



Water, Water Everywhere

We all know that three-quarters of the Earth is covered with water. Not surprisingly, 96.5% of it fills our oceans. It follows that there must be lots of land bordering those oceans. In fact, roughly 620,000 km of coastline surrounds the Earth's seas and over a third of the world's population, almost 2.4 billion people, live within 100 km of an oceanic coast. After all, who wouldn't want to watch a sunset over the ocean? Who wouldn't want easy access to goods and services from far off lands? But going to the seashore to enjoy the sunset is not the same as the seas rushing into the city streets to wreak havoc on the populace. That's the type of human-ocean interaction that geographer Dr Iris Möller and her colleagues are studying, to find ways to prevent the loss of life and property by encroachment of ocean waters into our human world.

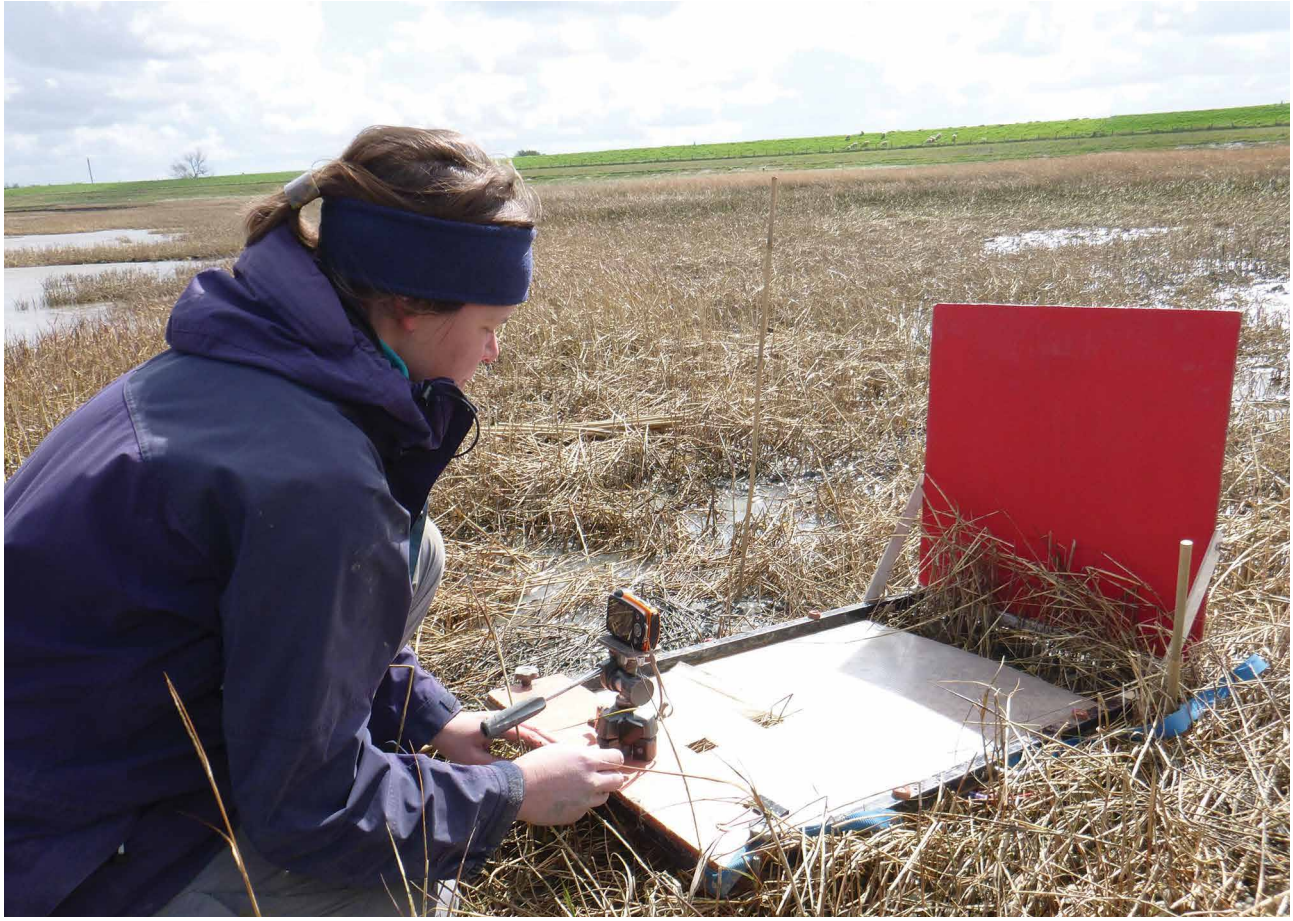
While ocean view property may be attractive, living close to the sea can be perilous. Britons remember the flood of 1953, where over 300 people died as the North Sea surged as far as London. In fact, over 1700 souls perished in the Netherlands from the flooding, due in large part to the lower elevation of that country, much of which is below sea level. More recently, New Orleans and surrounding areas of Louisiana and Mississippi in the US were devastated by Hurricane Katrina in 2005, which killed nearly 1,300 people. Much of New Orleans is below sea level and protected – or at least it was thought to have been protected – by a system of levees and floodwalls. However, some structures failed during the storm surge of Katrina. Besides, the storm surge itself was more intense than it might have been because of subsidence and erosion of the natural wetlands that make up the coastal areas of Southern Louisiana. In retrospect, healthy, vigorous coastal wetlands would have helped to dampen the tidal surge and diminish the flooding of New Orleans from the hurricane. In Louisiana, it seems that the degradation of coastal wetlands, along with old and defective levees and floodwalls, contributed to the loss of hundreds of human lives. This type of scenario is exactly what inspired Dr Möller to get into geography in the first place.

'I chose geography as my university degree course because I saw how critical our understanding of the connections between people and their environment is for human society, for without such an understanding we cannot continue to exist on our planet. Coasts are particularly interesting in this context,' Dr Möller tells Scientia. Throughout the time in her career, it became increasingly clear that a rise in sea level and altered climate, altered storminess, altered wave energy and water level fluctuations were all posing an ever-greater threat to populations close to the world's oceans. She believes that 'we need to learn to live and cope with these environmental pressures without making them worse by not understanding how our coastal environments help buffer us from their impact.' This is where she and like-minded colleagues are concentrating their research efforts – looking at our coastal geography and trying to understand how best to use it to protect humankind from the ever-present force of ocean waters. In particular, Dr Möller's expertise lies in understanding how coastal wetlands help protect the coast from flooding and erosion.

Bringing the Coastline into the Laboratory

It's difficult to go to where the ocean meets the land and do any meaningful experimentation by trying to modify the land

or the waves. After all, how varied is the coast? How unpredictable is the ocean? Forced by highly variable air pressure and winds, water levels and waves can change at very short notice. Atmosphere and ocean are inherently unpredictable beyond the most immediate future, and interesting things often happen



when no one is 'looking', or rather when researchers are not there recording with their instruments. Data collection for the study of real coastlines and their response to real ocean tides and waves is mostly anecdotal – if you happen to be on site when something happens, you can record it, provided the force of the waves does not destroy your instrumentation (as happened in one of Dr Möller's research projects on the Baltic sea shore in a winter storm surge). What other option is there? Bringing the coastline into the laboratory for controlled experimentation is similarly challenging. But that's exactly what Dr Möller and her colleagues did. They constructed a model of the coastline – specifically of a 200-square metre patch of marsh – indoors!

Together with the University of Hamburg, Deltares (a Dutch research organisation), and the Royal Netherlands Institute for Sea Research (NIOZ), Dr Möller's Cambridge Coastal Research Unit team used the Large Wave Channel facility at the University of Hannover's Coastal Research Centre – at over 300 metres in length, one of the world's largest wave tanks – to build a salt marsh. Salt marshes are areas of land that exist at the coast where the tide and waves allow mud to deposit. Over time, special salt-tolerant vegetation begins to grow and soil builds up. Every so often, the tide continues to cover these surfaces. This is where the energies of the ocean waves with their destructive power first hit the land. It is here that the plants and soil either stand up to the power of the oceans, or they let it go unhindered to travel inland and inflict damage on people and structures. Thus, this is an area of vital importance in the understanding of the interaction between the ocean and the land.

Using diggers, fork lift trucks and articulated lorries, Dr Möller and her team brought over 200 europallets of salt marsh from the coast into the wave tank in Hannover. She and her team basically constructed a full-scale controlled experiment on a real salt marsh, typical of many coasts of north western Europe and elsewhere in the world. In the 7-metre deep tank, they then subjected their re-assembled marsh to storm surge conditions: a giant wave making machine sent waves of increasing strength over the surface while using a variety of sensors to monitor the effects. 'We have, for the first time, been able to show how coastal marsh plants dampen waves and how marsh soil resists wave erosion during a storm surge,' Dr Möller explains. The team was able to assess how the marsh takes out the power of the waves by reducing their speed and height.

What they found was that, when submerged in up to 2 metres of water during a storm surge, the salt marsh surface causes enough interference to waves travelling over it that even storm waves are reduced by 20% in height over only a 40-metre distance. At least 60% of this reduction is due to the presence of a vegetation cover on the soil surface, the rest is due to the waves running up over the marsh surface itself. What's more, they discovered that the marsh surface had a very high resilience to vertical sediment removal, with less than 0.6 cm average vertical lowering in response to a sequence of simulated storm surge conditions. In other words, even during an extreme storm surge, the plants in the saltmarsh held on to the soil and didn't allow it to be washed away. In fact, both organic matter content and plant species exerted an important influence on both the variability and degree of stability of the soil surface. The surfaces covered by a flattened canopy of the salt marsh grass Puccinellia experienced a lower and less variable elevation loss than those

characterised by other species of grass that exhibited considerable physical damage through folding and breakage of the plants' stems as they were flicked back and forth by the waves' action. In other words, the plants that are present dictate how well the vegetation and the surface soil resists the tidal surge.

Besides getting some answers to questions about the process and timescale of recovery of salt marshes from extreme storm surge events from this unique experiment, the results from this experiment have implications for the proactive management and conservation of shallow coastal areas. Conserving salt marshes not only actively protects landward areas from wave attack but also increases resistance to vertical sediment removal – the plants help keep the soil from washing away. 'We now know that coastal wetlands are critical in protecting the land from waves and erosion and we know that their surfaces are very stable,' says Dr Möller. 'It is not surprising, that many wetlands are eroding at their seaward edge instead, where the surfaces that lie in front of them have no vegetation cover and can more easily erode downwards as sea level rises and storms become more frequent or stronger; we now need to understand those types of processes better to make sure we understand for how long we can rely on wetlands to offer us this valuable additional protection.' Research often generates more questions than answers, but, the idea that humans can perhaps plant and nurture marshland in specific ways to help protect against storm surges and flooding offers hope for a more sustainable future of ever increasing populations living close to the sea.

Translating Experimental Data into Policy

Dr Möller's research, along with the on-going research of others across the globe, is in agreement that natural coastal features are vital in protecting against tidal surges and flooding. In a paper published in Conservation Letters, Dr Möller and her colleagues opined that appropriate strategies to develop and preserve coastal ecosystems can provide considerable coastal protection benefits. Their experimental data supports this concept. However, this information has not been sufficiently accounted for in governmental coastal planning and engineering. Because of the team's work, evidence now exists that shows how and under what conditions salt marsh ecosystems can play a vital part in important areas such as wave and storm surge attenuation, erosion reduction, and in the longer-term, maintenance of coastal integrity. Because of their capability to self-repair and recover from the impact of extreme storms – as well as through the considerable benefits they provide – coastal wetland ecosystems can offer distinct advantages over the usual engineering approaches to some of these problems. Dr Möller and her colleagues encourage the use of existing knowledge to improve the incorporation of coastal ecosystems into policy, planning and funding for coastal hazard risk reduction. Indeed, Dr Möller believes that 'coastal geomorphologists like myself are now, more than ever before, willing and available to counsel governmental officials to develop appropriate programs to utilise coastal ecosystems to protect humans from floods and storm surge.'

Taking Aim at Future Research Modalities

Looking to the future, Dr Möller and her colleagues are looking at the use of drones and satellites to help them measure what coastal wetlands are composed of, such as different plants, different sized sediments, different amounts and sizes of channels through which the tide ebbs and flows. Her team are working towards finding ways that allow them to quickly assess how important any one wetland might be in a specific location for protecting those who live there against the high-water levels and high waves that happen during severe storms. If they can do that, they can plan much better how to use the coastal land behind the wetland and whether private or government agencies would want to intervene. 'We need to continue to work towards a better understanding of how coastal wetlands grow and remain healthy where their health is threatened, for example by sea level rise – which could "drown" them if it is too rapid – or by humans, who might be using them in destructive ways.' Dr Möller says. After all, we must not forget that, as well as benefiting from this environment economically, we also derive great pleasure from our natural seashores and enjoy the mere existence of this beautiful landscape. Understanding and caring for our coastal landforms and ecosystems will help them to care for us, so that we can continue to enjoy our coasts.

Meet the researcher

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Dr Iris Möller did her undergraduate studies at St. Hilda's College, Oxford University, and received her BSc in Geography with Honours in 1992. She then received an MPhil in Geography from the University of Wales, Swansea, in 1993, for a thesis entitled 'Post-fire vegetation recovery in Mediterranean-type ecosystems'. Dr Möller then attended Magdalene College, University of Cambridge, where she received her PhD in Geography in 1997, for a doctoral dissertation on 'Wave attenuation over saltmarsh surfaces'. She then joined the University of Cambridge's Coastal Research Unit as a Research Associate, after which she took up a Full-Time College Lecturer position in Physical Geography at Fitzwilliam College, University of Cambridge. In 2014, Dr Möller joined the academic staff of the Department of Geography of the University of Cambridge, where she is currently University Lecturer and Deputy Director of the Cambridge Coastal Research Unit (CCRU) where she works together with her colleague Professor Tom Spencer (Director of the CCRU), and a dedicated team of coastal researchers.

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KEY COLLABORATIVE PROJECTS AND FUNDING

Physical and biological dynamic coastal processes and their role in coastal recovery (BLUE-coast) (NERC Grant NE/N015878/1)
Valuing the contribution which COASTal habitats make to human health and WEllBeing, with a focus on the alleviation of natural hazards (CoastWEB) (NERC Grant NE/N013573/1)
Foreshore Assessment using Space Technology (FAST) (EU 7th Framework Prog. SP1-Cooperat. (FP7-SPACE-2013-1))
fast-space-project.eu
Resilience-Increasing Strategies for Coasts – toolKIT (RISC-KIT) (EU 7th Framework Collaborative Projects. (FP7-ENV-2013-two-stage))
risckit.eu
Coastal ecosystems as a form of coastal defence (The Isaac Newton Trust, Trinity College, Cambridge)
Wave dissipation and transformation over coastal vegetation under extreme hydrodynamic loading (EU Integrating Activity HYDRALAB IV, Contract no. 261529)
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UNIVERSITY OF CAMBRIDGE
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UNCOVERING THE CONNECTION BETWEEN OCEAN SALINITY AND TERRESTRIAL RAINFALL

For the first time, scientists have shown that salinity levels in the ocean's surface can be a predictor of rainfall on land. **Dr Raymond Schmitt** and his colleagues at the Woods Hole Oceanographic Institution in Massachusetts used records spanning 60 years to discover this compelling relationship. They've successfully correlated salinity levels in two different areas of the North Atlantic with rainfall in Africa and North America, and they're now on the hunt for other similar teleconnections.

Understanding the Global Water Cycle

If you ask physical oceanographer Dr Raymond Schmitt, he thinks our understanding of how water moves and is recycled on our planet is pretty elementary. 'I think most people have an incorrect picture of the global water cycle,' he says.

Dr Schmitt explains that when thinking of the water cycle, many people hark back to those over-simplified charts they first saw in grade school – the ones that show mostly land, rather than ocean, features. Indeed, if you Google 'water cycle' on the Internet, you'll see that he's right. Many images depict snow or rain falling on the tops of mountains, from where snow melts and flows into lakes and rivers or percolates into groundwater. They show water returning back to the atmosphere through evaporation from lakes, streams and oceans, as well as transpiration from plants – even trees are often drawn as huge features. But the ocean? If it is depicted at all, it's a minor part of the figure. 'I call it the big lie of hydrology, and it misleads many researchers so that they do not appreciate the oceanic dominance of the water cycle.'

In reality, these images should show much larger oceans, not only because of their shear size (covering 70% of the planet) but also because they are the number one source of freshwater. The evaporation from oceans is so vast, says Dr Schmitt, that the amount of water they yield (over 400,000 cubic kilometres a year) would flood the lower 48 states of the United States to a depth of around 55 metres. 'The oceanic water cycle completely dwarfs the terrestrial water cycle,' he emphasises.

Fortunately, flooding on this scale doesn't happen because most of this evaporated water (90%) falls right back into the ocean. The other 10% eventually makes its way to land as rainfall. This giant water cycle and the footprints it leaves behind – specifically changes in salinity on the ocean surface – have interested Dr Schmitt for a long time. 'If there's a little more evaporation from a particular region of the ocean – so this area gets saltier – some of that water is going to end up on land. And so I have long wondered whether there could there be a relationship between salinity changes and rainfall on land?'

Eastern North Atlantic – Africa Sahel teleconnection

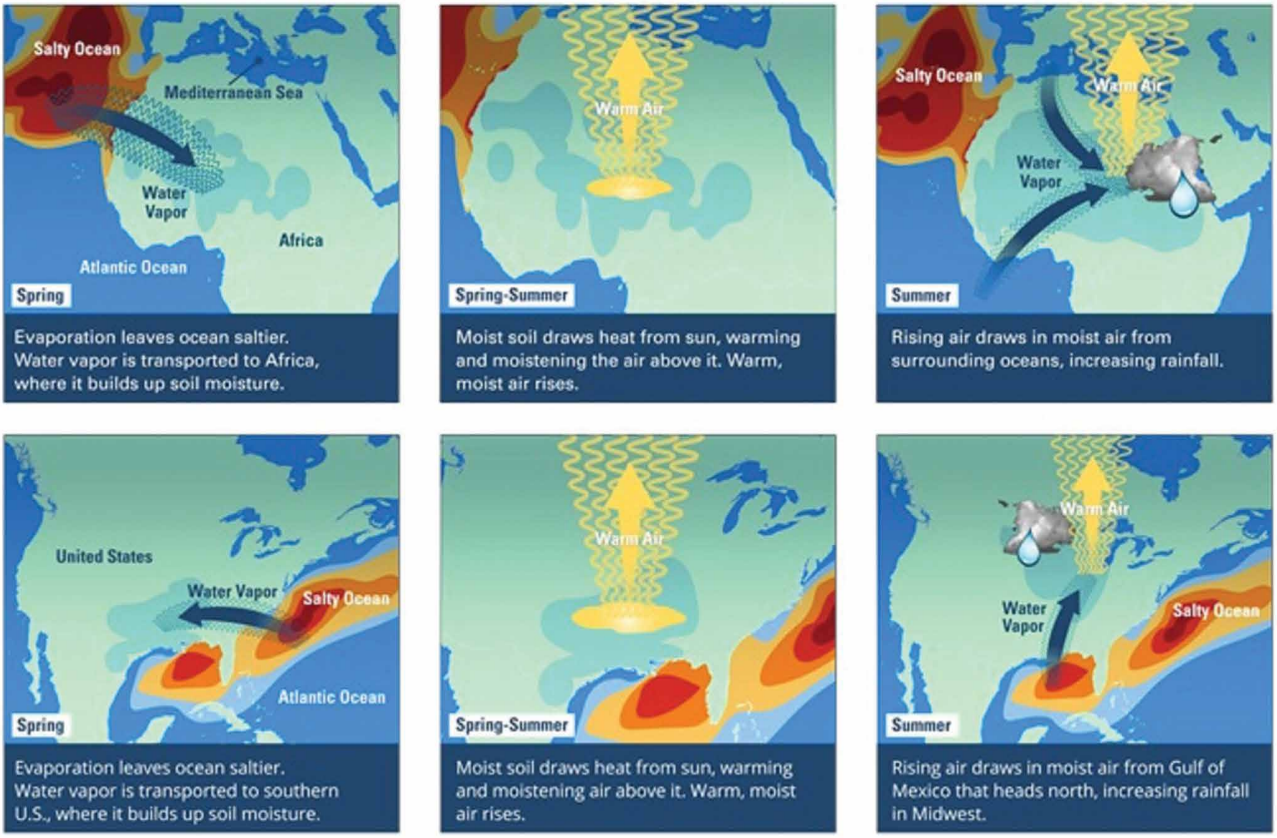
Dr Schmitt explains that he really started thinking about salinity-rainfall relationships back in 1993 after heavy rains flooded the Mississippi and Missouri Rivers in the central US. Significant amounts of water flowed into the Gulf of Mexico, creating measurably fresher seawater. For that to have happened, simple conservation of water and salt guarantees that some area of the ocean would have had to evaporate and become saltier beforehand to produce the extra rainfall on land.

'From our studies of evaporation-precipitation patterns we know that the areas of net evaporation and net precipitation happen to be about equal. So, if say the State of South Carolina gets a foot or two of rain over a few days, I know that some comparably sized area of the ocean lost a foot or two of water from its surface,' Dr Schmitt explains. He figured that loss would have to leave a 'salinity signal' large enough to show up in data from space satellites and the 'ARGO' array of ocean salinity monitoring buoys.

Dr Schmitt wanted to study these patterns for a long time, and finally two years ago a new post-doctoral student, Dr Laifang Li, brought new expertise on rainfall to his Woods Hole research group. 'I gave her this problem and she really struck gold with it,' he says.

The first thing Dr Li did was to home in on an area of high salinity in the eastern part of the North Atlantic. Dr Schmitt knew where this area – the so-called salinity maximum – was located, because of a previous study that he had overseen with NASA. The project, known as SPURS (Salinity Processes in the Upper Ocean Regional Study), used data from NASA's Aquarius satellite to map salinity patterns. Launched in 2011, Aquarius flew 657 kilometres above Earth and measured salinity in 100-kilometre wide swaths. As part of SPURS, scientists also deployed moorings and ocean robots in 2012 to verify the satellite measurements.

‘We find that salinity in certain regions of the ocean has predictive teleconnections with rainfall in certain regions on land’



CREDIT: Eric S. Taylor/Woods Hole Oceanographic Institution

Using this information, Drs Schmitt and Li examined salinity variations in the eastern North Atlantic and compared it with rainfall on neighbouring continents. For a long time, Dr Schmitt expected that water evaporating from that part of the ocean was ending up in the Amazon River region of South American, but he soon discovered he was wrong. As it turns out, the water was showing up on the other side of the ocean in Africa, in a region known as the Sahel.

Along with this surprise, the researchers also observed an added twist of a 3-month delay between ocean evaporation and precipitation on land. High salinity anomalies first appear in their patch of ocean in March-April, but peak rainfall in the Sahel doesn’t occur until June-September. ‘Our first thought was that the water would get transported from ocean to land within a matter of weeks – since the winds can be pretty quick,’ says Dr Schmitt. ‘So seeing the increase in precipitation months later was a mystery.’

But Drs Li and Schmitt eventually explained the puzzle by looking at other factors. They found that in the spring, when evaporation in the ocean increases (making them saltier), water begins falling on the dry African Sahel. As moisture increases in the soil, it causes it to behave much differently than if it was dry. Effectively, the moist soil is able to absorb more energy from the sun, which causes enhanced evaporation that supplies latent heat to the atmosphere. This latent heat of the evaporating water, in turn, fuels atmospheric motion that drives convection. Convection feeds on itself and intensifies storms, which then pull in more moisture from the North Atlantic and Mediterranean during the summer.

So, the moisture in the soil is the key, and without it, you don’t have conversion of solar energy to latent heat.

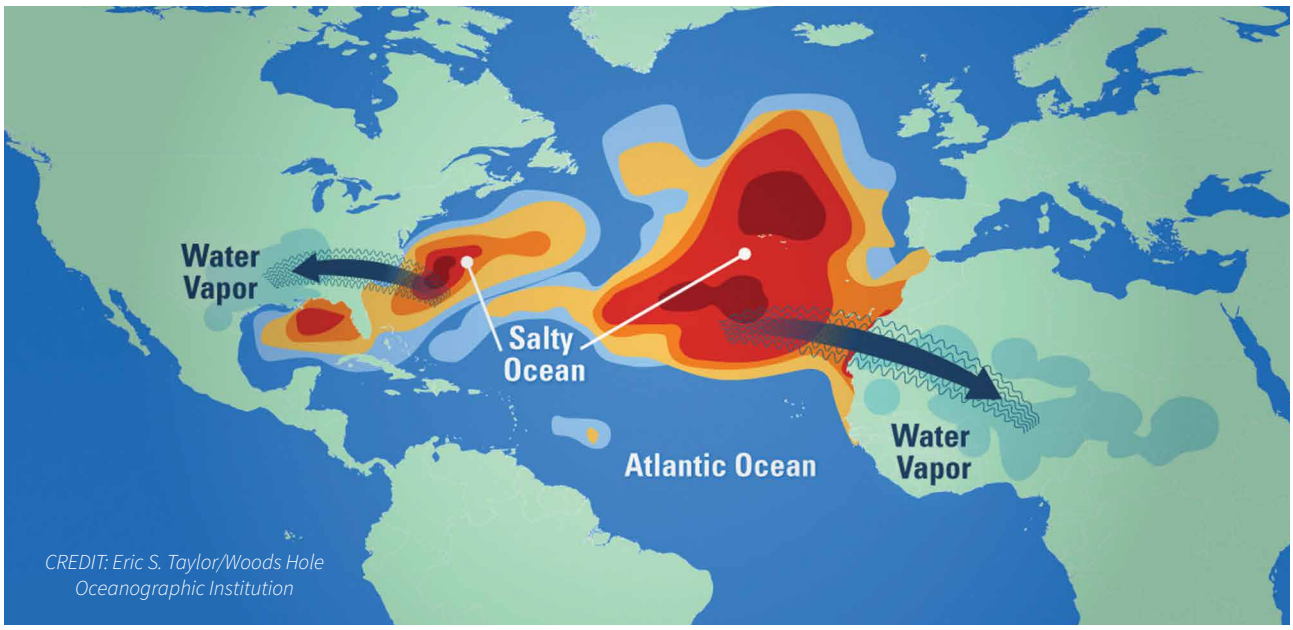
Western North Atlantic – US Midwest link

Using the same 60-year data set, Dr Schmitt’s group found another correlation. They observed that high springtime salinity anomalies in the western North Atlantic (off the US east coast) were followed by increased summer rain in the Midwestern region of the US. In addition, low salinity springs were a good predictor of summertime drought.

As with the Sahel connection, the researchers found a similar delay, or lag time, which again they attribute to soil moisture content. In those years with enhanced spring time evaporation (and resulting high ocean salinity), rainfall and flooding begin to saturate soils in the southern US, especially in Louisiana and Texas. As the sun’s energy evaporates water from the soil, the cycle of latent heating begins and increases atmospheric convection and storms. This causes more water to be drawn from the Gulf of Mexico and into an air pattern known as the Great Plains Low Level Jet, which carries the moisture northward into the Midwest in the summer.

Dr Schmitt was so convinced of this correlation that he showed up at the American Meteorological Society meeting in Minnesota in spring of 2015 and warned them of flooding to come that summer. This was after observing a marked high salinity footprint in the spring time that same year. ‘Our prediction proved to be very accurate. They did have a rainy summer,’ he says.

The 2015 phenomena resulted in record rainfall for Texas and Oklahoma, record



CREDIT: Eric S. Taylor/Woods Hole Oceanographic Institution

flooding in Illinois and the second wettest summer ever recorded in the Midwest. So much rain fell that the Great Lakes filled back up to historical levels after a long drought. The flooding also caused extensive agricultural damage and claimed 20 lives, highlighting the importance of weather awareness and predictability.

Salinity and weather predictions

In their publications, Drs Li and Schmitt make the case that salinity is a better predictor of rainfall than ocean temperature, which has been long been the standard. Temperatures on the surface of the sea can vary daily due to weather, unlike salinity, which could be a more reliable and accurate longer time signal. 'Salinity is kind of an integrator,' explains Dr Schmitt. 'It's an averaged indicator of the export of water and latent heat that's been going on for the past few months. And latent heating is the primary means by which the ocean drives the atmosphere; the sensible heating due only to air-sea temperature differences is an order of magnitude smaller.'

Their next target research area on their agenda is the eastern Tropical Pacific, where they plan to study salinity variations in a fresher region with the SPURS project and correlate them with terrestrial rainfall in other places. They've already begun a year-long physical sampling program in that part of the Pacific.

Dr Schmitt is hopeful that his recent publications will attract interest from weather and climate forecasters, who may consider incorporating ocean salinity into their models. Data collection in this field is improving considerably. NASA satellites such as Aquarius and now SMAP are measuring sea surface salinities and soil moisture from space, while other systems such as the ARGO profiling floats are monitoring salinity and other variables in-situ. Meteorologists should be able to significantly improve both rainfall and drought forecasts in places such as the African Sahel and Midwestern United States if they accurately model the transfers of water from ocean to land and the role of soil moisture in the system.

Climate change, by increasing temperatures and the amount of water vapour in the atmosphere, is bound to affect the vast water cycle over the ocean. But changes and trends can be hard to measure, especially on land. 'Wet areas should get wetter and dry areas should get drier,' Dr Schmitt explains. 'That's hard to see on land because mankind has interfered with the terrestrial water cycle to a great extent.' Examples of interruptive processes include river dams, groundwater pumping, agricultural irrigation and power plants, which cycle 40% of US freshwater.

In the ocean, however, humans aren't able to interfere, and a clearer trend has been emerging in the last several decades. 'Saltier areas are getting saltier, and the fresh areas are getting fresher,' says Dr Schmitt. He explains that individual oceanographers have actually noted this pattern in various oceans for a long time. 'The global picture was put together by some good Australian scientists a few years ago. And so we have this record of an intensifying water cycle over the ocean. There have to be impacts of that intensification on land in the form of more intense floods and longer droughts.'

The key to understanding ocean-land teleconnections are long records, which poses challenges for the science world. For one, the average length of a scientist's career (30–40 years) compels them to do much shorter-term experiments rather than wait for a long time to analyse and publish their findings. Secondly, sustaining long-term records requires a lot of forethought and more importantly, funding, which can be inconsistent, especially in the US where politicians sceptical of climate change want to kill any related funding. Sadly, says Dr Schmitt, 'there's kind of a war on science going on.'

But he believes we owe it to future generations to build and maintain a global ocean observing system. In regard to long term climate change, the ocean is by far the dominant storage place for heat, water and carbon on planet Earth, and must be understood to anticipate the threats of sea level rise, floods and droughts, hurricanes, ocean acidification and fisheries collapse. But regardless of concern about climate change, the future financial return to society on modest investments in ocean monitoring is enormous, he says. 'The more we know about the climate system the better we will be at predicting its' future state.' The practical advantages of improved seasonal rainfall forecasts for farmers, water and emergency managers, and society in general are obviously substantial.

Meet the researcher

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Dr Raymond Schmitt is a Senior Scientist and Physical Oceanographer at the Woods Hole Oceanographic Institution in Massachusetts. He received his PhD in Physical Oceanography at the University of Rhode Island after obtaining his BSc in Physics at the Carnegie Mellon University in Pennsylvania. His early work on the small-scale double-diffusive mixing phenomena of 'salt fingers' led him to his later interest in the water cycle and global salinity patterns. In 1997 Dr Schmitt was named as a J. S. Guggenheim Fellow and in 2012 became a Fellow of the American Geophysical Union and was appointed to the Van Allen Clark Sr. Chair for Excellence in Oceanography. Dr Schmitt has published or co-authored over a hundred papers, and continues to research a range of oceanographic topics, including the global water cycle and oceanic mixing. He also advocates for improving and sustaining a global ocean observing system. He participated in the National Research Council's panel on 'America's Climate Choices' and contributed to the report, 'Advancing the Science of Climate Change'. He has served on numerous advisory boards, currently including the Earth Science Subcommittee of the NASA Advisory Council.

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Dr Kristopher B. Karnauskas, University of Colorado, Boulder

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MORE WATER, MORE FIRE? THE SURPRISING LINK BETWEEN INCREASING GLOBAL HUMIDITY AND SEVERE WILDFIRES

Increasing global temperatures have led to a worldwide increase in atmospheric water vapour. Paradoxically, this is correlated with an increase in the severity of wildfires and droughts. **Research by Professor William Lau** and his colleagues at the Earth System Science Interdisciplinary Center, using a combination of satellite data analysis and atmospheric modelling, is trying to find out if global warming means worsening wildfire events.

Wildfires and Global Warming

It is easy to see how dry, dense woodland leads to runaway wildfires. A single spark from an ignition source, be it arson or lightning, and kilometres of woodland can be up in flames, often in a matter of minutes. Windy weather conditions can quickly fan these flames further, damaging property and wildlife habitats alike. The year 2015 saw 10.1 million acres of woodland burnt across the United States with a firefighting bill of $2.6 billion.

With prolonged droughts in the western and south western United States, there has been a huge increase in both the severity and frequency of wildfires. The burned acreage in 2015 was the largest scale destruction seen since records began and the low levels of soil and plant moisture, symptomatic of drought conditions, provide the perfect kindling for rampant blazes.

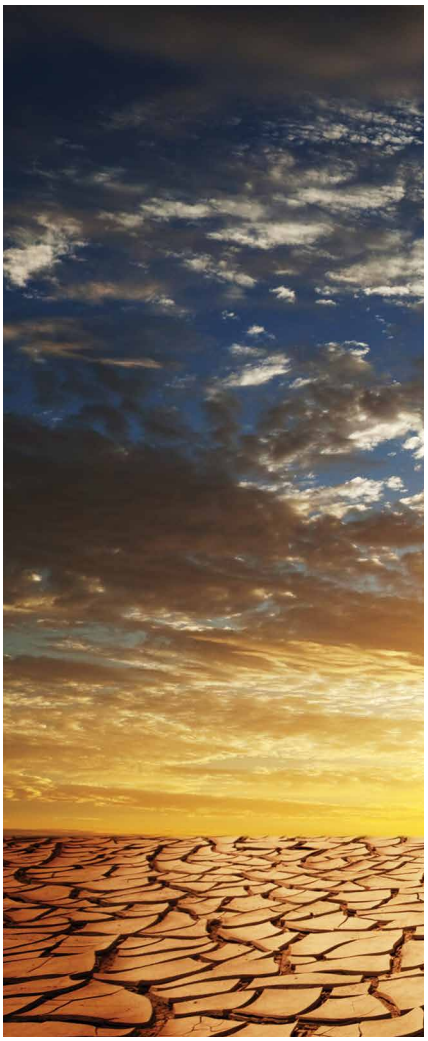
The bad news doesn't end there. Although the human and economic cost of wildfires may be obvious, wildfires pose an even more dangerous threat to the environment in terms of their contribution to global warming. When the trees burn down, there is not just the initial release of carbon dioxide and other greenhouse gases, but the destruction of forests means there are fewer trees to act as 'carbon sinks' to remove the excess carbon dioxide from the atmosphere. This leads to a vicious feedback loop, fuelling further environmental problems.

Given the severity of current wildfires and the grim predictions about the likelihood of future extreme weather events, it is imperative that we not only understand what causes wildfires but also learn how to predict when and where they might occur.

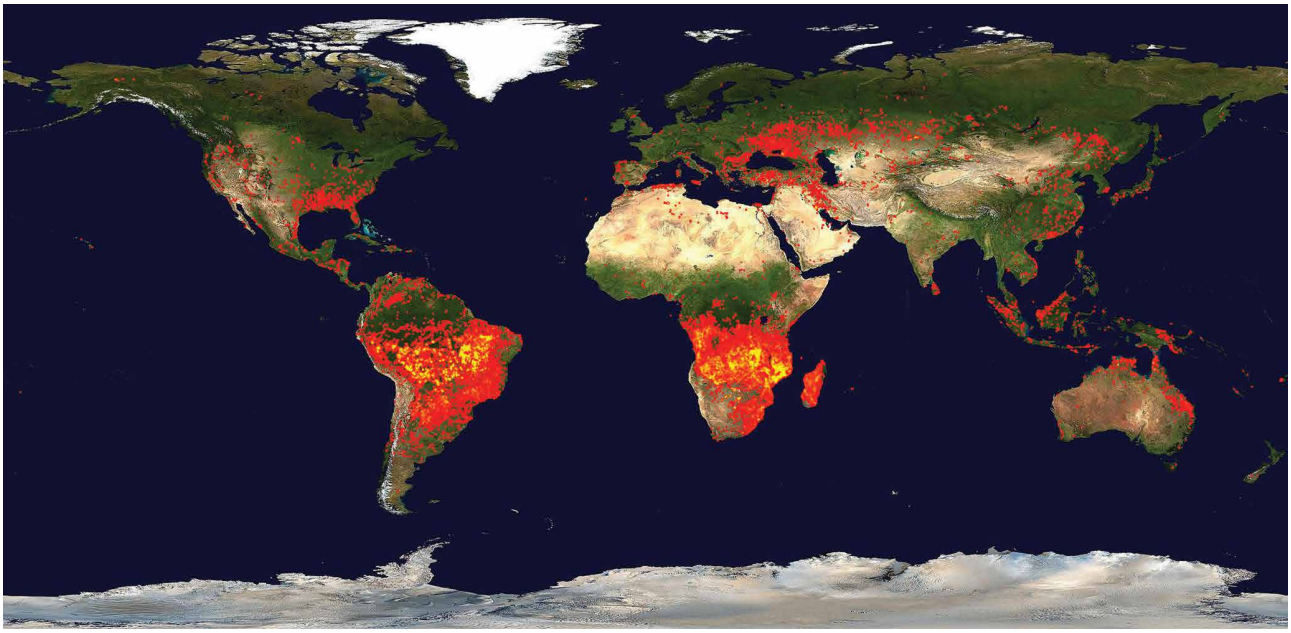
Firefighting and wildfire prevention efforts are largely dependent on meteorological data. However, the relationship between environmental conditions and the likelihood of wildfires is not as straightforward as it might seem. After all, not all droughts lead to the devastating fires seen in recent years and in fact, the increase of wildfires with rising global temperatures is actually something of a surprise.

This is because higher temperatures allow the atmosphere to hold more water vapour, meaning we should be seeing more of the humid conditions that are unfavourable for wildfire spreading. However, Professor William Lau at the Earth System Science Interdisciplinary Center states that 'we find that under greenhouse warming, the world is actually getting "relatively" drier', despite this increase in global water vapour levels.

Understanding this paradox is what has motivated Professor Lau's research looking at whether the increasing severity and frequency of wildfires can be predicted.



‘There is no doubt that we are living now in a warmer and wetter world under the effect of greenhouse warming. Therefore, it is perplexing that we are now seeing even more severe wildfires occurring around the world.’



Global Dryness and the Hadley Circulation

Why is it then that, despite there being more water vapour overall in the atmosphere, the world is becoming ‘relatively drier’? The answer lies in some of Professor Lau’s work looking at something known as the Hadley Circulation (HC).

HC is a gigantic overturning motion in the atmosphere that connects the tropics and the extratropics. In the ascending branch of the HC near the equator, warm, moist air rises, travels poleward at the upper troposphere, and then cools and sinks down to the surface at the subtropics and midlatitudes in the northern and southern hemispheres. The rising air at the equator leaves a region of low pressure there, whereas the cooler, drier air to the north creates a higher-pressure region as it sinks. Near the earth surface, the sinking air flows towards the equator, completing the circulation.

The impact of the HC is massive. It influences the global distribution of rainfall, clouds and relative humidity, and is responsible for the global weather and climate. Using computational modelling, Professor Lau has shown that carbon dioxide warming has led to the weakening and strengthening of components of the HC, in association with an overall reduction of tropospheric relative humidity. This leads to ‘tropospheric dryness’ that manifests as an increased risk of droughts in tropical and subtropical land regions, but also increased rainfall in equatorial regions.

The change in the HC is why certain parts of the world that are warming fastest are actually becoming ‘relatively drier’, despite an overall global increase in abundance of water vapour. Most worryingly, Professor Lau’s work predicts that under global warming, the HC will continue to intensify, and the areas of subsidence, which co-locate with the world’s deserts and semi-arid zones will continue to expand as the climate becomes even warmer. This could mean more widespread droughts and, potentially, the associated menace of wildfires.

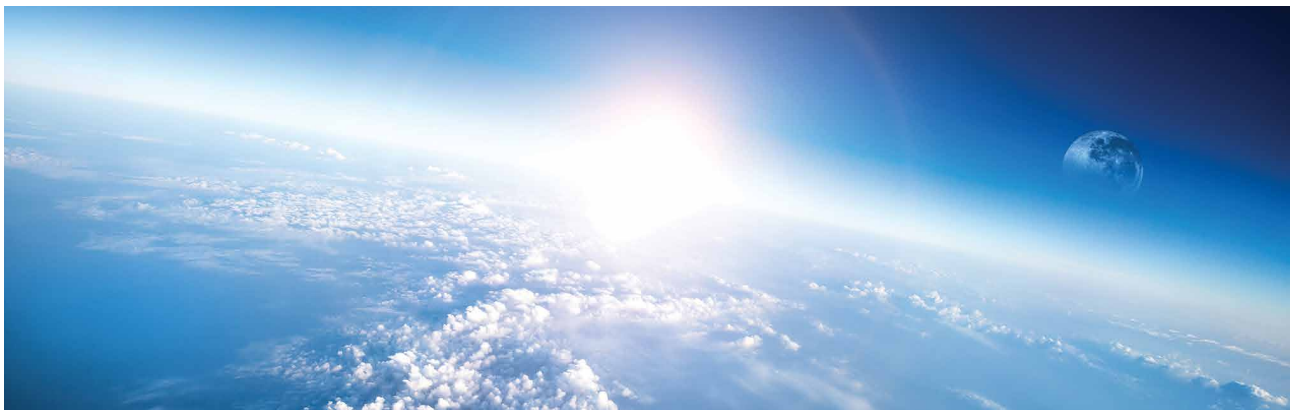
Most atmospheric phenomena are governed by these very complex and delicate feedback loops. Understanding the HC and its interactions with the regional weather and climate systems of the world, is an important part of predicting weather fluctuations and climate change.

Climate Modelling and Statistical Data Analysis

Computational models are one of the most powerful tools available for predicting future climate conditions. Theoretically, with a computational climate model it is possible to reconstruct environmental conditions from 10,000 years ago, or predict conditions 10,000 years into the future.

The challenges for researchers like Professor Lau and his colleagues are how to make those models accurate and useful. Models are validated by comparing their simulations with observed data from past events. This might include data collected from sources such as weather stations, and satellites. The simulations are then projected into the future based on a number of different environmental scenarios, for example, keeping emissions of greenhouse gases and/or air pollution aerosols at pre-industrial levels, at present levels, or reducing according to prescribed rates.

In his previous research, Professor Lau, was able to show ‘that there is predictability of precipitation events over the US on seasonal time scales’, through using a data analysis methodology called Empirical Canonical Correlation Analysis (ECCA). In the present



research, he and his team plan to use ECCA to identify variability and trends in the statistics, i.e., frequency, duration, and spatial coverage, for 'no-rain' situations, as a starting point for predicting wildfires. They will then seek the relationships of these statistics with a range of factors related to wildfires, such as flammability, fire fuel supply and surface vegetation characteristics in the regions of interest. Next, they will use climate modeling to see if the model can replicate the statistics. Because climate models have a complete set of physical variables for rainfall and wildfires, which observations lack, model simulation can help to better understand the physical 'feedback loop' underlying wildfires.

Finally, they plan to conduct numerical experiments under different emission scenarios, to examine possible trends in the no-rain statistics and related wildfires parameters. Being able to identify and predict trends in no-rain statistics is not just another way of making a weather forecasting more accurate, but can help us understand how physical processes related to wildfires are likely to be affected by changing conditions such as global warming.

Predicting Wildfires

What Professor Lau's team are now hoping to do is find ways of better predicting exactly how changes in environmental factors, like the HC, can impact wildfire frequency and severity. At present, although some of the factors that can contribute to the likelihood of wildfires are known, there are no robust 'environmental indicators' that can be used to accurately predict the occurrence or size of wildfire events.

By bringing together experts in atmospheric data analysis and modelling, Professor Lau's team are hoping to explore the relationship between elements of the atmospheric water cycle, such as temperature, rainfall, moisture level and winds, and wildfire characteristics. Lack of rainfall, and low relative humidity conditions lead to increased surface evaporation, and drier soil. Drier soil has a lower heat capacity and therefore can heat up more quickly. Higher air temperature increases evapotranspiration from vegetation and tree leaves, causing them to dry. Drier leaves increase fire flammability and provide more fire fuels. Hence, a warmer climate, reduced tropospheric humidity, decreased soil wetness and drier tree leaves, together with favourable meteorological conditions, such as strong wind, can contribute to a feedback loop that leads to more intense and widespread wildfires.

This is an immensely complex project, requiring the analysis of voluminous data from space and ground based observations, computer modelling and empirical data analysis, in order to make meaningful predictions about the behaviour of wildfires. Professor Lau, with over three decades of experience working at NASA looking at the impact of changes in atmospheric circulation on the Earth's water cycles, is uniquely qualified to bring together a wide range of experts to take a truly cross-disciplinary scientific approach to solving this problem.

Despite the associated contribution to greenhouse gas emissions and potential human destruction they can wreak, wildfires are not wholly bad and destructive events. Many plants rely on them to reproduce as the fires break open seed cases and break down organic matter to make nutrient-rich seedbeds for further growth. For areas where wildfires seem to occur almost seasonally, they are thought to contribute to biodiversity in the region. However, Professor Lau's research will help to assess the risk of destructive wildfires due to climate change relative to the 'natural' levels of wildfire events that sustain forest regrowth.

The current global temperature increases alone do not explain the increase in the frequency and severity of observed wildfire events in North America, which is where wildfires occur most frequently. Given that global warming does not just mean rising temperatures, but complex changes in surface humidity, seasonal cycles and physical weather such as wind conditions, the potential impacts of further global warming on wildfire frequency is not well understood. Professor Lau and his team at the Earth System Science Interdisciplinary Center are hoping to improve not just our understanding of how all these factors influence wildfire frequency, intensity and spread, but to find some type of 'environmental signal' that will mean that we are able to predict wildfire occurrence in North America on seasonal-to-interannual and longer timescales.

Looking to the Future

Although Professor Lau's research to date has focused on North America, he hopes to extend this work to examine wildfire-climate relationships and predictability across other regions in the world. Given the expectation that the droughts across large parts of North America are likely to worsen in the future and global temperatures will continue to rise, being able to predict potential locations and the severity of wildfires is essential for developing more effective prevention methods in the future. Preventing wildfires might not just be an issue of saving firefighting costs but also of limiting the potential damage of another contributing factor to global warming.

Meet the researcher

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Professor William Lau is a senior research scientist at ESSIC, and Adjunct Professor of the Department of Atmospheric and Oceanic Sciences, University of Maryland. He received his PhD in Atmospheric Sciences from the University of Washington, Seattle in 1977. After graduation, he was Assistant Professor at the Naval Postgraduate School before joining the NASA Goddard Space Flight Center in 1981. There, he served as the Head of the Climate and Radiation Branch, Chief of the Atmosphere Laboratory, and the Deputy Director for Science, Earth Science Division, NASA/GSFC. Professor Lau has been recognised for both his research and scientific leadership with the American Meteorological Society Meisinger Award for young scientist (1988), the NASA John Lindsay Award (1987), the Goddard Exceptional Achievement Medal (1991), the William Nordberg Award in Earth Science (1999), Distinguished Lecturer, Peking University (2016), Axford Lecturer, Asia Oceania and Geoscience Society (2017), and many others. He is a fellow of the American Meteorological Society and a fellow of the American Geophysical Union, and also served as the President of the Atmosphere Section, American Geophysical Union. Alongside these, he has served on numerous international science steering groups and expert panels on climate research.

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MEASURING HOW THE EARTH EXHALES

Atmospheric Scientist **Dr Merritt Deeter** at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado and his colleagues work with satellite data from NASA to measure levels of carbon monoxide and other pollutants released into the atmosphere around the globe.

Global Warming Versus Global Polluting

Tropical forests are critical ecosystems, both for those who live there and for the health of our planet. Burning of tropical forests creates a major air quality problem for both human and non-human inhabitants. And on the global scale, managing emissions from the burning of tropical forests is an important element of international strategies to combat global climate change. The fate of these forests should therefore be a concern for everyone.

Representing over half of the Earth's tropical rainforest, the Amazon Basin is an ecological goldmine, containing over 390 billion individual trees representing 16,000 species. Though environmental groups talk about the myriad of animal species that inhabit the Amazon forest, many of them endangered due to the destruction of the forest, the atmospheric effect of the great expanse of greenery is perhaps more noteworthy. Photosynthesis carried out by the Amazon's plants is responsible for the absorption of massive amounts of CO2 from the atmosphere, and the release of oxygen into the atmosphere on a daily basis – 20% of the earth's oxygen actually. For this reason, the Amazon, along with the other rainforests of the earth, are often called 'The Lungs of the World'.

Furthermore, half of the water in the Amazon is actually held in the trees themselves, and much of the rain that falls in the rainforest results from transpiration of moisture from the green leaves. Importantly, the sheer mass of vegetation alone, being organic material, represents a repository of approximately 17% of the global terrestrial vegetation carbon. However, this carbon stored in the trees and other vegetation is converted to atmospheric CO2 and other pollutants such as carbon monoxide (CO) if the forest is burned. This is the danger of deforestation – the cutting and burning the rainforest to produce farming and grazing land or for human roads and building – replacing active 'lungs' with massive amounts of CO2 and other gases. This is where Dr Merritt Deeter and his colleagues come in. They use data from NASA satellites and earth monitoring stations to visualise and measure gases released from the Amazon and other sites around the globe to better understand how the Earth's 'breathing' is being affected by human and natural processes.

Getting Data Is One Thing – Understanding It Is Another

'I'm generally intrigued by the application of technology to large-scale environmental problems, but I have a special interest in satellite remote sensing instruments and techniques,' Dr Deeter tells Scientia. While satellite-based methods for studying air quality and climate change have progressed dramatically over the last twenty years or so, like technology everywhere, the interpretation of the observations in these datasets is often still challenging. In other words, just because you get numbers from an orbiting satellite, you have to know what those numbers mean. If an infrared picture of the forest or the desert is red on your screen, does that mean the area is hot or cold? How do you interpret the raw data? How do you validate your final results with the actual conditions on the ground (or in the atmosphere)? Of course, you need the data first. That's what Dr Deeter uses a NASA satellite for – to obtain data on atmospheric concentrations of CO.

When You Want Data from Space, Get on Board with NASA

When one thinks of NASA, one thinks of astronauts and space shuttles. However, NASA has a long history of working on environmental issues. Dr Deeter's specific interest lies with NASA's satellite called Terra, the flagship of NASA's Earth Observing System. Launched in 1999 in a circular sun-synchronous polar orbit that takes it around the world every 99 minutes, Terra is about the size of a small school bus and contains five instrument packages for observing the various environmental systems of the earth. Terra's instruments include an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), a Clouds and Earth's Radiant Energy System (CERES), a Multi-angle Imaging Spectroradiometer (MISR), an instrument called Measurements of Pollution in the Troposphere (MOPITT), and a Moderate Resolution Imaging Spectroradiometer (MODIS). Dr Deeter's pet instrument in recent years has been MOPITT.

What Dr Deeter refers to as his 'day job' involves algorithm development for the MOPITT instrument. He describes MOPITT as a special type of radiometer which measures atmospheric CO concentrations using measurements in two distinct spectral regions. CO is toxic at high concentrations, and can also be converted into CO2 in the atmosphere, thus contributing to global warming. CO is also involved in the production of ozone, another health hazard. Atmospheric CO is generated primarily through combustion, such as fossil fuel burning and biomass burning. This biomass burning is the same thing that occurs in the deforestation of the Amazon, for example – vegetation is burned to clear areas for human endeavours. Dr Deeter leads the development of the algorithms and software used to generate the MOPITT CO data information that is made publicly available through NASA. He is also frequently involved in developing new applications for MOPITT data, such as the estimation of biomass burning emissions using data assimilation. In other words, if you want to know how much CO is being produced by the burning of the Amazon, Dr Deeter is your man.

MOPITT Versions Just Get Better and Better

MOPITT is designed to permit retrievals of tropospheric profiles of CO using both

‘I’m generally intrigued by the application of technology to large-scale environmental problems, but I have a special interest in satellite remote sensing instruments and techniques’

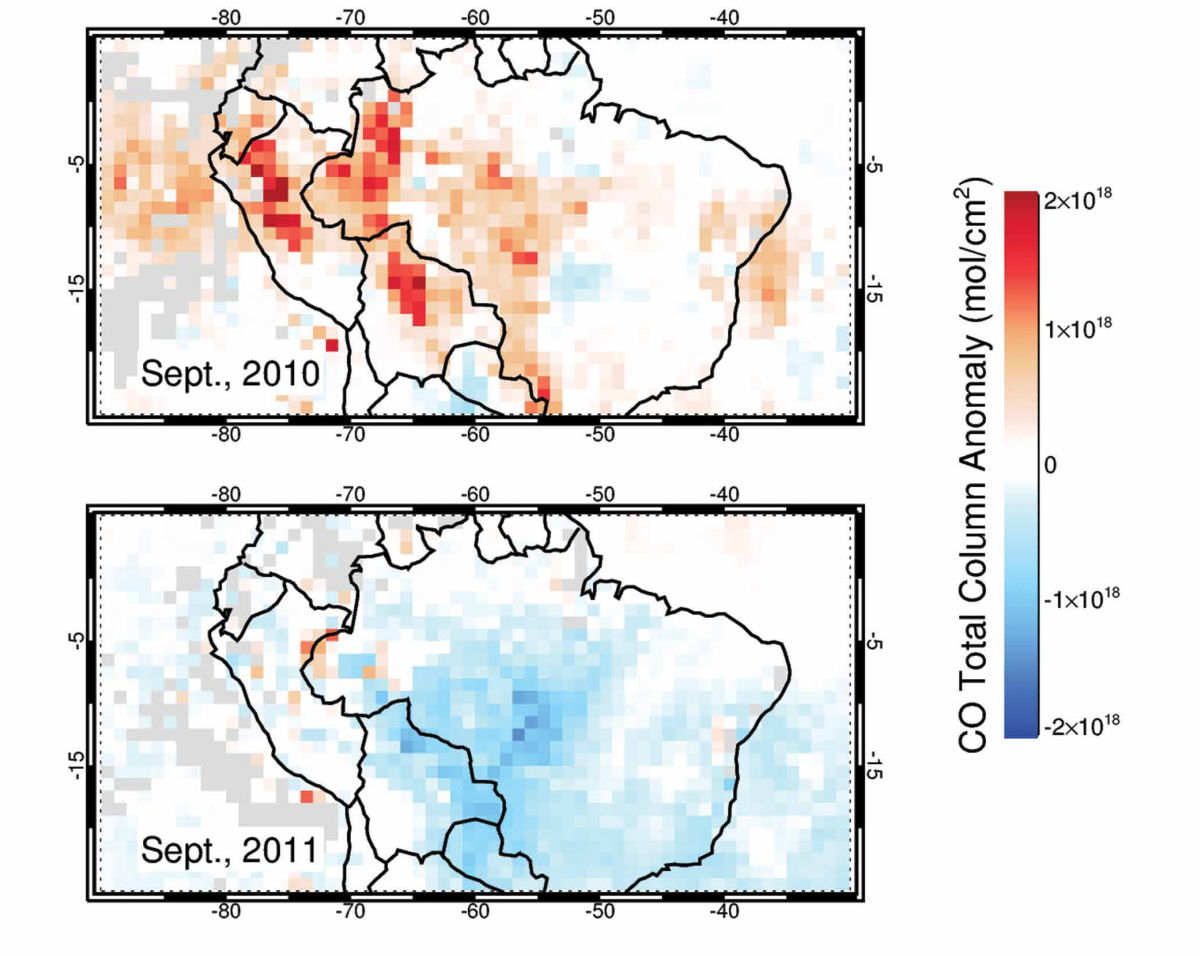
thermal-infrared (TIR) and near-infrared (NIR) observations. Such measurements of CO enable air quality forecasts, along with a variety of studies of pollution sources, transport, and atmospheric chemistry. MOPITT has been operational since 2000 and understandably there has been a learning curve in the development of the data processing software. Because of accumulated knowledge regarding the instrument, forward modelling methods, and geophysical variables, the MOPITT retrieval programming has improved continuously from the beginning.

The most recent version of MOPITT programming, Version 6, was developed by Dr Deeter and his NCAR team and was subsequently published in the journal Atmospheric Measurement Techniques. Dr Deeter and the group addressed a geolocation bias related to the orientation of the MOPITT instrument relative to the Terra platform and eliminated it in the new version. The improved geolocation data will benefit analyses of CO variability on fine spatial scales, including data derived from areas of urban pollution. They reduced a retrieval bias issue in the upper troposphere, which should help studies of trace gas variability in the upper troposphere and lower stratosphere. They also updated baseline CO calculations based on more a recent climatology model instead of older data, which should result in better background CO concentrations, particularly near regions of the actual CO source. Lastly, Dr Deeter and his group used a more recently available source of meteorological data, offering improved spatial resolution for atmospheric variables and a more physically appropriate source for surface temperature. Better programming means better CO data, which they were able to conclusively demonstrate by comparing Version 6 products with in-situ data. So, what does that data tell you?

Looking at Carbon Monoxide on the Amazon’s Breath

In a more recent publication in Atmospheric Measurement Techniques, Dr Deeter and his colleagues turned their attention to the Amazon. They analysed satellite retrievals of CO from MOPITT over the Amazon Basin, focusing on the MOPITT Version 6 ‘multispectral’ retrieval product that uses both TIR and NIR data channels. They validated their results based on local in-situ profiles measured between 2010 and 2013 at four sites in the Amazon Basin.

Their results showed a significant negative bias in retrieved lower-tropospheric CO concentrations that they thought might be due to



A comparison of CO emission patterns in the Amazon Basin as revealed in MOPITT observations for a drought year (2010) and a non-drought year (2011). Large-scale fires during the drought year resulted in exceptionally high CO concentrations, especially in the Western Amazon Basin. Results are presented as anomalies of monthly-mean CO total column relative to average values over the entire MOPITT mission and are based on the MOPITT Version 5 TIR-NIR product.

interference from smoke that obscures some areas when there is active biomass burning. They investigated this possible influence of smoke using ground measurements at two sites but it did not appear to be significant. Other possible causes of the mysterious bias are being investigated. They also compared TIR-only and TIR-NIR measurements and found enhanced sensitivity to CO in the lower troposphere for the TIR-NIR combination, especially during the Amazonian dry season. So using both sets of measurements at the same time was clearly beneficial.

All in all, their CO calculations were in agreement with historic values. However, an analysis of the history of monthly averages for the Amazon Basin showed that the largest CO emissions occurred in years when drought-driven fires burned very large areas. This may be a cause for alarm, since the more deforestation there is, the higher the likelihood of drought is. Recall that the Amazon vegetation produces much of its own rain. Less vegetation, less rain, more drought, more fires, more CO. It's a vicious cycle and one that data like Dr Deeter's can shed light on as his team's research progresses.

What Are the Group's Future Plans?

Dr Deeter's group and colleagues around the world have more work to do. 'My team is currently optimising the data assimilation system which integrates MOPITT observations and an atmospheric chemical transport model. The data assimilation system is being developed and tested by Dr Ave Arellano at the University of Arizona. A key element of this system is the representation of vertical mixing of biomass burning products in the chemical transport model,' he explains. In other words, when you burn the trees and the smoke rises, what happens to it and where does it go.

The height to which smoke plumes rise largely determines the direction the smoke travels and how quickly it disperses. For this challenge, he says, 'members of my team are developing a parameterisation for predicting smoke plume heights over the Amazon Basin.' This work is being led by Dr Maria Val Martin at the University of Sheffield (UK). When the assimilation system is complete and runs are conducted for specific years, the team will need to validate the assimilation results. That will involve comparisons of CO concentrations from the assimilation with independent in-situ measurements from a variety of sources including several field campaigns. Who knows? Maybe Dr Deeter and some of his group will have to put their boots on the ground in the Amazon rainforest and let it breathe on them directly.

Meet the researcher

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Dr Merritt Deeter received his PhD in Optical Sciences at the University of Arizona in Tucson in 1988. Dr Deeter then joined the National Institute of Standards and Technology in Boulder, Colorado, where he led a team of five researchers in the Optoelectronics Division developing fibre optic instruments. He and his team developed and characterised new optical materials and Dr Deeter was Principal Investigator on a project to develop high-sensitivity magnetic field sensors. He then studied Atmospheric Science at the University of Colorado in Boulder and received his MSc in 1997, thereafter joining the National Center for Atmospheric Research where he is now a Project Scientist III in their Atmospheric Chemistry Observations and Modeling Laboratory. Dr Deeter specialises in retrieval algorithm development for atmospheric remote sensing measurements, in particular the measurement of clouds and trace gases. He also works on radiative transfer modelling, validation methods, and data analysis. In particular, Dr Deeter is formerly the Principal Investigator on the project named Measurements of Pollution in the Troposphere (MOPITT), a satellite remote sensing instrument for monitoring the emission and transport of carbon monoxide around the world.

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TAKING A HARD LOOK AT AIR POLLUTION SO WE CAN ALL BREATHE EASIER

Research engineer **Dr Albert Presto** and his colleagues at Carnegie Mellon University's Center for Atmospheric Particle Studies use modern chemical analysis and computer modelling methods to try and understand pollution from our modern technology.

Oh, For a Breath of Fresh Air!

In 2008, one of the big scandals leading into the Beijing Summer Olympic Games was the Beijing air pollution problem. The news reports were replete with images of smog so dense that the buildings in the giant Asian city could barely be seen. Fortunately, the city and national governments took drastic measures to clean up the air, such as shutting down factories and other sources of particulate emission, and the games went without a hitch, at least from the standpoint of air quality. But the issue of air quality – or smog or pollution or whatever term one prefers to use – is not a new one. Residents of Los Angeles, California, beginning in the early 1940s experienced air pollution so bad that local historian Char Miller describes how 'parents kept their kids out of school; athletes trained indoors; citrus growers and sugar-beet producers watched in dismay as their crops withered; the elderly and young crowded into doctors' offices and hospital ERs with throbbing heads and shortness of breath.' Of course, in California and elsewhere in the US and other developed nations, exhaust emissions from millions of trucks and motor cars are often blamed for poor air quality. But automobiles aren't the only air pollution demon.

London's Great Smog of 1952 wasn't caused by automobiles – it was the proverbial perfect storm primarily caused by coal. A stretch of very cold weather and quiet wind conditions, coupled with the use of poor quality, sulphur-rich coal for home heating and industrial use, allowed for the emission of massive amounts of particulates, sulphur dioxide and other toxic gases, to the tune of more than 2,000 tonnes per day. Above ground transportation ceased – the Underground still functioned – and pedestrians literally could not see where they were walking, with visibility down to a metre or so at times. Medical facilities were taxed with cases of respiratory illness, especially in the young and elderly. Modern estimates put the number of deaths at over 12,000. Coal burning was the culprit, not motor vehicles. The bottom line was that fuel burning of whatever kind puts particulate matter and gases into the atmosphere that cause smog, whether in Beijing, Los Angeles or London.

Interestingly, modern research into the Beijing smog done by scientists at Texas A&M University led to a better understanding of the London Smog half a century before. Apparently, nitrogen dioxide and sulphur dioxide reacted in water droplets in the smog to produce sulphuric acid, which in London was concentrated when sunlight evaporated some of the water vapour. This sulphuric acid was deadly to the human victims in London. In contrast, ammonia gases from nearby agricultural activities in Beijing essentially neutralised the sulphuric acid, leading to a different outcome. It is this type of research – looking at particulates themselves that make up the pollution produced by vehicles, plants and other fuel users, as well as the chemical reactions that go on within the smog itself – that Dr Presto and his colleagues dedicate themselves to, in an effort to describe on-going pollution, understand how we create it and find ways that we can fix it.

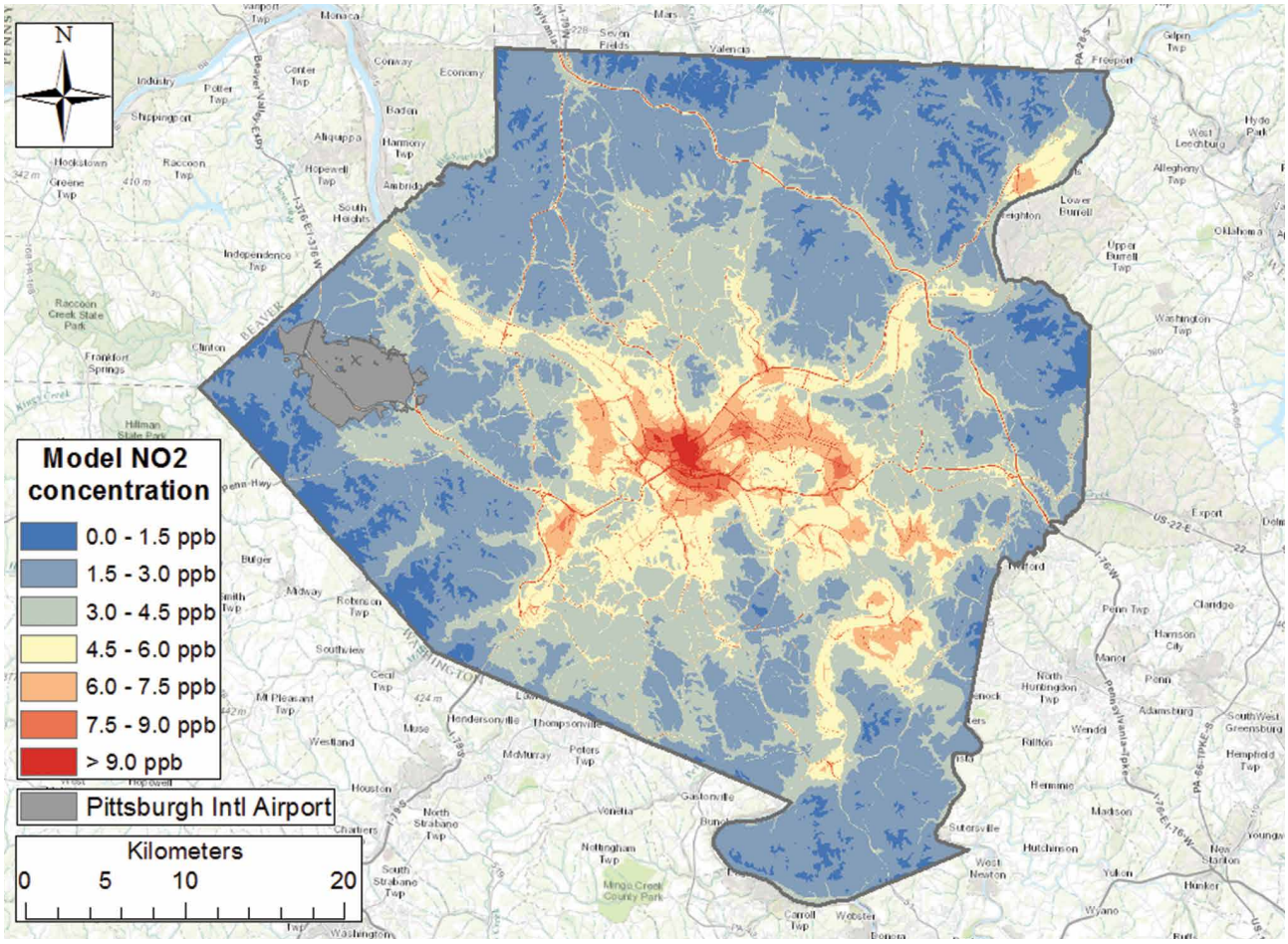
Don't We All Just Want Clean Air?

A common denominator of most global pollution is the burning of fossil fuels. Certainly, volcanic eruptions and other natural phenomena can cause problems – witness the Eyjafjallajökull eruption in Iceland in 2010 that disrupted international air traffic and deposited ash over much

of Northern Europe. But by and large, the common causes of air pollution, especially near large cities and other human concentrations, are industrial and motor vehicular exhaust from the combustion of oil, gas, coal and other fuels. To advance our understanding of the geographic distribution of pollutants, in the hope of developing ways to reduce them, Dr Presto and his collaborators use atmospheric measurements, laboratory studies, and mathematical methods.

Taking Pollution Science to . . . Monte Carlo

Since the 1950s and 1960s, scientists have been taking ever more accurate measurements of annual average concentrations of air pollutants to protect against conditions like those of London in 1952 or 1940s Los Angeles. However, there currently aren't many monitoring sites, limiting the capability of capturing intra-urban variations in pollution levels. Mobile pollutant mapping studies can measure pollutants at a



large number of sites during short intervals, but this snapshot analysis makes for substantial uncertainty in calculating annual mean concentrations, since levels vary over time. To quantify this uncertainty for existing sampling strategies and find ways to improve future studies, Dr Presto and his colleagues used the so-called Monte Carlo method on nationwide data from the US EPA Air Quality System.

The Monte Carlo method or Monte Carlo simulation is a computerised mathematical technique that looks at risk in quantitative analysis and decision-making. It was named after the famous casino because it provides a mathematical way to look at a range of possible outcomes and the probabilities of them occurring. In other words, what are your possible outcomes if you, say, draw a card versus if you hold'em? Seriously, though, the method was first developed by scientists working on the first atom bomb and now it's used by scientists in many disciplines to describe things that have a large degree of uncertainty, like Dr Presto's pollution data from too few monitoring sites or too short time intervals. Using this strategy, Dr Presto performs risk analysis by building a probability distribution of the outcome data and then recalculating results over and over, each time using a different set of random values from the probability functions. The Monte Carlo simulation then results in distributions of possible outcome values that Dr Presto can then use to make predictions and recommendations.

Dr Presto and his team found that the usual fixed sampling designs have much larger uncertainties than previously thought, but they produce accurate estimates of annual average pollution concentrations about 80% of the time. Mobile sampling has difficulty in estimating long-term exposures for individual sites, but performs better for groups of sites calculated together. The accuracy and the precision of both designs decrease when variation in the data rises, making it a challenge with sites impacted intermittently or randomly by local sources, like factory emissions that create wind-borne plumes. The more random or variable the data is, the harder it is to make it work. Dr Presto calculated that using reference sites to correct the measurements does not remove all the uncertainty associated with short duration sampling. However, they could tinker with that idea and obtain some possible answers.

Dr Presto and colleagues proposed reasonable methods for future mapping studies to reduce the uncertainties when estimating annual mean pollution concentrations. They recommend that future fixed sampling studies should involve two different week-long sampling periods over all four seasons. Furthermore, mobile sampling studies should employ five or more sites grouped together to estimate annual mean concentrations. The team's findings, which were published in the journal *Atmospheric Environment,* pointed to ways that pollution could be more accurately predicted with statistical number crunching of data that already existed and ways to plan for future data collection to get better results. However, measuring pollution and pollutants is one thing. Finding where they came from or what they are made of is another.

Studying the Evolution of Fossil Fuel Pollutants

Since the pollution in question here is from the burning of fossil fuels, then it is

necessarily organic – made up of carbon, hydrogen and oxygen. Just like in the Beijing and London smog, it appears that the chemicals in the pollutants – especially if they're dissolved in water vapour in the atmosphere – can interact chemically. To further explore this interaction, Dr Presto took his work to the chemistry lab.

In a paper he published in *Atmospheric Chemistry and Physics*, Dr Presto and his colleagues from Carnegie Mellon reported on experiments they performed using smog chambers. They wanted to look at the transformation of primary organic aerosol pollutants – the burnt fuel exhausted from fossil fuel burning engines – and the formation of secondary organic aerosols caused by exposure of dilute exhaust to sunlight and the atmosphere. They took exhaust emissions from a fleet of gasoline and diesel motor vehicles and gas turbine engines, and showed how the organic chemistry of the pollutants progressed after they were released from the engines. What they found was that these engines resulted in a combination of carboxylic acid and alcohol/peroxide formation – chemicals that are certainly important in atmospheric pollution. Basically, it's not just burned fuel that you have to worry about – it's also acids and alcohols that actually form in the exhaust when exposed to air and sunlight. Since over 50% of pollutants are organic aerosols, this could be a big problem. But this was lab work. What about getting out into the field again?

Checking Out the Air in Pittsburgh

Developing theories for measuring pollutants and working out the chemistry of the components in the laboratory is rewarding and important work. But Dr Presto and his group got up close and personal by applying some of their expertise to their own backyard – Pittsburgh in Pennsylvania. The team performed mobile monitoring of traffic-related air pollutants using Carnegie Mellon's 'Breathemobile' – a traveling lab they designed to map and monitor air quality. They drove this van around the Pittsburgh area, collecting data and increasing public awareness of the harmful impacts of air pollution. Their data revealed substantial geographic variability in particle-bound polycyclic aromatic hydrocarbons and black carbon, driven in large part by pollutant plumes from high emitting vehicles. These plumes were found to make up a disproportionately large fraction of the near-road particle-bound pollution and black carbon. To describe the pollution distribution, the team developed new statistical models and presented their findings at public meetings. And this idea – a mobile laboratory van – gave them a large amount of data to use to really get to the bottom of the pollution problem in Pittsburgh.

Pittsburgh was named – at least in 2014 – as one of the top ten most polluted cities by the American Lung Association. Dr Presto and his colleagues are actively attacking this problem with their Breathemobile and scientific expertise. By carrying out multiple studies investigating the type and distribution of pollutants in the Pittsburgh area, they have gained new insight into how pollutants spread throughout the city and where they tend to concentrate. Their results are making an impact too, as officials in both the city and state are taking a close look at the problem and Dr Presto's suggestions.

Meet the researcher

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Dr Albert Presto received his PhD in Chemical Engineering at the Carnegie Mellon University in Pittsburgh in 2005. He then carried out postdoctoral research until 2007 with the US Department of Energy's National Energy Technology Laboratory. Thereafter, he joined the faculty of Carnegie Mellon University, first as Laboratory Research Manager in the Centre for Atmospheric Particle Studies, and now as Assistant Research Professor in the Department of Mechanical Engineering and the Centre for Atmospheric Particle Studies.
Dr Presto's research addresses the contributions of primary and secondary pollution sources – cars and trucks, oil and gas wells – using ambient measurements, laboratory experiments, source testing of pollution sources, and atmospheric models. He also explores the environmental impact of these pollutants, particularly ozone and particulate matter, and their adverse impact on human health. To that end, Dr Presto collaborates with medical professionals to develop detailed studies of pollutant exposure on a local level, so as to better understand the relationships between pollutant emissions and human illness, such as childhood asthma. He has authored or co-authored over 40 articles published in peer-reviewed journals and other professional proceedings, and is a member of the American Association for Aerosol Research, the American Geophysical Union and the International Society of Exposure Science.

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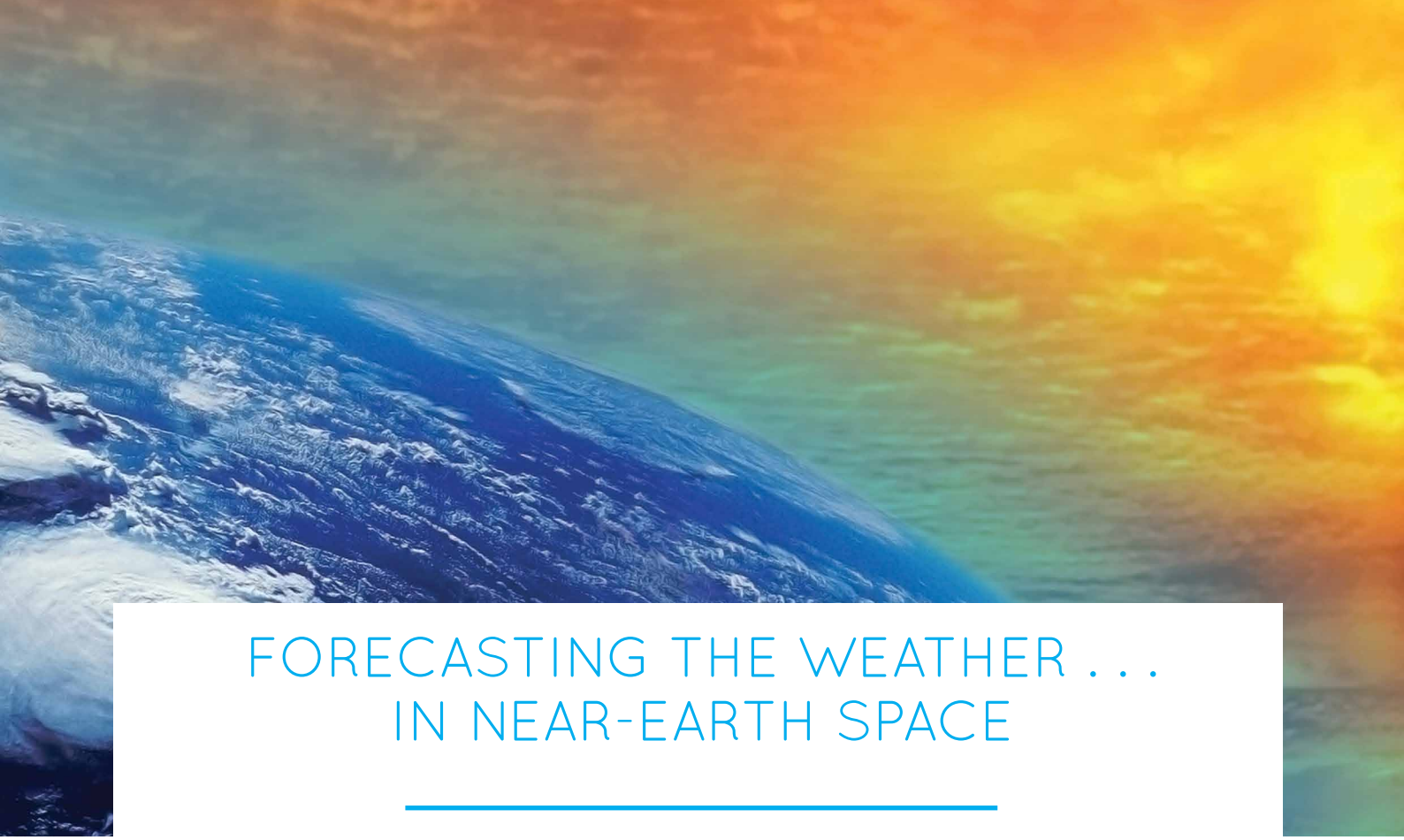
Carnegie Mellon University



FORECASTING THE WEATHER . . . IN NEAR-EARTH SPACE

As the last few articles have shown us, the devastating impact of human-induced climate change is becoming increasingly apparent. Terrifyingly, the effects of global warming, such as flooding, drought, wildfires and storms are expected to become more severe and widespread in the coming decades. The researchers introduced in our previous section are all working together through various means to mitigate the severity of this imminent global disaster. However, beyond the Earth's atmosphere, another danger lurks. While climate change leads to unpredictable and destructive terrestrial weather, the conditions surrounding our planet – or space weather – can also become disrupted, leading to serious problems here on Earth.

Space weather is caused by the continuous stream of charged particles released by the Sun – the solar wind – which comprises a plasma of highly energetic protons, electrons, helium nuclei and other particles. Luckily, Earth's outer core of molten iron generates a protective magnetic field, giving rise to the magnetosphere, which bends the paths of these charged particles, deflecting them away from the Earth's surface. Indeed, without the magnetosphere, life as we know it would not be able to survive.

Rather than releasing a steady stream of plasma, the sun can spew out enormous burst of particles and radiation, during events such as solar flares and coronal mass ejections – colossal magnetic rearrangements in the sun's atmosphere. Upon reaching Earth, this increase in the solar wind can compress the magnetosphere and transfer massive amounts of energy, resulting in phenomena such as geomagnetic storms, substorms and of course, beautiful auroral displays. During a geomagnetic storm, the increased electric current in the Earth's magnetosphere and upper atmosphere can affect the electricity we rely on, disrupting power lines, and even causing widespread blackouts.

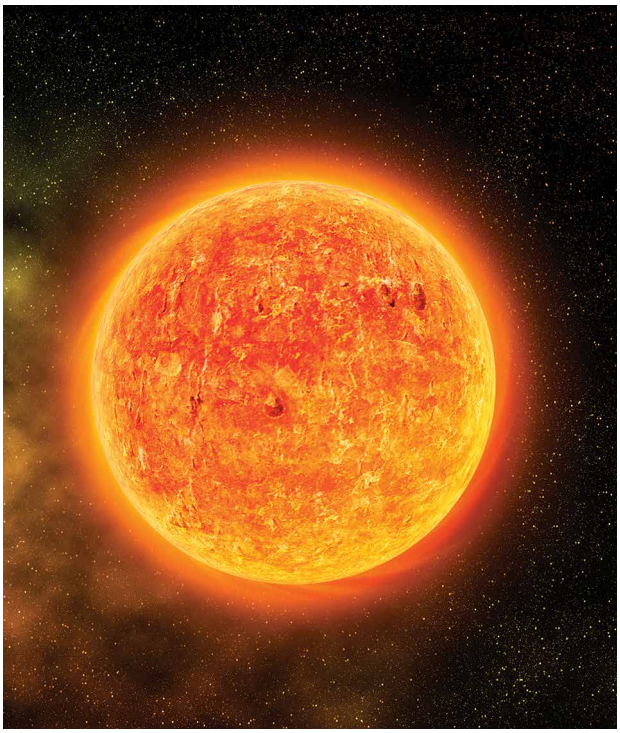
There are also numerous ways that increased solar wind and its effects on the magnetosphere can cause damage and disruption to satellites in orbit. As many of our communication systems, air-traffic control, weather forecasting, GPS and the internet rely on satellites to operate, their failure could ultimately lead to a rapid collapse of our society, with food supply chains soon breaking down.

For these reasons, and of course a desire to understand the interactions between our planet and the surrounding space, the scientists featured in this section probe near-Earth space to find the answers. To open this section, we have had the privilege of speaking with Professor David Sibeck, the 2015–2016 president of the American Geophysical Union's Space Physics and Aeronomy section. Professor Sibeck explains the huge importance of understanding near-Earth space, and discusses the American Geophysical Union's role in this fascinating field. We also asked him about his role as a NASA scientist, and some of the many high-profile projects he has worked on, including the Van Allen Probes mission.

Next, we feature the work of Dr Jian Du-Caines and her colleagues at the University of Louisville, who explore the interactions between Earth's atmosphere and near-Earth space. Specifically, Dr Du-Caines and her team look at phenomena such as atmospheric tides, planetary waves and gravity waves that arise primarily in the lower atmosphere, and can transfer energy to the middle and upper atmosphere. Over the past few years, they have made significant contributions to our understanding of how Earth's atmosphere interacts with near-Earth space dynamics in an effort to better predict space weather, which will allow us to protect our technology.

Also investigating the interaction between Earth's magnetosphere and the surrounding space is Dr Jesper Gjerloev and his colleagues at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland. His team developed a new system called 'SuperMAG' – a global network of organisations and agencies that operate more than 300 ground based magnetometers, to measure changes in the magnetosphere. Since these magnetometers cover numerous locations around the globe, their data can be combined to determine patterns and global behaviour. The team's results show that dynamical network analysis has huge potential to quantitatively categorise space weather events.

Our final article of this section introduces the ground-breaking work of Professor Vassilis Angelopoulos and his colleagues and students at the University of California, Los Angeles. To study the interaction of the solar wind with Earth's magnetosphere, his team use NASA research satellites – the famous THEMIS and ARTEMIS probes. In this article, we discuss the team's ground-breaking discoveries to date, along with their plans to launch a new mission called ELFIN, which has been designed and built by UCLA undergraduates, and aims to investigate electrons in the hazardous radiation belts around Earth.



AMERICAN GEOPHYSICAL UNION – SPACE PHYSICS AND AERONOMY

The Space Physics and Aeronomy (SPA) section of the American Geophysical Union (AGU) is the primary professional organisation for over 2800 scientists, engineers and space weather forecasters across the globe who are actively engaged in trying to understand and predict the physical processes linking the Sun's interior to the Earth's upper atmosphere. Addressing both problems of fundamental physics and those with societal consequences, the SPA section's members study topics ranging from coronal mass ejections to geomagnetic storms, and from the hazardous Van Allen radiation belt to aurorae on Earth and other planets. The Executive Committee of the SPA section works within the AGU to organise meetings, award medals and prizes to students and more senior scientists, advocate SPA section science, engage the public, and enhance the already high quality of AGU publications.

In this exclusive interview, we have had the pleasure of speaking with Professor David Sibeck, the 2015–2016 president of the AGU's SPA section. Professor Sibeck explains the huge importance of Space Physics and Aeronomy research, discusses the AGU's role in this fascinating field, and describes some of the ground-breaking work he has been involved with to date.

‘Probably the biggest challenge facing researchers in our field is choosing which of the many fascinating areas to work on’

To start, please mention some of the types of scientific research that fall under the category of Space Physics and Aeronomy.

Researchers within the SPA section study a wide range of processes that link the solar interior all the way down to the Earth’s upper atmosphere. Many, but not all, of these processes involve fundamental plasma physics, including magnetic reconnection, particle acceleration, and the generation of plasma waves. Given the immense breadth of the topics involved, the SPA section is divided into three subdisciplines. The Solar and Heliospheric subsection studies tremors within the Sun (helioseismology), transient solar brightenings known as solar flares that are often associated with the ejection of vast blobs of solar plasma known as Coronal Mass Ejections, Solar Energetic Particle (SEP) events, and the macro- and micro-structure of the solar wind. The Magnetospheric subsection studies the response of the magnetospheric bubble carved out by the Earth’s magnetic field to structures in the oncoming solar wind, including the microphysics of magnetic reconnection, the geomagnetic substorms that result in brilliant night-side auroral displays, and the processes that conspire to drive highly disruptive geomagnetic storms. Amongst other topics, the Aeronomy subsection considers the effects of magnetospheric particles precipitating into the upper atmosphere, the processes that create aurora, the structure of the ionosphere and its effects upon radio communication, and waves in the Earth’s upper atmosphere.

Many of the problems studied by researchers within the SPA section have practical applications in the rapidly developing field of Space Weather. Radiation in the form of SEP events in interplanetary space can harm astronauts on the way to, from, or at, the Moon or Mars. Radiation in the Van Allen belts poses a constant threat to the operations of communication and other spacecraft. This is particularly true during geomagnetic storms, prompting efforts to predict the occurrence of these hazardous events on the basis of numerical simulations employing observations of the Sun and solar wind as input. Disturbances within the ionosphere disrupt radio communications and Global Position System navigation, and can cause the complete collapse of power grids, as in the famous Hydro-Quebec outage of March 13, 1989. Variations in thermospheric properties can enhance drag and hasten the end of low altitude spacecraft missions.

The potential effects of space weather are so serious that they led to the recent (October 2015) release of a ‘National Space Weather Strategy’ by the National Science and Technology Council within the Office of Science and Technology Policy, outlining a series of urgent tasks for 7 United States governmental departments and 13 agencies.

What are the ways in which solar storms and other space weather events could affect our day-to-day lives? Describe one or two projects that the AGU’s SPA section is currently involved with to predict and mitigate the effects of a space weather disaster.

Although they can go unrecognised, space weather events affect our daily lives in many ways. Solar flares can cause radio communication blackouts. During intense SEP events, airlines reroute flights over the polar caps to lower latitudes to avoid passenger and crew exposure to radiation entering the Earth’s atmosphere. The flights take longer and there is a financial cost. Ionospheric storms and scintillations can cause errors of tens of metres in GPS-determined locations, an effect that can become important when landing aircraft during periods of low visibility. More extreme space weather events could disrupt communications or terrestrial weather observations by causing spacecraft to fail and disrupt electrical power grids at high latitudes. Currents induced by

space weather effects enhance corrosion in high latitude oil pipelines.

Researchers within the AGU's SPA section seek to understand and predict all of these space weather phenomena. They are developing first-principle physics based and empirical models to predict when SEP events will occur, the degree of 'hardening' required for prolonged spacecraft operations within the Van Allen radiation belts, the conditions under which GPS navigation can become hazardous, and the locations where power grids might be disrupted.

How does the AGU's SPA section work with policy makers to help us prepare for a devastating space weather event?

Scientists and engineers within the AGU's SPA section develop the empirical and first principle models needed to predict when space weather events will occur and the extent of the damage that they can cause. SPA section scientists serve on panels advising policy makers and are frequently called to testify and provide expert advice before the United States Congress. The AGU publishes a journal 'Space Weather' devoted to this topic and intended for a broad range of readers.

As a NASA scientist, you have been involved in many fascinating projects, including THEMIS and the Van Allen Probes mission. Please tell us a little about these projects, and the AGU's involvement.

I have been thrilled to serve as Mission Scientist for both the THEMIS and Van Allen Probes mission, helping to set the scientific objectives and encouraging researchers to extract the maximum information from both missions. Launched in 2007, THEMIS originally comprised five identical spacecraft in orbit around the Earth and an array of ground magnetometers and imagers look up at the night side aurora. In conjunction with the ground stations, the multiple spacecraft were used to separate spatial from temporal effects, a task needed to determine the magnetospheric origins of geomagnetic substorms and corresponding auroral brightenings. With that objective successfully completed, two of the spacecraft were repurposed and sent into orbit about the Moon, where they study the lunar environment to this day. The other three spacecraft continue to operate within the near-Earth magnetosphere, addressing a vast array of questions related to the nature of the solar wind–magnetosphere interaction.

Launched in 2012, the two Van Allen Probes spacecraft operate deep within the hazardous environment of the radiation belts. They carry comprehensive instrument packages to measure charged particles from energies of only 10 electron volts to those greater than 1,000,000,000 electron volts and both the AC and DC electric and magnetic fields in Earth's vicinity to provide information about the complex web of processes that energise, transport, and remove radiation belt particles from Earth's environment. The near-real time measurements that the space weather beacons on these spacecraft return in partnership with ground stations in a host of countries are provided free to the public and are being integrated into state of the art models that forecast conditions within the radiation belts.

The AGU is deeply involved in these missions and many more. AGU meetings are the places where we meet our colleagues, formulate plans to propose new missions, present initial results, try out our hypotheses, and find the best young scientists to come work with us. The AGU publishes our results in their technical journals and comprehensive monographs, and publicises our results in their EOS journal, which attracts a more general readership. It's a great partnership.

Finally, what do you see as the biggest challenges currently facing the field of Space Physics and Aeronomy?

I'm rather optimistic about the future of Space Physics and Aeronomy. Our field addresses both fundamental physical problems and problems with societal consequences. We have been and are fortunate in having a series of dedicated managers at all of our funding agencies in the United States who have the vision needed to plan for the future, who work in close partnership with each other, and who listen to our community.

Space is a big place. We all recognise the need for studies involving the cooperation of multiple agencies and nations, including careful planning and data sharing. There are exciting missions coming up like NASA's Solar Probe Plus and the European Space Agency (ESA)'s Solar Orbiter that will delve deep into the solar atmosphere and study the solar wind, the joint ESA and Chinese Academy of Sciences mission SMILE to view the Earth's magnetosphere in soft X-rays, and revolutionary new arrays of ground observatories like TREx that will comprehensively instrument the Canadian Arctic, thereby enabling detailed studies of the aurora and substorms. With the advent of cubesats, we have opportunities for more frequent missions carefully tailored to solve specific tasks, for example the recently selected NASA/Brazil SPORT mission to study the ionospheric space weather phenomena that disrupt communications at low latitudes. NASA's Explorer mission ICON will launch later this year to understand the interface between Earth's atmosphere and space. Dramatic advances in computing power make it possible to envisage real time space weather forecasting with increasingly realistic state of the art simulations.

It really is a great time to be a researcher in our community. Probably the biggest challenge facing researchers in our field is choosing which of the many fascinating areas to work on.

spa.agu.org

PROTECTING THE EARTH BY PREDICTING SPACE WEATHER

Atmospheric physicist **Dr Jian Du-Caines** at the University of Louisville and her colleagues explore the interactions between Earth's atmosphere and near Earth space to better predict space weather that can adversely affect life on Earth.

Everyone Talks About the Weather

Our weather – our Earth's weather – is always a topic of conversation. Of course, parents are worried about the weather when dressing their children for school. And polite conversation often devolves to 'how about this weather?' when awkward silence occurs. But what about *space weather* – does anyone talk about that? Who even knows what space weather is? As it turns out, space weather is vitally important to our way of life, particularly in technologically advanced societies. Our communication systems, travel and even national security can be affected by it.

The solar wind – massive amounts of ionised particles emitted from the sun and other solar eruptions – bombards the Earth's atmosphere daily. These particles interact with the Earth's magnetic field and produce numerous phenomena, such as the aurora borealis and aurora australis. They can also cause significant interruptions in the electric power industry, commercial aviation, GPS applications, satellites, and space flight. The solar wind's interaction with the Earth's thermosphere and ionosphere leads to the variable conditions in near-Earth space that we call 'space weather'.

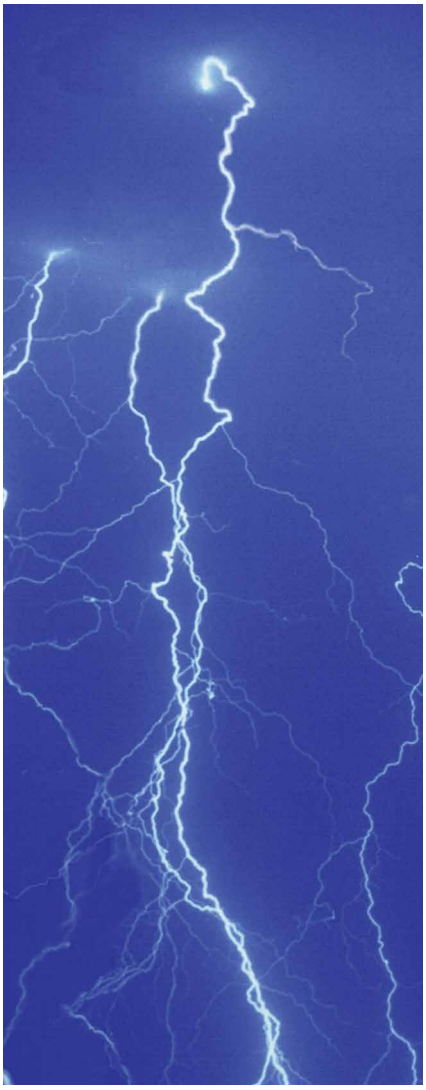
Unfortunately, our capability to predict space weather is on the same level as surface weather forecasting was around 50 years ago. We can predict severe space weather events, but only with minimal lead-time. Scientists – space weather forecasters – lack real-time data and only have limited weather model capabilities. This is where Dr Jian Du-Caines at the Louisville Atmospheric Science Program and her colleagues are concentrating their efforts. According to Dr Du-Caines, 'the big picture of our research is to study how the dynamics in the lower atmosphere impacts space weather variability and prediction.'

In other words, they are studying how the Earth's atmosphere interacts with near-Earth space dynamics in an effort to better predict space weather, allowing us to protect our technology and health from the effects of space weather. This branch of meteorological science and atmospheric physics is called *Aeronomy.*

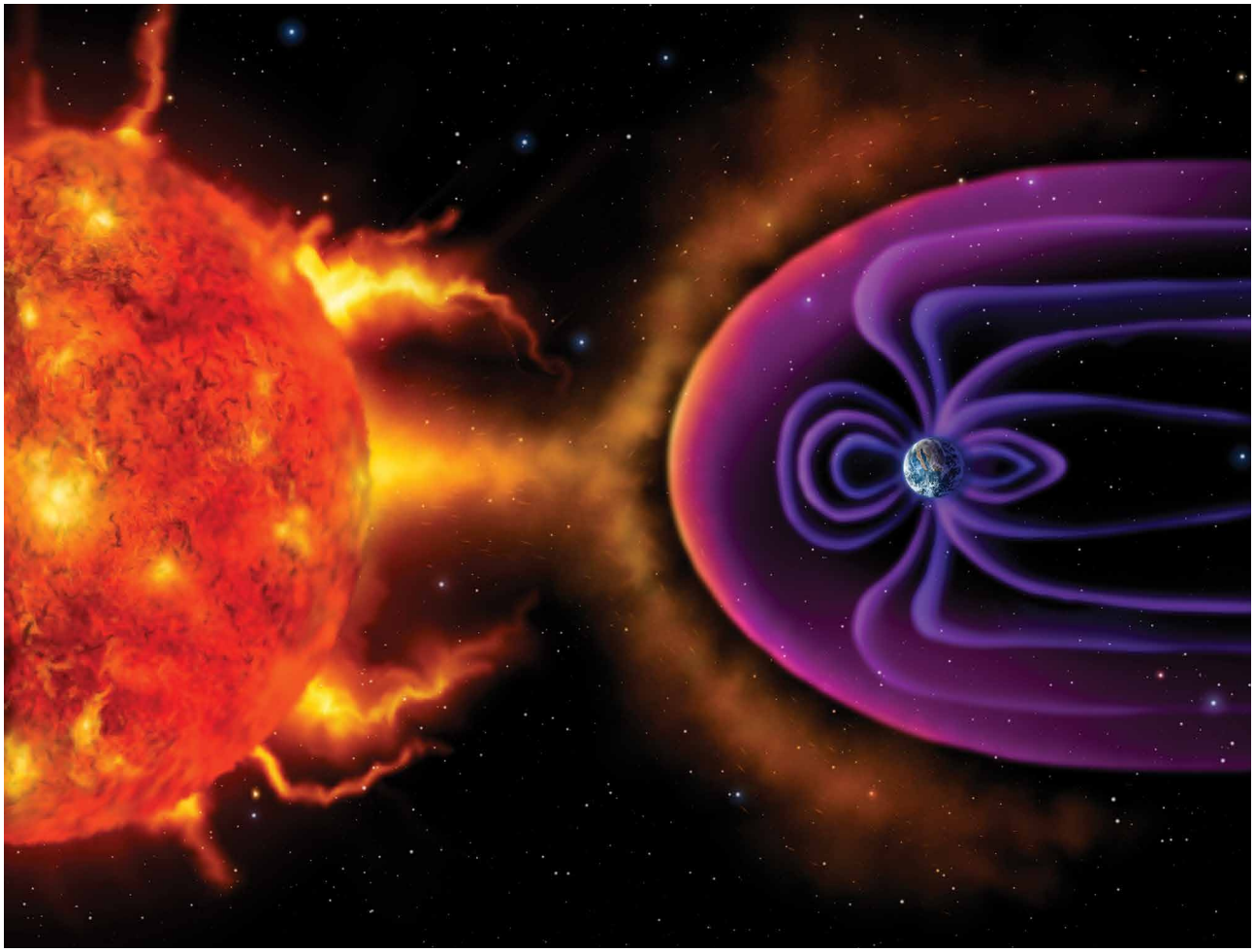
Understanding Weather on Earth to Predict Weather in Space

Usually, episodes of severe space weather occur when Earth is bombarded by the coronal mass ejections or solar flares. However, what most people don't realise is that the daily variability of space weather during quiet times can be markedly affected by the dynamics of the lower atmosphere. Specifically, such energy generators as atmospheric tides, planetary waves, and gravity waves that primarily arise in the lower atmosphere can transfer energy and momentum to the middle and upper atmosphere.

Currently, scientists estimate that these waves emerging from the lower atmosphere transfer about the same amount of energy to the upper atmosphere as that which comes from space during quiet geomagnetic conditions and medium solar conditions. 'Accurate day-to-day forecasting of space weather requires a better understanding of the temporal and spatial variability of these waves,' explains Dr Du-Caines. We need to know what the effects from these waves are in the ionosphere and thermosphere to be able to predict space weather, since about half of the driving force behind space weather comes from the lower atmosphere. For nearly a decade, Dr Du-Caines and her colleagues have made some important contributions to our understanding of the dynamics of the middle and upper atmosphere, particularly as it relates to atmospheric tides.



‘My main goal in the next five years in research is to better understand the temporal variability of atmospheric tides, especially their short-term variability, to better our space weather forecast capabilities, to publish high impact research results, and to train the next generation of researchers in Aeronomy.’



The Changing of the Tides

Atmospheric tides are global-scale periodic oscillations in temperature, density and wind, somewhat analogous to ocean tides. Atmospheric tides are driven by multiple forces, such as the daily solar heating of the atmosphere, the gravitational pull of the moon, interactions with planetary waves and convection heating in the tropics. Atmospheric tidal periods are integral fractions of a solar or lunar day, and can vary at different time scales, from short periods of a few days to longer periods of several months or years. In addition, atmospheric tides can have both migrating and non-migrating tidal components.

Migrating tides propagate westwards around the Earth at the same speed as the apparent motion of the Sun. These tides are generated when energy from the sun causes excitation in the troposphere and stratosphere, and therefore follow the Sun as it moves, from Earth’s standpoint, across the sky. The migrating tidal component should have the same amplitude along longitudes if measured at the same local time and latitude.

In contrast, non-migrating tides propagate either faster or slower than the apparent motion of the Sun and may travel westward, eastward or even remain stationary. Dr Du-Caines says that ‘the scientific community had held the misconception that migrating tides have much stronger amplitudes than non-migrating tides, and believed that non-migrating tides have a negligible contribution to the overall tidal field.’ This misconception led ground-based observers to believe that their tidal fields should be the same as long as they are observed at the same latitude. Dr Du-Caines and her colleagues proved this not to be the case in a series of studies they published over a period of seven years.

Writing on the Atmospheric Tides – Spatial and Temporal Variability

In 2007, the team published a paper in the *Journal of Atmospheric and Solar-Terrestrial Physics* that investigated the capability of an atmospheric model called the extended Canadian Middle Atmospheric Model (eCMAM). Using this model, the team studied migrating and non-migrating semidiurnal tides – tides that have a period of 12 hours. They simulated the atmosphere from the Earth’s surface to a height of 210 km, while

accounting for radiative heating, convective adjustment and latent heat release, as well as gravity-wave effects. They then compared their calculated results with real data from NASA satellites and ground radar stations in Jakarta and Kototabang, Indonesia. This was the first time that anyone had compared results from eCMAM with real ground and satellite measurements on atmospheric tides.

The team realised that the model could be tuned to obtain a closer agreement with real measurements. They found that the migrating semidiurnal tide is dominant at certain latitudes, but at other latitudes, non-migrating tides are stronger. Each tidal component has its own unique latitude-height structure and maximises at different latitudes, heights and times. Ground-based instruments observe a superposition of all the migrating and non-migrating tidal components of the same period. The total tidal fields can be very complicated and have strong geographic and temporal variability. So, the old belief that migrating tides – tides that are regular at the same latitude – were the 'normal' state of affairs was incorrect. Measurements would obviously have to be taken at different longitudes to adequately describe the tidal system.

In a paper published in 2010 in the *Journal of Geophysical Research: Atmospheres,* Dr Du-Caines and her colleague Dr William Ward, of the University of New Brunswick, applied the extended CMAM to a problem not many researchers had addressed before, the *terdiurnal* tides – tides that cycled every 8 hours, rather than every 12 or 24 hours. They showed the migrating and 10 non-migrating tidal components that varied with the seasons and both types, migrating and non-migrating, were significant. Once again, the old assumption that only non-migrating tides were significant was contradicted. It was also clear that these shorter period tides, cycling over 8 hours, were every bit as important as 12 and 24 hour tides. In fact, as Dr Du-Caines tells us, 'with the recent realisation that terdiurnal tides could vary significantly during some extreme atmosphere events, such as the sudden stratospheric warming, and cause space weather perturbations, this fundamental contribution to the study of terdiurnal tide will receive more attention in the years to come.' Her group – including students – continues to work on this fascinating subset of atmospheric tides. But it doesn't stop there.

Dr Du-Caines and her colleagues again turned the extended CMAM on a region where little research like this had been done – the polar region. They looked at diurnal, semidiurnal, and terdiurnal tidal components and found that basically all tidal components exhibit significant seasonal variations. Some tidal components are strongest during the same season in both the north and south polar regions. However, some tidal components reach their maximum at the same time but during opposite seasons in the polar regions. And yet other tidal components varied on a shorter than seasonal time scale. This different behaviour on the seasonal scale is still not well understood.

This first look gave some fascinating information that still needs to be correlated with real data from satellites. But the point remains – Dr Du-Caines and her group have done some ground-breaking work towards understanding atmospheric tides, and have dispelled some of the misinformation or misunderstanding that existed before they entered the game. This ground-breaking work also led to the award of a three-year National Science Foundation grant to look at how these atmospheric waves interact in the middle and upper atmosphere and a five-year NSF CAREER award to look at the physical mechanisms behind the inter-annual and seasonal change of the atmospheric tides. She and Dr Jens Oberheide from Clemson University have also been given a grant from NASA to study the short-term tidal variability on the order of a few days and correlate model calculations with NASA satellite data. The tides keep breaking in Dr Du-Caines' favour, for sure. But she doesn't restrict herself to simply studying atmospheric tides these days.

Looking Beyond the Tides of Progress and Spreading the Word

Dr Du-Caines has been looking at a number of different aspects of the atmosphere lately, including lightning, global relative humidity in the lower atmosphere and more recently, the basic dynamic state of the Earth's atmosphere. She even pays attention to the atmosphere of Mars! Of course, she will still continue to investigate the tides. Recently, Dr Du-Caines' and her postdoc Dr Quan Gan have been looking at vertical coupling between the lower and upper atmosphere due to obscure atmospheric waves such as one with a period of 6.5 days.

However, Dr Du-Caines feels that the transition from the study of seasonal/climatological atmospheric tides to a more big-picture understanding of tidal weather is a must, in order reach a point where we can actually predict space weather. She tells us that her 'main goal in the next five years in research is to better understand the temporal variability of atmospheric tides, especially their short-term variability, to better our space weather forecast capabilities, to publish high impact research results, and to train the next generation of researchers in Aeronomy.'

Meet the researcher

Dr Jian Du-Caines
Department of Physics and Astronomy
University of Louisville
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USA

Dr Jian Du-Caines did her undergraduate studies in China, receiving her Bachelor's degree from the Chengdu Institute of Meteorology in 1999 and her Master's degree in 2002 from the Lanzhou Institute of Atmospheric Physics. She then pursued graduate work at the University of New Brunswick in Canada, where her dissertation was entitled 'A mesosphere and lower thermosphere dynamics study using the Extended Canadian Middle Atmospheric Model (CMAM).' She received her PhD in 2007, followed by three years of postdoctoral work at the University of Cambridge in the UK. In 2011, Dr Du-Caines joined the Atmosphere Science Program in the Department of Physics and Astronomy of the University of Louisville, where she is now a tenure-track Assistant Professor.

Dr Du-Caines' research interests broadly cover how weather in the lower atmosphere impacts space weather variability and prediction. Her specific interests include middle-atmosphere energetics, dynamics and tides, the vertical coupling of atmospheric regions, and prediction of space weather. In addition to her research, Dr Du-Caines supervises PhD student research and teaches a number of undergraduate and graduate courses in meteorology, weather analysis and independent study.

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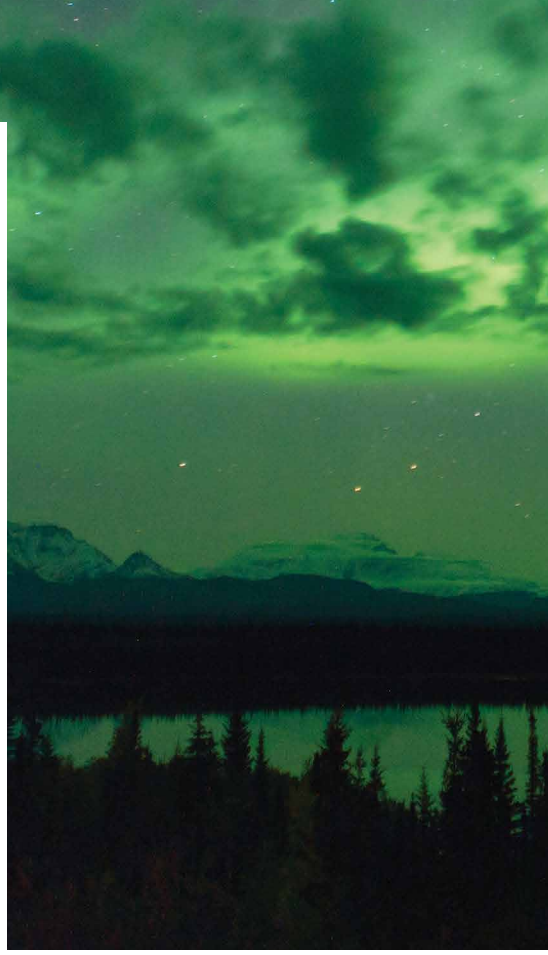
EARTH INTERACTIONS WITH SPACE – DO WE FINALLY UNDERSTAND THEM?

Space scientist **Dr Jesper Gjerloev** and his colleagues at the Johns Hopkins University Applied Physics Laboratory in Laurel, Maryland, are part of a world-wide consortium of scientists studying the Earth's interactions with near Space.



Mother Earth's Magnetic Personality

Due to its outer core of liquid iron, our Earth has a magnetic field that projects into the nearby surrounding space. Not only does this magnetic field affect such things as compasses, allowing explorers to determine direction, but it also interacts with the solar wind – streams of charged particles ejected from the Sun that bombard our planet. These particles are neither solid, liquid nor gas, but plasma – a fluid that consists of highly energetic ions. The conditions inside the Sun are so extreme that positive and negative ions move too fast to join together to form neutral molecules. Instead, they simply blast through space with their own intrinsic positive or negative charge.

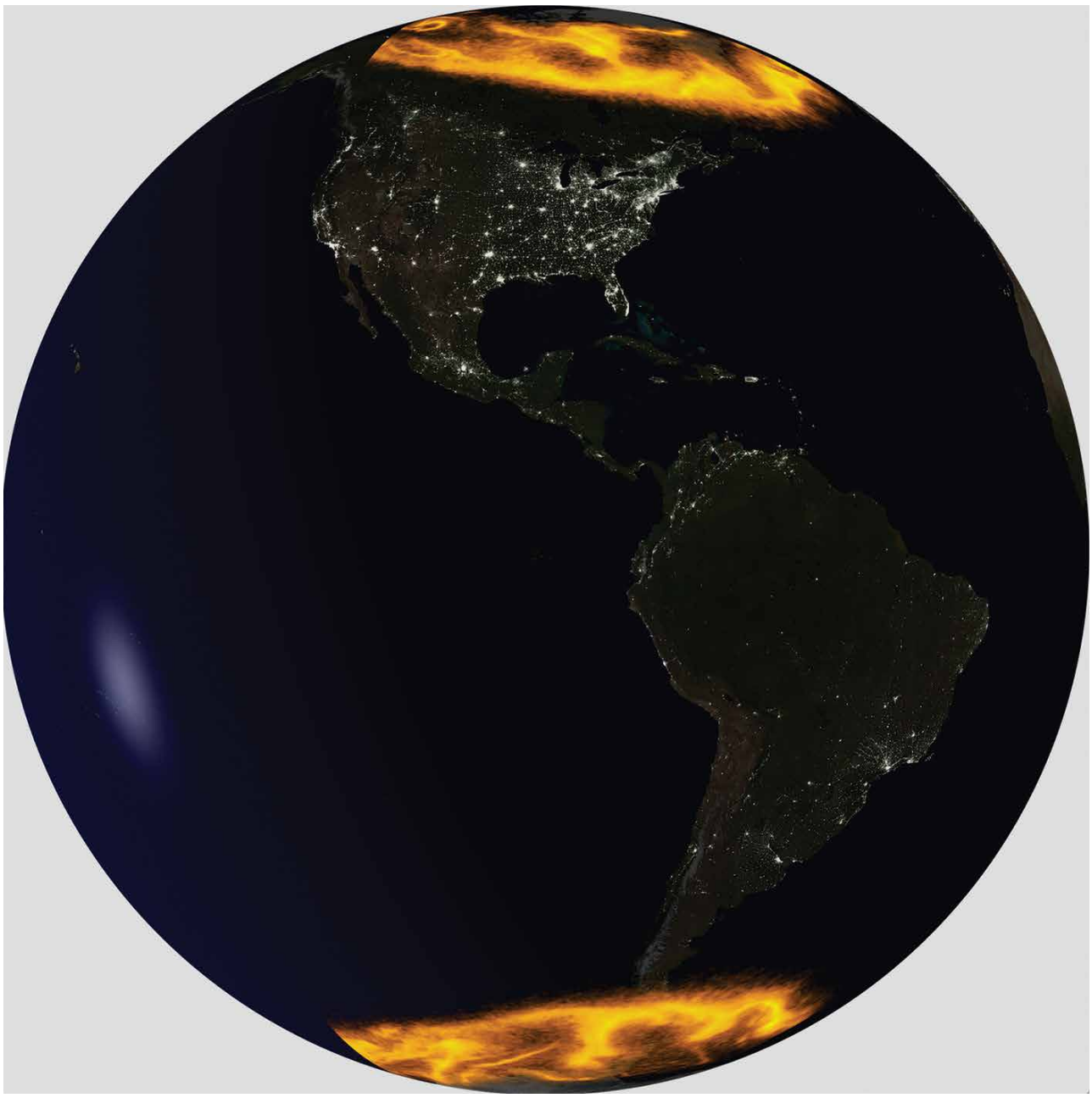
The volume surrounding Earth that has sufficient magnetic force to interact with the solar wind is called the magnetosphere. As the solar wind flows towards and by the Earth, it interacts with our magnetosphere, while at the same time, this stream of particles also affects the magnetosphere. On the day side of the Earth – that facing towards the Sun – the magnetosphere is pushed towards the Earth by the pressure the solar wind. On the night side, the solar wind that flows around the Earth pulls the magnetosphere so it stretches away from the Earth like the tail of a comet. On the day side, our magnetosphere extends over 90,000 kilometres above the Earth's surface, while on the night side the magnetosphere's 'tail' stretches over 6,300,000 kilometres into space, sometimes even encompassing the Moon. But in areas around the Earth, the interactions between the magnetosphere and the solar wind cause fascinating and even romantic phenomena like the aurora borealis and aurora australis, the Northern and Southern Lights. This is where Dr Jesper Gjerloev has directed his research pursuits – the interaction between the Earth's magnetosphere and the solar wind.

A Long and Winding Road . . . Ending in Space

Dr Gjerloev began his university studies in something seemingly more practical than space physics – engineering. However, he tells Scientia: 'After six months I realised that everything I was interested in and questioned the engineering professors about was dismissed as not important. Thus, I changed to physics at the University of Copenhagen and felt at home immediately.' His plan initially was to study earth physics, but in his third year he finally joined an earth physics class and actually found it boring. Just by luck, he took a class in space physics and was instantly hooked. As he remembers it: 'I asked so many questions the other four students got pretty annoyed with me, but I found the concepts absolutely fascinating.' He ultimately asked the professor if he could write his master's thesis on the topic of space physics. Although he was the first student for many years that had requested that topic, allowances were made. Perhaps it was not exactly the most sensible choice in terms of a career – after all, how much money is there in space? – but Dr Gjerloev felt there was no choice, since his eyes were now turned to the stars. Unfortunately, he won his Ph.D. funding at the engineering university – back where he didn't want to be. Luckily, after a year they sent him, of all places, to NASA-Goddard Space Flight Centre where he fit right in and stayed, focusing his doctoral thesis on auroral electrodynamics. His career direction was thus cemented.

Dr Gjerloev's passion is trying to understand the interactions of the solar wind, the

magnetosphere, and the ionosphere – the inner layer of the magnetosphere that consists of particles ionised in part by solar radiation. Because the Earth revolves around the Sun and rotates on its axis – not to mention the fact that the solar wind varies because of, for example, sun spots – the solar wind interacts with the magnetosphere in complex ways and the magnetosphere-ionosphere also interacts in complex ways. Of course, this arrangement is common to all magnetised bodies in the solar system, such as Jupiter, Saturn, Uranus and Neptune, and even some moons, like Ganymede. 'Unravelling the electrodynamic driving of the Earth's magnetosphere-ionosphere system is the first step toward building a scientific foundation for understanding general electrodynamic coupling processes between magnetospheric plasmas and a conductive ionosphere boundary,' Dr Gjerloev tells us.



'I have spent time developing systems that allow global and continuous coverage of this system.' One of those 'systems' that Dr Gjerloev founded and leads is called SuperMAG.

Scientific Social Networking

On December 15, 1832, the German mathematician Carl Friedrich Gauss presented a paper before the Göttingen Royal Scientific Society about a new instrument he had devised to calculate an absolute value for the strength of the Earth's magnetic field. The instrument could do this by suspending a bar magnet from a gold fibre and measuring its oscillations when it was magnetised and not magnetised. He had constructed a magnetometer. Soon after, other types of magnetometers were invented and centres proliferated around the world, measuring the Earth's magnetic fields here and there and making scientific pronouncements on many scientific issues. But as Dr Gjerloev tells Scientia, 'These magnetospheric interactions are global and highly dynamic.' Thus, a scientist measuring magnetospheric phenomena in, say, Berkley, California, will measure different magnetic results than scientists from Lancaster in the UK or from Moscow in Russia. The 'big picture' of the Earth's magnetic activity would actually be a correlation of the data from many independent magnetometer sites from around the world, reconstructing a dynamic three-dimensional picture of the Earth's magnetic activity. But even as more and more universities and other organisations put together magnetometer centres to study these issues, the problems of collecting data from diverse and distant centres became obvious.

Global magnetometer studies that use observations from observatories throughout the world are inhibited or even prevented by a number of complications. First, the data has to be collected and correlated properly. Second, we must isolate the contributions to the measured magnetic field which are due to the electrical currents flowing between the Earth and space. This is done by carefully subtracting the Earth main field and local magnetic effects – such as from local metal deposits – from the measured field. Thirdly, all centres must use the same coordinates, both spatial and temporal. In other words,

everyone has to use the same 'map' of the world and their clocks must be perfectly synchronised. Finally, artefacts and errors must be accounted for.

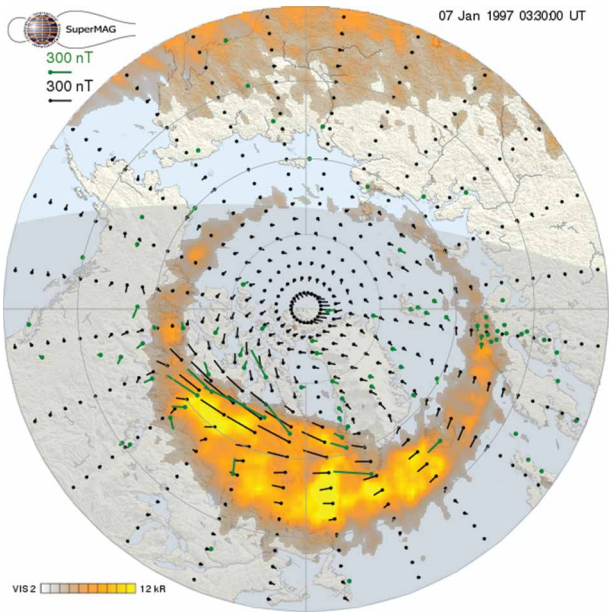
To solve these problems, as well as to make the data from magnetometer centres available for others besides the scientists involved in the data collection, Dr Gjerloev and like-minded scientists developed a new system called 'SuperMAG', a global collaboration of organisations and agencies that operate more than 300 ground based magnetometers. SuperMAG is conceptually a Facebook or iCloud for magnetometer centres. It provides a collection and correlation system to give easy access to validated ground magnetic field perturbations in the same coordinate system, identical time resolution and with a common baseline removal approach. This system allows scientists, teachers, students and the general public to log on and have easy access to measurements of the Earth's magnetic field all in the same 'language'. And Dr Gjerloev is the principal investigator of the SuperMAG collaboration.

Getting the World Together

How do we understand how currents transfer momentum and energy to and from the ionosphere and find the link between the dynamic multi-scale current filaments and the complex auroral display? Electrical currents are fundamental to the interaction between a magnetised body like the Earth and the surrounding space plasma. Such currents represent the dominant mechanism of momentum and energy transfer. Terrestrial currents mediate the motion of enormous volumes of magnetospheric plasma rushing earthward. With faster rotating planets, such as Jupiter and Saturn, scientists have seen that extensive regions of heavy plasma encircling the planets are swept up and accelerated by these currents to the planetary rotation rate, ultimately forming giant magnetodiscs. Dynamic currents of multiple scales – whose complexity is visually manifested by magnificent aurorae – communicate the momentum and energy exchange between the distantly separated magnetosphere and the ionosphere.

Aurorae are the lower manifestation of an enormous system of electrical currents flowing in space along the planet's magnetic field lines. These field-aligned currents (FACs) or 'Birkeland currents' are now known as the primary means of energy and momentum transfer between the magnetosphere and ionosphere. FACs couple the two into a single electrodynamic system held together by complex electric and magnetic fields and the mutual exchange of plasma. In a long list of articles, Dr Gjerloev and co-workers promoted the idea that the aurorae provide a natural reference frame to organise measured electrodynamic parameters. Without imaging, the observations are made blindly, without an understanding of what phenomena the observations are related to.

Because simple statistical treatment of this type of data tends to smear out the very features of interest, and insight into the underlying physical processes is limited, Dr Gjerloev and his team have recently published the first analysis of substorms using dynamical networks obtained from the full available set of ground-based magnetometer observations in the Northern Hemisphere. They essentially constructed a network – like Facebook or LinkedIn – linking magnetometer data from more than 100 sites and determined patterns and global behaviour. Their results were surprisingly promising and indicate that dynamical network analysis has the potential to quantitatively categorise space weather events.



'The social impact of the solar wind-magnetosphere-ionosphere system is increasing as we become increasingly dependent on space-born assets as well as many other technological systems that are affected.'

However, the team's work is not over yet. As Dr Gjerloev wistfully says: 'Space physics as a discipline that is in its infancy. Processes viewed as fundamental for the system are still not completely understood because of limited observational support.' There are just too few data points yet and much is still to be discovered and understood. This is partly due to the massive range of scale sizes that play a role, as well as the complexity of the system.

Where Do We Go from Here?

Going forward, Dr Gjerloev faces a number of difficulties. He believed he has two main hurdles to overcome. 'First, the social impact of solar wind-magnetosphere-ionosphere science is increasing as we become increasingly dependent on space-born assets as well as many other technological systems that are affected' he explains. In other words, the more satellites and space stations we have in orbit – technology we depend on for communication and other vital services – the more imperative it is that we know how the magnetosphere-solar wind dynamics affect those delicate electronics. Secondly, there's always the issue of scientific curiosity. Despite decades of research, Dr Gjerloev says that 'we are still at the infancy in our understanding of the system.' One obvious problem is our inability to make predictions. The whole magnetosphere-solar wind system is highly complex, dynamic and structured, in addition to being heavily under sampled. While the northern hemisphere is well-covered with magnetometers, the Earth's southern hemisphere has notable gaps in coverage. 'As a result, the field is left with simplistic models and quasi-religious beliefs,' says Dr Gjerloev. Instead of falling into the political chaos that has swallowed the climate change controversy, Dr Gjerloev wants his science to be based on data – data collected worldwide, correlated and calibrated – that even school children can access and study it.

Meet the researcher

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Dr Jesper Gjerloev received his PhD in Space Physics from the Technical University of Denmark, Lyngby, in 1998. His doctoral thesis focused on auroral electrodynamics from work performed at NASA-Goddard Space Flight Centre in Maryland in the USA. In 2003, Dr Gjerloev joined the Senior Professional Staff at the Johns Hopkins University Applied Physics Laboratory where today he is the Lawrence R. Hafstad Fellow. He is also Adjunct Professor in the Department of Physics and Technology at the University of Bergen, Norway.
Dr Gjerloev's research interests focus on space science, in particular the coupling of the Earth's magnetosphere and ionosphere and its relationship to space storms and aurorae. He founded and is the PI of SuperMAG, a worldwide collaboration of organisations and national agencies that currently operate more than 300 ground based magnetometers to collect data on the Earth's ground magnetic field perturbations.

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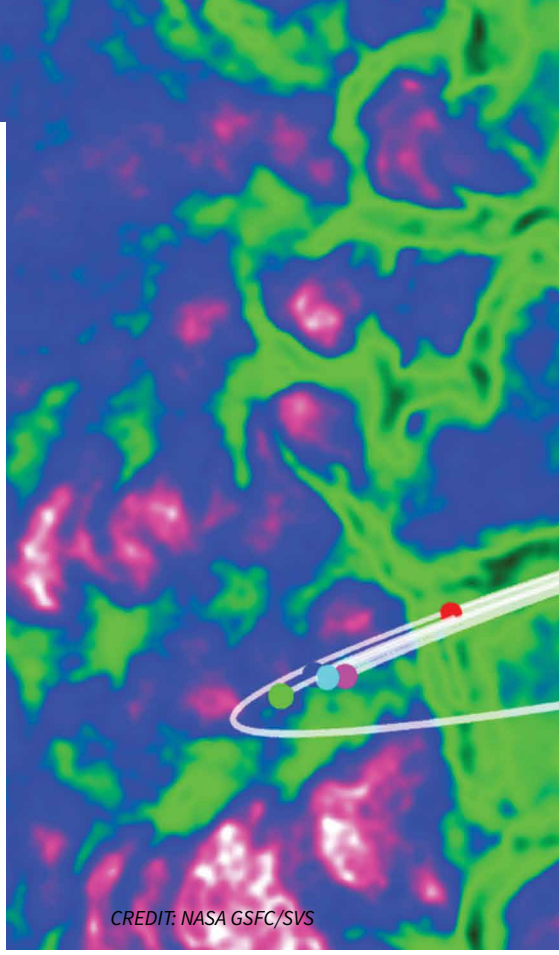
FROM THEMIS TO ELFIN: EXPLORING NEAR EARTH SPACE

Dr Vassilis Angelopoulos and his colleagues at the UCLA Earth Planetary and Space Sciences Department in California study the interaction of solar radiation with the Earth's magnetosphere using multiple NASA research satellites. Their aim is to protect our modern technology from being ravaged by solar storms while educating the next generation.



CREDIT: NASA GSFC/SVS

Too Much of a Good Thing

The Sun is ultimately the engine of all life on Earth. The radiation from our Sun powers our atmosphere, provides our food and supports the Earth's entire biosphere. Without energy from the Sun, all life would end and the Earth would eventually become a cold, dark planet. But on occasion, the Sun puts out a little too much energy in the form of solar flares.

First described back in 1859 by the amateur astronomers Richard C. Carrington and Richard Hodgson, a solar flare is a sudden and massive release of magnetic energy – on the order of millions of hydrogen bombs – that travels outward into the solar system, interacting with objects in its path. In particular, ionised particles and magnetic fields released from solar flares, in the form of coronal mass ejections, interact with Earth's magnetic field, and can cause huge damage to electrically sensitive equipment. This is important for us on Earth, since our civilisation has become increasingly dependent upon complex electronics.

Solar storms and solar flares can disable satellites, threaten orbiting astronauts and overload electric transformers on Earth. In fact, former US President Obama warned that such phenomena could 'significantly degrade critical infrastructure – could disable large portions of the electrical power grid, resulting in cascading failures that would affect key services such as water supply, healthcare, and transportation.' In other words, solar storms might cause system wide power failures that don't just turn off the lights. They could also lead to a massive human toll when food, water and other necessities cannot be distributed, leading to disease, famine and even death on a global scale.

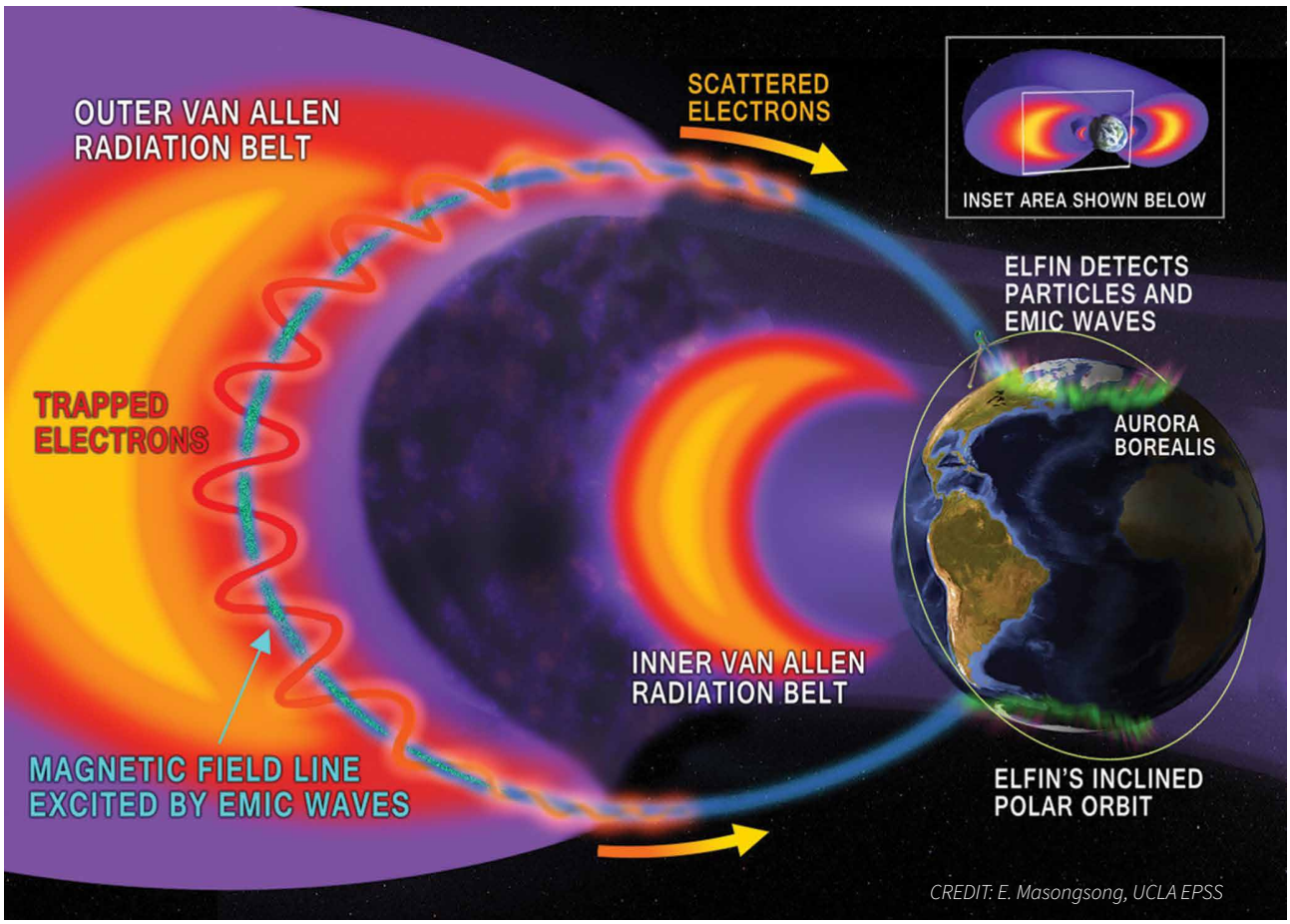
This is exactly the scenario Dr Angelopoulos and his colleagues are interested in forecasting and preventing from happening. He tells *Scientia* that he and his team have been 'studying space weather, and in particular one aspect in greater detail: how does solar energy become converted into the harmful radiation that zaps satellites, threatens astronauts and creates space electrical currents which can fry transformers of the power grid on the ground?' This energy conversion, which powers damaging magnetic storms, is not easy to figure out, but by using advanced satellites orbiting the Earth and the Moon, Dr Angelopoulos and his team are making some headway.

Probing Energies in Near Earth Space

As the energy released from the Sun – called the solar wind – flows past the Earth, it interacts with the Earth's magnetosphere. The solar wind is composed primarily of high-energy plasma – matter that is so energised that it becomes ionised, with electrons being ripped from atoms and molecules. Since plasma is ionised and therefore magnetic, it interacts with magnetic fields, like the magnetic field of the Earth. The Earth, with its spinning metallic core, is after all a large magnet, with a north pole and a south pole. The resultant magnetic field surrounding the Earth – the magnetosphere – deforms the solar wind and diverts its flow, while the solar wind deforms the magnetosphere as well. On the dayside of the Earth, which faces towards the Sun, the pressure of the solar wind compresses the magnetosphere closer to the Earth. On the night side of the Earth facing away from the Sun, the solar wind drags the magnetosphere out over great distances, forming a tail similar to that of a comet. The interaction between the magnetosphere

CREDIT: NASA GSFC/SVS

and solar wind causes massive bursts of energy that can often be seen from the Earth's surface as aurorae – dramatic light shows especially at higher latitudes. In the northern hemisphere, aurorae are termed the aurora borealis, while in the southern hemisphere, it's the aurora australis. Up until a decade ago, the mechanism by which aurorae and other solar wind phenomena were generated were not well understood. However, since 2007, satellite probes have been exploring the regions of space where the solar wind and the Earth's magnetosphere interact, sending back information to explain what's going on in our



CREDIT: E. Masongsong, UCLA EPSS

neighbourhood. These probes are the result of a major effort by Dr Angelopoulos and his colleagues at UCLA. Under the mission names of THEMIS and ARTEMIS, the probes have been exploring the physical processes occurring between the magnetic field and solar wind, to understand the causes of the aurorae and magnetic storms in the Earth's magnetosphere. Here we discuss the team's ground-breaking discoveries to date, along with their plans to launch a new mission – called ELFIN – which aims to investigate electrons in the hazardous radiation belts around earth.

THEMIS: Looking for Answers from The Gods

Formally, the THEMIS project is entitled the 'Time History of Events and Macroscale Interactions during Substorms'. But a double entendre points the name to Themis, the Greek goddess of justice, wisdom and good counsel. The daughter of the sky god Uranus and the Earth goddess Gaia, Themis is the perfect patroness of scientists studying the auroras and other manifestations of the Earth's interaction with the solar wind in the sky.
Dr Angelopoulos' group and NASA designed the THEMIS mission to determine where and when the energy exchange occurs between the solar wind and the magnetosphere relative to the ground. According to Dr Angelopoulos, they did this by lining up the five THEMIS probes and tracking the flow of energy to determine its origin with sufficient time resolution. In other words, they mapped the flow of energy as it moved from the solar wind plasma through the magnetosphere. Their findings were published in the journal *Science*.

'We found that the trigger of the energy release is magnetic reconnection, a process whereby magnetic field lines – visualised as stretched rubber bands – are broken and then re-connected to form two loops that are allowed to contract,' Dr Angelopoulos explains. 'The field line contraction results in transferring energy released by reconnection towards the Earth, which then accelerates particles to high energies and creates the space currents.' The energy is thus transformed from magnetic flux to kinetic energy, thermal energy and acceleration of particles. This is how aurorae are formed from the deformations of the magnetosphere by the solar wind. But it was still not clear exactly how the energy was actually converted. One thing they noticed was that the energy release was only in a small location in space, usually about 25 Earth radii away from Earth at the night side. But the Earth's magnetosphere's tail is very large, stretching much further than that. So why is this energy release so localised?

To figure this out, Dr Angelopoulos and his team tallied the total energy in the system, measuring where that energy is converted and estimating whether that energy conversion is sufficient to give the results they actually saw. But the total energy coming from the solar wind was difficult to measure without a spacecraft far enough from Earth where good estimates of the magnetosphere tail size could be made, say greater than 30 Earth radii. Since the radius of the Earth is about 6400 km, that means over 192000 km – about half way to the Moon. The scientists realised that they could not coordinate the furthest THEMIS probes from Earth well with the closest ones because their orbits were significantly interfered with by the moon. So, in Dr Angelopoulos' words, 'rather than trying to beat the moon, we decided to join it.'

ARTEMIS: Getting the Most Out of What You've Got

In a strategy that enabled NASA to extend the THEMIS probes' mission and save millions of dollars, the team used the remaining fuel on two of the THEMIS probes to raise their orbits and enter Moon orbit, about 60 Earth radii from home. This new mission was called ARTEMIS – 'Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun'. The objectives of this new mission were to study the lunar space environment and to get into the Earth's magnetosphere's tail and make estimates of the total magnetic energy content. The repurposed probes could also be better aligned with the remaining three THEMIS probes to determine where the energy conversion was occurring. In a paper published in Science, Dr Angelopoulos and his group reported that the energy conversion occurs within extremely thin sheets of electrical currents in space. At only about 10 km thick, these current sheets or magnetic fronts can convert all the available energy from magnetic energy into particle energy.

So first of all, the kinetic energy of the solar wind is converted into magnetic energy in the Earth's magnetospheric tail. This magnetic energy is then converted back into particle energy when the magnetic fields reconnect. It is the conversion of that energy back into particle energy that ultimately powers the aurorae. This conversion also heats up the magnetospheric plasma and energises the Van Allen radiation belts – areas on the inner part of the magnetosphere that sequester energised particles. In other words, the 'weather' in space around our Earth is in large part determined by the solar wind blasting away at the Earth's magnetosphere. This causes storms, substorms and other phenomena, and just like our terrestrial weather, we would like to be able to predict our space weather. Dr Angelopoulos and his team are up for that.

Into the Future – ELFIN

In order to develop quantitative models of space weather, you have to understand the correlation and self-organisation of the energy conversion regions into one large magnetic storm. Dr Angelopoulos believes that this will require multiple small satellites that can make multi-point measurements over broad areas in space with sufficient spatial resolution. So, he and his team have now embarked on a miniaturisation effort with the potential to radically change how they conduct space research. 'Rather than using classical spacecraft, we would be using flotillas of space buoys,' he explains. 'There is a trend to capitalise on CubeSat technology to help advance space instrumentation. We are looking to do that for energetic particle detectors.'

A CubeSat – also called a U-class spacecraft – is a miniaturised, cubic satellite made primarily with off-the-shelf electronics. Relatively cheap and small, CubeSats are used extensively with the International Space Station and its scientific projects. Dr Angelopoulos' team are now in the process of building a CubeSat that can be used in fleets launched in the magnetosphere. Their proposed mission is called ELFIN – Electron Losses and Fields Investigation.

Designed and built by UCLA undergraduates, ELFIN's goal is to investigate high-energy electrons that travel at relativistic speeds in Earth's radiation belt, and to understand how they become knocked out of their cyclical orbits by low frequency electromagnetic waves. This process scatters the electrons that are then guided by the Earth's magnetic field and fall into the atmosphere. Then, at an altitude of about 100 km above the poles, these electrons finally lose their harmful energy, generating auroral displays in the process. This effective emptying of the radiation belts moderates increases in electron fluxes caused by solar events. 'We need to understand these loss processes to assemble the full picture of how space radiation is driven by solar particles,' Dr Angelopoulos explains.

But that's not the only expected benefit of ELFIN. There is already a great reward being reaped at UCLA – ELFIN and its CubeSats are at the forefront of higher education. Dr Angelopoulos proudly tells *Scientia* that the project provides opportunities for students to work in a professional environment and develop critical thinking and problem solving abilities that are much needed in research and industry. Dr Angelopoulos' vision is that innovation and discovery come from transcending disciplinary boundaries and approaching problems holistically. His students are exposed to a fast-paced research environment with realistic goals and obstacles. Furthermore, with information readily available through Internet resources, teaching students how to critically and effectively process information towards generating new knowledge or products becomes the new role of academia. Dr Angelopoulos' ELFIN project is more than just checking space weather around the Earth. With ELFIN he's trailblasing a new way of teaching science at the university level.

CREDIT: E. Masongsong, UCLA EPSS

Meet the researcher

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Dr Vassilis Angelopoulos received his PhD from the University of California at Los Angeles in 1993, for a thesis on Space Plasma Physics. After receiving his doctorate, he worked as a post-doctoral researcher at the Applied Physics Laboratory at Johns Hopkins University. After working as a research physicist at the University of California at Berkeley, Dr Angelopoulos joined the faculty at UCLA in 2007 where he is now Professor of Space Physics.

Dr Angelopoulos' primary interest is the study of how particles are accelerated by and in the Earth's magnetosphere, and how the upper atmosphere, the ionosphere and the lunar environment respond to space currents driven by the solar wind. Dr Angelopoulos is the Principal Investigator of the ELFIN Cubesat nanosatellite mission, supported by grants from NASA and NSF. He is also Principal Investigator of THEMIS – a five satellite and 20 ground based observatory mission proposed and managed by the UC-Berkeley's Space Science Laboratory – and Principal Investigator of the ARTEMIS project – a two satellite lunar mission. Dr Angelopoulos has authored or co-authored more than 500 articles published in peer-reviewed journals and other professional proceedings.

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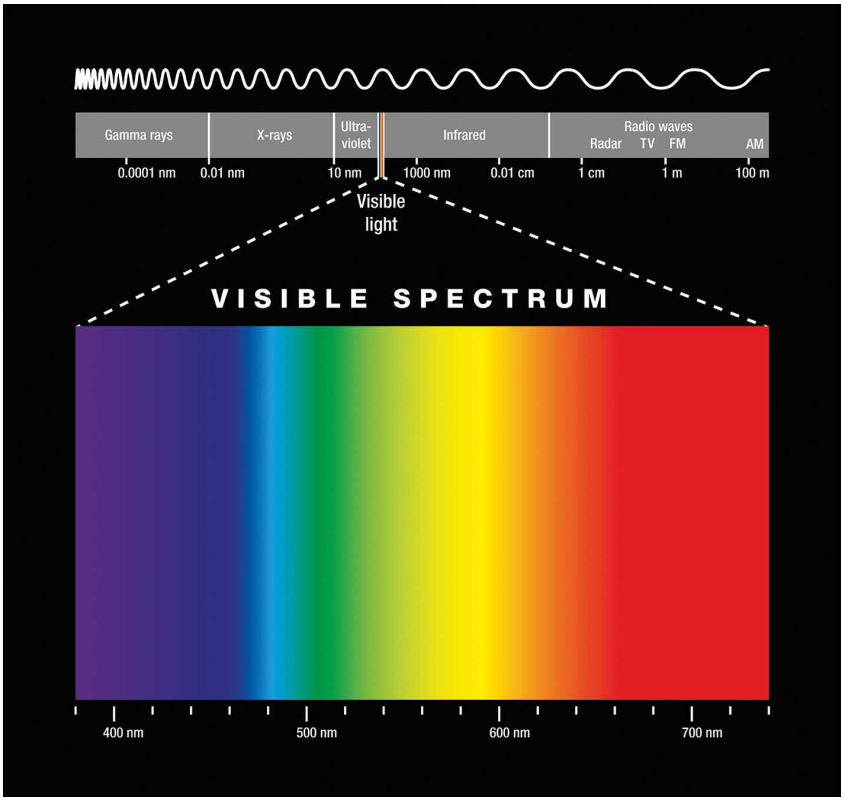
VISUALISING THE INVISIBLE

From near-Earth space, we now venture beyond our solar system to explore the depths of the cosmos. In this section of the edition, we celebrate the innovative techniques that scientists employ to observe and obtain new information about the Universe, enlightening our understanding of everything from black holes to habitable exoplanets, and from neutron stars to elusive dark matter.

Much of the knowledge we possess about the Universe has been gained through observations made by scientists using optical telescopes, which typically collect light in the visible region of the electromagnetic spectrum. But this rainbow of colour that our eyes can detect, from violet light oscillating at a wavelength of around 370 nanometres, to red light at around 700 nanometres, is only a tiny portion of the light available. In fact, the wavelengths of electromagnetic radiation span from gamma rays at around 0.001 nanometres (or one trillionth of a metre), through X-rays, ultraviolet, optical, infrared, microwaves and finally radio waves – with wavelengths from millimetres to kilometres! Each of these radiation types can offer us unique information about the cosmos, from ludicrously high-energy gamma ray burst released by rapidly rotating, high-mass stars as they collapse to form neutron stars or black holes, to the cosmic microwave background – the afterglow of the big bang.



Indeed, the field of radio astronomy has witnessed tremendous growth over the past few decades. In addition to uncovering the cosmic microwave background, radio astronomy has also led to the discovery of pulsars – neutron stars that rotate several times per second and emit periodic bursts of electromagnetic radiation. Radio astronomers have also shed light on quasars, highly luminous galactic centres comprising a supermassive black hole surrounded by an orbiting disk of gas, and numerous galaxies that are highly luminous at radio wavelengths. In the future, it is hoped that radio astronomy may even help us to find extra-terrestrial intelligent life, as an

advanced civilisation may rely on radio waves for their communication systems, just like ourselves.

This is one of the many ambitious goals of the Square Kilometre Array (SKA) Organisation, a collaboration between 10 countries which is headquartered at the Jodrell Bank Observatory near Manchester, UK. The SKA Organisation is currently constructing the Square Kilometre Array – an array of radio antennae spanning over two sites, set to become the world's largest and most sensitive radio telescope once it begins operations in 2020. To introduce this section of the edition, we have had the pleasure of speaking with Professor Philip Diamond, Director General of the SKA Organisation. In this exclusive interview, Professor Diamond explains how this telescope will test the limits of Einstein's Theory of General Relativity, search for distant objects related to the beginning of our Universe, and hunt for life in other worlds.

From low energy radio waves, we jump across the spectrum to the relatively high-energy X-rays. Here, we introduce Kimberly Arcand, Visualisation Lead for NASA's Chandra X-Ray Observatory – a space telescope that orbits high above the earth, collecting X-ray signals and sending down data about the high-energy universe. Kim's passion is to make science more accessible to broader audiences by improving the ways in which we visualise astronomical objects. As part of her work, Kim and her colleagues teach students how to take astronomical data and then use it to create their own images. Combining both computer science and astronomy, the young students recolour and merge images derived from orbiting telescopes such as Chandra – teaching them to use real NASA data just like scientists do.

Another much loved space telescope is the Hubble Space Telescope, which was launched into orbit in 1990 and has since been collecting data in the ultraviolet, visible and near-infrared wavelengths. This is the telescope of choice for Dr Bart Wakker and his colleagues at the University of Wisconsin-Madison, who use Hubble to gather data on hidden matter that exists between galaxies. Surprisingly, only 10% of the normal 'baryonic' matter in the Universe actually resides inside galaxies, while the remaining 90% remains outside, where it forms the filamentary structures of the Cosmic Web. This matter is basically invisible, as it does not emit electromagnetic radiation like stars, supernovae and galactic centres discussed above. Therefore, Dr Wakker and his colleagues need to employ clever approaches in order to visualise the distribution of this elusive matter.

THE SQUARE KILOMETRE ARRAY: THE WORLD'S LARGEST RADIO TELESCOPE

CREDIT: SKA Organisation, Rob Millenaar (ASTRON)

CREDIT: SKA Organisation

Comprising thousands of radio dishes and up to a million antennae, the Square Kilometre Array (SKA) will be the world's largest radio telescope. Referred to as the next generation of radio telescope, this instrument will be tens of times more sensitive and hundreds of times faster at mapping the sky than today's best radio astronomy facilities. The design of this remarkable array at both of its sites in Australia and South Africa is already well underway, and is set to be up and running by the early 2020s.

The project is an international partnership with 10 countries currently funding and forming the international SKA Organisation, with the international headquarters located at the Jodrell Bank Observatory near Manchester, UK. Here, we have been lucky enough to speak to Professor Philip Diamond, Director General of the SKA Organisation, who tells us all about the project – arguably one of the most ambitious science enterprises on earth.

‘Just in its first phase, the telescope will produce some 160 terabytes of raw data per second that the supercomputers will need to handle. That’s the equivalent of more than 35,000 DVDs every second.’

CREDIT: Alex Cherney/terrastro.com

You lead a large team of people who are designing and will ultimately construct the SKA telescope. Please tell us a bit about the timeline and the different phases involved – when will construction start, when will it end, and when can astronomers start using it?

Indeed, within the headquarters we have close to 60 staff, supported by over 100 research institutes and companies with 600+ scientists and engineers around the globe, all currently participating in an international effort to deliver the SKA. Due to this monumental effort, the SKA has successfully passed a number of important milestones towards construction.

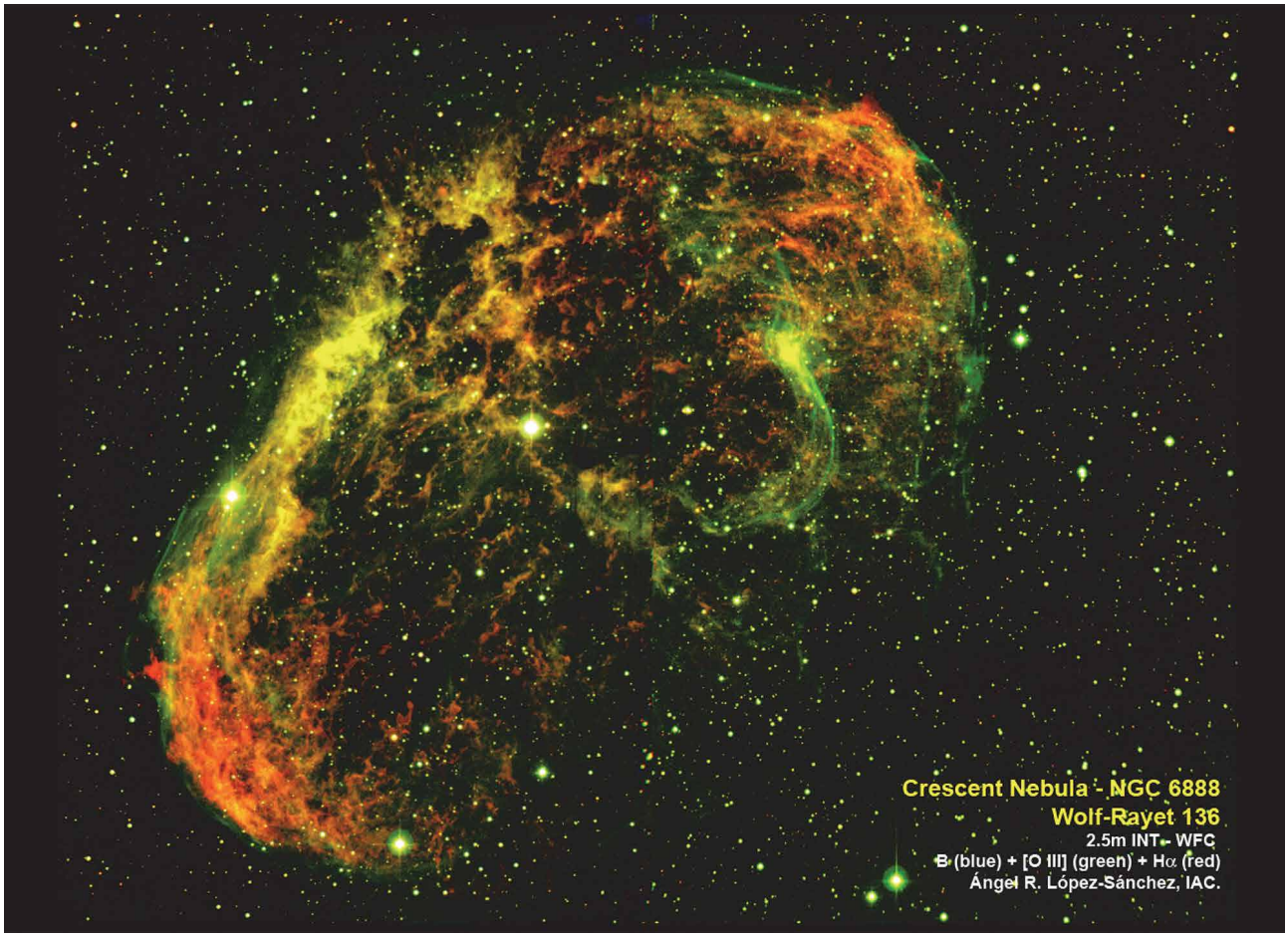
Regarding the timeline of the project, as it stands today, the project has now entered its final pre-construction phase (or detailed design phase), which essentially consists of fine-tuning the design of the telescope before construction of SKA1 (the first phase of the project) starts towards the end of 2018. The decision to adopt a phased-approach, SKA1 and SKA2, for building the SKA was mainly to manage risk and to allow for technological evolution, building upon a decade of substantial investment in precursor telescopes, technologies, and design studies.

So, with the current schedule, SKA1 is planned to start construction in 2018, with early science planned for early 2020s. The full implementation and construction of the full SKA will require more than a decade and will rely on further refinement of some of the enabling technologies over the coming years.

The array will cover a combined area of about one square kilometre over its two sites – how many radio dishes will this include, and what are the benefits of covering such a vast area? Is this the largest telescope array of its kind?

There will be two different types of instruments, SKA-low and SKA-mid, each located in Australia and South Africa respectively. Both will use different antenna technologies, with SKA-low using dipole antennas, and SKA-mid having parabolic antennas. Each antenna design is best suited to receive signals at different frequencies.

SKA-low, located in Western Australia, will consist in its first phase (SKA1-low) of over 130,000 antennas and will receive very low frequencies, similar to those on which you receive FM radio stations. SKA-mid, in South Africa, will consist in its first phase (SKA1-mid) of around 200 dishes and will operate at higher frequencies, similar to those used for mobile phone signal transmission.



The popular perception of a radio telescope is that of a single large dish. However, due to structural and engineering limits, there is only so big you can build a dish before it doesn't become feasible. So, to build bigger telescopes, astronomers use a technique called interferometry, using large numbers of smaller antennas connected together by optical fibre network, and so working as a single virtual telescope, called an array. So, the more antennas you have, the larger the effective collecting area and the greater the sensitivity to be able to detect very weak cosmic radio signals. This is why we spread more antennas over such vast areas, which also means that the images made are of finer resolution than is possible with large, single antenna dishes.

There are other telescopes similar to this design. Examples include the Karl G Jansky VLA located in the US, the ALMA telescope located in Chile, or the VLBI which has stations located across the globe. However, no one has ever attempted the sheer size and scale which is that of the SKA.

A combination of unprecedented collecting area, versatility and sensitivity will make the SKA the world's premier imaging and survey telescope over a wide range of radio frequencies, producing the sharpest pictures of the sky of any current radio telescope.

Tell us a bit about the technology – how will the radio dishes at the two sites work together to collect signals?

The SKA project requires substantial technology development particularly in Big Data and ultra-fast computing. It could well be the world's largest public data project.

Every single telescope will be connected to a central core which will combine the data from each via correlators into more manageable sized data packages. These will be then carried around the globe by high speed links, to the computer screens of scientists working on the immense amounts of information being gathered.

Just in its first phase, the telescope will produce some 160 terabytes of raw data per second that the supercomputers will need to handle. That's the equivalent of more than 35,000 DVDs every second.

To face this challenge, the SKA project is teaming up with companies like IBM, Intel, Nvidia, Cisco, Amazon Web Services and others to look at innovative solutions such as cloud computing, graphic processing and energy-efficient chips.

What are the aims of the SKA project and what types of astronomical phenomena do you hope to observe once construction is complete? Gives us a few examples of what will be possible using the SKA that our current technology can't do.

The SKA will be a very versatile instrument. It will allow observation of very distant phenomena – related to the beginning of our Universe – as well as of much smaller and nearer objects – such as planets in other solar systems. Both kinds of observations require a very good sensitivity on large fields – something that is far beyond the capability of current state-of-art radio facilities. More information here.

Explain how astronomers will be able to examine the limits of general relativity using the SKA?

General Relativity has passed successfully many tests so far – including very recently that of the discovery of gravitational waves by the LIGO

and Virgo collaborations. A very stringent test for general relativity is however to probe it in the vicinity of extreme objects such as back holes. The SKA will allow this kind of study through timing of pulsars – extremely compact and fast rotating neutron stars emitting beamed radiation, which therefore appear to emit a pulsating signal – especially those which are in binary systems. In this case, the time of arrival of the pulses will depend on the details of the orbit, which is determined by the underlying gravitational theory.

Tell us a bit about the planned SKA galaxy surveys. How will collecting this data help us to test models of dark energy and the primordial universe, for example?

Galaxies are luminous objects forming where the concentration of dark matter is the highest. As such, they can be used to 'trace' the distribution of dark matter in the Universe, that would be otherwise invisible. This distribution depends on the balance between gravity and dark energy, acting as an attractive and as a repulsive force respectively, as a function of cosmic time. Therefore, the number and spatial distribution of galaxies in the Universe allows placing very strong constraints on the cosmological model, and on dark matter and dark energy in particular.

Will the SKA be used to search for life on other planets, and if so, how?

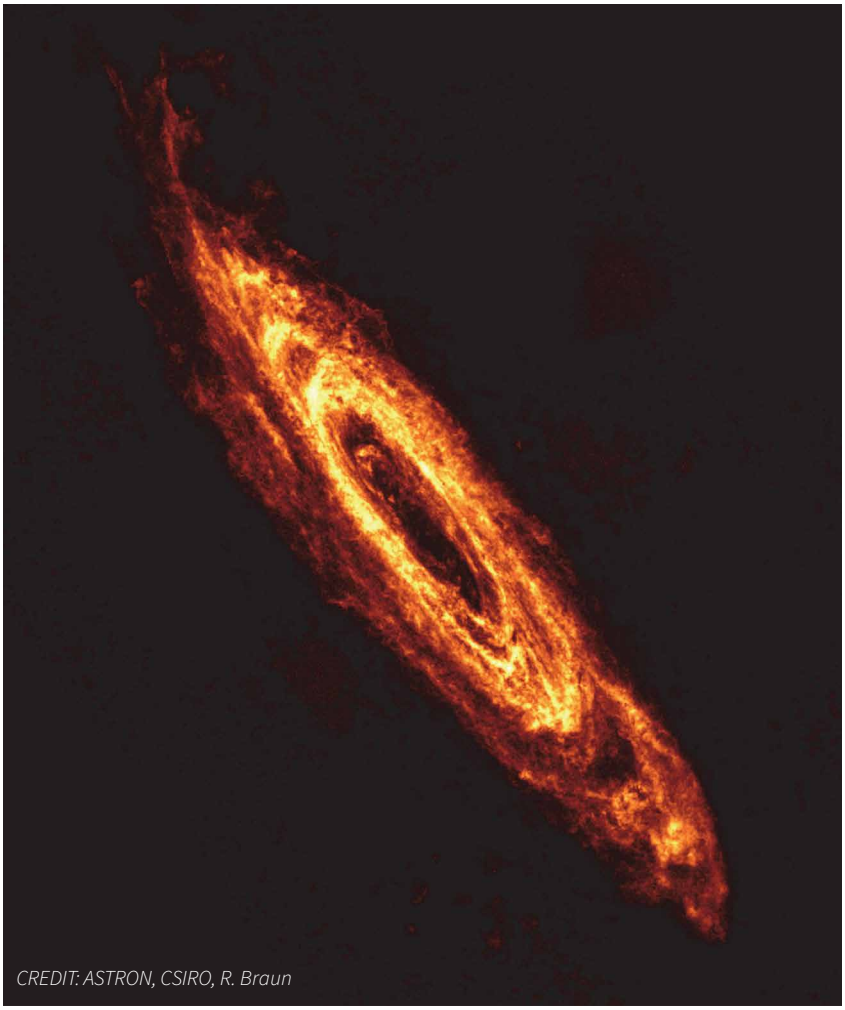
Yes, the search for life on extra-solar planets is one of the science objectives of the SKA. This will be pursued by looking for suitable planets – rocky planets, therefore exhibiting line emission typical of dust grains and potentially of heavy molecules that are the building blocks of life, such as amino-acids. In addition, the SKA will also look for artificial transmissions that would confirm the existence of intelligent life and technology.

Finally, what possible discoveries using the SKA are you personally most excited about?

I am excited by the entire SKA science case, the broadest science case of any facility on or off the Earth. However, on a personal basis and building on my own personal research, there are two areas that I hope to use the SKA to explore. One is magnetism; radio astronomy gives us as fantastic, unmatched tool for exploring magnetic phenomena in the cosmos, from the magnetic fields that permeate galaxies and even the inter-galactic medium, to those that shape the structure of stellar nurseries and planetary nebula. SKA will revolutionise studies of magnetism and I intend to be part of that.

The other area in which I have spent many years working is using radio astronomy to study the signals from atomic and molecular lines. The SKA, with its huge sensitivity, will be well-placed to detect the weak lines from heavy molecules, even amino-acids, a constituent of DNA and therefore one of the building blocks of life. I also intend to work in this field with the SKA.

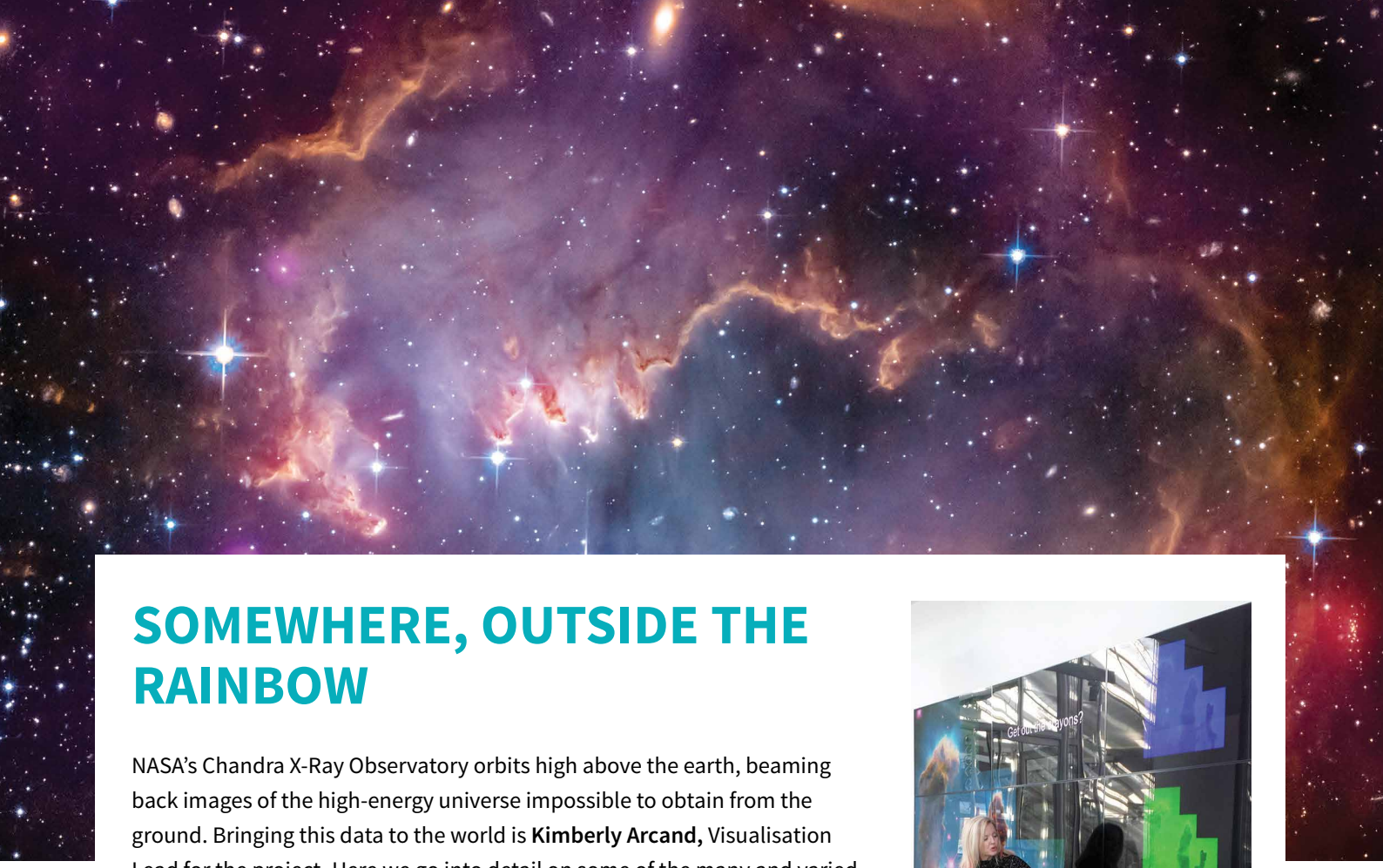
'The SKA, with its huge sensitivity, will be well-placed to detect the weak lines from heavy molecules, even amino-acids, a constituent of DNA and therefore one of the building blocks of life.'



CREDIT: ASTRON, CSIRO, R. Braun

SKA SQUARE KILOMETRE ARRAY

www.skatelescope.org



SOMEWHERE, OUTSIDE THE RAINBOW

NASA's Chandra X-Ray Observatory orbits high above the earth, beaming back images of the high-energy universe impossible to obtain from the ground. Bringing this data to the world is **Kimberly Arcand,** Visualisation Lead for the project. Here we go into detail on some of the many and varied programs she is involved with.

Outer Space. It encompasses distances we can barely fathom, temperature ranges we can hardly comprehend, and shines in wavelengths which we can never see.

Take our Sun, for example, a fairly small star at a mere 1,392,000 km in diameter. Most of us can't hold that number in our heads – it's too far outside anything we've experienced. We can try to visualise it by comparison to distances that we know – say, the distance between New York and London. That's 5,500 km, which means it would be around 252 trans-Atlantic flights. Assuming each flight is 7.5 hours then you'll be spending 78 days in an aeroplane. 78 days' worth of aeroplane food – now that is a number we can get our heads around.

But it gets even more difficult when we start looking at larger objects. Alpha Centauri, our nearest neighbouring star, is 4.3 lightyears away – converted to kilometres we get 41 followed by twelve zeroes. Twelve! You and your aeroplane food would be dust long before you even came close to your goal, and this is before we start trying to wrap our heads around deeper space objects like supernova remnant Cassiopeia A, a mere 10,000 light years away.

So how do we bring these distances and these objects down to our mortal world of commuter jets and slow-moving traffic? This is where the work of scientific communicators and researchers such as Kimberly Arcand of NASA's Chandra X-ray Observatory comes in. Her job involves taking arcane data and scientific information and finding the best way to make them understandable for all walks of life.

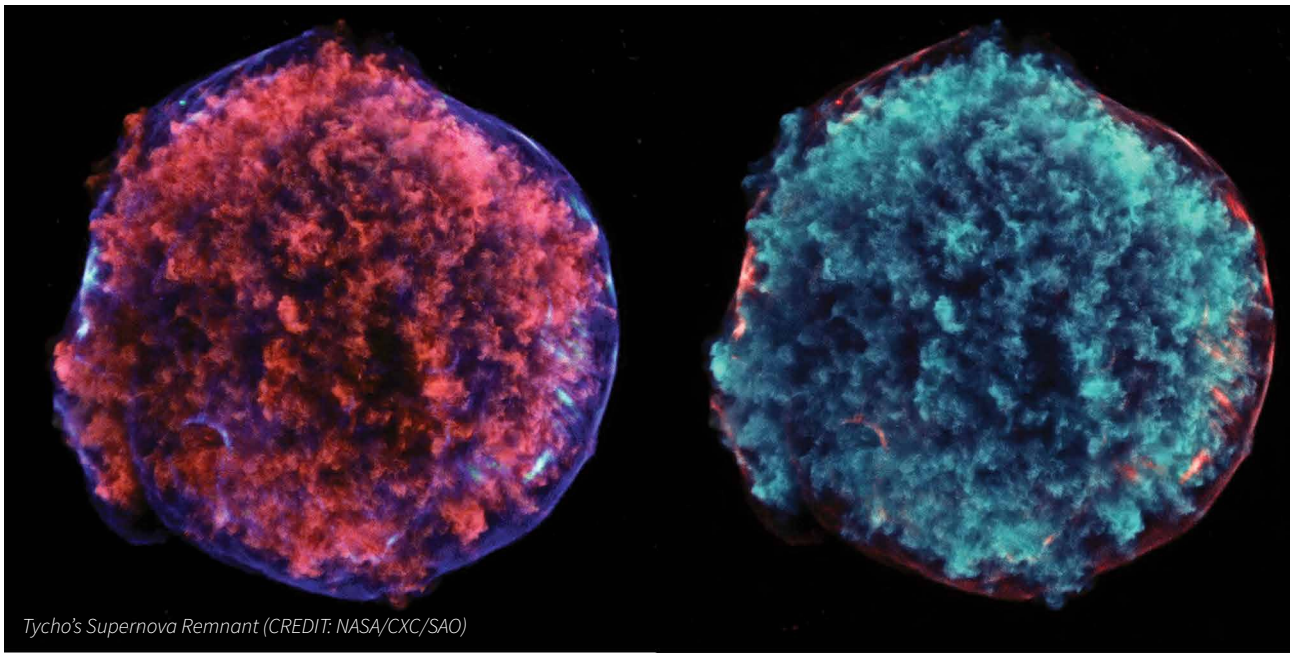
254 Shades of Grey

When we look out our windows at the world passing by, we see reds, blues, greens, all the colours of the rainbow. But the rainbow we see is a tiny, tiny part of the rainbow we could be seeing, if only we had the ability. Infrared cameras, radar, X-ray telescopes: all of these rely on being able to 'see' wavelengths which are invisible to our naked eyes. But once detected, how do we visualise this information? What colour is that radar image or ultraviolet source?

One traditional approach used by scientists has been to ignore the problem entirely, plotting all information on a scale from black (no signal) to white (100% signal) and then dividing everything else into various shades of grey. This is unambiguous, you can easily see how different parts of the image relate to others by examining how bright they are. But it becomes difficult when different images are merged – is this bit of grey part of the first image or the second? It also misses the chance to include important information. We see in colour and are thus skilled at interpreting and understanding multi-coloured images (unless levels of colour blindness come into play).

But translating the invisible world into glorious colour brings its own challenges. As Kim comments: 'There are human biases that are introduced in that translation process. There are many choices that must be made along the pipeline, from cleaning the data

‘It’s an honour to serve the public in any way, working on a publicly funded program as I am. I’m well aware that I’m not saving the world with my job, but I am hopefully helping to make a difference in someone’s day.’



Tycho’s Supernova Remnant (CREDIT: NASA/CXC/SAO)

and removing artefacts to more aesthetic issues such as mapping colour.’ The way we respond to colour affects our interpretation of the imagery.

Take recent work by her group, in which they surveyed a number people regarding their perceptions of various astronomical images. The information was drawn from data outside the visible spectrum and thus was represented using ‘false-colour’ imagery, in which the colour in the pictures isn’t the same as we would see looking through a pair of binoculars (because of course, we couldn’t see it at all). High-energy regions were marked in blue, low energy in red. This makes perfect sense to an astronomer, because high-energy objects are hotter, and hotter objects are blue. However most of us think of red as being the colour of heat, despite this not being the case. Want to check this? If you were to stick your hand in a candle flame, the blue part of the flame is far hotter than the red… but kids, don’t try this at home!

This mismatch in beliefs means that effectively showing scientific data to non-expert audiences requires scientists to reflect on some of their standard approaches. What is important is in getting the information across to the audience, not slavishly holding to a single manner of representing it. But most importantly, we also need to explain why these colours were chosen and what they represent.

The vast majority of questions which came up during the survey asked about the colours of the astronomical objects – do they really look like that? Are those colours real? In a world of easy photoshopping and Instagram filters we tend to distrust the images we see, and thus scientists need to be transparent about what they are actually presenting to the world.

Science for Everyone

Why is this important? Does it really matter that science looks pretty? Should it be optimised for just the people who research the data? Definitely not. Science and scientific discoveries affect all of us, they underlie the modern world in which we live. Unfortunately, however, science is often portrayed and perceived as being just one of those things that nerds do. That perspective, however, can actually limit the people who are interested in the field and so becomes self-selective – the more your 5-year old thinks that science is for nerds, the less likely they are to be interested in learning it themselves.

This is particularly a problem for girls, who are consistently underrepresented in a number of the STEM fields (science, technology, engineering and mathematics). The typical example here is computer science, for which only 10–20% of computer science degrees are awarded to women. However, it is also very noticeable in fields such as astronomy where female participation rates range from 15–35% (this applies to those amongst the stars as well – only 75 of the 560 astronauts trained so far have been women).

A number of new community-based programs exist to encourage young girls to develop an interest in computer science, but few equivalents exist for the field of astronomy. To attempt to fill this gap, Kim Arcand has been involved in developing public engagement programs from her position at the Chandra Observatory. Her and her colleagues most recent work has combined computer science and science imaging, teaching students how to take astronomical data and then use them to create their own imagery. Built on a simplified coding language known as PencilCode, the program takes young students through some standard stages of recolouring and merging images derived from orbiting telescopes – using real NASA data just as an astronomer would.

Tedtalk (CREDIT: Tracy Karin Prell)

This type of hands-on program that provides authentic scientific learning experiences is a vital part of encouraging young minds to see science as a thing of possibility and interest. Although those who take part may be many years away from beginning their careers, they can see that science and associated fields are more than just hideaways for geeky guys with, perhaps, underdeveloped social skills. Science is fascinating and should be accessible to everyone – boys and girls, burnt hands and all.

Touching the Stars

One of Kim's latest attempts to making science more accessible to broader audiences involves improving the visualisation of astronomical objects. How? By shrinking them down to scales which we can hold in our hands. To achieve this mammoth act of scaling, they started with one of the most striking radio sources in the sky, Cassiopeia A. Cassiopeia A (Cas A for short) is what is known as a supernova remnant, the last remainder of a star's final, dramatic moments. Supernovae occur when some large stars (much bigger than our Sun) run out of fuel for their inner fusion reactions, collapse under their own weight, and then rebound with enough energy to blow themselves apart. This turns the now ex-star into a rapidly expanding cloud of incredibly hot gas and plasma, shining brightly in almost every part of the electromagnetic spectrum we care to examine.

Cas A is well-loved by astronomers because the supernova was both relatively close (a mere 11,000 light years!) and relatively recent – this means that it is perfect for in-depth studies at a multitude of wavelengths. Imaging from the different orbiting observatories allows us to 'see' the remnant in visible, infrared and X-ray spectra; faint filaments in the visible spectrum become blinding clouds in the X-ray images.

Even better, the combination of these spectra provides information on how the gaseous shock-wave is moving. As parts of the cloud move towards or away from us, the wavelength of the radiation they emit will seem to be a little higher or a little lower than it should – a process known as Doppler shifting. Just as you can tell whether the police are coming towards you or driving away by the shifted tone of their siren, so can astronomers decide if part of the supernova remnant is moving towards or away from us.

By combining this information together, then modifying a piece of software which was originally designed for medical scans of human brains, researchers have managed to create a 3-dimensional model of Cas A. It's great news for those who work on computer models of supernovae for a living, but even better for the rest of us because the model can be fed directly into a 3D printer. Have you ever wanted to hold a supernova in your hands? Poke at a very, very much smaller representation of its hypersonic shockwave? Enjoy the irony of trying not to break the surprisingly fragile representation of two 'jets' of supernova material, each of which are in actuality moving at about 14,000 km every second?

By being able to do this, to ask these kind of questions, researchers such as Kim Arcand help to bring the idea of astronomy to a much wider audience than would otherwise be possible, from young learners to the visually impaired. You may or may not be a regular reader of astronomical papers on ArXiv, but the little model of a dead star sitting on your desk helps to keep the idea of the wider, ridiculously larger universe in your thoughts. As she comments, 'the visual is also only one side of the equation.'

Coloured galaxies, printed supernovae, public engagement programs for underrepresented groups, incidentally working at NASA, one of the most beloved government agencies in the US. How does Kim Arcand actually find the time to do all of this? She enjoys the challenge, laughingly commenting 'I have the opportunity to learn something new every day and I take full advantage of it. That's incredibly important to me.' Every day brings something new, every day another challenge and another possible success. I, for one, am curious to see what tomorrow brings.

CREDIT: Adeline & Grace Photography

Meet the researcher

Kimberly Kowal Arcand

Visualisation Lead for NASA's Chandra X-ray Observatory

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Kim Arcand has a long history of bringing science to the public, starting from her early career in parasitic and infectious diseases and stretching through to her current role as Visualisation Lead for NASA's Chandra X-ray Observatory. She is an award-winning producer and director, and a leading expert in studying the perception and comprehension of high-energy data visualisation across the novice-expert spectrum. She has spear-headed the creation, distribution, and evaluation of large-scale science and technology communications projects. As a science data 'story teller', Kim combines her background in molecular biology and computer science with her current work in the fields of astronomy and physics. She presented the TEDx talk 'How to hold a dead star in your hand' in April 2016 and co-wrote the non-fiction books 'Your Ticket to the Universe: A Guide To Exploring the Cosmos', 'Light: The Visible Spectrum and Beyond' and 'Coloring the Universe: An Insider's Guide to Making Spectacular Images of Space'.

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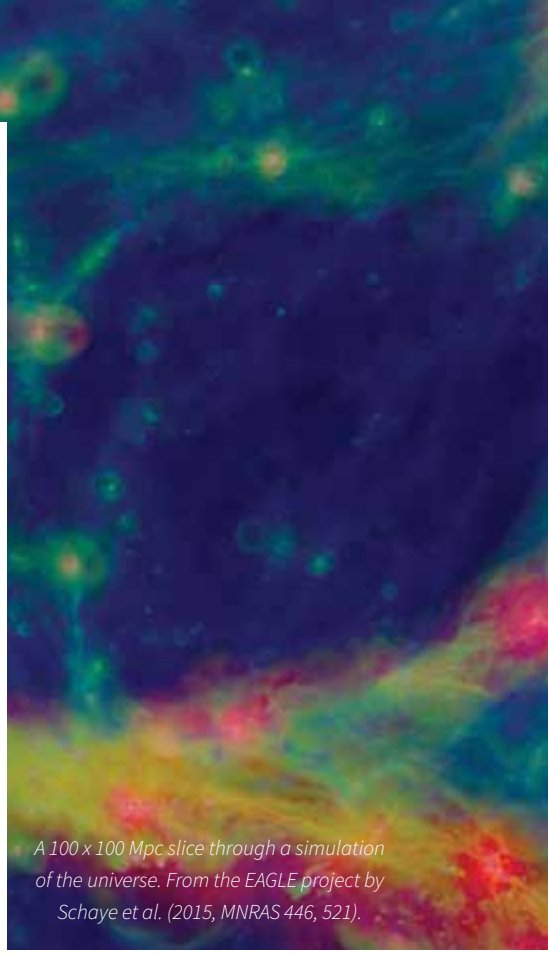
NASA's Marshall Space Flight Center manages the Chandra program. The Smithsonian Astrophysical Observatory controls Chandra's science and flight operations.

USING THE HUBBLE TELESCOPE TO INVESTIGATE THE UNIVERSE'S HIDDEN BARYONS

Astronomer **Dr Bart Wakker** and his colleagues use the Hubble Space Telescope (HST) to gather data on hidden baryonic matter and the composition of the Universe.



A 100 x 100 Mpc slice through a simulation of the universe. From the EAGLE project by Schaye et al. (2015, MNRAS 446, 521).

Getting Closer to Far, Far Away

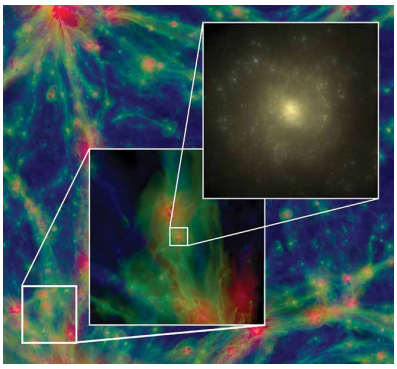
From the era of Galileo and Copernicus up until now, our knowledge of space has primarily been obtained visually – by looking at the skies with the naked eye or with an ever-improving array of telescopes. Today, in order to avoid some of the haze and interference of Earth's lower atmosphere, astronomers set up observatories and telescopes on high mountains. Even better still, we've now set up our most modern telescopes high above the Earth, in orbit. This completely avoids interference from the Earth's atmosphere and gives a much clearer view of the rest of the Universe. But that only lets us see better what we can see – what's visible to our telescopes.

The well-known Hubble Space Telescope, for example, is in low Earth orbit at an altitude of about 540 km, obtaining high-resolution pictures and spectra of the cosmos by collecting near-infrared, visible and ultraviolet radiation emitted by stars and other galactic objects. However, much matter in the universe does not emit radiation, visible or otherwise. This is where Dr Wakker and his colleagues, Drs Taesun Kim, Blair Savage, Audra Hernandez and David French, all at the University of Wisconsin-Madison, have been doing some out-of-the-box thinking in using the Hubble Telescope to scope out the Universe. By visualising the invisible, they are trying to understand the flows of gas between the intergalactic and circumgalactic medium around galaxies, to determine how galaxies obtain gas needed for star formation.

How Do You Visualise Something That's Invisible?

When someone brings up the topic of galaxies, the first thing that comes to mind is the Milky Way, our own neighbourhood of stars, gas and dust that stretches about 100,000 light years across. And then there's the Andromeda galaxy, one of the Milky Way's nearest neighbours. In fact, we generally think of our Universe as composed of individual, discrete collections of stars or galaxies with lots of empty space in between. This is quite incorrect, however. In recent decades, astronomers have determined that galaxies represent just a small fraction of the contents of the Universe.

The so-called 'empty space' between galaxies still contains matter, though not in a state that emits light we can see through usual methods. So, what is this matter that we can't see and how do we even know it's there? Because of the way that the Universe appears to be constructed, scientists can calculate the total amount of energy needed to make the universe behave the way they observe it – the way the stars and galaxies move and interact. But the matter we can actually see isn't nearly enough to contain that amount of energy. This is where so-called 'dark matter' and 'dark energy' come in. From calculations and observations astronomers and cosmologists believe that over 70% of the required energy to 'run' the Universe is 'dark energy'. So far, we don't know what produces dark energy. Perhaps it's some sort of 'tension' in space, or something other yet-unexplained function of space-time. More than that, another quarter



of the Universe's energy resides in 'dark matter', an unknown particle that does not interact with electromagnetic fields, weak-force fields, or strong-force fields.

Finally, only 4% of the total energy exists as 'baryonic matter' – mainly normal protons and neutrons. There are also many lighter electrons and a miniscule amount of more massive atomic nuclei and atoms, but these do not contribute significantly to the mass. And of this 4% baryonic matter, Dr Wakker tells us that just 10% resides inside galaxies and galaxy clusters, representing only 0.4% of the universe's energy. This 0.4% is what emits the light that we can study directly. However, the remaining 90% of baryonic matter, representing around 3.6% of the universe's total energy, exists outside galaxies. This is what Dr Wakker and his colleagues are interested in.

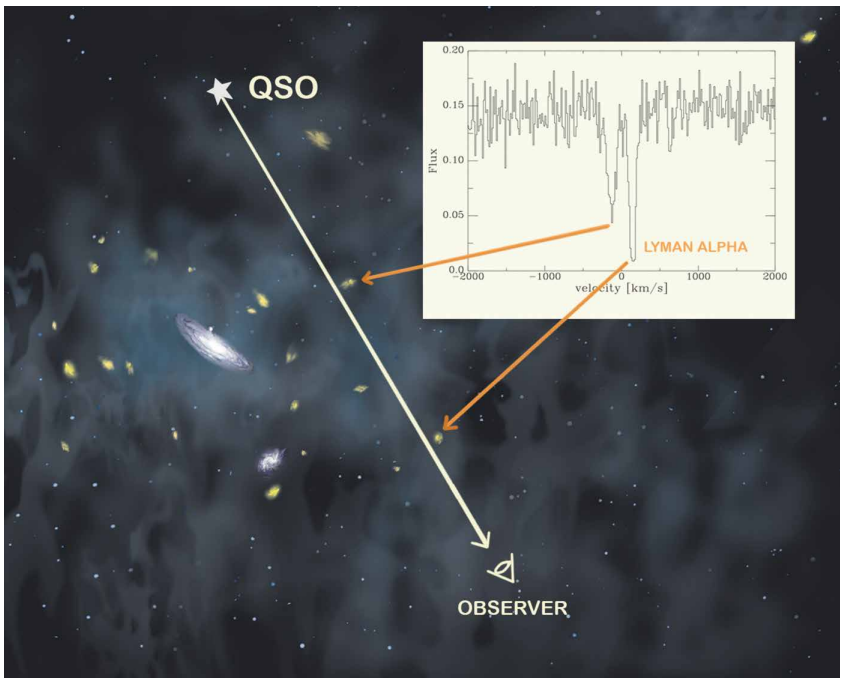


Illustration of the method used to find the intergalactic gas. Light from a quasar (QSO) passes through the tenuous ionised gas surrounding a galaxy. Near denser concentrations of the gas (the yellowish blobs), some of the gas contains sufficient neutral hydrogen to produce the Lyman alpha absorption line in the spectrum.

'Normal matter is the only thing we can observe directly, so the existence of dark matter and dark energy is derived from its motions,' Dr Wakker tells Scientia. 'What is less well known, even to many professional astronomers, is that of that 4% of the gravitational energy of the universe that is made of normal matter, only about 10% is actually *inside* galaxies.' It turns out that galaxies are just the regions of space where the matter has concentrated enough to form stars. After all, stars emit light – electromagnetic radiation – so we can see them.

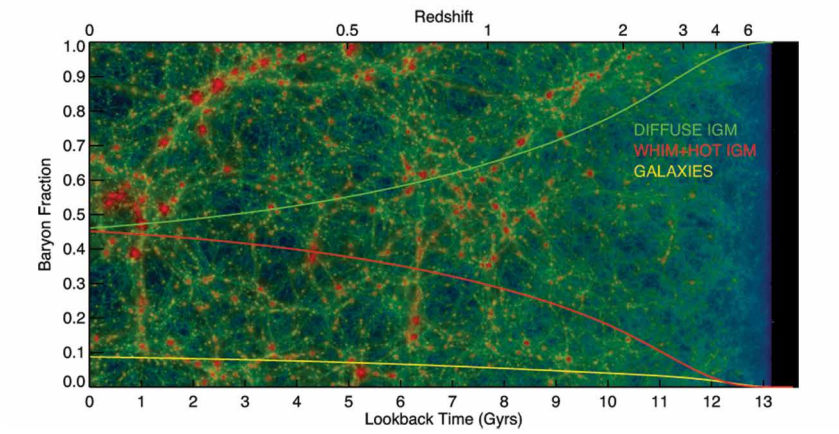
Astronomers now think that galaxies form near concentrations of dark matter, which was first proposed by the Swiss astronomer Fritz Zwicky in the 1930s and observationally confirmed by Vera Rubin and collaborators in the 1970s. Dark matter is a crucial ingredient in cosmological hydrodynamic simulations – computer computations that analyse the motions of visible astronomical objects and calculate what the motion means in terms of the gravitational fields that are in play causing the motion. In such simulations, the universe starts out mostly uniform after the big bang, but small density fluctuations cause dark matter to aggregate into clumps and filaments, forming what is called the 'Cosmic Web'. The dark matter pulls on the normal matter. But while dark matter only feels gravity and forms centrally-condensed clumps, the normal matter undergoes friction, and not all of it can fall into those clumps. The small fraction that does forms the visible galaxies.
Probably about half of the invisible baryonic matter (the protons and neutrons) is in the circumgalactic medium, the region of space near galaxies where there are very few stars. In fact, Dr Wakker has done research to show that it can stretch out to as far as 300 kiloparsecs (about 1 million lightyears). In addition, he has provided evidence that the other half is indeed associated with the Cosmic Web, rather than individual galaxies.

So how do we visualise something invisible? Dr Wakker says we can look at its shadow, so to speak. Some of this matter absorbs light emitted from galaxies behind them, and does so at a characteristic wavelength of ultraviolet radiation. This signature absorption allows us to see them basically as shadows in space, absorbing radiation from quasars and stars behind them. The most prominent absorption line is the hydrogen Lyman alpha line, corresponding to a neutral hydrogen atom in the ground state absorbing an ultraviolet photon with a wavelength of 121.5 nm. In intergalactic space, there is a balance between protons finding an electron and forming a neutral hydrogen atom, and ultraviolet photons ionising those atoms. The combination of gas density and radiation intensity is such that only about one hydrogen atom in a thousand to one in a million is neutral. But because there is so much hydrogen, this is sufficient to cause an observable feature in the spectrum that we can measure. This is where Dr Wakker has been concentrating his efforts.

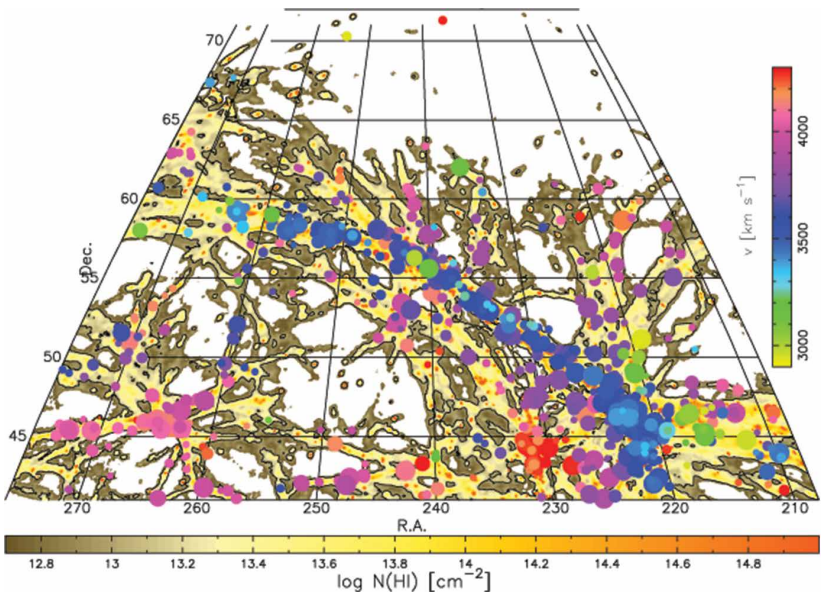
Looking for Hidden Matter Between Galaxies

According to Dr Wakker, 'in the simulations, about half of the remaining baryonic matter tries to fall into dark matter gravitational wells, but gets shock-heated to temperatures of over a million degrees. The other half is too far from the dark matter wells and stays distributed over large regions of space.'
This means that most normal matter is spread throughout intergalactic space in a volume that is about a million times larger than that occupied by galaxies. This is called the 'intergalactic medium' (IGM). The slightly denser regions in the IGM can be observed because of their interaction with electromagnetic radiation – these denser regions absorb light from background objects such as quasars, producing absorption lines in the spectra. About 30% of the baryonic matter is in a relatively cool (10,000 Kelvin) intergalactic phase that contains trace amounts of observable neutral hydrogen. The remaining 60% of baryons are in the hot phase, which is extremely difficult to observe, and has been directly detected only a few times.

'My work is focused on determining the properties of the IGM, both close to galaxies, as well as on larger scales,' Dr Wakker tells Scientia. He says that this type of study can come in several forms. The first and most common approach involves observing a quasar, finding absorption lines in its spectrum, and identifying the lines by comparing with laboratory spectra. These absorption lines occur at many different redshifts, corresponding to different distances and velocities that the gas clouds are moving away from us. Then one can see if there are galaxies at similar redshifts to the absorption line and measure the projected physical separation – called the 'impact parameter' – between the absorber and the galaxy. Studying the properties of the absorber as a function of impact parameter then reveals information about the gas around galaxies. This tells us that there is gas that is on its way to accrete and grow galaxies and also that there is gas that was ejected from the galaxies.
Another observation that can be made is to



Evolution of the Cosmic Web over a Hubble time, from a 270 million particle cosmological hydrodynamic/N-body simulation by Davé et al. (2009).



Simulated observable neutral hydrogen column density (yellow/grey) relative to the locations of galaxies in the simulation (coloured dots).

take a set of quasar sightlines and a galaxy catalogue and find every sightline passing close to a galaxy. Then you can search for absorption – or lack of it – in the spectrum of the quasar. This is the approach Dr Wakker took. Since at large distances our knowledge of the galaxies is limited to bright galaxies and small areas in the sky, Dr Wakker and his group concentrated on the nearest galaxies – those closer than 150 Megaparsec, which is about 500 million lightyears or a mere 4.6 x 10^{21} km. Out to this distance, astronomers' list of bright galaxies is almost complete.

What Dr Wakker found was that for relatively luminous galaxies that are brighter than one tenth the brightness of our Milky Way, absorption due to intergalactic gas is always present out to a distance of 300 kiloparsec (~1 million lightyears), as compared to galaxy diameters of 5–20 kiloparsec. Apparently, galaxies are surrounded by a huge halo of tenuous gas that is highly ionised, indicating that there are about a million protons for every neutral hydrogen atom. Taking this into account, it is possible to deduce that the amount of material in galaxy halos is about five times the amount inside the galaxies themselves. This proves that our initial assumption – that the space between galaxies is empty space – is quite wrong. More matter surrounds galaxies than exists within them. But that's not all. Dr Wakker also looked at the distribution of the Cosmic Web.

Mapping the Cosmic Web

In a paper published in *The Astrophysical Journal*, Dr Wakker and colleagues shared results of their research on the structure and distribution of the Cosmic Web. In this paper, they first made a map of the distribution of galaxies on the sky. This map clearly showed the Cosmic Web – galaxies distributed in long, linear structures, or filaments. Using quasar absorption-line observations, Dr Wakker measured the gas associated with a Cosmic Web filament. He found that there was gas only out to 2 Megaparsec of the axis of the filament, even though this gas is not in the gravitational wells of individual galaxies. As one gets closer to the axis, the density of the gas becomes higher and the velocity structure more complex. By comparing the amount of gas observed to a simulation of the intensity of ionising radiation, he could obtain a clearer picture. Dr Wakker found that the distribution of gas perpendicular to the filament axis was more concentrated than that predicted by the simulation. 'We still need to compare our findings to more than one simulation to know whether this is a problem with the simulation we used or a more general issue in the predicted distribution of dark matter in Cosmic Web filaments,' he tells us.

Looking to the Future

So far, Dr Wakker's data on the Cosmic Web filament has been based on one filament sampled by 20 sightlines. But he keeps on analysing Hubble Telescope data and is making progress. He and his group have obtained 68 orbits of Hubble Telescope time to observe a second filament using 60 sightlines, which will give more reliable statistical information. These observations are planned for 2017/2018. 'We are also working on using the Hubble Telescope archive to create a much larger sample of quasars – 500 instead of 75 – and galaxies – 100,000 instead of 10,000 – to map out their halos and determine the properties of the gas as function of galaxy inclination, azimuth, type, size, environment, etc.,' he explains.

This is exciting work in the advancement of scientific understanding of space itself. The funding from these studies also is vitally important for Dr Wakker. His work depends entirely on his ability to secure grant funding. This keeps Dr Wakker on his toes, not only exploring the final frontier for scientific reasons, but for academic survival.

Meet the researcher

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Dr Bart Wakker carried out his undergraduate and master's studies at the University of Amsterdam, where he finished cum laude at both levels and received his respective degrees in 1981 and 1983. Between his undergraduate and master's studies, he was a Summer Student at CERN in Geneva. Dr Wakker then went on to achieve his PhD in Astronomy in 1990 from the Rijks Universiteit Groningen in The Netherlands. Following several years of postdoctoral research at the University of Illinois at Urbana-Champaign, he moved to a second postdoc at the University of Wisconsin-Madison, where he currently works as a Senior Scientist, supporting his position there with his own research grants. Dr Wakker's research interests include the observational study of gas in the halos of galaxies and elsewhere in space. He investigates how this gas interacts with and drives the evolution of galaxies. Dr Wakker also seeks to understand the motions, abundances and physical conditions in Galactic high-velocity clouds and how they trace the Galactic Fountain, tidal streams and infall, as well as the properties of the intergalactic medium, especially in relation to the galaxies. He has authored or co-authored about 250 articles published in peer-reviewed journals and other professional proceedings and has been awarded over $5,000,000 in grant support over the years

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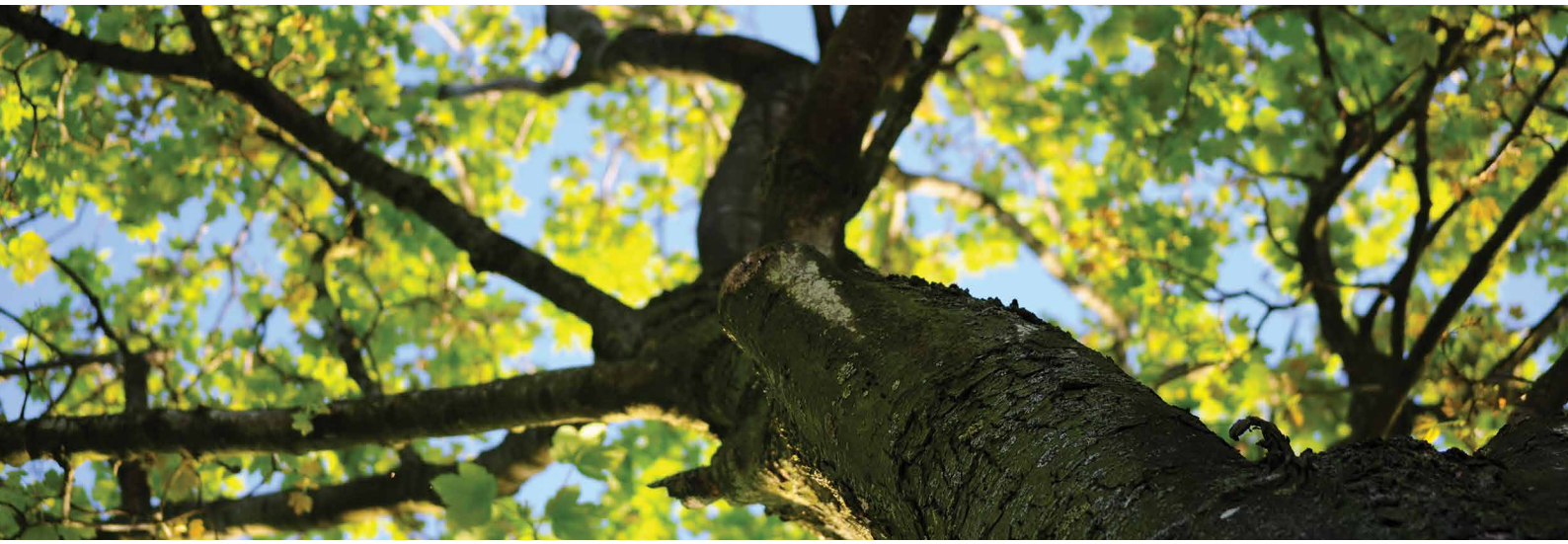
Trees for Cities

Breathing life into your neighbourhood



WHO WE ARE

Trees for Cities is the only charity working on an international scale to create greener cities. Since 1993, we have engaged over 70,000 people to plant over 650,000 urban trees in parks, streets, schools and housing estates across the UK, as well as internationally, revitalising these areas and improving the lives of the people who live in them. We strengthen communities through volunteering opportunities and inspire children to grow and eat good food and to connect with nature.

WHAT WE DO AND WHY WE DO IT

We focus on planting trees and greening community spaces where the social and environmental impact on local people is greatest. In London this might mean planting trees to clean the air or transforming unused community spaces into vibrant green areas, making our communities happier and healthier places to live, whilst in Nairobi it's planting fruit trees for food and sustainable livelihoods.

HELP US PLANT A MILLION URBAN TREES BY 2020

To date we have planted over 650,000 trees in cities. We have now set ourselves an ambitious new target to strive to plant 1 million urban trees by 2020. Help us meet this exciting new milestone…

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DONATE ONLINE AT
www.treesforcities.org/donate/

FIND OUT HOW TO GET INVOLVED AT
www.treesforcities.org/get-involved/

MISSION

- Planting trees and greening cities worldwide.

VALUES

- **People-led:** Although our reach is global, we value the importance of a local focus. We always work through and within local communities to strengthen them and empower their members.
- **Quality-driven:** Both the quantity and quality of the trees we plant are at the forefront of our planning so that we constantly strive to maximise the impact of our projects to the environment and society.
- **Delivery-focused:** We are an organisation that gets things done. What we talk about, we do – effectively, efficiently and on-time.

WHY TREES MATTER

- Trees help our environment and the impact of climate change:
- They remove 4m tonnes of carbon from the UK atmosphere each year (Forestry Commission 2010)
- They can cool the air by 2 - 8 degrees C
- Trees absorb water , lowering stress on storm water drains and mitigating flood risk
- A single mature oak tree can host up to 423 different species of invertebrates that support birds and mammals
- Each year Trees for Cities plant around 65,000 trees in cities worldwide, revitalising cities and enhancing the lives of the people that live in them.