A Launch Collection of Accessible Climate Articles

CLIMANOSCO

Climate knowledge, directly with climate scientists

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A Launch Collection of Accessible Climate Articles

Why Accessible Climate Articles?

Climate change is one of the major challenges of the 21st century. But climate change can be difficult to track with the senses. We hear a lot about it, but what do we really know about it? How important is it? How do we take it into account?

We present hereafter our launch collection of accessible climate articles. These accessible climate articles offer a direct mirror of the real science. The researchers, these makers of new scientific knowledge, are here talking directly to you about their research.

What is Climanosco?

Climanosco is a non-profit organization open to climate scientists and to all citizens, world-wide, interested in the climate. Its main goal is to publish state-of-the-art climate science for everyone in a reliable, understandable and free format. It builds a community of citizens and climate scientists. It offers a platform to people to inquire about climate sciences and to participate alongside with climate scientists in the making and the communication of science. It is a bottom-up initiative set to make a change by raising climate literacy around the world.

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A new way to quickly estimate climate change impacts on rivers and streams

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We outline a new method that offers quick insights into how the amount of water in rivers and streams will be impacted by warmer temperatures and future precipitation change. This method yields comparable results to more conventional model-intense climate change impact studies and is faster and cheaper to implement, making it a practical alternative for those exploring future water supply changes in places with limited computational access. Using rivers and streams in the Pacific Northwest of North America as an example, we share what this new method can (and cannot) do, and highlight the steps one could take to quickly begin exploring how climate change could impact their water supply.

Geographical Sector(s): Canada, North America, USA

Subject Area(s): Climate of the Future, Impacts, Water

Why develop a new approach?

Climate change, through rising temperatures and changes in precipitation, will change where and when water is available for ecosystems and human communities. Understanding what these changes might be at a local, river basin scale is valuable for planning purposes. For example, people who manage reservoirs in the Yakima River basin in the state of Washington, USA, need to know how much water to expect in the rivers in each season so they can decide how much water they need to store and when to release it throughout the year to avoid both floods (too much water) and water shortages (too little water). These water managers, like many throughout the world, are being asked to find a delicate balance between water supply, which comes as rain and snow, with increasing water demands for growing food, letting fish swim, and enabling growing communities to prosper. As such, to prepare for the future, we need to better understand how climate change may alter where, when, and how much water is in our rivers and streams.

Estimating how the amount of water flowing in a river or stream will change in the future is often time-consuming and expensive, limiting its usefulness to those with adequate resources. Conventional approaches typically begin with information on spatial scales larger than 150 km as provided by global climate models. To make that information more locally relevant, it is converted to information on spatial scales of 5 km through extensive use of statistics and multiple, linked computer simulations of the world's climate system and water cycle. Whenever new information from global climate models becomes available, the first link of the model chain changes, and the whole chain of computer simulations needs to be redone.

A quick, new method developed by [J. A. Vano et al., 2015] addresses these challenges by providing an inexpensive, yet comparable estimate of the nature of future changes, without having to run the time-consuming chain of models used in the conventional approach. This new approach, termed the “seasonal sensitivity approach”, begins by first understanding the sensitivity of streams and rivers to temperature and precipitation change. It then uses these sensitivities to characterize changes across the landscape and provide estimations of the amount of water in a river according to what global climate models project for future climate in the region. This quick estimate of future change can give resource managers important context and aid decisions on how further investigations of climate change impacts should proceed. [J. A. Vano et al., 2015] demonstrate this approach in a data-rich environment, where the approach could be adequately tested. Importantly, however, these tests show potential for the approach to also be useful in places in the world that have less data and resources.

Where should this approach be used?

The seasonal sensitivity approach was developed in the Pacific Northwest of North America, with a focus on five diverse locations, including the Yakima River. This region depends heavily on mountain snow accumulation to determine when and how much water is available to use in each season. Each year the amount of water in streams or rivers, which we refer to as streamflow, is much bigger (on average, three times more) than the amount of space available to store water in man-made reservoirs. Therefore, any change in when the water arrives can have serious implications on water management. As such, it is important to understand the impact of climate change on streamflow in each month throughout the year. This approach is well suited to the challenge of understanding seasonal change and is particularly helpful in locations where the ability to store water is small relative to the total amount of water that flows in the river or stream throughout the year.

Other locations can store a larger portion of their annual streamflow, and therefore may be less concerned with seasonal changes. For example, the Colorado River basin can store over four times the total amount of water on average that flows in the river throughout the year. In places like this another approach such as the one outlined in [J. A. Vano and D. P. Lettenmaier, 2014] may be more useful.

What does the approach provide?

The seasonal sensitivity approach identifies locations more likely to experience changes in seasonal water availability because of warming temperatures and precipitation changes. It does this through:

Sensitivity Maps

Maps of seasonal sensitivities indicate locations that are more or less sensitive to changes in temperature and precipitation in both the warm (April to September) and cool (October to March) seasons. Most notably, in the Pacific Northwest, intermediate elevation river basins (1500-2500 m), which is the elevation range in the Yakima River, are the most sensitive to changes in cool season temperatures. Warmer temperatures at these elevations during the cool season result in more rain than snow and snow that melts earlier in the year. This increases streamflow in the cool season and subsequently reduces streamflow in the warm season.

Lower and higher elevation locations are less sensitive to warming than intermediate elevation locations, but for different reasons. Lower elevation locations are less sensitive because cool season temperatures are warm enough such that most of their precipitation already falls as rain instead of snow. In contrast, higher elevation locations are less sensitive because cool season temperatures are cold enough that the same amount of warming applied to intermediate elevation locations does not change the snowfall to rainfall and snow is still able to persist. Said in Goldilocks terms, temperatures of intermediate elevation locations in the Pacific Northwest are neither too hot nor too cold, but are at just the right temperature to be noticeably affected by modest temperature increases, especially in the cool season.

Short-cut Streamflow Estimates

While sensitivities to simple temperature and precipitation perturbations can help us identify places most vulnerable to future change, managers really want to know how streamflow is projected to change under future climate conditions. By using both sensitivities from hydrologic models and projected temperature and precipitation changes from global climate models, we can quickly calculate short-cut estimates of future monthly streamflow for 30-year average time periods (e.g., from 2030–2059).

Comparisons of future streamflow changes between the quick, efficient seasonal sensitivity approach and the computationally intense conventional approach done by [A. F. Hamlet et al., 2010]) were strikingly similar for a variety of different locations (see [J. A. Vano et al., 2015] for direct comparisons). For example, in the Yakima River, both approaches showed us that streamflow, which currently peaks in the late spring from melting snow, is going to increase in the wintertime and subsequently decrease in the spring and summer. This shift to more water in the river earlier in the year is problematic because this water system depends on late-spring snow melt to refill reservoirs for summertime irrigation. To avoid summertime water stress, water managers and planners in the basin now know they must find ways to manage the water without relying on melt from late-season snowpack.

The seasonal sensitivity approach works best when: (1) sensitivities to small changes are proportional to sensitivities to larger changes (referred to here as the principle of linearity), and

(2) when changes in individual seasons added together equal the amount of change seen when a change is applied throughout the year (referred to here as the principle of superposition). When tested, these two principles applied to most locations and seasons throughout the Pacific Northwest, and thus we have increased confidence the seasonal sensitivity approach can provide quick estimates of how the region's rivers and streams will be impacted by climate change, without having to do the more involved conventional approach.

What does the approach not provide?

The seasonal sensitivity approach provides an overview of likely long-term average changes (for example, 30-year averages) on a monthly or seasonal basis. While it can be an inexpensive alternative to other more resource intensive approaches, it does not provide the same level of detail. For example, it does not provide daily or monthly streamflow sequences. The approach is intended to capture the nature of changes in seasonality, not absolute streamflow amount, especially in summer and when temperature increases are large.

The seasonal sensitivity approach is not appropriate in places where sensitivities depend on the size of the applied change in temperature or precipitation (i.e., violates the principle of linearity) or where the additive effects of changes in temperature and precipitation during each season are not equal to the effects of temperature and precipitation changes applied year round (i.e., violates the principle of superposition). These principles should be tested before implementing this method. If tests for linearity and superposition identify locations where assumptions are not appropriate, estimations of future change require more careful consideration. However, all is not lost. Instead, these tests have identified locations where something interesting is happening and more understanding of the underlying physical processes may be quite valuable.

How does it work?

Below is a step-by-step guide that highlights how the method works. We intend these steps to simply illustrate what is involved. To see five examples in the Pacific Northwest and more specifics on how to implement this in your region, please refer to [J. A. Vano et al., 2015].

Step 1.
Obtain simulated historical streamflow:
Run a hydrologic model to estimate how water flows through a river basin, simulating weather (e.g., temperature and precipitation), basin-specific characteristics (e.g., topography, soil, and vegetation types), and important physical processes (e.g., evaporation of water to the atmosphere and infiltration of water into the soil).

Step 2.
Obtain simulated streamflow with an annual temperature perturbation:
Run the same hydrologic model again, keeping everything the same as in Step 1 except increase the temperature every day of the year by 0.1°C.

Step 3.
Compute annual temperature sensitivities:
Compare the streamflow generated in Step 1 and Step 2. Calculate how much streamflow changes per °C increase in temperature. This value is the annual temperature sensitivity.

Step 4.
Compute seasonal temperature sensitivities:
Repeat Steps 2 and 3, but change the temperature only in the cool season (October to March) or only in the warm season (April to September), or only in the fall, winter, spring, and summer. These values are seasonal temperature sensitivities.

Step 5.
Compute precipitation sensitivities:
Repeat Steps 2, 3, and 4 but instead of changing temperature, change precipitation by 1 % and calculate how much streamflow changes per % increase in precipitation. These are values of precipitation sensitivities.

Step 6.
Estimate future monthly streamflow:
Multiply temperature and precipitation sensitivities, calculated for each month using perturbations done in the four seasons (48 values for temperature, 48 values for precipitation) by the seasonal temperature and precipitation changes that come from the global climate models. This calculation, applied to monthly historical streamflow values, will give approximate values of future monthly streamflow.

Take home message

How the amount of water in rivers and streams will respond to climate change depends on many factors, including the season, a river basin's elevation, vegetation, soil, and changes in temperature and precipitation. We have outlined an approach that provides a relatively quick way to account for these factors in understanding what future changes in streamflow might be, both spatially and, on average, in every month throughout the year. This approach provides reasonable first-order estimates, when compared with more conventional approaches, of future streamflow change in a diversity of rivers in the Pacific Northwest, demonstrating a technique that could be employed in rivers throughout the world.

Acknowledgements
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Are humans to blame for the heat experienced in Geneva in the summer of 2015?

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Since the dawn of the Industrial Revolution, humans have been changing the chemical composition of the atmosphere by burning fuels such as coal, oil, and natural gas. These gases are known to scientists as "greenhouse-gases". Greenhouse-gases are vital to sustain life on Earth, but rapidly increasing concentrations of them can have catastrophic consequences. The word 'catastrophic' is perfectly fitting here, because, as will be demonstrated in this article, it is now believed our greenhouse-gas emissions play a large role in the occurrence of extreme weather events that cause billions of dollars worth of damage to infrastructure, and bring about tens of thousands of human deaths every year. We additionally explain how extremes occurring over spatial scales smaller than what climate models can resolve, such as a heatwave over the city of Geneva in Switzerland, can be attributed to human activity – the first study of its kind to use such an approach.

Geographical Sector(s): Global

Subject Area(s): Climate of the Present, Extremes

An Analogy

A heatwave was responsible for killing 70,000 people in Europe in 2003, and there is strong evidence suggesting human activity was responsible for significantly increasing the chance of that heatwave [C. Schaer et al., 2004]. Before we jump ahead, let's take a step back and use an analogy to help our readers understand why scientists in this field often use probabilistic language, i.e., "the burning of fossil fuels increased the odds/chance/frequency/probability of this extreme event", and not "this extreme event was (or was not) caused by the burning of fossil fuels". Picture a scenario in which you are commuting on the highway. Driving faster can increase the odds of an accident, but is does not imply that when an accident does occur, a high rate of speed was the cause. This is because a number of other factors could have caused the accident: for example a wet road or a driver in a nearby vehicle who had too much alcohol at dinner. A statement like "the chance of an accident was increased by X percent because of the increased speed" may be technical, but is a rigorous way to answer the question. A

controlled experiment would need to be performed to be able to attribute a certain increase in speed to the chance of an accident – for example suppose we create two hypothetical scenarios/cities in which all factors (except speed) that could potentially cause an accident are kept constant: same alcohol consumption, same number of slippery roads, same number of people texting while they drive, etc. If the only difference is the average speed of vehicles (say 60 km/h vs 100 km/h), and we count the number of accidents that occur in each scenario: say 10 vs. 20 respectively, we can conclude that increasing your speed from 60 km/h to 100 km/h increases your chance of having an accident by 100%.

Transforming the Analogy to the Climate System

The 'speed' in our analogy represents the concentration of greenhouse-gases in the atmosphere; the 'intoxicated/texting drivers' and 'wet roads' represent natural variability in the climate system – those aspects within the system which can still cause the damaging/harmful event we are studying; and lastly an accident represents an extreme weather event. Extreme weather events that we are typically interested in are events unusual enough to cause harm to human health or infrastructure. In this study it is defined as the highest 5-day average temperature in a 10 year period. So how do we attribute the chance of an extreme event to human activity then? We generate the two 'scenarios' as would equally be required in the above analogy. Because we do not know what the current world would look like had humans never existed, one popular way to answer the question is with complex climate models describing (as best we can) the physics and dynamics of the climate system. When models are extremely complex as in the case of climate models, they are run by super-computers that can make calculations and process information at rates much faster than any desktop computer could.

The Experiment

One advantage of climate models is that one can alter aspects of them to see how they would behave under certain 'different' situations. We run a climate model under two different scenarios and then count the number of extreme weather events ('accidents' in the analogy) that occur in each scenario. One scenario is the world as it is now with greenhouse-gas concentrations and sea surface temperatures set to current values. The second scenario is a world without human industrialisation: we reduce carbon dioxide and methane concentrations in the atmosphere and we cool the ocean appropriately. We run the model under each scenario many times so that enough extreme events are simulated such that we can get statistically significant samples of extremes in both cases [P. Pall et al., 2011].

So Did Humans Actually Increase the Probability of the Heatwave Over Geneva?

When it comes to heatwaves, all the models currently used by scientists agree that the chance of these events occurring over almost all parts of the Earth have increased as a consequence of human activity through our greenhouse-gas emissions. In our study we found that attribution

statements (e.g., "driving at 100 km/h increases your chance of an accident by 100%") for heatwaves hardly change between heatwaves occurring over a spatial domain the size of the canton of Geneva, and heatwaves occurring over larger spatial domains, i.e. over Switzerland and over Europe. Correlations between attribution statements for heatwaves occurring over large spatial scales versus ones for events occurring over small spatial scales show an extremely high correlation (~0.97). In other words, results show that human greenhouse-gas emissions have similarly altered the probability of the occurrence of these events over both spatial scales. Such a result suggests the chance of heatwaves occurring beyond the smallest scale at which weather is computed in the models (e.g. over spatial scales the size of Geneva), have also almost certainly increased as a consequence of the greenhouse-gases we as humans have emitted [O. Angelil et al., 2014]. Final results suggest our emissions since the Industrial Revolution may have increased the likelihood the Genevan heatwave by a factor of 2-8 times depending on the model used.

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Can somebody clear the air? How air quality and climate change are connected.

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Air pollution and climate change are different phenomena, but are connected in a number of ways. The same sources emit both air pollutants and greenhouse gases, many air pollutants affect the Earth's energy balance and thereby affect climate change, and a changing climate will affect air quality. Policy options to address either air quality or climate change cannot be formulated and applied in isolation, as most will often affect emissions of both greenhouse gases and air pollutants. This article outlines the basics of what air pollutants and greenhouse gases are, how they affect air quality and climate change, and where they come from. The connections between these two environmental phenomena are also addressed.

Geographical Sector(s): Global

Subject Area(s): Aerosols, Air, Climate of the Future, Climate of the Present, Lower Atmosphere, Pollution and Climate

On September 30, 2015, Stephen Colbert's Late Show covered Chinese President Xi's announcement that China would address its greenhouse gas emissions. Colbert followed this up by stating that the agreement was a response to the 'growing public anger about the noxious air that often envelops Chinese cities', and jokingly stating that the first step to reducing their emissions would be 'trading in their Volkswagens,' a reference to the recent emissions testing cheating scandal ["The Late Show with Stephen Colbert: China finally wants to clear the air", 2015]. While these all have to do with emissions into the atmosphere, these various headlines he brought together are addressing different issues: air pollution and climate change. As someone who spends their days thinking about air pollution as well as climate change, I find examples such as this both encouraging (that it is being covered in the popular media), and discouraging (that – at least in this case – the science behind these issues isn't fully understood by the media). Let's consider Colbert's statements in a bit more detail. The major greenhouse gas responsible for climate change is carbon dioxide (CO_2). CO_2, however, is not an air pollutant because it doesn't have any direct effect on human health, and therefore any changes in CO_2 emissions will not have an effect on the 'noxious air'. The emissions for which Volkswagen installed software to cheat the emissions testing system was for nitrogen oxides (aka NOx), which is an air pollutant, but not a greenhouse gas. Reducing the NOx emissions would therefore not have a significant effect on global climate change. However, one could characterize air pollution and climate change as 'two sides of the same coin' – different but closely related – as this article will go on to explain.

Air pollution and climate change are indeed different phenomena, but they are affected by many of the same things: 1. emissions sources such as automobile exhaust, energy production or industry; 2. the properties and chemical processes affecting the emitted compounds; 3. policy options to reduce or mitigate these emissions.

What are air pollutants and why are they important?

Air pollutants are typically regulated by governments around the world because of their adverse effects on human health and ecosystems ["http://www3.epa.gov/airquality/urbanair/", 2015]. These regulations limit the amount of pollutants that can be emitted into or are allowed to be in the air. For example, the World Health Organization has recommended limits based on studies of adverse human health effects for a number of air pollutants including particulate matter, ozone, nitrogen dioxide, and sulfur dioxide [WHO, 2006]. Air pollutants are typically grouped based on whether they are gases (e.g. ozone and nitrogen dioxide) or solids (e.g. particulate matter). In addition, some pollutants are emitted directly into the atmosphere from a variety of sources, so they are referred to as "primary pollutants". Other pollutants are formed in the atmosphere from primary pollutant emissions, these are referred to as "secondary pollutants". For example, ozone, the main component of 'smog', is not emitted directly; rather, it is formed in the atmosphere from nitrogen dioxides and volatile organic compounds (VOCs) like benzene, among other gas-phase pollutants. Primary pollutants such as carbon monoxide or methane can also be formed "secondarily" in the atmosphere as a result of chemical reactions. Ozone's relevance as a "secondary pollutant" comes from the fact that in order to control the concentrations of ozone in the air, concentrations of the primary pollutants (VOCs, NOx, etc) have to be reduced.

Particulate matter (PM) includes a variety of different pollutants including, but not limited to: organic carbon, black carbon, sulfate (from sulfur dioxide), nitrate, mineral dust, and sea salt. The composition of PM varies depending on the environment and sources of pollutants. For example, the composition of PM in the middle of a megacity such as Jakarta will be different from that in the middle of the Sahara. PM is typically referred to and regulated based on its size (PM1 - smallest; PM2.5 - moderate size; PM10 - largest). These designations refer to the particles' diameters - 1, 2.5, and 10 μm and smaller, respectively. Similarly to the gases, particles can be emitted directly ("primary") or formed in the atmosphere ("secondary").

Air pollutants are bad for human health. Air pollution contributes to premature mortality and morbidity, pulmonary disease, asthma, and other respiratory illnesses. The vast majority of adverse health effects from air pollution can be attributed to particulate matter, with a much smaller proportion of ill effects attributed to ozone [M. R. Heal et al., 2012] [S. S. Lim et al., 2012]. The Global Burden of Disease study attributed 3.3 million deaths to outdoor air pollution in 2010 [S. S. Lim et al., 2012]. Smaller particles are a greater health concern than larger ones, not least because smaller particles travel farther into the lungs and even into the bloodstream. There is also variability within specific particle sizes depending on their composition: initial studies suggest that long-term exposure of PM2.5 containing a high black carbon fraction may have larger mortality effects than other PM2.5 mixtures [K. R. Smith et al., 2009].

What are greenhouse gases and how do they affect the climate?

Carbon dioxide (CO_2) is the most important greenhouse gas for climate change. Other greenhouse gases include methane, halocarbons (CFCs, HCFCs), nitrous oxide (N2O), and even ozone. Ozone is both an air pollutant and a greenhouse gas. Greenhouse gases (GHGs) alter the energy balance of the Earth, which in turn drives climate change. Radiative forcing is a measure of this change in the net energy balance [T. F. Stocker et al., 2013]. Greenhouse gases in the atmosphere can be compared to a blanket covering the planet. Just like blankets keep you warm at night, the GHG blanket around the Earth regulates the temperature of the Earth. But now, we've been adding thickness to this blanket in the form of increased GHG emissions, thereby causing global warming. But unlike the blankets on our bed, we can't just remove them when it gets too hot. The top bar in Figure 1 indicates the

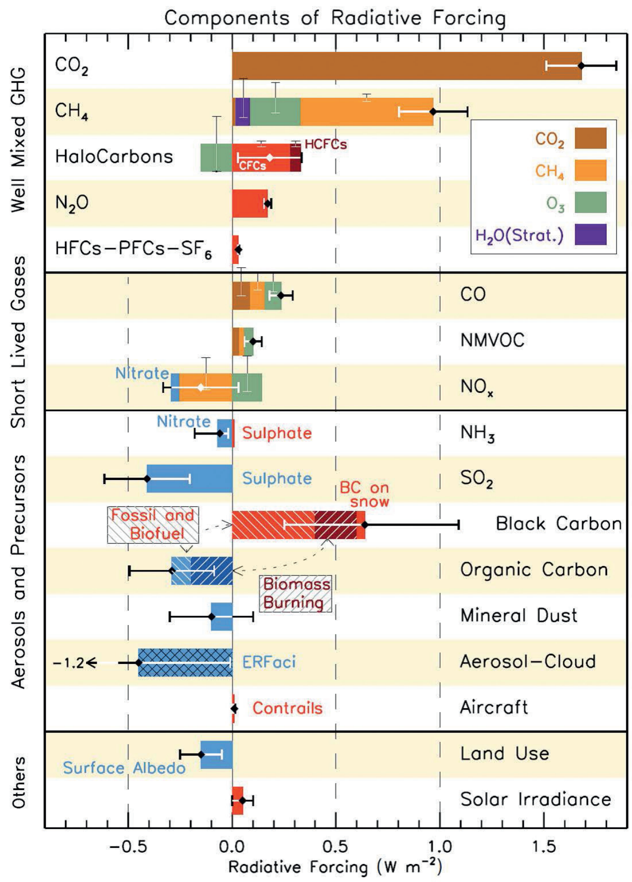

Figure 1. Warming or cooling attributed to greenhouse gases and air pollutants (depicted in terms of radiative forcing) since pre-industrial times (1750). The components are generally grouped by their lifetime in the atmosphere, as per the vertical labels on the left side. Warming is indicated by bars extending to the right, cooling by bars extending to the left. Source: [T. F. Stocker et al., 2013]

amount of radiative forcing that CO_2 has contributed to since pre-industrial (1750**) times.

What are the emission sources of air pollutants and GHGs?

Air pollutants and greenhouse gases are emitted from many of the same sources. Fossil fuel combustion is a dominant source for both. The transportation sector – specifically cars – is a significant source of emissions of CO_2, particulate matter, nitrogen oxides, carbon monoxide, and volatile organic compounds. Similarly, energy generation and use is also a significant source of CO_2 emissions, as well as PM, sulfur dioxide, and nitrogen oxides [E. von Schneidemesser et al., 2015]. The amount of pollutants emitted in these situations depends on governmental regulations – sulfur dioxide emissions from coal fired power plants were capped in the US by the Clean Air Act in the 1990s. At this point, sulfur dioxide emissions from power plants in the US and Europe are minimal compared to Asia, where the sulfur content in fuels and fuel gas controls are much less regulated. In addition, biomass burning, whether from residential combustion (burning wood in a fireplace), waste burning, or naturally occurring forest fires, is also a significant source of not only CO_2, but also particulate matter including organic carbon and black carbon, carbon monoxide, and nitrogen oxides. Agriculture is a significant source of methane, specifically from cows and rice cultivation, but also as a source of volatile organic compounds and particulate matter.

How long do GHGs and air pollutants stay in the atmosphere and why is that important?

How long air pollutants or greenhouse gases stay in the atmosphere is often referred to as their "lifetime". The lifetime of air pollutants ranges from hours to months. The end of their "lifetime" comes when they are either rained out, naturally settle out because of gravity, or react with other pollutants in the atmosphere to create something new. The lifetime of the greenhouse gas CO_2, for instance, is of the order of a century. Other greenhouse gases such as halocarbons (CFCs or HCFCs) or nitrous oxide (N2O, aka laughing gas) range from a couple of years to hundreds of years. Methane falls right in the middle, with a lifetime of about a decade.

Atmospheric lifetime is important because it determines the scale of the problem – how far the pollutants or GHGs can be transported by winds. Global circulation patterns mean that longer- lived gases – those in the atmosphere for a number of years – will become mixed across the hemisphere. When the lifetime is even longer, they will end up distributed all over the globe, like CO_2 [J. H. Seinfeld and S. N. Pandis, 2006]. Air pollutants with much shorter lifetimes don't often make it beyond the immediate surroundings from where they were emitted before being removed from the air. This is why the extreme air pollution in China remains a largely Chinese and Asian problem, whereas CO_2 emitted in China or elsewhere is a global issue. Thus, if China decided to drastically reduce emissions of air pollutants, as it did during the Beijing Olympics, significant improvements would be visible within days to weeks. In contrast, the lack of international action toward reducing CO_2 means that the effects of climate change will continue to be a global issue with increasingly detrimental effects for generations to come. Even if we started reducing CO_2 emissions immediately the effect on climate change (warming) wouldn't be felt for roughly a century due to its lifetime.

How do air pollutants affect climate change?

Some air pollutants also have an effect on climate change. For example, as mentioned earlier, ozone is both an air pollutant and a greenhouse gas. However, because of its short lifetime in the atmosphere (ca. weeks), reducing ozone would lead to relatively immediate reductions in the warming – like shedding a layer of the blankets. The bars in Figure 1 show the amount of change to the radiative forcing that pollutants and greenhouse gases have contributed since 1750 to the present (2011) [G. Myhre et al., 2013]. In the Figure, "primary" emissions are labeled with the black text next to the bars. The effect that these primary emissions, e.g. CO_2 or CO, have had on radiative forcing (warming or cooling) is depicted by the length of the horizontal colored bars. As indicated earlier, CO_2 (the top bar in brown) has the largest bar, indicating that it has had the largest effect on radiative forcing, which is why it is of primary concern for addressing climate change. Carbon monoxide (CO; 6th bar from the top of the Figure) has had a much smaller effect on radiative forcing, as indicated by the much shorter bar. CO itself is not a greenhouse gas. Therefore, it does not have a direct effect on radiative forcing. However, it contributes to the formation of secondary pollutants such as ozone that do effect radiative forcing, and because of this, its bar is composed of multiple colors reflecting CO_2 (brown), methane (orange), and ozone (green), gases that CO influences to affect radiative forcing.

The top-most section of the plot shows the amount of radiative forcing from GHGs. The middle two sections include the gas-phase air pollutants, and the components contributing to particulate matter (labeled here as 'aerosols and precursors'). Aerosols refer to the mixture of solids, liquids, and gases that also contain particulate matter. Aerosols or particles affect the radiative forcing of the atmosphere through their effect on light absorption and scattering. Generally, the darker particles absorb incoming radiation (including sunlight), contributing to warming (red bars to the right), while the lighter particles scatter incoming radiation, thereby contributing to cooling (blue bars to the left) [E. von Schneidemesser et al., 2015]. This can be compared to the different temperatures one might notice if walking barefoot in summer. For example, a blacktopped parking lot would be much warmer on bare feet than white paving stones or concrete. While most aerosol components contribute to cooling, such as organic aerosol and mineral dust, black carbon – the primary component of soot – contributes significantly to warming. This is particularly relevant in snow covered areas, such as the polar regions or the Himalaya, where black carbon deposited onto highly reflective surfaces (e.g. white snow or ice) can reduce the amount of reflected sunlight, ac-

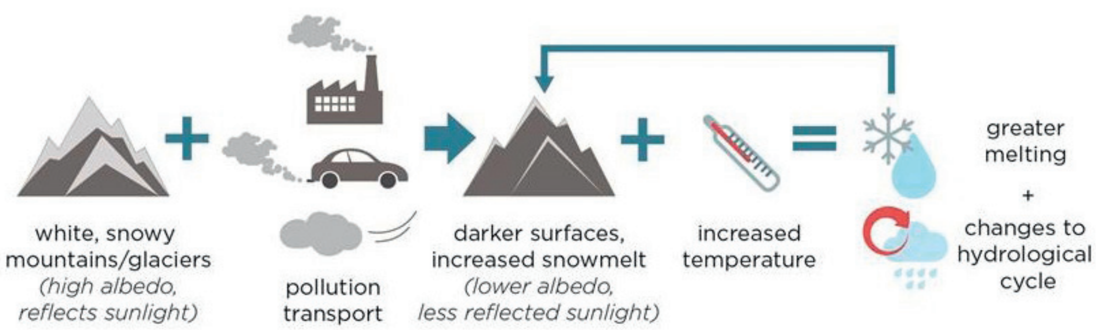

Figure 2. The feedback loop from increased particulate matter emissions, specifically darker particles such as black carbon, and the effect on climate change and ecosystems. The changes to the hydrological cycle also have implications for human health. Figure reproduced from [E. von Schneidemesser et al., 2015].

celerating melting. This can lead to a feedback process that causes further warming, as shown in Figure 2 [E. von Schneidemesser et al., 2015]. Consider, for example, the case of Asia and the Himalayan glaciers. Black carbon or other dark colored particles emitted from vehicles, open fires used for cooking and heating, or brick kilns in Asia are transported (blown by the wind) north toward the Himalaya, where these dark particles are then deposited onto the glaciers. These dark particles decrease the reflective properties of the snow and ice surface, which means that more sunlight is absorbed than usual, and this leads to an increase in the temperature. This in turn can cause further melting, etc. This is known as a "feedback loop". Such a process, of which there are many, are ways in which air pollutants influence climate change, particularly those relevant to regional scale climate change.

How does climate change affect air pollution?

Not only do air pollutants affect climate change, but a changing climate will also affect air pollution. For example, ozone, as a "secondary" pollutant, is formed in the atmosphere from chemical reactions of primary pollutants in the presence of sunlight and warm temperatures. Under a warmer climate, conditions will favor ozone production and concentrations are expected to increase. Generally, future climate conditions will make it harder to achieve a given air quality goal. This means that greater emission reductions will be needed under a future climate compared to those needed today to reach the same target [S. Wu et al., 2008].

Win-win options for addressing both climate change and air pollution

Figure 3 provides a nice summary of the 'two sides of the same coin' aspect of air pollution and climate change, by considering the implications of changing concentrations of GHGs and air pollutants in the atmosphere. From left to right in the graphic, human activities, such as driving and energy consumption, lead to increases in emissions of both GHGs and air pollutants. These emissions pollute the air and change the Earth's energy balance. These in turn increase the global temperature, change weather patterns, harm human health, and damage crops and ecosystems. An awareness of both of these environmental issues, their

unfortunate side effects for air quality, specifically for emissions of nitrogen oxides and PM.
There are however, "win-win" options that would benefit both environmental issues, such as energy efficiency and renewable energies, such as wind or solar power [M. Williams, 2012]. The atmosphere is a part of the global commons, and modern civilization has caused significant changes to its composition. Understanding that many sources emit both greenhouse gases and air pollutants,

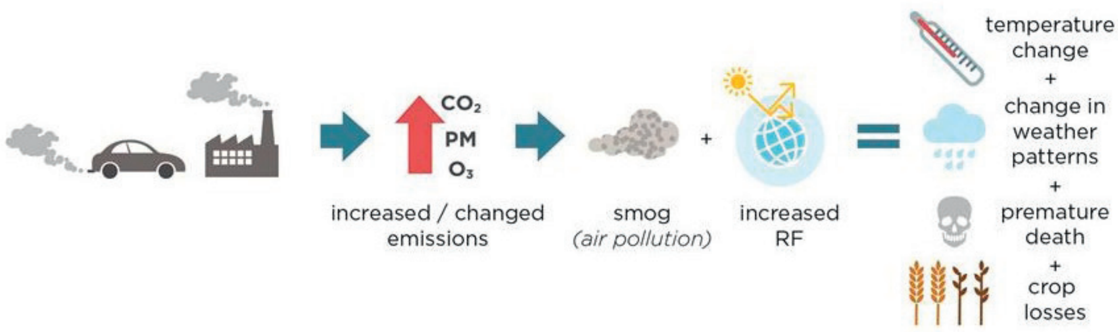

Figure 3. The implications of changes in atmospheric composition, specifically GHGs and air pollutants, for climate change, human health, and ecosystems. Figure reproduced from [E. von Schneidemesser et al., 2015].

and that air pollutants affect climate change and vice versa is crucial for how air quality and climate change are approached from a policy perspective. Acknowledging these linkages and recognizing that it is important to address these issues in a coordinated way can foster informed decisions that avoid trade-offs and take advantage of synergies among mitigation options. This is true not only for policy makers, but all of us. We can all act to improve our air quality and mitigate climate change – by cycling or walking instead of driving, and when we choose to drive, by maintaining the vehicles we drive to make sure they meet the emission standards and considering efficiency in our choices when we purchase them; by choosing wind and solar energy, and if we use a fireplace for residential heating by choosing efficient combustion technologies to minimize air pollutant and CO_2 emissions. It also presents an opportunity on a grand scale for research and development to tackle these societal challenges, such as the redesign of our cities toward zero emissions targets, the transition to renewable energy options, and the transformation to a sustainable society.

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Choose you own scientific experiment: Triggering debris flows and flash floods

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Published Article v. 1

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Landslides and flash floods result in many fatalities around the globe. Understanding what triggers these events is therefore vital, although how to approach this problem is not straight forward. After background information for the experiment and some guidelines, two options are presented to learn more about the triggers of debris flows: (A) using rainfall or (B) the atmospheric conditions. You can then choose the option that appears more useful and interesting to you (you can always go back and read the other experiment afterwards). The article then ends with a reflection on the results.

Geographical Sector(s): Europe, France

Subject Area(s): Air, Climate of the Present, Extremes, Impacts, Weather

Background

Sitting beside the Faucon torrent, you enjoy the cool mountain breeze. You hiked up here after lunch, as you have recently moved to this region in the South East French Alps and wanted to explore the area. You notice that the surrounding mountain peaks, visible when you started out, are now capped with fluffy, marshmallow-like clouds. There is little snow around you at the moment, but you think about the coming winter when the valley will be shrouded in snow, perfect conditions for winter activities. To get a better look down at the Ubaye Valley, you move away from the torrent. You notice, however, the previously innocent looking clouds are growing to a rather monstrous size, and the cool breeze has turned much stronger. Rain begins to fall, although from what you can see, it appears much heavier further up the mountain. A dull roar builds from the direction of the torrent. Pausing, you turn your head towards the noise. Suddenly a mass of … what is that, water? … rushes downstream. It is not like the normal water however. It is dirty, sludgy, and contains rocks, damaging houses along the way. You hurry back towards the residential area below to see if you can help.

When you arrive, you talk to the locals and find that thankfully no one was hurt[1] . Somewhat concerning is that you hear this sort of thing had happened before. Every year or so, this phenomenon occurs somewhere in the area, either here or other torrents in the valley [J.-C. Flageollet et al., 1999]. In some instances, it is only water, termed a 'flash flood'. In other instances, rocks, dirt, and other sediment are mixed in with the water, resulting in a 'debris flow'. With a bit more probing, you discover that previous research found that these debris flows and flash floods (or 'flash events'), have previously been associated with melting snow and high-intensity storms [J.-C. Flageollet et al., 1999]. Will this continue in the future?

You know that the climate is changing. Warmer temperature may reduce the amount of snow, possibly reducing the number of flash events, although warmer temperatures may lead to more high-intensity rainfall events so the number may actually increase [P. Pall et al., 2007]. You decide to investigate further to see if you can find a link between the climate and these flash events. Maybe in doing so, you can use your results as part of an early warning system, or to better understand how the number of flash events may change in the future. Or perhaps even in other areas people can use your experiment set up to see what is happening in their own region. First however, you have to establish a link.

Start of the experiment

You decide to look for thresholds. The goal of a threshold is to divide days when an event occurs, like a flash event, from the days that they do not occur (which in this experiment is many days, as most days there are no debris flows or flash floods). Thresholds are often used as part of early warning systems, such as in the example of rainfall warnings where a warning is given out when the rainfall amount exceeds a threshold.

Data for the Ubaye Valley is available from 1979 to 2010. Part of the data will be used to develop the threshold: 1989-2004 (termed the calibration period as this is the data used to form or calibrate the threshold). On either side, you have two validation periods: 1979-1998 and 2005-2010. The data from these two validation periods will be used to test your thresholds from the calibration period. If the threshold still does a good job separating the events in the validation period, the threshold works. Otherwise, it will be back to the drawing board. Now you just have to decide what data you will use.

One option is to use rainfall measurements. Rainfall is what you think is actually triggering the debris flows, and there are four measuring stations located near the main river (rain gauges). You have daily measurements of how much rain fell for the entire calibration and validation periods.

Another option is to look to the atmosphere to see what is causing the rainfall (atmospheric conditions). You realize that every time it rains, a flash event does not occur. And there is data available for many different atmospheric properties covering all of Europe for both your calibration and validation periods.

If you decide to use rainfall measurements, proceed to experiment A. If you decide to branch out and take the less obvious path and use atmospheric conditions, proceed to experiment B.

Experiment A

You decide to stick with rainfall. You know that this is a typical approach when considering debris flows around the world (e.g. [M. Jakob et al., 2012], [N. K. Meyer et al., 2012], [J. Zhuang et al., 2015]). These rainfall thresholds are typically based on the intensity and duration of the rain, and in some cases how much rain fell in the preceding days [F. Guzzetti et al., 2008]. While ideally you would like to use records of how much rainfall fell every hour, you only have daily data. So you test a variety of rainfall parameters (1 day and 10 days together, 1 day by itself, 2 days and 7 days together etc.) using statistics to see what threshold and combination works best.

You find that the best parameters are daily rainfall combined with rainfall over the preceding four days from a rain gauge sitting in the middle of the catchment. More rainfall in the four days before the flash event means that when the heavy rainfall arrives, not much water can be absorbed into the ground, and will therefore more likely lead to a flash event. The threshold works well in the calibration period – most of the values are above the threshold. While some of the non-flash days are above the threshold too, most are below. So far so good. When looking at the validation periods however, most of the flash events are below the threshold – not so good. Although you do not get too disheartened, as similar results were found in other studies too (e.g. [N. K. Meyer et al., 2012]).

You start to wonder about using rainfall for your threshold. You think back to the day on the Faucon torrent when you witnessed the debris flow. It wasn't raining that hard where you were standing, and maybe this was also true for the rain gauge. You also remember the sunny weather in the morning. All the rain fell in a short time, and perhaps the debris flow would not have occurred if the rain had been spread out over the entire day. So maybe this event was actually one of the days below the threshold! You wonder if you would have had better results with experiment B.

Experiment B

You decide to take the unusual route of using atmospheric conditions. If there was a simple relationship between rainfall and debris flows, it may have already been found by now. And in the process of developing the threshold, maybe you will learn a bit more about what is actually causing the rainfall. But which atmospheric properties to use?

You brush up on some previous studies. Back in the 1970s, [R. A. Maddox et al., 1979] found that just under half of the flash floods in the United States were caused by thunderstorms that developed locally (local convection). In contrast, the other flash floods were associated with large scaler weather features, such as cold fronts and low pressure systems. Fast forward to 2010s, [O. Nuissier et al., 2011] used the distribution of low and high air pressure over Europe, combined with wind and a relative of temperature (the technical term is adiabatic wet-blub potential temperature) to identify heavy precipitation events. Numerous studies also used a variable called CAPE (e.g. [S. Niall and K. Walsh, 2005], [R. Trapp et al., 2009], [D. M. Romps et al., 2014]). CAPE stands for 'Convective Available Potential Energy', which is a measure of how much energy would you get if you took a small parcel of air near the surface and gave it a little upward nudge. If the air parcel flies high into the air, as in a thunderstorm, the CAPE values would be high. So you decide to use this variable CAPE (CAPE and flash events are starting to sound a bit like a super hero story, but nevertheless), along with other variables that you found in the other studies including temperature, wind, air pressure, and specific humidity (how much moisture is in the air).

You first split all your flash events into those where you think the rainfall was generated locally (most of the flash events), and those which you think are caused by large scale features like cold fronts. After testing the different variables, high CAPE and specific humidity near the mountain tops work best as a threshold for locally generated flash events. And this makes sense – high CAPE means all your air parcels will be very buoyant, and with lots of moisture, condensing to form rain or hail when they get high enough. For large scale events, specific humidity and temperature work as the best thresholds in the calibration period.

The results for the locally generated flash events work well. Most of the flash events are above the threshold in the calibration and validation periods. However, your large scale atmospheric flash events do not work so well. While most of the large scale flash events are above the threshold in the calibration period, only one of the 10 events are above the threshold in the validation periods. Maybe two variables are not enough for these events.

You start to wonder about using atmospheric conditions. You learnt that most of the flash floods and debris flows in the Ubaye Valley look to be caused by locally generated thunderstorms, just like you saw near the Faucon torrent. However, you could not find a good threshold for the other events. Furthermore, how easy would it be to use your results in an early warning system? Maybe it would have been better to use experiment A.

Reflection

You look back at your experiment (or experiments if you read both of them). It is not always a straightforward decision about what properties to use when trying to understand the triggers different natural hazards. And what worked in your area for the hazards you looked at (debris flows and flash floods), will not necessarily be the same for others. Using atmospheric variables can provide information about the mechanisms behind rainfall-triggered events, but this may not be as easy to interpret as just using rainfall, or as easy to incorporate into early warning systems. Therefore, rainfall thresholds may be better to use for early warning systems, but you would need to test them out with forecast data. Or if you decide to look at climate change, you could use the atmospheric thresholds to see how locally generated flash events change compared to the large scale ones. Either way, you go and put the kettle on, and start to think about which experiment you will start next.

Figure 1: A view of the Ubaye Valley

Footnotes

[1] The description is loosely based on the August 2003 event in the Faucon torrent. As described above, no one was hurt during the event, although the cost was estimated to be 2.5 million euros.

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Could climate engineering save the Greenland Ice Sheet?

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Engineering the climate through albedo modification (AM) could slow, but probably would not stop, melting of the Greenland Ice Sheet. Albedo modification is a technology that could reduce surface air temperatures through putting reflective particles into the upper atmosphere. AM has never been tested, but it might reduce surface air temperatures faster and more cheaply than reducing greenhouse gas emissions. Some scientists claim that AM would also prevent or reverse sea-level rise. But, are these claims true? The Greenland Ice Sheet will melt faster at higher temperatures, adding to sea-level rise. However, it's not clear that reducing temperatures through AM will stop or reverse sea-level rise due to Greenland Ice Sheet melting. We used a computer model of the Greenland Ice Sheet to examine its contributions to future sea level rise, with and without AM. Our results show that AM would probably reduce the rate of sea-level rise from the Greenland Ice Sheet. However, sea-level rise would likely continue even with AM, and the ice sheet would not regrow quickly. Albedo modification might buy time to prepare for sea-level rise, but problems could arise if policymakers assume that AM will stop sea-level rise completely.

Geographical Sector(s): Arctic, Greenland

Subject Area(s): Climate of the Future, Geoengineering, Ice & Snow, Sea Level

What is albedo modification?

How does it work, and why is it risky?

Albedo modification (AM) is a possible technological solution to the problems caused by climate change, but it is also untested and risky. Many human activities that produce economic growth also emit greenhouse gases. These greenhouse gases cause surface air temperatures to rise because they trap infrared radiation near the earth's surface. Albedo modification interrupts this process by putting reflective particles into the upper atmosphere. Some of the sun's rays then bounce off these particles instead of warming the ground and the lower atmosphere, leading to reduced surface air temperatures. There are other possible climate-modifying technologies that could be called albedo modification, but injecting reflective particles into the stratosphere is the most commonly-discussed AM technique.

If it worked, albedo modification might reduce surface air temperatures faster and more cheaply than reducing greenhouse gas emissions. AM was partly inspired by volcanic eruptions, which also put reflective particles into the upper atmosphere and reduce surface air temperatures [P. J. Crutzen, 2006]. For example, the eruption of Mt. Pinatubo in 1991 reduced globally-averaged surface air temperatures by up to 0.5 C [D. E. Parker et al., 1996]

[A. Robock et al., 2009]. Achieving a Pinatubo-sized reduction in surface air temperatures using AM might cost a few billion dollars per year [A. Robock et al., 2009]. This cost is a small fraction of the world's yearly economic output, which is trillions of dollars. On the other hand, producing a Pinatubo-sized temperature reduction via reducing greenhouse gas emissions would take much longer [D. Archer et al., 2009]. Substantial emissions reductions would carry large economic costs. Removing carbon dioxide from the atmosphere is even more speculative than AM and would likely be very expensive [K. Keller et al., 2008] [K. Z. House et al., 2011] [H. J. Schellnhuber, 2011].

However, temperatures would rise very quickly if albedo modification were initiated and then suddenly stopped [H. D. Matthews and K. Caldeira, 2007] [M. Goes et al., 2011]. The reflective particles only stay in the upper atmosphere for a few months or years, so new particles must be injected into the upper atmosphere continuously in order to maintain AM's benefits [A. Robock et al., 2009]. If a conflict or an economic crisis interrupted the delivery of new particles to the upper atmosphere, temperatures would rise quickly to the level they would have achieved if AM had never begun [H. D. Matthews and K. Caldeira, 2007]. This sudden increase in temperatures might be more disruptive to human societies than if nothing were done about climate change.

Albedo modification also comes with other important risks. We refer interested readers to Alan Robock's article, "20 reasons why geoengineering may be a bad idea," for information on these additional risks [A. Robock, 2008].

Causes and consequences of sea-level rise

Greenhouse gas-driven climate changes increase flooding risks for people living near present- day coastlines through sea-level rise [A. Parris et al., 2012] [E. Spanger-Siegfried et al., 2014]. As surface air temperatures increase, glaciers and ice sheets melt more rapidly. The water from this melting ice runs into the oceans, raising globally-averaged sea level. The ocean also warms with the atmosphere, leading to additional sea-level rise through thermal expansion. Tides and storms can flood previously-protected areas when they stack on top of the long-term sea-level rise from melting glaciers and expanding ocean water [E. Spanger-Siegfried et al., 2014].

Could albedo modification prevent or reverse sea-level rise?

Some scientists have argued that, if sea-level rise is caused by surface air temperature increases, then a technology for reducing temperatures would also reduce sea-level rise. For example, a recent report by the US National Academy of Sciences "recommends an albedo modification research program be developed" [Committee on Geoengineering Climate:

Technical Evaluation and Discussion of Impacts et al., 2015]. This report discusses sea-level rise as a consequence of climate change, implying that AM could prevent sea-level rise. An opinion piece including one of the NAS report's authors suggests that AM could help avoid "... major ice sheet collapse," which would lead to large sea-level rise [D. W. Keith et al., 2010]. Another study concludes that AM could completely stop sea-level rise from the Greenland Ice Sheet [P. J. Irvine et al., 2009]. One study even argues that sufficiently strong climate engineering could reverse sea-level rise [J. C. Moore et al., 2010]. These studies arrived at their conclusions using computer models of the relationship between climate forcing and sea-level rise, and between temperature and Greenland Ice Sheet melt.

The great ice sheets and their contributions to sea-level rise

However, the ice sheets are an important unknown in predicting future sea-level rise, and the relationship between surface air temperature and ice sheet melt is complex. Small glaciers contain enough water to raise globally-averaged sea level by about 0.5 m [V. Radic and R. Hock, 2010], and thermal expansion could contribute perhaps a few meters to sea-level rise over the long term [J. A. Church et al., 2013]. On the other hand, if all the ice locked up in ice sheets melted, sea level would rise by about 70 m. Greenland holds ~7.3 m of this total amount, and the remainder is locked up in the Antarctic ice sheets [J. L. Bamber et al., 2013] [P. Fretwell et al., 2013]. This amount is many times the maximum contribution from all other sources.

The Antarctic Ice Sheets respond to ocean temperatures, not surface air temperatures. Air temperatures over Antarctica are so cold that the Antarctic Ice Sheets don't lose much mass by surface melting. Instead, the Antarctic Ice Sheets lose mass by discharging solid ice into the oceans. The delivery of warm waters by ocean currents to the edges of the Antarctic Ice Sheets accelerates this process. One recent climate modeling study showed that albedo modification would not prevent warm waters from reaching the edges of the Antarctic Ice Sheets [K. E. McCusker et al., 2015].

It's also unclear that albedo modification would prevent sea-level rise from the Greenland Ice Sheet. Melting of the Greenland Ice Sheet depends on the size of the ice sheet, as well as surface air temperatures. The ice sheet collects fresh snow on its accumulation area, which is the high, cold part of the ice sheet's surface where snow that falls remains all year. It loses mass from its ablation area, which is the low, warm part of the ice sheet's surface where new snow partly or completely melts by the end of the summer. If the accumulation area shrinks relative to the ablation area, the ice sheet may continue to melt even if albedo modification causes temperatures to go down again.

Using a computer model to estimate future sea-level rise from the Greenland Ice Sheet, with and without albedo modification

What would happen to the Greenland Ice Sheet if albedo modification reduced surface air temperatures? Because ice sheets are complicated systems, we used a computer model of ice sheet behavior to answer this question [R. Greve et al., 2011]. The ice in the ice sheet flows under its own weight, moving ice from the center of the ice sheet toward the edges [R. B. Alley et al., 2010]. Ice sheets also collect snow and melt on their upper surfaces, slide over rock and sediment underneath, and discharge solid ice to the oceans along their edges. Sophisticated computer-based ice sheet models include all these processes.
Many other studies have used computer models to examine the behavior of ice sheets. In particular, a number of previous scientific papers examine the hysteresis behavior of ice sheets, in which the size of the ice sheet's response depends on the direction of the temperature change. However, these earlier studies do not tell us directly about albedo modification's potential effectiveness in reducing or reversing sea-level rise.

Climate scenarios with and without albedo modification

Models of the Greenland Ice Sheet need projections of future temperature change to estimate how much melt might happen on the ice sheet's surface, and therefore how much the ice sheet will contribute to sea-level rise [R. A. Bindschadler et al., 2013]. We estimated future temperature changes without albedo modification using an existing climate model simulation [J. Schewe et al., 2011]. Other scientists had already run a climate model far into the future, assuming that human activities put large quantities of greenhouse gases into the atmosphere. In this simulation, surface air temperatures over Greenland rose by about 11 C over the next few centuries. The world as a whole warmed by a much smaller amount, even in this somewhat extreme simulation.

Albedo modification has never been tested, and we can't be sure how governments or individuals might use it to control temperatures. To create scenarios of temperature change with AM, we assumed that AM could either prevent additional surface air temperature increases, or it could gradually return temperatures to present-day values. We called these two types of scenarios "stabilization AM" and "temperature drawdown AM," respectively. Both of these scenario types assume that AM is effective in changing surface air temperatures, and that the AM program is maintained for hundreds of years. We then ran the ice sheet model into the future using the different temperature scenarios.

What does the computer model say about albedo modification's effects on future Greenland Ice Sheet changes?

If greenhouse gas emissions are high and AM is not implemented, sea-level contributions from the Greenland Ice Sheet are small by the year 2100, but become large over the long term in our simulations. The ice sheet is clearly in trouble at the end of the present century, when the simulated rate of sea-level rise from the Greenland Ice Sheet is many times its observed present-day value. The ice sheet melts away almost completely by the year 3000, leading to a large increase in global mean sea level. In such a warm future, there would be additional sea- level rise from sources other than the Greenland Ice Sheet.

We assessed albedo modification's effects on sea-level rise by comparing our simulations that include AM to those that don't. These comparisons show that the rate of sea-level rise from the Greenland Ice Sheet is smaller with AM than without AM. However, melting of the Greenland Ice Sheet generally continues after AM begins. Also, the ice sheet does not grow back appreciably, even with AM.

Not surprisingly, the Greenland Ice Sheet's contributions to sea-level rise depend on whether AM draws down surface air temperatures, or simply stabilizes them. Temperature drawdown reduces the rate of sea-level rise more than does temperature stabilization. If AM stabilizes temperatures, the ice sheet continues to lose mass indefinitely. If AM draws down temperatures instead, the ice sheet shrinks for up to 150 yr before regrowing very slowly. The rate of regrowth is always a tiny fraction of the rate at which the ice sheet melts away before AM begins.

The ice sheet's size also affects albedo modification's ability to reduce sea-level rise from the Greenland Ice Sheet. Beginning temperature drawdown AM within the next few decades stops mass loss from the Greenland Ice Sheet. If AM begins later, the ice sheet is smaller and therefore already committed to additional ice loss.

How does our work relate to what other scientists have said?

Why did we get different results from other scientists who have studied this question? At least two earlier studies concluded that geoengineering would prevent or even reverse future sea- level rise. Geoengineering is a term that describes most methods for intentionally modifying the climate, including AM. One of these other studies used a very simple model of sea-level rise from all sources, driven by greenhouse gases and geoengineering [J. C. Moore et al., 2010]. However, this simple model is missing a key feature of the real Earth system. In this simple model, sea-level fall in response to temperature decreases is just as fast as sea-level rise in response to temperature increases. However, ice sheets melt much faster than they grow [J. D. Hays et al., 1976] [J. E. Hansen, 2007] [A. Grinsted et al., 2010]. Another study used a model of the Greenland Ice Sheet much like the one we used [P. J. Irvine et al., 2009]. However, this study's base scenario, with no albedo modification, involved smaller surface air temperature increases than ours. The Greenland Ice Sheet shrinks less, and is easier to "save" with AM, if surface air temperatures are smaller in the no-AM scenario.

Why do we have confidence in our results, and how could other scientists improve on our work? There are many computer models of ice sheet behavior that give different answers. The model we used accounts for most of the behavior of ice sheets, but it leaves out some processes that could cause the ice sheet to disappear more quickly. This simplified model runs quickly, allowing us to carry out the many long simulations required by our experimental design. If other scientists were to repeat our experiments with more-advanced ice sheet models, they would probably reach similar conclusions, even though their sea-level rise estimates might be higher or lower.

Other scientists could extend our work by investigating scenarios where greenhouse gas emissions are lower. Our model simulations are based on a scenario called "RCP 8.5," which assumes that world society makes relatively little effort to reduce greenhouse gas emissions. We refer interested readers to G. P. Wayne's "Beginner's Guide to Representative Concentration Pathways" [G. P. Wayne, 2013] for information on other potential scenarios.

Conclusions

Given the results above, albedo modification might not prevent sea-level rise, even if it has a strong effect on surface air temperatures. The Greenland Ice Sheet continues to contribute to sea-level rise in almost all of our simulations, even those that include AM. This additional sea-level rise could cause problems if planners assume that AM will completely stop sea-level rise. Because the ice sheet also regrows very slowly, AM will not simply restore the Greenland Ice Sheet to the way it was before large-scale greenhouse gas emissions began. However, albedo modification probably would reduce the rate of sea-level rise from the Greenland Ice Sheet. This slowdown could be beneficial if policymakers use the extra time to plan for more sea-level rise.

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El Niño dynamics and long lead climate forecasts

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El Niño-Southern Oscillation (ENSO) is a climatic phenomenon in the tropical Pacific arising from interactions between the ocean and the atmosphere on timescales ranging from months to years. ENSO generates the most prominent climate alterations known worldwide, even very far from where it forms. It affects weather extremes, landslides, wildfires or entire ecosystems, and it has major impacts on human health, agriculture and the global economy. Reliable forecasts of ENSO with long lead times would represent a major achievement in the climate sciences, and would have huge positive societal and economic implications. Here we provide a review of our current understanding of ENSO as a major source of climate predictability worldwide, emphasizing four main aspects: 1) differences between weather and climate forecasting, and existing limitations in both types of prediction; 2) main mechanisms and interactions between the atmosphere and the ocean explaining the dynamics behind ENSO; 3) different theories that have been formulated regarding the oscillatory behavior and the memory sources of the phenomenon; and 4) the upper limit in its potential predictability and current research endeavors aimed at increasing the lead time of climate predictions.

Geographical Sector(s): Global, Pacific Ocean

Subject Area(s): Earth, Impacts, Ocean, Water, Weather

Weather and climate forecasting: are they the same thing?

Weather has a large influence on our daily life: fair weather encourages outdoor activities, such as hikes, walks or trips to the beach, while poor weather is more likely to keep us indoor. The importance of weather in our daily activities explains the widespread use of weather forecast information by a broad audience. It is thus no surprise that recent technological advances have lead to the development of products and applications that go beyond traditional weather forecasts on TV: in short, weather science and forecasting is nowadays just one click away on any electronic device.

Nonetheless, weather forecasts are known to become inaccurate when used at long lead times.

Models used to produce forecasts typically solve mathematical equations based on physical laws to describe how the atmosphere evolves from an initial state over a given time interval [V. Bjerknes, 1904]. This procedure can be repeated to know any future state at very distant times. But unfortunately, our knowledge of any past or present atmospheric state is incomplete and inaccurate, as we cannot put a thermometer and a rain gauge at every single location and altitude of the troposphere, which is the atmospheric portion of the air column where weather happens. The error associated with this inaccurate picture of the initial state, even if very small, quickly grows at each time step, so that in a matter of days, weather predictions are no better than a coin toss [P. D. Thompson, 1957]. This is why the behavior of the atmosphere can be described by mathematical equations (that is, it is a deterministic system), but its future evolution cannot be accurately predicted at lead times longer than a couple of weeks at most (that is, it features a chaotic behavior), due to the fast-growing increase over time of errors in the initial conditions [E. N. Lorenz, 1965]. And this limit is indeed an inevitable constraint in weather predictability, which would not be eliminated even if we had the most powerful supercomputer and the most sophisticated model of the atmosphere [E. N. Lorenz, 1982].

If weather forecasts are limited to a couple of weeks, does it mean that nothing can be known about the future evolution of the atmosphere months-to-years ahead? To answer this question, we must first understand that the atmosphere is only one element of a more complex system, which also comprises the hydrosphere (oceans, rivers, lakes), the cryosphere (sea ice, snow cover, glaciers), the lithosphere (topography) and the biosphere (ecosystems, human activities), and which is bounded by the outer space. The atmosphere is constantly being influenced, and to some extent determined, by its neighbors, which have their own variability on different timescales. This interaction with external factors shapes the variability of the atmosphere and is at the base of climate forecasting, which allows for extended forecasts on seasonal and longer time scales. For instance, we know that in the extratropics the incoming solar radiation is larger in late spring and early summer, and therefore in a very simplistic manner we can be quite confident that temperatures in the northern hemisphere will be higher in July than in January.

In this regard, the upper ocean is a privileged actor in climate forecasting, because it constantly exchanges energy and humidity with the overlying atmosphere [J. Shukla and III J. L. Kinter, 2006]. Importantly, temperatures in the ocean are more persistent than those in the atmosphere, and therefore the ocean slowly imprints its inertia, which warms or cools the bottom part of the atmosphere over relatively long periods. Warm air, which is less dense, is forced to ascend, while cold air subsides, being denser: these motions affect the distribution of air masses and horizontal and vertical winds in the whole tropospheric column, and are also communicated to distant regions by a sort of “atmospheric bridge”, collectively known as climate teleconnection [J. D. Horel and J. M. Wallace, 1981]. As a result, the longer inertia of temperatures in the upper ocean generates persistent changes in the state of the atmosphere that are potentially predictable months-to-years in advance because they do not arise from the chaotic atmosphere itself [D. J. Karoly, 1989].

El Niño dynamics, teleconnections and predictability

There are many different phenomena in the ocean that generate predictable changes in the atmosphere. The most prominent one is El Niño-Southern Oscillation, or ENSO, a climate feature resulting from the interaction between the ocean and the atmosphere in the tropical Pacific basin [C. S. Meinen and M. J. McPhaden, 2000]. The coupled nature of this phenomenon arises from oceanic anomalies that affect the overlying atmosphere, as well as atmospheric anomalies that in turn modify the state the ocean. Here, the word “anomaly” refers to the departure of a climate variable from its normal or expected value, so that for instance the anomaly is warm in a mild winter day and cold in a harsh winter day. This simultaneous bidirectional interaction between the ocean and the atmosphere sometimes amplifies an initial temperature, pressure or wind anomaly (referred to as positive feedback), while in other situations, the ocean or the atmosphere tends to stop or limit the growth of any initial change that occurs in either of the components (negative feedback).

In the tropical Pacific, the ocean and the atmosphere work perfectly together and amplify initial anomalies in climate variables, which explains the large magnitude of ENSO and its worldwide impact [J. Bjerknes, 1969]. The dominant winds in the tropical Pacific are the trade winds, which blow from the eastern to the western part of the basin, piling up warm waters in the western tropical Pacific, an area commonly referred to as the warm pool [J. N. Brown and A. V. Fedorov, 2010]. Air above these warm waters is warmer, and hence less dense, than air elsewhere. Therefore, these air masses tend to rise and then to diverge as they reach the top of the troposphere [J. Ballester et al., 2011]. Part of this lifted air returns to the eastern Pacific along the equator and descends near an area of cold temperatures next to central America. This closed circulation loop in the equator, with surface westward winds, rising air in the western Pacific warm pool, eastward moving air in the upper troposphere and descending motion over the eastern Pacific cold waters, indeed represents one of the main positive feedbacks of the global climate system [S. I. An et al., 2005]. As a consequence, the stronger this loop, the larger the accumulation of warm waters in the warm pool, and thus the east-west contrast in upper ocean temperatures. In turn, the larger the contrast in ocean temperature, the stronger the rising and descending motions and the atmospheric loop.

But sometimes, other processes can stop and revert the growth of this coupling. It can either be that the trade winds weaken and therefore the accumulated heat in the warm pool is released to the east [K. Wyrtki, 1975], or it can be that the east-west difference in upper ocean temperatures is weakened and therefore the atmospheric circulation is reduced. In either case, the initial oceanic or atmospheric anomaly is transmitted to its counterpart, so that the atmospheric loop and the east-west temperature difference are weakened or even reversed. Under these conditions, the eastern Pacific becomes warmer than average, and the trade winds are weaker than normal. This situation is referred to as El Niño, which means "Christ child" (or "little boy") in Spanish, given that it normally peaks around Christmas. The opposite conditions, with strengthened trades and east-west temperature contrast, are known as La Niña ("little girl"). Both El Niño and La Niña typically persist for almost a year, from early summer to late spring of the following year.

These events generate large-scale climate changes in very distant regions that affect weather extremes, landslides, wildfires or entire ecosystems, with major impacts on human health, agriculture and the global economy [S. D. Changnon, 2003]. For example, during the 1997-98 El Niño, California and the southern states of the United States were plagued by storms, whereas the northern half of the country experienced temperatures significantly colder than usual, and below normal precipitation and snowfall [S. A. Changnon, 1999]. Regarding human health, the state of the ocean has been found to modulate or even anticipate the effects of several diseases in distant continental regions, such as malaria, cholera or dengue [B. A. Cash et al., 2013]. For instance, a recent study [J. Ballester et al., 2013] showed that ENSO is associated with enhanced activity of Kawasaki disease [X. Rodó et al., 2014] on opposite sides of the north Pacific basin, through large-scale tropospheric winds [X. Rodó et al., 2011]. Strikingly, the worldwide impacts of ENSO are potentially predictable from several months to a few years ahead [M. Collins, 2002]. This is why the study of the mechanisms behind ENSO has been a hot topic in climate sciences during the last decades.

El Niño and La Niña: a never-ending power switching

During a La Niña event, stronger than normal easterly trade winds pile up warm waters in the surface layer of the western Pacific warm pool. Due to the continuous effect of winds, part of these accumulated water masses are forced to sink, bringing warm anomalies down to the typically colder subsurface [J. Ballester et al., 2015]. The warm waters are therefore stored in the ocean subsurface, at about 100 to 200 meters [J. Ballester et al., 2016a]. They persist there, buried and isolated from the influence of the atmosphere, well after La Niña starts to decay and the basin returns to its normal state (that is, absence of El Niño and La Niña conditions). At this stage, the seed leading to the onset and growth of an El Niño event is already planted in the ocean subsurface. As soon as a fortuitous weakening of the trade winds happens for at least some weeks to a few months, the subsurface warm waters are favored to propagate to the east [G. A. Vecchi and D. E. Harrison, 2000]. If the accumulated heat and the relaxing of the trades are strong and long-lasting enough, the subsurface heat is able to reach the surface waters in the eastern Pacific [F. F. Jin, 1997]. When this happens, the warm ocean weakens the east- west temperature difference in the tropical Pacific, which in turn weakens the wind circulation loop in the equatorial Pacific. In this way, the ocean and the atmosphere start working together again in the same, albeit opposite direction, leading to the growth of an El Niño event.

Similarly, El Niño also plants the seed for the growth of a La Niña event in the ocean subsurface. The subsequent oscillatory power switching between El Niños and La Niñas is however very irregular. For example, two consecutive El Niño or La Niña events can sometimes occur one after the other, while in many other instances, they are a few years apart. This irregularity is due to the delicate relationship between the strengthening and weakening of the trade winds, and the storage and release of memory in the ocean subsurface as temperature anomalies. This memory arises because subsurface anomalies persist over long periods of time and their effect is delayed, rather than immediate. Winds change their direction and speed in a very rapid and irregular fashion, hence it is not very common to have relatively long temporal stretches during which the trades are either strengthened or weakened in a coherent way. This happens, for example, during the mature phase of El Niño or La Niña, when temperatures in the ocean surface are playing an active role by driving the wind circulation loop described above. Wind anomalies leading to and triggering an El Niño or La Niña event are instead rather weak, which makes it difficult to anticipate the release of the subsurface ocean memory far in advance.

The long-lead prediction of ENSO: the final frontier

The mechanisms behind ENSO are nowadays relatively well understood, but it remains difficult to make predictions at lead times longer than 9 months [A. G. Barnston et al., 2012]. The predictions of ENSO that are issued in northern hemisphere spring are still unable to foresee whether an El Niño or a La Niña will occur at the end of the year. This problem arises because no strong early sign of an incoming event is found in the atmosphere or the ocean surface this early in the year, but only eventually in the ocean subsurface [D. Chen and M. A. Cane, 2008]. Many other weather phenomena take place in the tropical Pacific during this season, which potentially mask any incipient premonitory signal of the growth of an El Niño or La Niña event [X. W. Quan et al., 2004]. Nonetheless, once this spring barrier in climate predictability is overcome, the subsequent phases of the event become much easier to predict.

There is still debate in the community as to what extent this predictability barrier can be overcome: some scientists link it to difficulties in predicting the propagation of the ocean memory through the subsurface, while other scientists argue that the heat stored at depth propagates to a large extent independently from the chaotic and difficult to predict atmospheric winds [G. A. Vecchi et al., 2006]. Efforts are currently directed towards improvements of ENSO predictions at long lead times. Some unprecedented studies have shown that successful predictions are indeed possible 2 years in advance, suggesting that the unpredictable nature of the atmosphere (that is, its chaotic nature) is not a major limiting factor of its predictability [D. Chen et al., 2004], but forecasts providing this predictive capacity are not operational yet. The key for any potential improvement in the lead time of the predictions is the use of the memory stored in the ocean subsurface, for which innovative approaches are being considered. For example, a recent study successfully performed retrospective forecasts of El Niño events at long lead times of at least two and a half years, showing that the theoretical limit of ENSO prediction should be sought much longer than the commonly accepted spring barrier [D. Petrova et al., 2016]. This achievement would be an unprecedented milestone for the climate sciences, modeling, forecasting and services [J. Ballester et al., 2016b], as a major result arising from years of intense research with huge positive societal and economic implications.

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Global warming might be on hold, but it's not cancelled

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Instrumental measurements of surface temperatures are available back to around 1850. Based on these, we can estimate the annual mean global temperature. Global temperatures are clearly rising, mainly because of increasing amounts of greenhouse gases, like for example CO_2 and methane, from use of coal, oil and gas and deforestation. Since 1998, a paradox seems to have appeared, where the global temperature has stopped rising even with a steady increase in release of greenhouse gases into the atmosphere. This period has popularly been called the "global warming hiatus" or "paused warming", and it has been used to cast doubt on whether man made global warming is really happening, or that it can be called off. By using 17 different global climate models, and also available temperature observations, we have tried to figure out why the temperature increase might stop, what is actually happening, whether it has happened before or it may happen again in a warmer world, and which regions have higher chances of experiencing "hiatus" periods lasting for a decade or so.

Geographical Sector(s): Global, Pacific Ocean

Subject Area(s): Climate of the Future, Climate of the Past, Climate of the Present

The greenhouse effect is keeping Earth habitable

Already in 1824, Joseph Fourier [J. B. J. Fourier, 1824] discovered the "greenhouse effect". Using the distance from the Sun and the size of the Earth, his calculations showed that the amount of solar radiation hitting Earth was not enough to keep the Earth as warm as it is. It should be a lot colder (estimated to be around 33°C colder) than observed, implying no life on Earth, at least not life as we know it today. There had to be something keeping the Earth warm. This "something" is what we now call the greenhouse effect, acting as an insulating blanket around the planet. As a continuation of this, John Tyndall in 1861 [J. Tyndall, 1861] and Svante August Arrhenius in 1896 [S. A. Arrhenius, 1896] published scientific articles on how different gases in the atmosphere have the ability to absorb heat, stating that an increase in the concentration of CO_2 (and other heat trapping gases and particles) in the atmosphere would lead to increased global temperatures. So far we have seen an increase of around 0.8°C in the global temperature since the observational record started in 1850. We estimate that by 2100 the Earth will warm between 1 and 6°C relative to the temperatures in 1850 depending on the total amount of greenhouse gases we put into the atmosphere by then. This warming doesn't sound like much, but the temperature difference between the last Ice Age and the present climate is only 5°C. We have to go back more than 3 million years to find a climate that is 2-3°C warmer than it was around 1850.

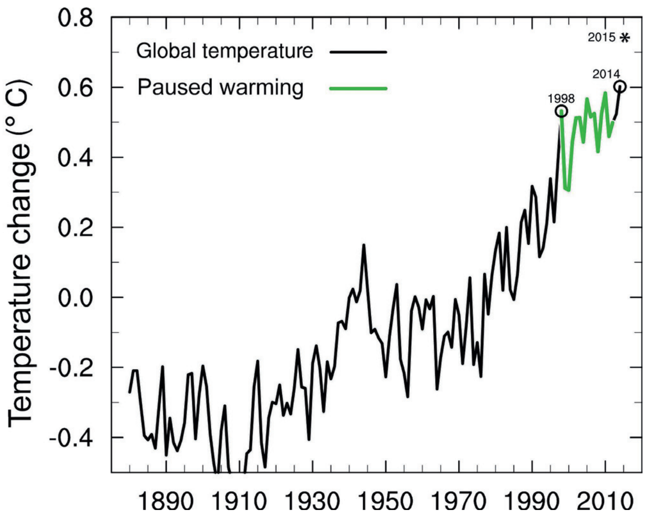

Figure 1. The black line shows the change in measured annual mean global surface temperatures relative to the mean temperature during the period 1961-1990. The green line shows the period referred to as the "paused warming". * shows the temperature change by end of 2015. Source: Helge Drange/University of Bergen.

In 1979, Jule Gregory Charney and a group of colleagues [J. Charney et al., 1979] found that even when we have a global warming, the global temperature will not increase year by year, but will vary around a gradual, long-term warming. You can see this in the first figure, where there are rarely two years in a row where temperatures increase despite an undeniable long-term warming. Short-term variations like these can be due to variations in the amount of solar heating (or more heat reflected back to space from the surface or cloud tops) or ash from volcanic eruptions reflecting solar radiation back to space and acting to cool down the surface temperatures for a couple of years.

The ocean can even cause longer periods of paused warming. There are two reasons for this. One is that the ocean has a higher heat capacity than the atmosphere, which means that you need much more energy to heat up a liter of water than a liter of air by one degree. The second reason is often called "natural variability". This is when the ocean absorbs heat at the surface, and brings this heat to the deep abyss as the water circulates the world oceans. This heat can be stored in the deep ocean for decades or more before it is brought to the surface again and released to the atmosphere. So by only measuring the temperature at the surface of the Earth, we don't capture what is going on in the deep ocean or high up in the atmosphere.

Some people argue that climate models are unfit for the task of saying anything about the observed pause in global warming due to the failure of predicting it in advance. This is not necessarily the case. Climate models are replicas of the climate of the Earth, but they generate their own natural variations, and these variations might not coincide in time with the same variations in the real climate. The global warming that is in addition to these variations are on the other hand the same. However, if we search for periods in the models where this type of paused warming occurs, we can compare these to the observed periods and potentially understand what is happening and why.

A paused global warming has happened before and it will happen again

Based on the observed temperature, we find that periods of paused warming actually happen more often than we might expect. If you pick random, 10 year long periods from observed temperature since 1910, approximately every third pick would be a period without warming, despite an undeniable long-term warming. If we do the same exercise with temperature taken from global climate models, we get almost the same number. Paused warming periods are therefore simulated in climate models, just not necessarily at the same time as in observations. These paused warming periods will still occur in the future with increasing temperatures, but not as often and maybe not lasting as long as today.

Climate models are unique in that they allow us to do experiments in order to learn how the climate of the planet works. Such experiments are, obviously, impossible to do in reality. So, if we run the climate models without putting the extra greenhouse gases into the atmosphere, we will pick paused warming periods half of the time. This is exactly what we would expect for a planet that isn't warming, a warming period is as likely as a cooling period. When we put greenhouse gases into the atmosphere and the planet warms, paused warming periods occur less often because the cooling needs to overcome the steadily increasing temperature. Imagine two kids on a seesaw, like in the top part of the second figure. If the kids have the same weight, and push by the same amount, the kids will spend half of the time above and half of the time below the middle. Now, focus on the one on the right hand side. The kid represents the global temperature, which spends half the time warmer than average and half colder. The weight of the kid on the left hand side represents the greenhouse effect. When the kids have the same weight, the climate system is in balance and we don't have any long term warming or cooing. If you replace the left hand kid with an adult, like in the lower part of the figure, the weight distribution becomes uneven. The extra weight of the adult represents the global warming. The climate system is no longer in balance, but it's warming. Now the temperature is not likely to be cold as often, or for as long, because the kid stays higher up for longer. Even if the adult pushes the ground, the kid will likely not reach the ground, or if it does the kid will "fly" into the air. This "flying" illustrates the increasing temperatures due to global warming. If the temperature would increase by for example 0.3°C without global warming, and the global warming over the same period is 0.1°C, the total warming would be 0.4°C ("flying" 0.1°C higher than otherwise). The heavier the grown-up, or the larger the global warming, the harder it is for the kid to reach the ground. If the globe warms up too quickly, the natural occurring temperature variations are too small or short-lived to compensate for the effect of the global warming.

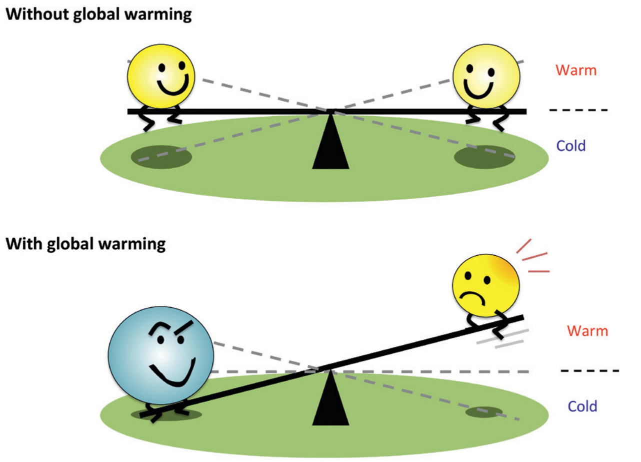

Figure 2. The upper part illustrates a climate system in balance. The kid on the right hand side of the seesaw represents the global temperature, and the weight of the left hand kid represents the greenhouse effect. When the right hand kid is above the middle point, the global temperature is warmer than the mean, and when it is below, it is colder than the mean. The global temperature alternates between the two states, spending around half of the time above and below. The lower part represents the climate system when we have global warming, illustrated by a heavier adult on the left hand side. The weight distribution becomes uneven, and the kid will spend more time in the air, being warmer than normal. It is harder for the kid to now reach ground and be colder than normal the heavier the adult is. This illustrates that it is less likely to get paused warming periods when we have global warming.

The above can also be done locally, where people actually live, not just for global temperatures. We can now pick 10 year long periods at every place on the Earth. Not all places on the Earth will warm equally in the future. The tropics will warm less, and the poles more, compared to the global mean warming. Likewise, land will warm faster than the oceans. If the globe as a whole warms by 2°C relative to the average temperature for the period 1850-1900, the Arctic may warm by more than 10°C and the tropics only by 1oC. There might even be regions experiencing a decrease in temperature because of changes in for example the Gulf Stream, which transports warm water from the tropics towards the north. By changing where the warm water ends up, some regions might be colder than they were. For these regions we can expect to pick a lot of 10 year long paused warming periods. The Arctic is also a special place. Even though we expect a large warming, we still expect to pick a lot of 10 year long paused warming periods because the natural variations are also large. The opposite is the case for the tropics. It will only warm slightly, but the mostly local natural variations are also small in comparison. So, different regions contribute differently to the global temperature because the amount of warming and the natural variations vary regionally.

The oceans are slowing down the surface warming

Several reasons have been proposed to explain periods of paused warming. Satellites measure how much solar radiation is coming from the Sun and how much heat is lost to space from the Earth. These observations show that the Earth receives more heat than it loses. We would therefore expect the surface temperatures to increase, not decrease. This rules out the Sun as a cause for the recent paused warming, and also indirectly the volcanoes, which would be picked up by the satellite measurements. Since we don't see higher temperatures on the Earth's surface, the heat that the Earth receives must be hiding somewhere in the climate system. To find out what is happening, we should ideally have observations of every location around the world, over the full depth of the ocean and the full height of the atmosphere, for a long period of time. Unfortunately, we don't.

But fortunately, the climate models come to our aid. One great aspect with climate models is that heat can't hide anywhere because the model generates "observations" everywhere, in the oceans, on land and in the atmosphere, at all times. All changes in temperature and heat and other properties can be checked, like the amount of solar radiation reaching the outer part of the atmosphere or hitting the Earth's surface, the amount of greenhouse gases in the atmosphere, the number and strength of volcanic eruptions and changes in the vegetation. This gives us a fantastic possibility to check and see where the heat is hiding. Afterwards we can then check whether our findings from the models are plausible also in reality, using real observations.

We have used 17 different climate models that are all based on physical equations of how the Earth's climate works: how low and high pressure systems move around; how the ocean and atmosphere take up and exchange heat; how sea ice melts and freezes; and how the Gulf stream moves heat from the warm tropics to melt sea ice in the cold Arctic and more. What they have in common is that when paused warming periods occur in the climate models, the tropical Pacific Ocean sea surface is colder and the deeper part of the ocean is warmer than usual. In this way, the sub-surface waters in the Pacific Ocean can store large amounts of heat. The way the ocean manages to do this is by the help of the atmospheric winds above.

In the tropics the wind blows from east to west, pushing the water in front of it in the same direction. Because of the rotation of the Earth, the water at the surface will move slightly northwards north of the equator, and slightly southwards south of the equator. So, the winds act like a snow-plow along the surface, leaving a wake behind it, which has to be filled. The wake is filled by colder water from deeper down in the ocean. If the winds are stronger than usual, more of this cold water reaches the ocean surface, leading to surface cooling. Since the area of the tropical Pacific Ocean is so big, the surface cooling leads to a lowering of the temperature at the Earth's surface. When the opposite is true, with weaker than usual winds, less of the cold sub- surface water will reach the ocean surface. This leads to a warmer than usual ocean surface, and by that a warmer surface of the Earth as a whole. These variations are known as La Niña (when the ocean surface is unusually cold) and El Niño (warm surface ocean), or more general the Pacific Decadal Oscillation if we look at the whole Pacific and on longer time scales, and not just the tropical region.

Can we observe what the models tell us?

Indeed, what the models show can also be seen from available observations. In 2013, Kevin E. Trenberth and John T. Fasullo [K. E. Trenberth and J. T. Fasullo, 2013] published a scientific article where they compared observations of the surface temperature between two periods: A period with strong surface warming (1976-1998) and a period without surface warming (1999-2012). Interestingly, their findings show exactly what the models show: During the paused warming period, the tropical Pacific Ocean was unusually cold due to stronger than normal winds blowing over the ocean, pushing more water away from the South American coast, leading to upward motion of cold, sub-surface water.

In short, it is too early to call off the global warming just yet. Depending on the amount of greenhouse gases we put into the atmosphere, the planet as a whole will still warm, and 10 year periods of paused surface warming might still happen. During these periods, it is likely that the Pacific Ocean hides the heat from being visible by the atmosphere. This hiding game will not last forever, and when the heat reaches the ocean surface, the Earth's surface temperature will increase again, like in the past. With increased global temperature as a result of continued release of greenhouse gases to the atmosphere, paused warming periods will occur less often and become shorter in duration, but they will nevertheless occur.

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Limitations in our knowledge of the Sun's variability and impact on stratospheric ozone

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Changes in the Sun over the 11-year solar cycle modify the amount of ozone in the atmosphere over the tropics above 20 km. It is thought that the temperature change resulting from the induced variations of ozone may lead to an impact on the surface climate. Knowing by how much the solar ultraviolet light changes over the cycle is key to understanding the size of that influence. We provide a new model dataset of solar irradiance variability and compare it to the standard model used in climate studies, and to solar observations. We have shown that our model agrees better with an older instrument observing solar irradiance than the standard solar model for climate, though the two solar models and the older observations display much lower solar cycle variability than more recent observations. We discuss the differences and the uncertainties in the measurements. We also demonstrate that the true effect of solar ultraviolet changes on ozone is highly uncertain. This is important to be aware of since our understanding of the Sun's impact on climate depends, in part, on getting the solar cycle changes in the ultraviolet correct.

Geographical Sector(s): Global, Tropics

Subject Area(s): Air, Earth, Middle Atmosphere, Sun, Upper Atmosphere

The energy, or irradiance, from the Sun varies, most famously, from maximum to minimum activity and back again, in a cyclical fashion over the '11-year solar cycle'. This irradiance variation is driven by changes in magnetic fields at the Sun's surface that form large sunspots, which decrease the energy released from the Sun, and small bright regions, faculae, that enhance the energy coming from the Sun, particularly in ultraviolet light (see Figure 1). The lower part of Figure 1 shows the sunspot number (SSN) varying from solar minimum in 1996, to a maximum around 2001-2002, before returning to solar minimum in 2008; similarly, in the upper plot ultraviolet light increases and decreases with the sunspot number, and so ultraviolet energy from the Sun is highest when the sunspot number is at its maximum. The Sun is also thought to vary on century-long time scales. As the primary energy source driving the climate system, any changes in the energy output of the Sun should lead to a modification of the climate system.

While the Sun has had little impact on the current global changes in climate [T. F. Stocker et al., 2013], changes in its energy output are thought to have a regional impact on surface temperature and precipitation, particularly in the northern hemisphere over North America and Europe [S. Ineson et al., 2011].

The signal, in e.g. the Earth's surface temperature, from a varying Sun is small compared to other factors influencing the climate, and difficult to identify. It is possible to extract it from observations statistically (e.g. [J. Austin et al., 2008]), but another approach to understand the solar influence is to use atmospheric and climate models to see how the Earth system responds to an applied change in

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The process begins high over the tropics

This influence is thought to be initiated high in the atmosphere over the equator, where the Sun's high-energy ultraviolet light (at wavelengths shorter than 320 nm) is absorbed, forming an 'ozone layer', mainly between 20 and 60 km, with a maximum around 25 km. This region of ozone forms because oxygen molecules, 'O2', are highly abundant in the atmosphere and because high levels of short wavelength ultraviolet light are most readily available at these altitudes (they are usually absorbed before reaching the surface). Ultraviolet at wavelengths shorter than 242 nm break apart the O2 to form two O atoms that immediately combine with other O2 molecules, due to their high-abundance, forming ozone, or 'O3'. There is a competing effect from wavelengths shorter than 320 nm, which destroy ozone. Nevertheless, when the Sun is more active, and therefore giving out more ultraviolet light, the ozone production process wins-out over the destructive one, leading to more ozone being produced at solar maximum. The solar cycle response is strongest over the equatorial tropics due to the highest amount of energy per square meter being received there.

Both productive and destructive ozone processes lead to absorption of energy from the ultraviolet light that excite the O, O2 and O3. Eventually, the excited particles bump into nearby ones and the energy gets distributed in the local atmosphere, which heats up.

At this altitude in the atmosphere, there is a general, time-averaged, circulation pattern of rising air at the equator, pole-ward flow at mid-latitudes and descent near the poles. We can detect this flow if we average over lots of observations. This circulation is driven by waves, propa-

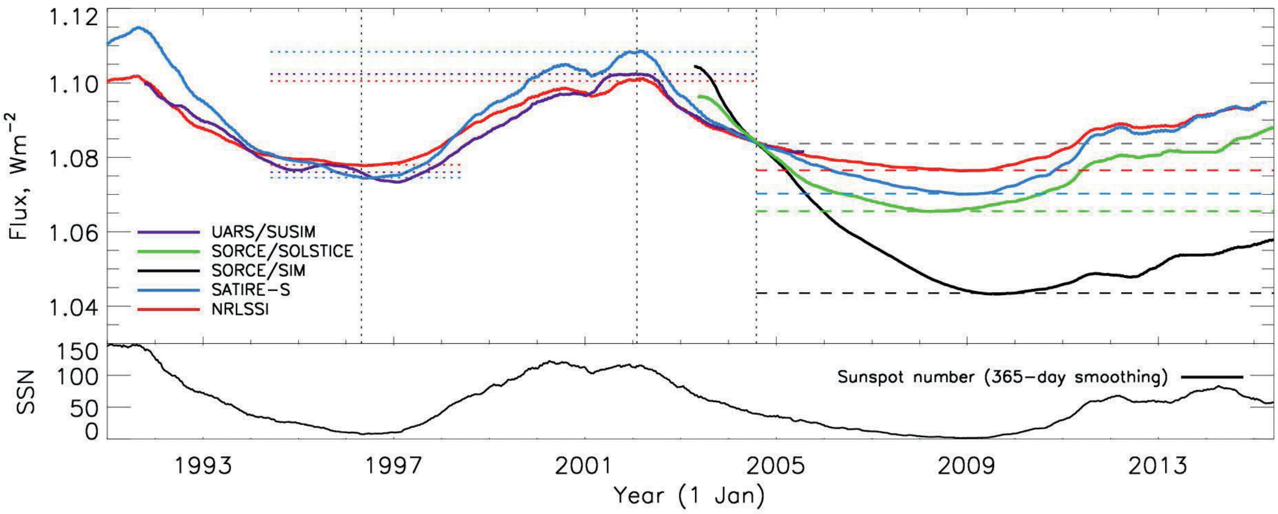

Figure 1: (top) The solar cycle changes in the ultraviolet band integrated between 242 and 260 nm. The absolute levels of all time series have been shifted to give the same absolute value as the SATIRE-S model around August 2004. Shown are the observations from the older SUSIM instrument (purple), and the newer SORCE observations from SIM (black) and SOLSTICE version 12 (green) and the solar models SATIRE-S (blue) and NRLSSI (red). Dashed lines (right) indicate the level of solar minimum around 2008 in each dataset, while dotted lines indicate the approximate solar minima and maxima values around 1996 and 2002, respectively. All datasets have been smoothed by averaging over 365-days. (bottom) The smoothed sunspot number (SSN) for the same time period as in the top plot.

gating up from near the surface that break, like waves on the beach, dump their energy and drive the circulation.

The circulation pattern is also influenced by the temperature difference between the equator and the pole, because more energy from the Sun arrives at the equator. Nature likes to even out differences in temperature, so a wind begins to flow, carrying warmer equatorial air to the colder poles. But, as it travels there, the rotating Earth deflects the wind and a jet of air forms and surrounds the winter-time pole. This jet acts as a barrier, preventing exchange between a cooling, nighttime pole, and the warmer air at lower latitudes. This enhances the strength of the jet.

The increased energy from the Sun at solar maximum leads to an even larger difference in temperature between the equator and the pole. This modifies the poleward transport, leading to a slowing of winds near 50 km above the mid-latitudes. This slowing typically begins around October during periods of high-solar activity [S. Ineson et al., 2011]. The presence of this slower wind affects how the upward propagating waves travel through this high altitude region, and they deposit energy in a different place. As a result, the jet that forms close to the pole becomes perturbed and, over the following months, descends to the lower layers of our atmosphere, where our weather forms. It is thought to disrupt the winds travelling from North America, across the Atlantic, and into Europe. Solar minimum conditions tend to bring cooler winters in Northern Europe with less rain, while North America, Greenland and southern Europe are warmer. The impact is much less pronounced in the southern hemisphere.

Larger changes in ultraviolet lead to a larger climatic response

We see this Sun-induced effect, on the surface temperature over Europe, extracted statistically from observations [T. Woollings et al., 2010], and also from models [S. Ineson et al., 2011]. The signal found in models is proportional to the magnitude of the changes in the ultraviolet over the 11-year solar cycle. The very first step in the whole chain that leads to changes in our weather may be the change in ultraviolet light, though other studies suggest

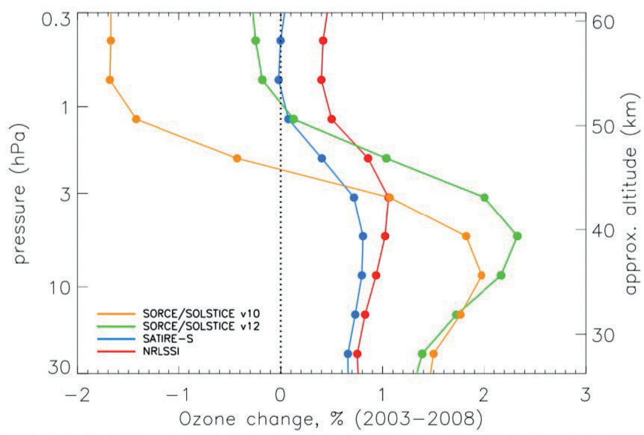

Figure 2: The ozone change between 2003 and 2008 (~65 % of the solar cycle) between 25 and 60 km averaged between 20 S and 20 N. Shown are changes in ozone from a 2D atmospheric model: SOLSTICE/SORCE version 10 (purple), SOLSTICE/SORCE version 12 (green), the SATIRE-S model (blue) and the NRLSSI model (red). Note that the negative response in SOLSTICE has shrunk from ~-1.6 % to -0.3%, between versions 10 and 12, near to 60 km.

that particles emitted from the Sun may also contribute [M. E. Andersson et al., 2014]. The problem is that the stability of our direct measurements of the Sun's ultraviolet light from satellites spanning several decades is low, and so the size of the solar cycle changes are highly uncertain.

The important ultraviolet wavelengths for ozone production are below 242 nm, and for destruction below 320 nm. From the perspective of observations, there are essentially two satellites showing either 'small' or 'large' solar cycle change in the ultraviolet. The lower solar cycle changes, of between 1 and 10 % (always with higher variability at shorter wavelengths), were observed by the SUSIM instrument (see Table 1 for information on acronyms) from 1991 to 2005 [L. E. Floyd et al., 2003]. The larger changes, by up to five times, were observed by both SIM and SOLSTICE instruments, collectively on the SORCE satellite, from 2003 to present [G. Rottman, 2005]. Forcing climate models with these larger ultraviolet changes (see Figure 1) leads to a climate response more similar to observations than when using the smaller changes [S. Ineson et al., 2011]. However, these observations only cover a relatively short period and at most just one solar cycle. To investigate the Sun's impact on climate, longer records are needed covering several cycles or more, so that the signal can be seen in (or extracted from) the high variability of the climate system. Therefore, to extend to such long periods requires 'solar models' to calculate variations in energy coming from the Sun.

From the model perspective, there are essentially two options for atmospheric and climate research: SATIRE-S [K. L. Yeo et al., 2014] and NRLSSI [J. Lean et al., 2005]. This publication [W. T. Ball et al., 2014] represents the first reconstruction of changes in the Sun from the SATIRE-S model that covers every date from 1974 to 2009 and all wavelengths from 115 to 160,000 nm and thus becomes extremely useful for investigations of solar impacts upon our climate (Subsequently, SATIRE-S has been updated by [K. L. Yeo et al., 2014]). SATIRE-S is constructed in a different way to NRLSSI. The latter is empirically derived from direct irradiance observations, while the former recreates irradiance using images of the Sun to identify dark sunspots and bright faculae and then calculate their brightness using model calculations. SATIRE-S displays solar cycle variations in the ultraviolet similar to the SUSIM instrument. Compared to the much larger ultraviolet changes from the SORCE satellite, both models are quite similar. But, in the ultraviolet between 250 and 300 nm, SATIRE-S displays changes between solar maximum and minimum twice as large as NRLSSI (see Figure 1). This has important consequences for ozone as these wavelengths dominate the destruction processes of ozone high over the equator.

Uncertainty rules

At this stage it is important to point out a few caveats: (i) the large ultraviolet changes observed by the newer SORCE observations have an uncertainty range that covers both models and the older SUSIM observations; (ii) it

Acronym	Full name	Type	Other info
SATIRE-S	Spectral and Total Irradiance Reconstruction (Satellite Era)	Model, semi-empirical	1974-Present
NRLSSI	Naval Research Laboratory Spectral Solar Irradiance	Model, empirical	1950-2011
SUSIM	Solar Ultraviolet Spectral Irradiance Monitor	Instrument	Onboard the Upper Atmosphere Research Satellite (UARS), 1991 2005
SOLSTICE	SOLar STellar Irradiance Comparison Experiment	Instrument	Onboard the SOlar Radiation and Climate Experiment (SORCE) satellite, 2003-Present
SIM	Spectral Irradiance Monitor	Instrument	Onboard the SOlar Radiation and Climate Experiment (SORCE) satellite, 2003-Present

Table 1: Explanation and expansion of acronyms for models and instruments mentioned in this article.

is thought that the newer, larger observed changes result from damage to the space-based instruments from the solar ultraviolet light, which leads to a change in how the ultraviolet is detected by the instruments - if not properly accounted for this leads to a much larger variation observed than there really was ([W. T. Ball et al., 2011]; [J. Lean and M. T. DeLand, 2012]; [I. Ermolli et al., 2013]); (iii) though both instruments on SORCE show large changes, SOLSTICE and SIM do not agree with each other either, with SIM showing even larger variations, so we focus here on the smaller, but still large, changes from SOLSTICE; (iv) it is not possible to completely discount SOLSTICE based on the information discussed here, so we should consider the variations as possible; and (v) it is possible that the surface responses in climate models do not agree so well with those extracted from observations because the models are not adequately simulating the waves that drive the high-atmosphere circulation, or feedback from ozone is not fully included. Changing how these waves are considered in the models may lead to a response similar to the observations, but using a lower forcing.

The large, SOLSTICE-like ultraviolet changes are interesting not just because of their potential to affect northern hemisphere winter climates, but also because when applied to a simple model of the atmosphere they produce a response between 50 and 60 km that looks more like those of recent satellite observations of ozone: unexpectedly at these altitudes it appears that when the Sun is near solar maximum, less ozone forms, though more forms below; and, conversely, at solar minimum there is more. The NRLSSI solar model has not been able to produce this decrease in the atmospheric model at maximum, only an increase. We show that the SATIRE-S model can produce this negative response, because of the larger ultraviolet changes above 250 nm. But, the change in ozone simulated using SATIRE-S is tiny compared to that of SOLSTICE (see Figure 2). Thus, this result from the ozone observations appears to support the larger SOLSTICE changes.

However, as more SOLSTICE observations accumulate, better assessments of the data can be made, and improved corrections can be applied to update the data. The results described above for climate, and for the ozone response, have used earlier versions of the data. We have shown that a change from version 10 to 12 of the SOLSTICE data has led to a factor-of-six decrease in the strength of the negative ozone response to the solar cycle above 50 km (Figure

2). It is still negative, but much smaller. Though not calculated here, it is reasonable to assume that by considering the large uncertainties on SOLSTICE, one cannot make any conclusion about the validity of the SOLSTICE-like solar cycle changes by using ozone observations alone. In addition, it is clear that newer versions of the observed solar cycle changes from the newer SORCE satellite will mean that earlier studies cannot be compared with newer ones that use different versions of the data. Therefore, conclusions based on the earlier data probably need to be revisited. Uncertainty is normal, but it is also important to be careful not to make claims that are too confident in light of such uncertainties.

More observations and further analysis are needed

We have provided a new model dataset of solar irradiance variability and compared it to the standard solar model used in climate studies, and two sets of observations. We have found that our solar model, SATIRE-S, agrees better with the older observations than NRLSSI model, though the two solar models and the older observations display much lower solar cycle variability than newer observations fro the SORCE satellite. We have discussed that SORCE solar cycle ultraviolet changes have a large uncertainty. We have also demonstrated that the true effect of different solar ultraviolet irradiance on ozone is highly uncertain. This is important to be aware of since one of the ways the Sun is thought to influence the climate is through a process that is initiated by ozone absorption over the tropics.

There are several avenues one can take to resolve this uncertainty and here two are suggested. First, a new mission to observe changes in solar ultraviolet light is due to launch in 2017 and, after several years of operation, it may be able to give fresh insights, and lower uncertainties, as to how the Sun varies over the solar cycle. The second is to use multiple observations, both of our Sun, our atmosphere and multiple chemicals within it, combined in a way to infer more about changes in our star over decades and centuries. Since the results from new direct observations are years away in the former approach, the latter seems the more an appropriate one to take in the meantime.

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Surface lakes on Greenland will spread further inland as the climate warms

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Published Article v. 1

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Cite Article as: Amber A Leeson, Surface lakes on Greenland will spread further inland as the climate warms, Climanosco, 1 Sep. 2016.

Each summer, a rash of lakes forms from ponded meltwater on top of the Greenland ice sheet. These ‘supraglacial’ (on top of ice) lakes can drain through the ice sheet, delivering their contents to its base. The ice sheet slides on a thin film of water, and when extra water is added to this film (for example from a draining supraglacial lake) the sliding (‘flow’) happens a bit faster. At present, under-ice pipe-like features enable excess water to drain out from under the ice sheet quickly and efficiently. However, in recent years supraglacial lakes have begun to form further inland, potentially supplying water to the base beyond the reach of these features. Here, we use a computer simulation of lake initiation and growth to show that the inland spread of supraglacial lakes will continue as the climate warms; by 2060, 100 % more of South West Greenland and 50 % more of the whole ice sheet will be populated by supraglacial lakes. Of these ‘new’ lakes, up to half will be large enough to drain, delivering the water they contain to the base of the ice sheet and all of these new lakes will form at locations where we would expect to see an ice sheet speed-up with the addition of more water at the base. If the ice sheet flows faster, it can thin out and melt quicker, thus contributing to global sea level rise. Supraglacial lakes and their impacts are not currently considered in our best predictions of future ice sheet change. Given that they possess significant leverage to affect ice sheet flow, and that they are likely to form (and drain) at locations more sensitive to their impact in future years, it is clear that they need to be accounted for in these predictions as a matter of priority.

Geographical Sector(s): Arctic

Subject Area(s): Climate of the Future, Ice & Snow

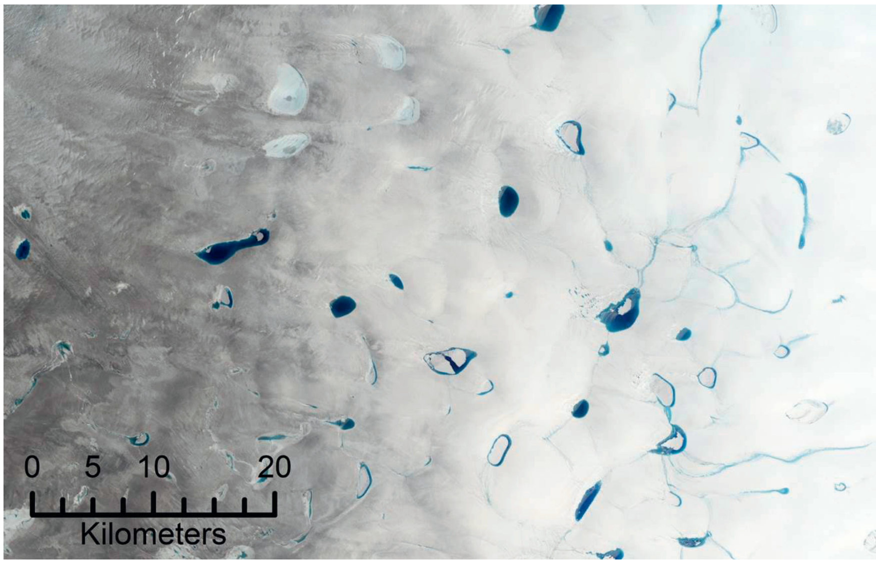

Figure 1: Supraglacial lakes on Greenland from the Landsat-8 satellite

What are supraglacial lakes and why are they important?

Supraglacial lakes appear every year during the spring and summer on much of the Greenland ice sheet and on some Antarctic ice shelves. They form when water from melted snow and ice pools in surface hollows. Because they appear dark blue, they absorb more of the heat from the sun than the white ice which surrounds them and so the ice at the bottom and sides of the lake melts faster allowing the lake to grow [M. Tedesco et al., 2012]. When a supraglacial lake reaches a certain size, the weight of water it contains can break apart the ice it is sitting on, causing all the water to gush down into the ice, and even reach the rock underneath [M. J. Krawczynski et al., 2009]. Glaciers and ice sheets slide on a thin film of water at their base which causes them to 'flow' downhill and towards the sea very slowly, like thick pancake batter. If this film of water gets thicker, for example because a supraglacial lake has drained, then the ice can flow faster. Just like pancake batter, if ice flows faster then it spreads out and we end up with a thinner ice sheet. Because air temperatures are warmer at lower altitude (closer to the Earth's surface), this exposes a greater ice area to above-zero temperatures and so melting. This is particularly important in the interior of the Greenland ice sheet – away from the edges – because the ice is normally thick, high, and cold here.

Motivation for this study

Since 1971, supraglacial lakes have spread inland on the Greenland and now cover a much greater area than they did historically [I. M. Howat et al., 2013]. Most of this change has occurred since around 1995 and is likely due to rapid and extreme climate change in the Arctic during this period [E. Hanna et al., 2012]. At the locations where they are currently found, their ability to affect ice sheet flow is moderated by large pipe-like features that form in the bottom of the ice, and can remove any excess water from the base quickly and efficiently [C. Schoof, 2010]. These 'pipes' form when under-ice (subglacial) streams grow large enough, and flow fast enough, to carve channels in the ice overhead. For example they are abundant beneath the edges of the ice sheet where there is a very large amount of water from melting but rare in the interior where there is less water and the weight of the ice sheet presses any potential channels closed. Recently however, supraglacial lakes have begun to form in the interior of the Greenland ice sheet beyond the reach of

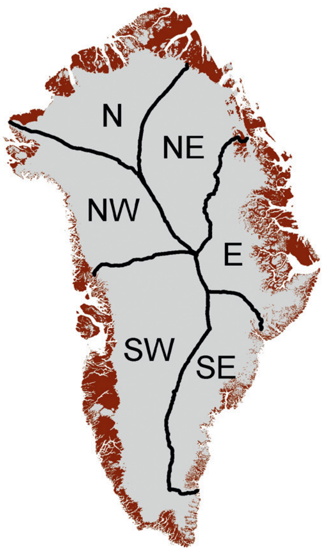

Figure 2: Map of Greenland's drainage basins.

these features and flow here has sped-up a little bit each year since 2009 [S.?H. Doyle et al., 2014]. Despite the fact that climate change is set to continue in coming years, the impact of this warming on where supraglacial lakes form has not yet been considered. Further, the potential impact that they may have on future ice sheet shape has not been included in forward projections of ice sheet change. Since ice lost from the Greenland ice sheet through melting and iceberg calving contributes significantly to global sea level rise (10 % over the last ~20 years [J. A. Church et al., 2013]), it is important to understand all of the processes that affect the ice sheet, in order to produce reliable predictions of global sea level in the future.

Simulating supraglacial lake evolution

In this study a computer simulation of lake initiation and growth (a 'model' [A. A. Leeson et al., 2012]) was used to predict supraglacial lake evolution every year between 1971 and 2060. The model uses equations describing the flow of water over a surface (the ice) or through a porous material (the overlying snow) to route estimates of meltwater runoff over a very finely detailed map of surface height measured by satellite, allowing the model to pond in surface depressions and form lakes. Here, we focussed on an inland region of South West Greenland near Leverett and Russell Glaciers, because the flow of the ice is known to have sped-up here in recent years [S.?H. Doyle et al., 2014]. We can decide whether our model is doing a good job by comparing simulated to observed supraglacial lake evolution. In this case, we predict an inland

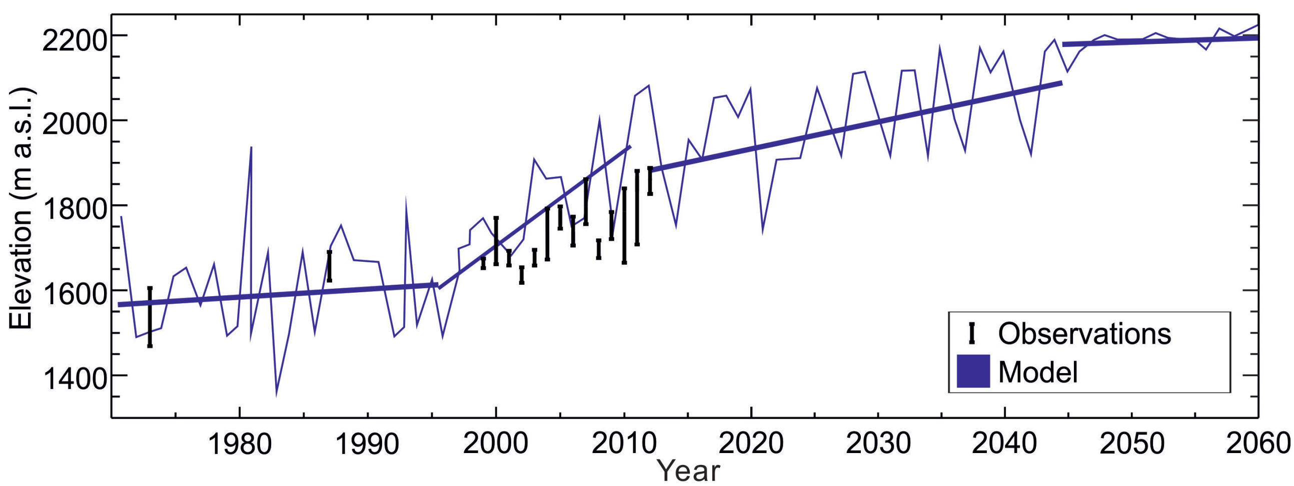

Figure 3: Maximum elevation (in metres above sea level - m a.s.l.) of supraglacial lakes on Greenland in 1971-2100; lakes which are higher up are also further inland. Observations are given as a vertical black line which gives a range of possible values. Simulation results are shown in blue (thin), thick lines are used to calculate change per year.

spreading of lakes of 56 km (~70 % further inland) since the 1970s - just a little over the observed figure of 53 km (~67%) derived from satellite imagery [I. M. Howat et al., 2013] - and so we can have confidence in our model. Whilst satellite observations are important (if a thing is observed then we know it to be true) and are necessary to validate computer models, computer simulations offer an advantage in that they are continuous, whereas satellites are unable to take a picture of the earth's surface at night time or if it is obscured by cloud. Using our model we can 'fill in the gaps' of the satellite record and show much more clearly that this recent inland spreading of lakes was relatively slow until 1995 (0.5 km per year) and six times faster since then (3.0 km per year). This dramatic change corresponds to a 2.2°C air temperature rise in South West Greenland, compared to average conditions, which is the most extreme temperature change in this region since records began [E. Hanna et al., 2012].

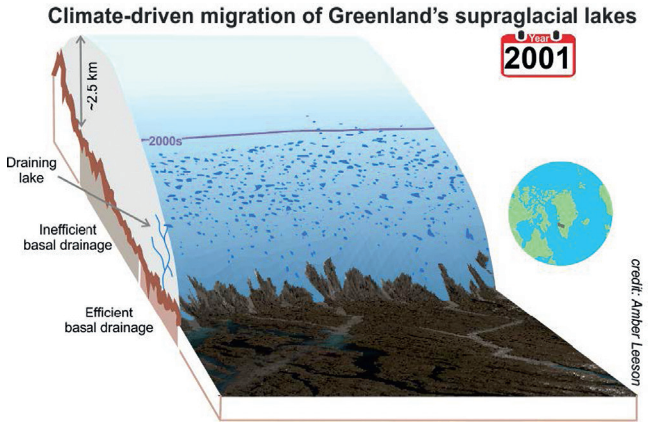

Figure 4: Supraglacial lake distribution simulated by the Supraglacial Lake Initiation and Growth (SLInG) model in the Russell Glacier catchment each year between 2000 and 2100 (perspective view). ["https://www.climanosco.org/files/manpics/9963_LeesonA_Anim1.gif", A. Leeson]

How will the distribution of supraglacial lakes change in the future?

The recent rapid warming in the region is thought to be due to both human-induced climate change and natural variability [X. Fettweis et al., 2013]; a particular wind pattern in the upper atmosphere that brings warmer and dryer weather to Greenland has been repeated more frequently than usual in recent years. Based on normal conditions, our model predicts that supraglacial lakes will continue to spread inland in future years, although at about half the present rate. By 2060 we can expect at least twice as much of South West Greenland to be lake-covered; beyond ~ 2050 the lakes spread out of the area we are able to simulate with our current data. However it seems likely that supraglacial lakes could appear over all of the south western part of the Greenland ice sheet by 2100, especially since regular melting is expected to occur over this entire region from about 2050. To investigate potential future changes to supraglacial lake distribution elsewhere on the ice sheet, we looked at the relationship between the maximum elevation at which lakes currently form (the ice sheet gets much higher in the middle) and how far North they are. We then calculated how much higher up (as a %) lakes will likely get in South West Greenland by 2060 and applied this percentage increase to the rest of the ice sheet. Using this method we determined that 50 % more of the entire ice sheet will be lake covered by 2060.

What are the implications of this change?

Because supraglacial lakes are darker than the surrounding ice they absorb more heat from the sun - just like black tarmac on a sunny day. The result of this is that the ice at the bottom and sides of the lake melts twice as fast as the ice surrounding the lake [M. Tedesco et al., 2012]. Across the whole ice sheet, this only adds up to about half a percent of total melting at present but will increase to around 1 % (of total melting, 7-9 Gt per year) by 2060 if the area covered by lakes increases as expected. Perhaps more worrying is the potential that these 'new' lakes have to drain and perturb the flow of the ice sheet. Using the thickness of the ice, and the weight of water required to break it apart, we identify that up to half of the 'new' lakes will be large enough to drain and deliver their contents to the ice sheet base. The latest projections suggest that

Greenland will contribute up to 22 cm to future sea level rise [J. A. Church et al.,2013]. However, these estimates do not include the potential effects of supraglacial lakes on melting and ice sheet flow. Although our findings show that their contribution to melting is likely to be modest in future, it is clear that supraglacial lakes large enough to drain will in fact spread far inland as the climate warms, suggesting that predictions of future ice sheet state should be revised to account for this. It is now a matter of some urgency that the effects of supraglacial lakes be accounted for in these predictions and establishing the degree to which the inland spread of SGLs will affect ice sheet flow in coming years is of particular concern.

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The impact of climate change on Australian Aboriginal hunter-gatherers and their response over the last 35,000 years.

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Published Article v. 1

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In a recent article, I (and my colleagues) present models of population change for key regions across Australia over the last 35,000 years. We use these models to test an archaeological method (the use of numbers of radiocarbon dates as an indicator of human behaviour), explore the relationship of Aboriginal people and climate change, and to provide a status update for Australian archaeological research. We find that the archaeological technique is reliable, albeit with well-documented caveats that the user needs to be aware of. We find a close relationship between Aboriginal population and climate change for much of the last 35,000 years, with increasing divergence of the records in the last 6,000 years as numbers of people increase and techniques were developed to survive environmental shifts. We identify key areas of future research for the Australian archaeological community, including the need to fill spatial gaps across parts of the continent, and to focus on key temporal periods where significant change in society appears evident.

Geographical Sector(s): Australasia
Subject Area(s): Climate of the Past, Human Activities

Introduction

Despite over 60 years of archaeological research in Australia, our understanding of the past populations and behaviour of Aboriginal society is still poorly understood. The broad narrative is widely known, including colonisation of the continent at about 50,000 years BP, abandonment, retraction and decline in populations through the Last Glacial Maximum (LGM) (24-18,000 years BP) – a particularly cold and arid period– and slow recovery followed by exponential growth and innovation in the last 5,000 years. However, the extremely large size of Australia (~7.7 million km2) – a significant portion of which is hard to access – combined with the small number of researchers has severely limited the amount of archaeological and palaeoclimatic data available or interpretation, and this has checked the development of any narrative. Other issues have also played a role, including the lack of statistical and computational programs for the necessary analysis, and the siloing of researchers to their respective disciplines as two examples.

More recently, new methodological advancement and the publication of key palaeoclimatic and archaeological data have allowed us to further explore the Australian past. In [A. N. Williams et al., 2015], we use these new techniques and resources to provide a definitive account of past Aboriginal populations and behaviour across Australia over the last 35,000 years. In addition, we explore two other main themes: exploration and testing of an archaeological method using radiocarbon dates, which I elaborate on below; and much needed future direction for Australian archaeological research.

Methods

It is the role of the archaeologist to understand and interpret the behaviour of past societies. Traditionally, this has involved the careful excavation of sites known to have been inhabited by prehistoric people in the past. The changing number of stone tools, or other human created debris, recovered as one digs down provides an indication of whether there were more or less people at a given time, as well as other information on their behaviour. Such changes can be provided a chronology or timeframe through various dating methods of material recovered, most notably radiocarbon dating. Radiocarbon dating has been established since the 1950s, and represents a core tool of the archaeologist. Basically, all living organisms absorb carbon through inhalation or absorption of CO_2 (carbon dioxide) in the atmosphere, a proportion of this is slightly radioactive. When a living organism dies, the radioactive carbon that has been absorbed begins to decay, and we can measure this decay to work out the age of the organism at the time of its death. For archaeologists, it means a wide range of materials can be dated to work out how old a site, feature or layer is.

One of the key restrictions of excavation of a single site, however, is that it provides very localised information, producing a narrative for only a small spatial area, or group of people. In recent years, archaeologists have been exploring ways to combine information from a number of these sites to provide a larger picture of human behaviour. One of the more successful approaches to do this has been the accumulation and manipulation of the radiocarbon dates. By assuming each radiocarbon date recovered from an archaeological site reflects a prehistoric person at that location and point in time, by adding the number of dates together, we can produce a graph of increasing or decreasing people across the landscape. Since archaeologists have recovered relatively few dates compared with the world's population, it must be highlighted that the translation of dates to population is not a direct one, but rather a qualitative indication of the direction and amount of change through time, with more (less) dates suggest more (less) people, but not a specific value. (There are techniques that can convert this data to quantitative values and provide actual population numbers, but this was not part of this publication). This approach (known variously as 'dates as data', sum probability analysis or time-series analysis) was developed in the 1980s, but in the last few years has reached a zenith, and is now commonly found in the archaeological literature across the world. Of course, with all new archaeological techniques, there are questions about its reliability, and researchers that remain sceptical (see Williams and Ulm, 2016 for discussion) – and putting these concerns to rest is actually the main focus of our latest research.

We used some 5,000 radiocarbon dates recovered from 1,750 sites across Australia, and spanning 35,000 years ago to present, to test and verify the 'dates as data' approach. Our testing included: 1) the correlation of the radiocarbon dates with a recent synthesis of the past climate of Australia (Figure 1) – the assumption being that some form of human response would be evident with key climatic shifts, especially in more arid areas where Aboriginal populations would have been responsive to worsening conditions; and 2) the comparison of the data with some 90 records from archaeological sites across the continent - effectively the use of the traditional methods and records of people's behaviour from individual sites, and its relationship (or not) with the larger record produced by the radiocarbon dates.

The radiocarbon dates were divided into four regions that were comparable to the recent Australian climate synthesis, and encompassed the tropics, the arid centre, the temperate east coast, and Tasmania (Figure 2). Comparison of each of the dates as data graphs for these regions with the climate records for the last 35,000 showed a good and close relationship for the most part. This was especially the case during the LGM and Antarctic Climate Reversal (14-12,000 years BP), two periods of extremely cold and arid conditions, with data in all regions dropping to very low levels and suggesting Aboriginal people were almost wiped out. All records showed an increasing population after these events, and most notably during very warm and wet conditions between 9-6,000 years BP (an event known as the mid-Holocene climatic optimum). While there was disparity between the archaeological and palaeoclimatic records after this time (as outlined in the opening paragraphs above), comparison of the dates as data graphs with the 90 or so archaeological site records continue to show close similarity. Therefore, through the use of both testing approaches, we were able to conclude that the use of radiocarbon dates as a proxy for Aboriginal population was reliable. While I do not elaborate here, we do, however, include extensive discussion around the approach, and highlight a range of assumptions and limitations that the researcher needs to be aware of when using the technique, most notably site specific and regional sampling bias that result in artificial peaks in the data. An example of this is the Willandra Lakes system, where researchers have undertaken hundreds of dates on an area known to have been intensely occupied at the LGM, and thereby creating a large peak at around 21,000 years BP that is not reflected elsewhere in Australia.

Findings and Conclusions

[A. N. Williams et al., 2015], we compared behaviour and population size of past Aboriginal society in Australia with the climate record of the last 35,000 years. We found that Aboriginal society was strongly influenced by climate change for much of this time, with populations declining, or regions abandoned, in cold and dry periods, and the reverse when conditions improved. Importantly, we found that this human-climate relationship changed following a period of previously unseen wet and warm conditions between 9-6,000 years BP (before present), which allowed population to grow and reach a critical mass. After 6,000 years BP, we do not see populations mirror climatic events, but rather we see society adapt and weather change through the appearance of technological innovation (e.g. complex hunting equipment) and social complexity (e.g. evidence of ownership through rock art; and the formation of the Dreamtime religious system), resulting in continuous growth and expansion up until the settlement of Europeans in the late 18th Century.

While elements of the above story have long been known and understood in the Australian archaeological literature, this is perhaps the first time all the threads have been pulled together to weave a single narrative that explains how and why Aboriginal society has developed and thrived in one of the most arid countries in the world. For the modern day Australian, it presents an important part of the formative history of the nation, as well as highlighting some of the potential trials and tribulations that may need to be faced as climate changes into the future (e.g. areas likely prone to increased aridity and reduced fertility with climatic downturns). For the archaeologist, the paper provides a status update on Australian research, and presents regional models of population change through time, with which they can compare their records and identify areas of future investigation and research.

Finally, we identify future directions for Australian archaeological research. Through the 1950s – 1990s, there were large themes in Australian research, such as the origins of Aboriginal people, timing and location of initial colonisation of Australia, and human behaviour through the Last Glacial Maximum to name a few examples. More recently, however, research has become quite insular, and includes intense focus on individual sites or specific stone tool types, and revisiting previous sites and findings. There are a number of quite valid reasons for this shift. However, we highlight the need to re-consider the larger picture for Australian prehistory, and we propose a number of possible directions to do this. Specifically, we identify a number of regions that have yet to be investigated by archaeologists or researchers, and which are critical to understand how Aboriginal people moved and utilised the continent. These primarily include areas between the different regions, such as the Channel Country dividing the temperate coast and arid centre, where we should see evidence of Aboriginal people's response to even minor climate change; and the Murchison that divides the southwest corner of Australia (which contains some of the earliest evidence of Aboriginal people at Devil's Lair) and the arid core, similarly to understand the movement of people across this region. We also highlight a number of specific timeframes that more work is needed, most notably between 18-10,000 years BP, and 9-6,000 years BP – the former due to massive decline in population, to understand their recovery and survival through this period; and the latter to identify how and when the technological and social innovation outlined above was initiated and established, buffering populations from future climate deterioration.

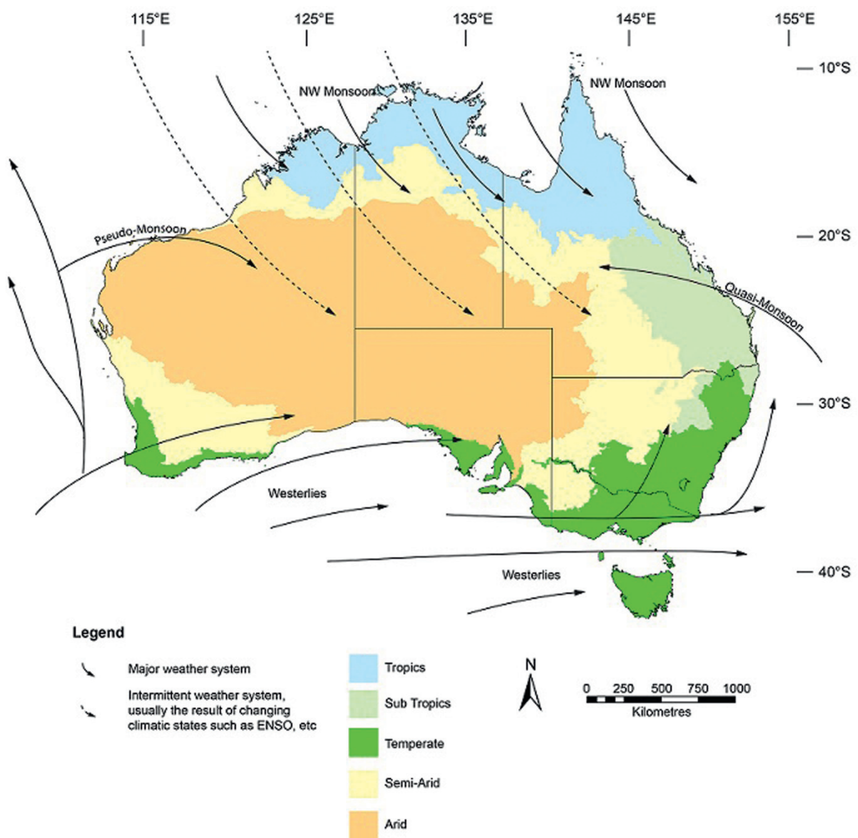
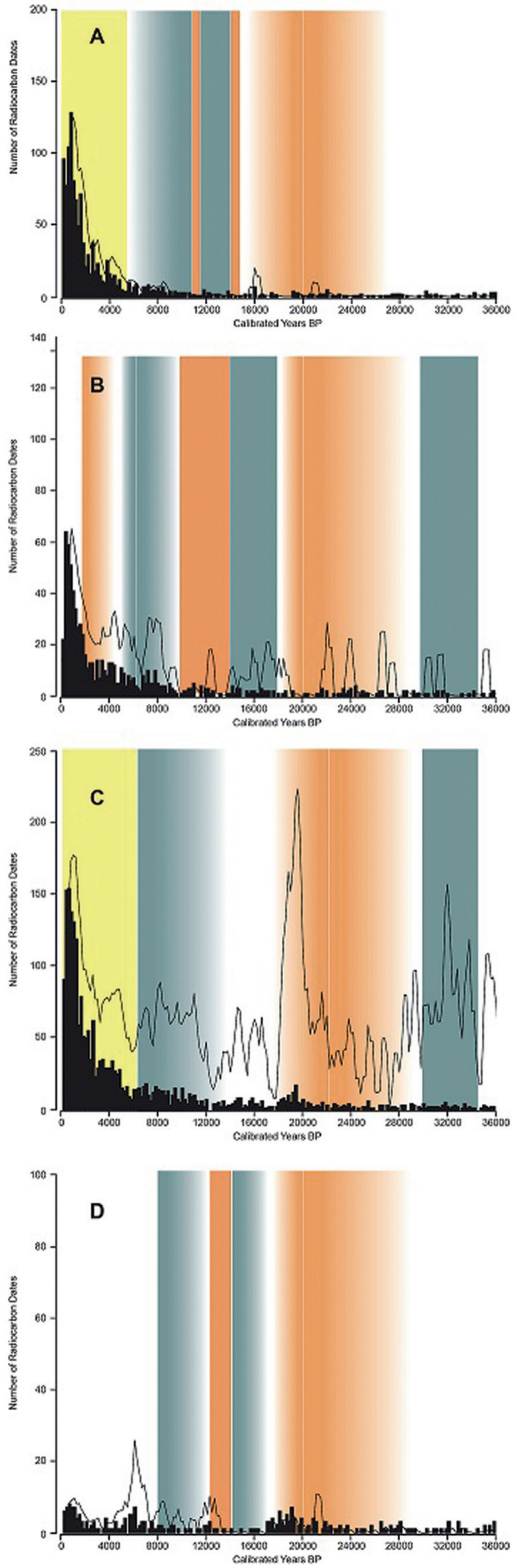


Figure 1: A summary of the main weather systems in Australia. To the north, rainfall is driven by the movement of the summer monsoon across the top end and, in certain conditions, into the arid interior. To the south, rainfall is driven by the winter westerlies, which make incursions along the southern fringe and across the southeast corner. The interior of Australia receives rainfall through the interaction of these major systems, as well as other minor systems resulting from them. Figure reprinted from [A. N. Williams et al., 2015], Copyright (2015), with permission from Elsevier.



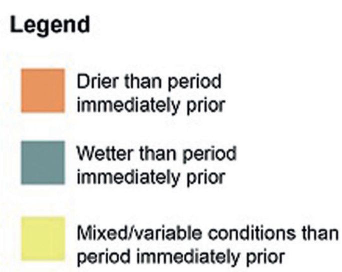


Figure 2: The changing Aboriginal populations through time based on radiocarbon data in: A) the tropics; B) the arid interior; C) the temperate east coast; and D) Tasmania. The black bar chart represent the number of radiocarbon dates, and the black line is the same data statistically corrected for taphonomic loss of older sites through time (see [A. N. Williams, 2013] for further discussion). The data is interpreted as an increase (decrease) reflecting more (less) people. Please note that the graph should be read qualitatively, (rather than literally), with the number of radiocarbon dates at a particular point simply providing the trend in population change compared with other time periods, not actual numbers of people. The climatic conditions at each time period is presented as different colours. Figure reprinted from [A. N. Williams et al., 2015], Copyright (2015), with permission from Elsevier.

Further Reading

[P. Hiscock, 2008]
[J. M. Reeves et al., 2013] [M. A. Smith, 2013]
[P. M. Veth, 1993]
[A. N. Williams and S. Ulm, 2016]

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What do historical temperature records tell us about natural variability in global temperature?

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Published Article v. 1

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Global average surface air temperature can change when it is either 'forced' to change by factors such as increasing greenhouse gasses, or it can change on its own through 'unforced' natural cycles like El-Niño/La-Niña. In this paper we estimated the magnitude of unforced temperature variability using historical datasets rather than the more commonly used computer climate models. We used data recorded by thermometers back to the year 1880 as well as data from "nature's thermometers" – things like tree rings, corals, and lake sediments – that give us clues of how temperature varied naturally from the year 1000 to 1850. We found that unforced natural temperature variability is large enough to have been responsible for the decade-to-decade changes in the rate of global warming seen over the 20th century. However, the total warming over the 20th century cannot be explained by unforced variability alone and it would not have been possible without the human-caused increase in greenhouse gasses. We also found that unforced temperature variability may be the driver behind the reduced rate of global warming experienced at the beginning of the 21st century.

Geographical Sector(s): Global

Subject Area(s): Climate of the Future, Climate of the Past, Climate of the Present

Global Temperature Change

The long term warming of the globe over the 20th and 21st centuries is one of the most recognized measures of human impact on the planet. However, in order to assess the human contribution to global warming, it is critical that we understand the natural drivers of global temperature change. Our study attempts to do just that by quantifying how large natural 'unforced' changes in global temperature can be. Before we delve into the methods and results, I will provide some background on global temperature change and what is meant by 'forced' and 'unforced' temperature variability.

Temperature, in essence, is a measure of energy. All changes in global average air temperature come about due to an imbalance in the atmosphere's energy budget [P. T. Brown et al., 2014]. Think of it this way – the atmosphere has an energy budget similar to how you may have a financial budget. In order to accumulate wealth you need to make more money than you spend. Similarly, in order for the global temperature to increase, the atmosphere needs to accumulate more energy than is lost. The Earth receives all of its energy from the sun, but a certain amount is reflected back to space off of things like clouds, snow and ice. The Earth also releases something called "infrared energy" to space. When the global temperature is stable, the amount of solar energy coming in equals the amount of energy reflected and released to space, creating a balanced energy budget.

There are many factors that can change the Earth's energy budget and thus the average surface temperature. Forced temperature change is a change in temperature that is imposed on the ocean/atmosphere system from a source that is considered to be outside of the ocean/atmosphere system. Examples of "forcings" include changes in the brightness of the sun and changes in concentrations of greenhouse gases due to human fossil fuel burning. However, global surface temperature can also change naturally without any outside forcing. Fittingly, this is referred to as "unforced" temperature change. Unforced temperature changes come from natural ocean/atmosphere interactions that can cause an imbalance in the Earth's energy budget. The El-Niño/La-Niña cycle in the Pacific Ocean is the most well known example of unforced variability. During La-Niña years, an unusual amount of energy is taken up by the Pacific Ocean, which causes a net loss of atmospheric energy and thus short-term global cooling. The opposite of La-Niña is El-Niño. During El-Niño years, excess energy enters the atmosphere from the Pacific Ocean causing an energy surplus and short term global warming. Natural variability in clouds and snow/ice can also change how much solar energy is reflected back to space and thus can affect the average surface air temperature (see [P. T. Brown et al., 2015a], [P. T. Brown et al., 2015b], [P. T. Brown et al., 2016] for more details).

The relationship between forced and unforced temperature changes can be compared to the relationship between a man and a dog out for a walk (Figure 1: A and B). In this analogy the path of the man represents forced temperature change (such as human-caused increases in greenhouse gasses) and the path of the dog, relative to the man, represents unforced temperature change (such as El-Niño/La-Niña cycles). Forced temperature changes are relatively deterministic and predictable; therefore imagine that the man walks his dog on the exact same route every day. On the other hand, unforced temperature change is somewhat random and unpredictable, therefore imagine that the dog is easily distracted and continuously redirects her attention from object to object over the course of each walk. It is important to note that the dog is on a leash so she can only wander a certain distance away from the man before the leash restricts her. This means that the path of dog will eventually reflect both the movement of the dog and the movement of the man. In the real climate system we can only observe

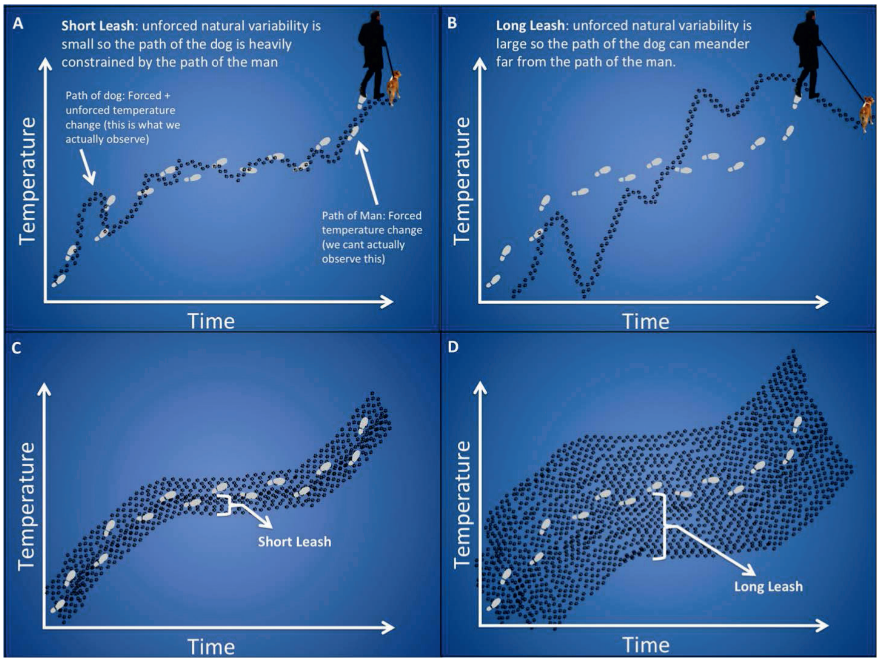

Figure 1: Man walking dog analogy for global average surface air temperature variability. The path of the man represents forced temperature change. The path of the dog, relative to the man, represents natural unforced temperature variability. A longer leash represents the potential for larger unforced temperature variability. The path of the dog represents the actual observed temperature change, a combination of the forced (movement of man) and the unforced (movement of dog) influences on temperature change.

the path of the dog – the combined result of forced and unforced temperature change. This means that we must figure out the extent to which the path we see is affected by the man and the extent to which it is affected by the dog, if we want to understand the causes of temperature change over any given period of time.

Now, imagine that the man walks the dog one hundred times and follows the exact same route each time - the path of the dog would be slightly different each time. Analogously, if we could go back in time to the beginning of the 20th century and re-run climate history with the exact same changes in greenhouse gasses (as well as other global temperature forcings that I have not mentioned), the temperature progression would be slightly different each time because unforced variability would be different.

Notice that if the leash linking the dog to the man is short, the path of the dog will closely match the path of the man (Figure 1: A). If the man walks the dog one hundred times, the path of the dog will look similar each time since the dog cannot stray very far from the man (Figure 1: C). However, if the leash is long (Figure 1: B), the dog can stray a reasonable distance away from the man (Figure 1: D). Knowing the length of the leash (or the size of unforced temperature variability) in the real climate system is of critical importance for understanding what is causing the temperature to change at any given time.

Determining the magnitude of unforced variability will also help us predict how global temperature might change in the future. As humans put more greenhouse gasses into the atmosphere every year, the forced temperature change will continue on his upward trajectory. If the magnitude of unforced variability is small then we should expect to see global temperatures follow this upward progression closely. However, if the magnitude of unforced variability is large, then the global temperature might deviate from the steady upward progression for decades at a time.

The most commonly used tool for determining the size of unforced natural variability is the "global climate model". Global climate models are computer programs that use our knowledge of physics and geography to simulate the Earth's oceanic and atmospheric circulations. Thus, these climate models actually simulate energy imbalances in order to estimate global surface temperature changes. When a climate model is run, it simulates a single possible trajectory of the temperature progression. The size of unforced variability is inferred from a computer climate model by running it many times with the same forced temperature changes but with slightly different histories of natural unforced cycles – histories that could have happened. This is analogous to figuring out the length of the leash by observing the height of the sum of the dog's paths (Figure 1: C and D).

Our new way to estimate the size of unforced variability

Several recent studies have suggested that global climate models might underestimate the magnitude of unforced natural temperature variability ([P. T. Brown et al., 2015a]; [K. L. Swanson et al., 2009]; [M. G. Wyatt and J. Peters, 2012]). Considering this, it is valuable to estimate the size of unforced variability from an independent source. In our study, we estimated the size of unforced variability by examining the historical record of temperature change in two types of datasets. We used the "instrumental record" from the year 1880 to 2013, which represents the temperature record measured directly with thermometers. This record is relatively short, so we also used "proxy reconstructions" of temperatures from the year 1000 to 1850. Proxy reconstructions represent estimates of historical temperature that come from "natural thermometers" present in the environment. Some examples of natural thermometers include tree rings, corals, pollen, ice layers, stalactites, and lake sediments.

We used a statistical method called "Multiple Linear Regression" in order to separate forced from unforced temperature variability in these records. Our Multiple Linear Regression technique noted how much of the temperature variability in the past was correlated with changes in forcings. Any temperature variability that was correlated with changes in forcings was not counted as part of our estimate of unforced variability. We then used this estimate of unforced temperature variability to create our own simulations of unforced variability over the 20th and 21st centuries. We did this with a statistical method called "noise modeling". Our noise modeling technique used a computer's random number generator to create thousands of hypothetical temperature trajectories over the 20th and 21st centuries with the same amount of unforced variability as what we found in our historical datasets (Figure 2). These trajectories represented alternative histories – again the range of temperatures that could have occurred with the same forced temperature change. They were also used to represent the range of possible outcomes that we might expect to observe under future increases in greenhouse gasses. We used this new data to address two main questions:

1.
Is unforced natural variability large enough to account for the decade-to-decade variability in the rate of global warming over the 20th century?

2.
Does the reduced rate of global warming over the beginning of the 21st century indicate that forced temperature changes slowed drastically, or is unforced variability large enough to make global warming hiatus periods inevitable in the long run?

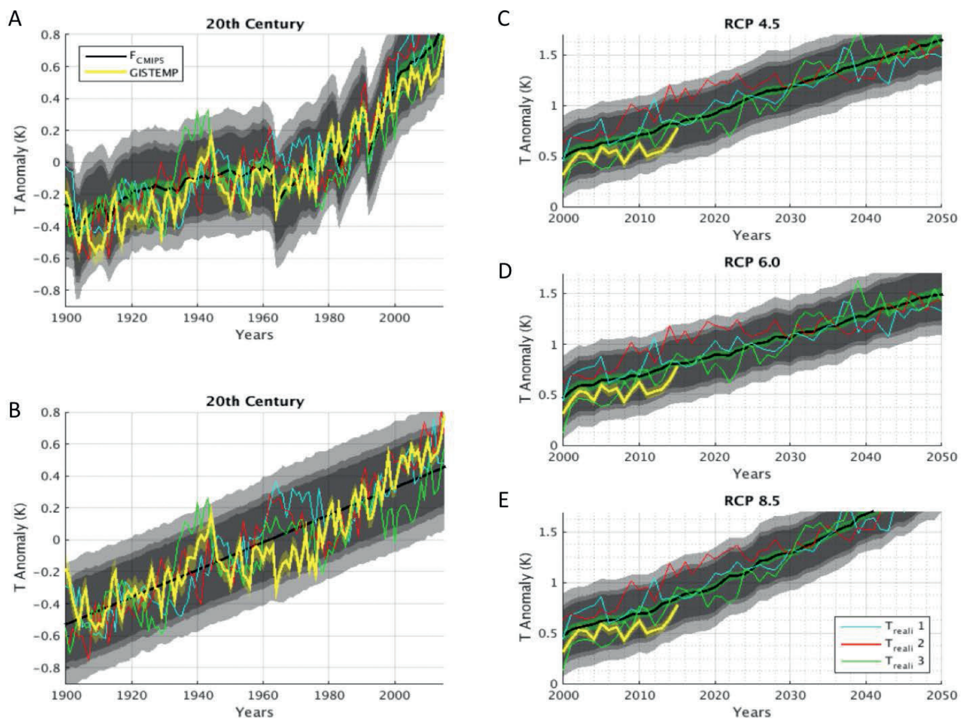

Figure 2: Estimates of forced variability and the range of unforced variability for global average temperature.
The black line represents forced variability (analogous to the path of the man in Figure 1) while the gray shading represents the range of unforced variability that we found in our study (analogous to the length of the leash in Figure 1). The yellow line is the observed temperature progression while the green, blue, and red lines represent alternative temperature progressions that could have occurred with the same forced variability but different unforced variability. Panels A and B show two different possibilities for forced variability from 1900 to 2015 while panels C, D and E show three different possibilities for forced variability over next several decades. Figure reproduced from [P. T. Brown et al., 2015b].

Implications of our new estimate of the size of unforced variability

We found that unforced variability is large enough to have accounted for decade-to-decade changes in the rate of global warming over the 20th century (Figure 2: B). This means that unforced variability is a little bit larger than most global climate models have traditionally indicated. However, our results made it clear that unforced temperature variability is not large enough to account for the total global warming that has been observed since 1900. Therefore, our study confirms that forced temperature changes, such as those from human-caused increases in greenhouse gasses, were necessary for the Earth to have warmed as much as it did over the past century [N. L. Bindoff et al., 2013].

Our findings also have implications for the first decade of the 21st century. We know that well- mixed greenhouse gasses, which cause forced temperature change, increased substantially since the turn of the century. However, global temperatures rose very little between 2002 and 2013. If unforced variability was found to be very small, the above two observations might imply that greenhouse gasses don't cause as much warming as previously thought. However, since we found that unforced variability is relatively large, it suggests that the temperature we observe can meander substantially away from the underlying forced temperature changes. Therefore, we should not be surprised to see a period of a decade-or-so without global warming even as the forced temperature change continues on its upward trajectory (Figure 2: A). This is simply a situation where the man is progressing upward while the dog is walking down. The leash may be longer than previously thought but there is still a leash. As long as the man continues on his upward trajectory, the leash will eventually pull up on the dog (Figure 2: C, D and E) and the long term global warming trend will continue.

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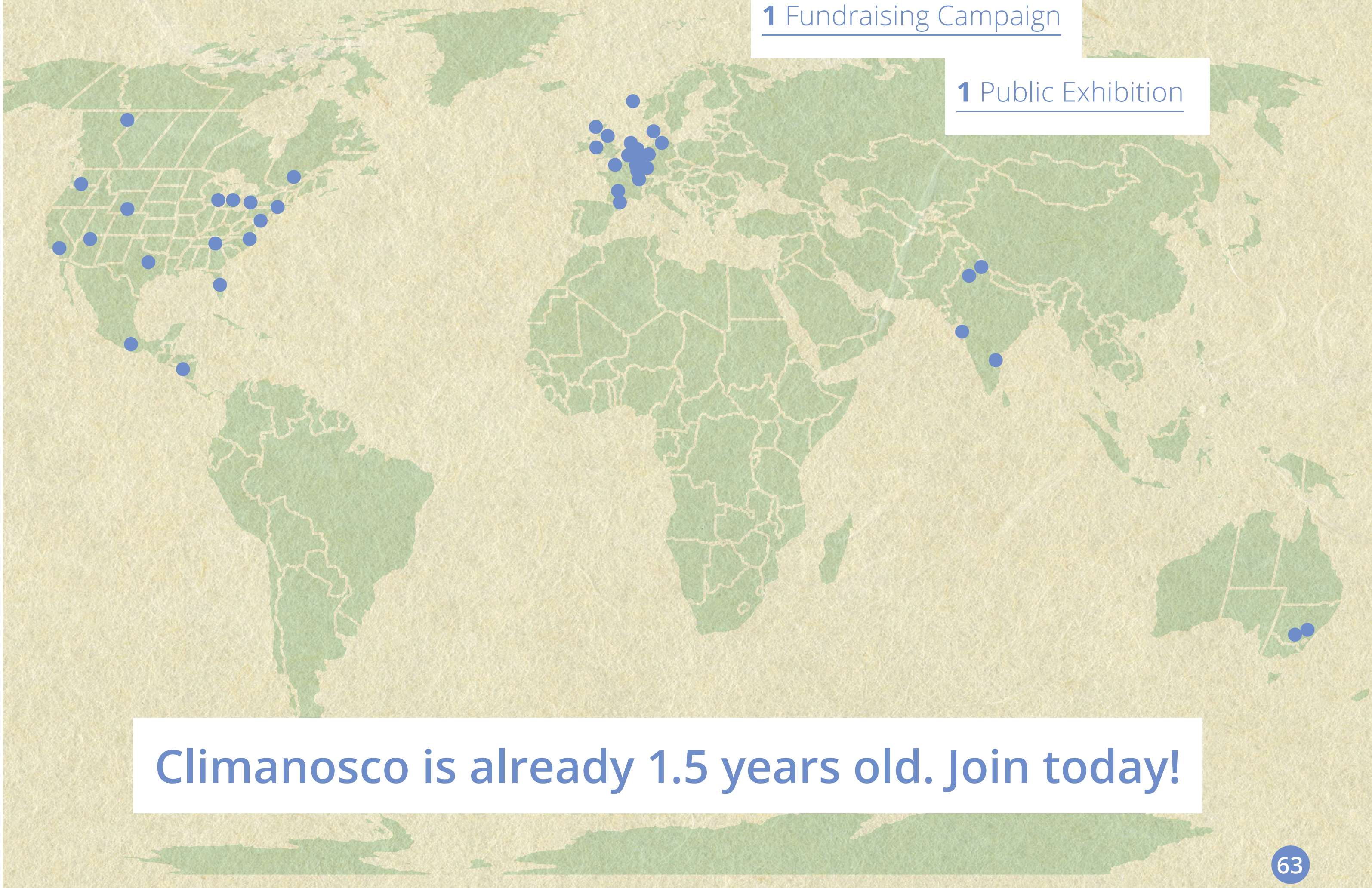

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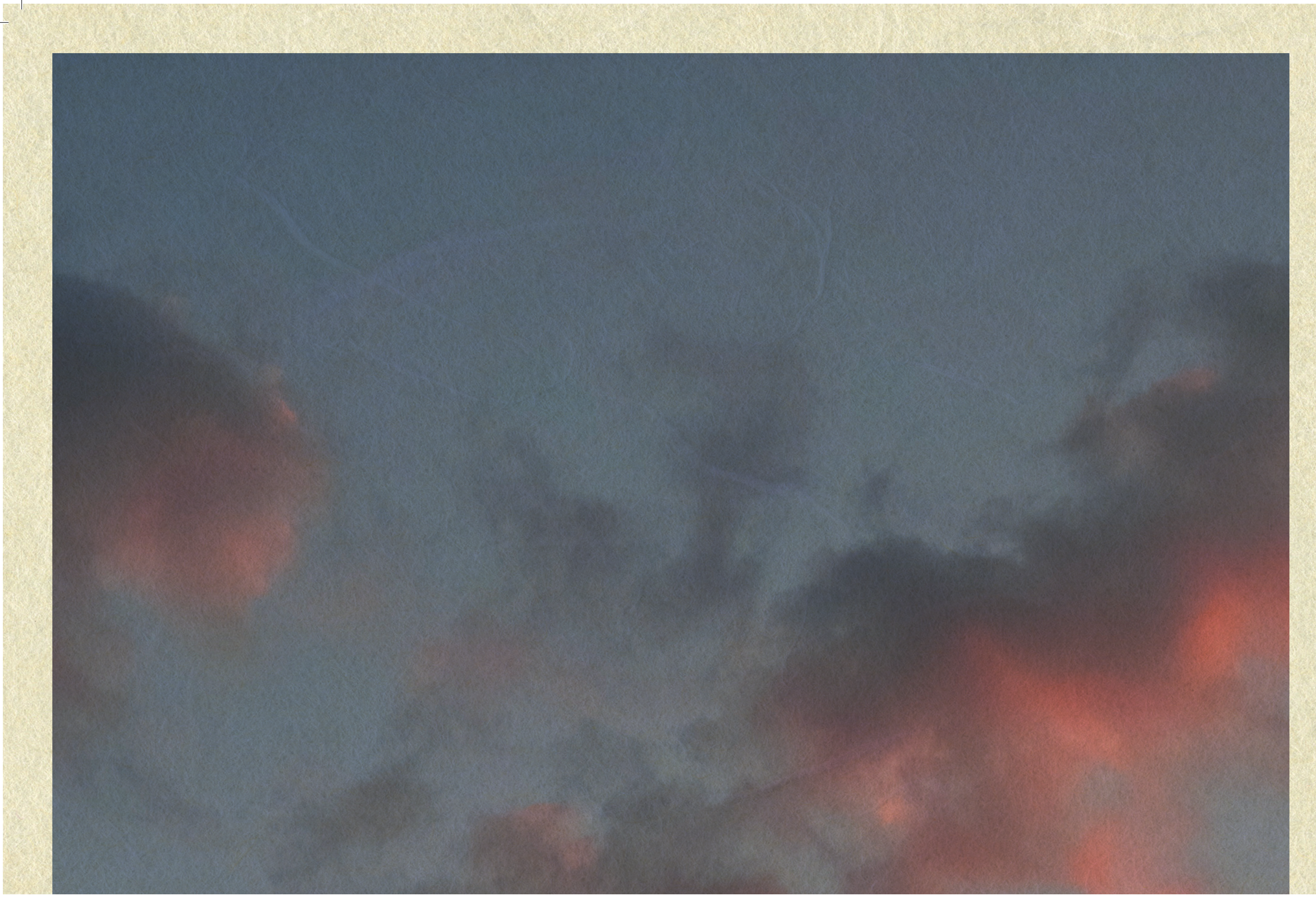

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