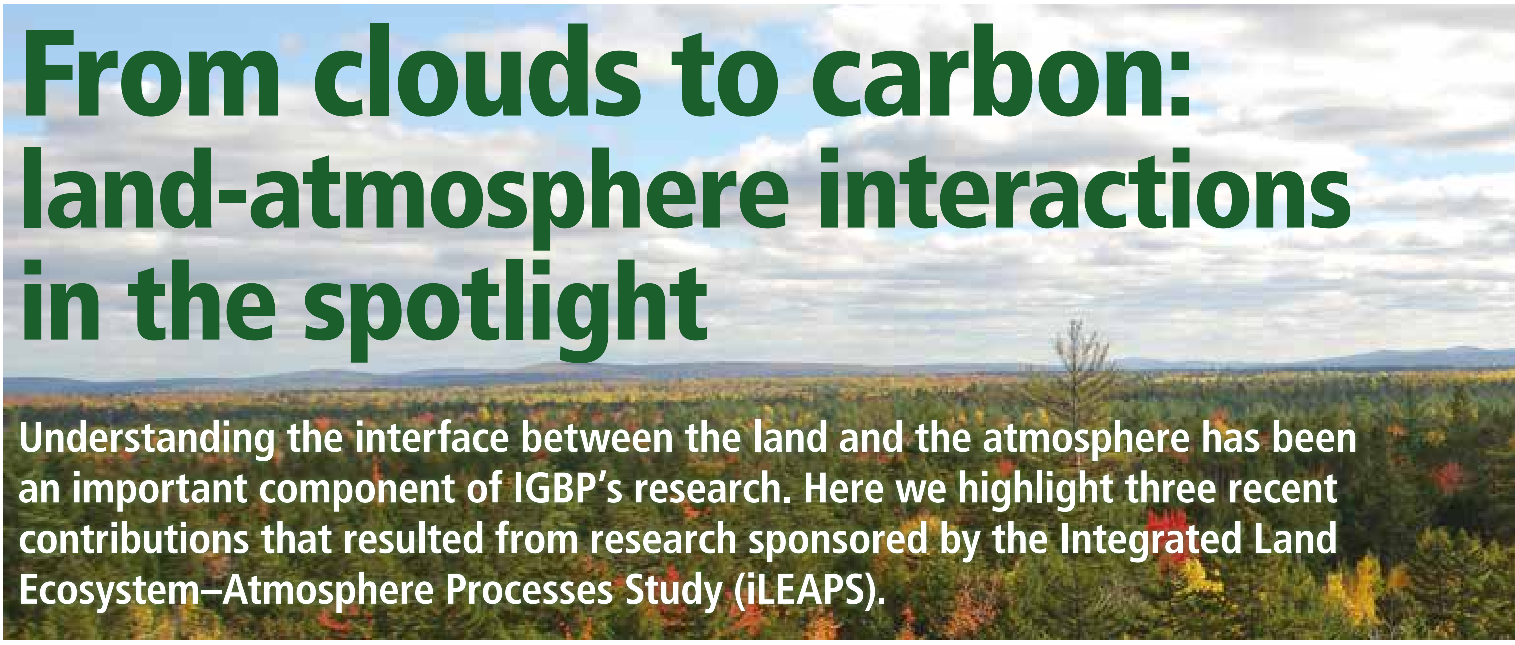


From clouds to carbon: land-atmosphere interactions in the spotlight

Understanding the interface between the land and the atmosphere has been an important component of IGBP's research. Here we highlight three recent contributions that resulted from research sponsored by the Integrated Land Ecosystem–Atmosphere Processes Study (iLEAPS).

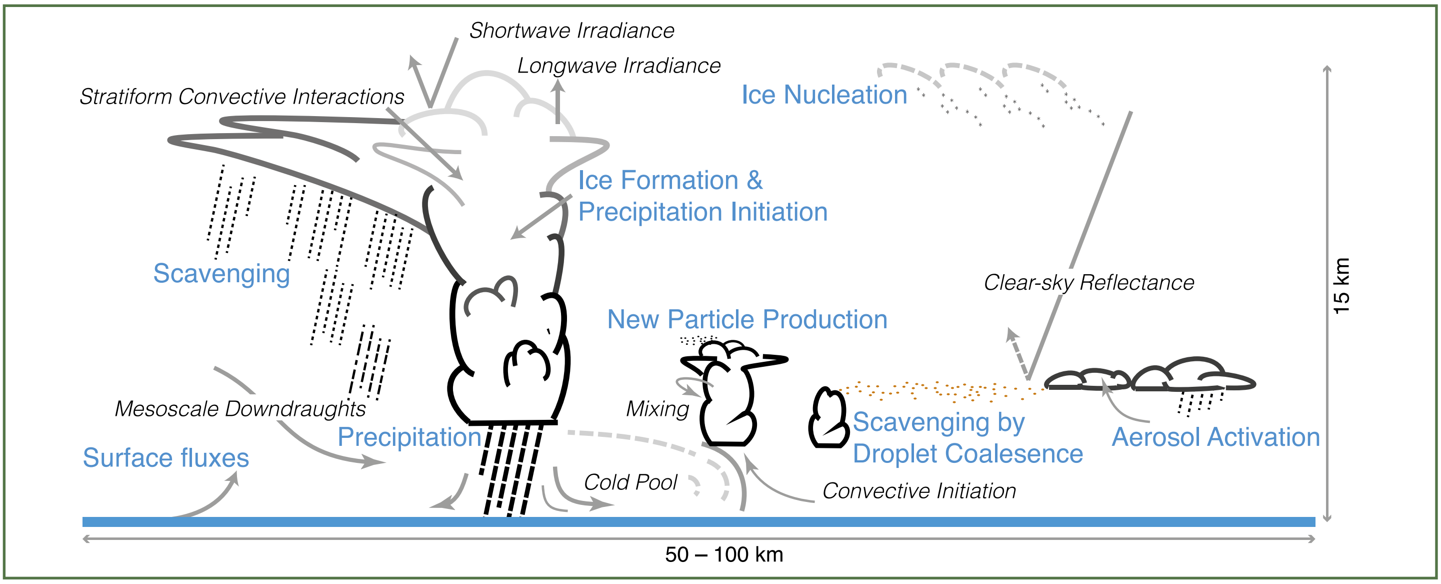
The little things matter

Annica Ekman

A cloud can make a big difference. Not only when we step out of the door and either sunshine or rain hits us, but also from the perspective of climate. Clouds regulate climate by affecting surface temperatures and precipitation patterns. We have known for a long time that cloud formation relies on tiny particles in the air. Yet, taking stock of these particles in global climate models and describing how they influence cloud formation is difficult: it requires a lot of computing power. But does adding this type of complexity really make the simulated climate more realistic? Recent research shows that the effort is worthwhile and that the way we treat the little particles does matter.

Atmospheric particles can be as small as viruses and as large as beach sand. They consist of dust from soils, sea salt from oceans, pollen from forests or organic matter. Human activities contribute to a large number of particles; the particle concentration in the atmosphere has increased drastically during the 20th century, causing a polluting haze over many regions. The haze inhibits sunlight from reaching the ground, which results in an overall cooling of the Earth's surface.

Particles can also cool the Earth indirectly by triggering cloud formation: in the absence of particles the relative humidity would have to increase above several hundred percent to form cloud droplets. Although the number of cloud droplets increases with increasing particle concentrations, the size of droplets decreases. Imagine a jar of breadcrumbs: if you pour some water into the jar the breadcrumbs will swell up. If you pour the same quantity of water into a jar with more breadcrumbs, they will not swell up



Schematic depicting the myriad aerosol–cloud–precipitation related processes occurring within a typical General Circulation Model grid box. The schematic conveys the importance of considering aerosol–cloud–precipitation processes as part of an interactive system encompassing a large range of spatiotemporal scales.
Source: Boucher O *et al.* (2013) Clouds and Aerosols. In: Stocker T F *et al.* (eds) *Climate Change 2013: The physical science basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA.

David Hollinger

as much. The higher the number of cloud droplets the brighter the resulting cloud. Such a cloud reflects more sunlight and tends to cool the Earth's surface.

Most climate models today factor in the relationship between atmospheric particle number and the number of cloud droplets. But models tend to greatly simplify the real-world complexities. For example, not all particles in the atmosphere are suitable as surfaces for the condensation of cloud droplets; some particles are not soluble in water and some are so small that the droplets cannot grow efficiently. So in our previous example, the jar would contain not only breadcrumbs but also different types of candy: adding water would make some of the candy swell up slowly whereas other candy would hardly be affected. Such complexity is now accounted for by a handful of models providing data for the latest Intergovernmental Panel on Climate Change (IPCC) Assessment Report. In the models, cloud droplets form easily on some particles but not on others unless the relative humidity is very high. Some particles are not amenable to cloud formation at all.

I recently examined the surface-temperature trends during the latter half of the 20th century generated by three types of models: a) complex models in which the number of cloud droplets is dependent not only on the size and composition of the particles but also on the simulated relative humidity; b) simpler models in which all types of particles can increase the number of cloud droplets; and c) very simple models in which there is no relationship between the particle concentration and the number of cloud droplets. I found that the surface-temperature trends generated by the complex models did a better job of reproducing observations than the simpler models. As also shown by Wilcox and colleagues, I found that models that completely ignored the relationship between the numbers of atmospheric particles and cloud droplets provided an even poorer match with the observed surface temperatures.

It is encouraging that the models get better at reproducing observations when we use a more realistic description of the relationship between atmospheric particles and clouds. But the improved performance comes at a significant cost in terms of computing power and time. We are yet to find the optimal combination of complexity and computational cost. Which relationships between atmospheric particles and clouds do we absolutely need to include in global climate models? Which relationships can we ignore or represent in simpler terms? Such questions are at the forefront of current research and we hope to have even clearer answers in the coming years.

ANNICA EKMAN is Associate Professor at the Department of Meteorology at Stockholm University, Sweden.

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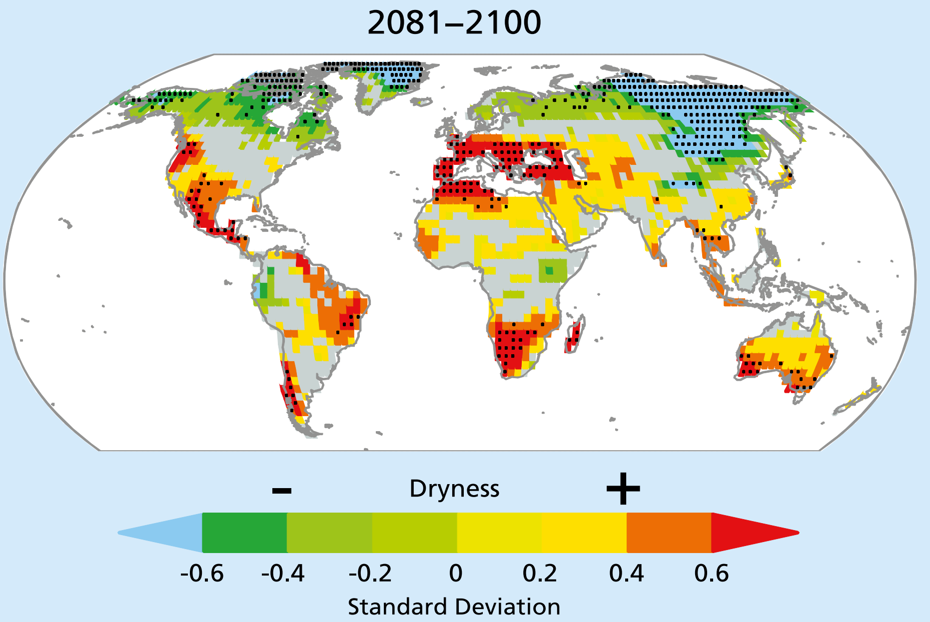
Climate extremes and the carbon cycle

Markus Reichstein

Plants, animals and humans react to concrete environmental conditions, not to averages. Take, for instance, crop yields during two years with very similar mean temperatures: if one of the years experienced extreme heat or cold waves whereas the other year did not, the crop yields from each year would be very different. That is why recent Intergovernmental Panel on Climate Change (IPCC) reports emphasised climate variability and extremes (for example, IPCC 2012). The assessments conclude that we can almost certainly expect more heat waves by the end of this century. Not only that, many regions will also experience an increase in the likelihood of heavy precipitation or droughts in the future.

Climate extremes can affect the terrestrial carbon cycle: one example is the 2003 European heat wave, which released carbon that had accumulated over several years. However, not all climate extremes – statistically defined – affect ecosystems to the same degree. For example, an extremely cold spell of -40°C is unlikely to matter much in a region that commonly experiences -30°C during the month of January. Society is thus ultimately interested in the impacts of such events.



Droughts are likely to intensify in the 21st century. The figure shows the change in annual maximum number of consecutive dry days (precipitation <1 mm) for the period 2081-2100 based on model projections. Increased dryness is indicated with yellow to red colours; decreased dryness with green to blue. From IPCC (2012)

Bearing this in mind, we (Reichstein *et al.* 2013, Zscheischler *et al.* 2013) looked directly for impacts of extreme climate events in Earth observation and modelling data. Our focus was on photosynthesis, which is a part of the carbon cycle. We first bracketed extreme events in terms of duration, region and intensity. For each event we then estimated both how much carbon would have normally been taken up by photosynthesis in the affected region and how much was actually taken up during the event. The difference between these two quantities is a measure of the effect of the extreme event.

According to the available global data, disturbances to the carbon cycle led to around 3 Gigatons per year less carbon taken up by photosynthesis during the last decade; this is roughly equivalent to the annual net land carbon uptake in the last decade. At least 80% of these disturbances were related to climate extremes and their effects – droughts, heat waves, cold spells, heavy precipitation and fire – of which droughts were the most important. Events involving multiple stressors tended to have a disproportionally larger effect. As climate extremes increase in frequency, intensity or duration we may expect substantial reductions in the quantities of carbon dioxide taken up by photosynthesis. Previous work has shown that year-to-year changes in net carbon uptake are driven more by photosynthesis than by respiration (for example, Schwalm *et al.* 2010, Shi *et al.* 2014). This implies a positive feedback whereby climate change leads to reduced carbon uptake, which in turn exacerbates climate change (including climate extremes). Interestingly, higher carbon-dioxide concentrations in a future world are likely to lead to more efficient use of water by plants (see “Fertilising the forests” on this page), which might help to alleviate the effect of droughts.

In our datasets 200 of the largest carbon-cycle disturbances, occupying only 8% of the surface area on average, explain more than 80% of the global interannual variability of carbon uptake by vegetation. In this way extreme events may influence the year-to-year variations in the rate of increase of atmospheric carbon-dioxide concentration. However the estimates are subject to considerable uncertainties. We thus argue for a concerted effort to understand climate extremes and their impacts. In particular, we underscore the need for improvements in Earth-system and other types of models so that biological processes such as mortality and adaptation, as well as ecosystem internal feedbacks, may be improved (Bahn *et al.* 2013). ▮

MARKUS REICHSTEIN is the Director of the Department of Biogeochemical Integration at the Max Planck Institute for Biogeochemistry, Jena, Germany. He is a member of the Scientific Steering Committee of iLEAPS.

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Fertilising the forests

Trevor F Keenan
Andrew D Richardson

Atmospheric carbon dioxide has increased from 260 parts per million (ppm) approximately 150 years ago to over 400 ppm today (http://scrippsco2.ucsd.edu). Despite efforts to regulate emissions, we continue to emit this gas through the burning of fossil fuels, cement production and altered fire regimes. In fact, atmospheric carbon-dioxide concentrations are rising faster than what worst-case scenarios predicted. At the current rate, concentrations are expected to double by the end of the century.

Carbon dioxide is, of course, a boon to plants and its increased concentrations in the atmosphere enhance photosynthesis – the so-called “fertilisation effect”. This in turn could stimulate carbon sequestration, thereby dampening the future rate of increase in atmospheric carbon dioxide. Much depends, however, on how efficiently plants use water while sucking up carbon dioxide. The ratio of water loss to carbon gain, or water-use efficiency, is a key to the global cycles of water, energy and carbon. How efficient would water use become in response to the expected doubling of atmospheric carbon dioxide by the end of the century?

There has been little conclusive evidence of a direct response of the terrestrial biosphere to rising atmospheric carbon dioxide. We don't quite know what caused the recently reported increases in growth rates in a variety of forests (for example, McMahon *et al.* 2010). The evidence provided by experiments is also equivocal. This is not surprising, given the difficulties in translating results from proxies and controlled experiments to natural ecosystems. The response of water use in natural forest ecosystems is thus the subject of considerable debate.

We decided to harness the information provided by FLUXNET, a network of over 500 globally distributed measurement sites. Each site measures continuously the fluxes of carbon and water between the land surface and the atmosphere. As part of a US National Oceanic and Atmospheric Administration funded project we analysed the observations made in 21 temperate and boreal forests in the northern hemisphere. We found a substantial increase in water-use efficiency during the past two decades across all sites. Of course, this observation by itself does not imply enhanced fertilisation. There are multiple processes that could lead to the observed trend.

We systematically assessed each of these competing hypotheses (for example, nitrogen deposition or increased drought) and found that the observed increase is indeed most consistent with a strong carbon-dioxide fertilisation effect. Modelling points to the partial closure of stomata – small pores on the leaf surface that regulate gas exchange – in response to continuously increasing atmospheric carbon-dioxide levels. This indicates a dynamic response of plants to reduce the amount of water they transpire as atmospheric carbon-dioxide levels rise.

Note that the observed increase in forest water-use efficiency is larger than that predicted by existing theory and 13 terrestrial ecosystem models we tested from the North American Carbon Project. The expected theoretical response is based on the results of experiments that have guided the development of models (de Kauwe *et al.* 2013). A larger observed response could indicate that the experimental results, which correspond to a sudden increase in ambient carbon-dioxide levels in controlled environments, do not adequately capture the responses in natural environments to gradual increases in carbon-dioxide levels over decades. Alternatively, it could indicate that other unknown factors have contributed to the trend we observed. For example, it was recently suggested that changes in air quality may be responsible for about 10% of the trend observed at some sites in the US (Holmes 2014; Keenan *et al.* 2014).

Regardless of the cause, it is clear that temperate and boreal forests are using water more efficiently. This has several implications for ecosystem function and feedbacks to climate. Increased efficiency could lead to increased crop yields; increased water availability in drought-prone regions; increases in surface temperature and the planetary boundary layer; increased sea-level rise; and drought in parts of the world that rely on water transpired in other regions.

The increase is also associated with trends of increasing ecosystem-level photosynthesis and net carbon sequestration (Keenan *et al.* 2013). As current terrestrial-biosphere models do not capture such trends, they will not predict these indirect effects either. Resolving our understanding of the underlying physiology is fundamental to our ability to make realistic projections of future changes to the Earth's biosphere and the resulting feedbacks to the atmosphere and climate.

TREVOR F KEENAN is a Research Fellow at the Department of Biological Sciences, Macquarie University, North Ryde NSW, Australia.

ANDREW D RICHARDSON is Associate Professor at the Department of Organismic and Evolutionary Biology, Harvard University, Cambridge MA, USA.

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Chris Vogel

Autumn as seen from an eddy-covariance tower over the UMBS mixed forest in the USA.