

## Climate research must sharpen its view

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*Human activity is changing Earth's climate. Now that this has been acknowledged and accepted in international negotiations, climate research needs to define its next frontiers.*

The 2015 Paris agreement<sup>1</sup> at COP21 has liberated climate research from discussing what is already known – the world is warming and humans are largely responsible. As society aims to limit further warming by reducing greenhouse-gas emissions, climate research must probe deeper into the unknown.

Here we argue that basic climate research can sharpen its view by casting the challenges ahead into a few simple yet powerful guiding questions: ***First, where does the carbon go? Second, how does the weather change with climate? And third, how does climate influence the habitability of the Earth and its regions?***

These questions require additional context before they can begin to guide research. “The carbon” is anthropogenic, but its input into the climate system occurs against the background of a highly dynamic and variable natural carbon cycle. “The weather” is produced by an interplay of thermodynamic and dynamic processes, which crucially determine circulation and rainfall patterns, and whose variability and future change are particularly uncertain<sup>2</sup>. “The habitability” includes those factors that societies can successfully adapt to – or cannot.

These three simple-sounding questions pose profound scientific challenges. But they do much more than that. They point to the heart of what society *needs* to know if it is to make informed decisions on possible responses (although not necessarily to the heart of what society is currently *requesting* to know about climate change). For example, for mitigation efforts to succeed, verification of the emissions reductions pledged by the individual countries in the Paris agreement<sup>1</sup> must be based on sound scientific methods<sup>3</sup>. Changes in rainfall patterns, such as the long-term Australian rainfall decline<sup>4</sup>, are strongly linked to changes in the circulation of the atmosphere and oceans, and yet the mechanisms for such regional changes remain poorly understood<sup>5</sup>. Possible limits in societies’ ability to adapt to changes in climate, such as physiological limitations to coping with heat stress<sup>6</sup>, will first be reached on regional scales<sup>7</sup>, but where and when remains uncertain.

## Where does the carbon go?

How the anthropogenic carbon is processed in the climate system has crucial and poorly understood aspects both in the short and the long term. During the next few decades, the implementation of the Paris agreement will pose the question of whether individual countries fulfil their pledges toward emissions reductions and whether their self-reporting is reliable. Science-based verification of reported emissions at least on a regional scale will be essential for building confidence in the treaty regime. This need for confidence-building is reminiscent of the situation prior to the Comprehensive Nuclear-Test-Ban Treaty (CTBT) of the early 1990s, banning all nuclear test explosions. One science challenge was to ensure that the seismic network could provide the information necessary for distinguishing suspected underground nuclear explosions from earthquakes. Advances in science and data processing led the CTBT's verification network to be widely considered up to its task. Similarly, climate science should be ready to support any potential future verification regime for the Paris agreement<sup>3</sup>.

The scientific challenges are substantial. In principle methods exist to estimate regional anthropogenic surface carbon fluxes from local flux measurements and inverse modelling relying on ground- and space-based atmospheric concentration measurements. But identifying the anthropogenic part of changes in surface fluxes – crucial in any verification regime – is complicated by internal climate variability. For example, during an El Niño event atmospheric carbon concentration tends to be elevated, due to the dominating reduced uptake by the land surface combined with the reduced outgassing in the warmer tropical Pacific. And the ocean carbon sink, the largest contribution to which comes from the Southern Ocean, shows substantial decade-to-decade variability, probably from variability in weather patterns<sup>8</sup> that are difficult to simulate realistically in today's climate models.

Looking ahead toward the second half of this century, the question shifts to the magnitude of the feedback between climate and the carbon cycle. There is general agreement that the feedback is amplifying – in a warmer climate, less carbon will be taken up by the land and by the ocean, and a larger fraction of the anthropogenic carbon will remain in the atmosphere, further enhancing climate change – but the magnitude of the feedback remains uncertain. The uncertainty arises somewhat differently for the ocean sink and the land sink<sup>9</sup>. For the ocean sink the basic processes are generally known (circulation, vertical mixing, and the sinking of biological material), but not the magnitude and sometimes even the sign of the expected changes in these processes, especially the impact of ocean acidification on ecosystems. On land there is substantial uncertainty concerning the processes that determine the carbon–climate feedback. For example, there is extensive scientific debate about the importance of nutrient limitation (nitrogen and phosphorous supply) for future land carbon uptake. Additionally the land biosphere, and associated carbon cycle, relies on water availability, but the future is unclear with uncertainty in circulation and water cycle changes – a topic we turn to next.

## **How does the weather change with climate?**

Humans do not truly experience climate. Instead, individuals experience day-to-day variability – the weather. Many human and natural systems are highly sensitive to weather time scales of a few weeks or less, including high-impact weather events, such as heat waves, floods and wind-storms. Hence, the question of how the weather changes with climate is of great importance, and yet, it remains profoundly difficult to answer. Why is this so?

Weather is the combined result of the atmospheric circulation embedded in the larger-scale climate structures and of local-to-regional thermodynamic processes interacting with the weather patterns. Weather arises because circulation systems respond to the differential heating from the sun by transporting energy from where it accumulates (at the surface and at low latitudes) to where it can be more effectively and efficiently radiated back to space. These circulation systems, whether the towering cumulus clouds carrying monsoon rains or the patterns of warm and cold fronts in the mid-latitudes, are highly dynamic and encompass processes that interact across a wide array of scales. It is no wonder that attempts to link their behaviour to something as aggregated as the state of the climate are still so rudimentary.

What we have learned is that small-scale processes, which play an important role in shaping circulation responses in a changing climate, cannot be explicitly represented in the resolved equations of global weather and climate models, due to both limited understanding and inadequate computational resources. Instead, these processes must be described through their overall statistical effects – a technique known as parameterisation. An example is atmospheric moist convection, which expresses itself in a range of well-known clouds, from fair-weather cumulus clouds to isolated thunderstorms to cloud clusters on the scale of continents. The presence of moist convection is often associated with severe storms and extreme precipitation, its absence with heat waves and drought. And while it is well known that convection tends to organise in storms or rain belts, it remains a scientific challenge to understand what determines the strength and pattern of this organisation<sup>10</sup>.

Weather is noisy. In many regions of the Earth, day-to-day, week-to-week and year-to-year variations in the weather can be large. Just think of the passage of a cold front in the extra-tropics, in which the temperature can change by ten or more degrees centigrade in a few hours. Understanding and predicting how this internal variability (noise) influences our evolving climate and weather<sup>11</sup>, especially on the scales where society lives, is critical to inform decisions on mitigation and adaptation. Internal variability also complicates the attribution of changes in regional climate, but long-term signals are now beginning to emerge from the noise in different locations for temperature, extremes, and precipitation<sup>12</sup>. However, the attribution of shorter-timescale (decadal) signals to their causes remains in its infancy.

## **How does climate influence the habitability of the Earth and its regions?**

Changes in the climate will shape changes in both the natural and the human environment. Of particular importance will be those changes that might exceed the limits within which particular species, including humans, can adapt<sup>13</sup>. Prominent examples of such changes are regions of heat stress beyond the physiological limits, declining water availability, and the loss of land surface associated with rising sea levels. Climate science must therefore explore where and when habitability limits will be reached. This question is intimately linked to changes in the weather and its extremes, but goes well beyond and provides a handshake to the biological and social sciences.

There is growing evidence that heat extremes are increasing in many regions, and climate simulations consistently project further increases<sup>13</sup>. In some mid-latitude and subtropical regions, the likelihood of severe heat waves will be enhanced by feedbacks with soil drying<sup>7</sup>. In the humid tropics, unprecedented climates are expected to emerge owing to low inter-seasonal variability and are likely to cause intolerable heat-stress conditions regularly<sup>6</sup>. Forty per cent of the world's population currently live in tropical regions, and much of their livelihood is based on outdoor labour. This is exacerbated by the fact that nations in these regions have a limited adaptive capability to adverse conditions<sup>13</sup>. Answering the critical question of when and where heat stress might exceed the physiological limits of the human body<sup>6</sup> requires major progress in our understanding and predictive capability of local heat and moisture extremes<sup>7</sup> in addition to a tightening of our estimates of climate sensitivity<sup>5</sup>.

The global water cycle — from the formation of clouds, to the release of precipitation, to land surface hydrology including its interaction with the atmosphere, to water storage and release in the cryosphere — remains one of the least understood natural cycles. Hence, the predictions of this cycle in a changing climate are amongst the most uncertain<sup>13</sup>. This constitutes a major challenge in ascertaining future water availability and its regional distribution for agriculture, industry and domestic use.

Even if atmospheric greenhouse-gas concentrations are stabilised, sea level will continue to rise for centuries; the largest uncertainty in the estimates of future global sea-level rise is due to melting ice sheets<sup>14</sup>. In addition to inundating low-lying coastal regions, sea level rise increases the severity and frequency of storm-driven and tidally driven coastal flooding<sup>14</sup>, thus threatening the habitability and productivity of large portions of the land surface.

## **The challenges ahead**

Answering our three guiding questions requires breakthroughs in the basic understanding of how climate works. Breakthroughs cannot be planned, but their achievement can be aided by the right strategies. First and foremost, climate research must maintain the right balance between fundamental discovery and the application of its new-found knowledge to societal needs. Without a strong

fundamental-discovery basis to support this balance, climate research and hence the society at large will repeatedly be caught off guard by the multitude of surprises that the climate system presents. Consider some recent surprises – the record-breaking Arctic sea ice decline in 2007, the surface-warming slowdown of the early 21<sup>st</sup> century, the 2010 Russian heat wave and drought, the pan-Greenland surface ice melt in 2012, and the 2014/2015 El Niño that wasn't – to appreciate the challenge they posed to understanding, but also to appreciate how a strong foundation of basic research has effected rapid progress on these challenges once they arose.

Basic research is also required to prepare humankind for unlikely but possible future surprises, caused perhaps by nonlinearities in the climate system that might compound the threat to habitability, from a combination of very large greenhouse-gas emissions and very high climate sensitivity. This type of research may not immediately provide society with better climate information, but it is crucial for building a robust knowledge base from which climate preparedness for society is drawn.

Another crucial strategy relies on having the intellectual agility to critically interrogate ideas – and their articulation in climate models – through observations. This strategy has two key ingredients, in addition to the free flow of new ideas. First, we must build the best climate models we can<sup>10</sup>. This will very likely require a substantial reduction in the grid-spacing used by the models, allowing greater reliance on the explicitly represented physical laws and less on parameterisations. Achieving this model improvement will likely benefit from a small number of international flagship programs that push the boundaries of current scientific and technological capability. It also requires improved efficiency of computer codes and a massive increase in computational resources.

The second key ingredient to interrogating our ideas comprises a sufficiently powerful combination of sustained long-term climate observations that monitor the overall trajectory of the system and its components. Highly agile and targeted observational efforts both from space and the ground are also needed to scrutinise the mechanisms that underpin major unknowns. For example, reliably measuring all components of the water cycle, from soil moisture to the extraction of water from the surface by turbulent fluxes and plants to water vapour and clouds in the atmosphere to precipitation concurrent with key quantities describing the atmospheric circulation remains a major challenge – yet one that must be met.

The research compelled here is not new; however, the guiding questions provide a new lens on the basic climate-research agenda, aiding its communication to other scientific disciplines, to the public, and to policy-makers. Many of the societal demands for climate information cannot currently be robustly met because of the lack of basic understanding. To create this understanding and thus to effect the needed gains for society, climate researchers must mobilise to tackle the science challenges that we have outlined. The human spirit is alive in climate research, as witnessed by responses to the surprises encountered in the past, but a growing influx of the best scientific talent is needed to prepare for the surprises that are to come.

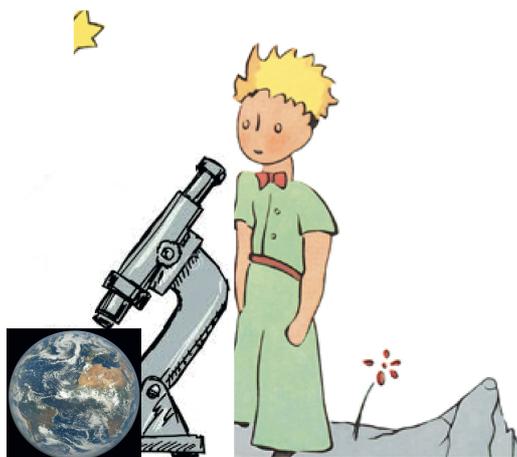
## 1. Acknowledgments

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### 3. Graphics



An allegory for unbridled curiosity that meets the deeply humane spirit – both epitomised by The Little Prince – and that sharpens its view on Earth’s climate.

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