PROJECTION AND PREDICTION

Climate sensitivity on the rise

Recent observations of Earth's energy budget indicate low climate sensitivity. Research now shows that these estimates should be revised upward, resolving an apparent mismatch with climate models and implying a warmer future.

Kyle C. Armour

Global climate models predict an uncomfortably large range of warming from unabated greenhouse gas (GHG) emissions. The most sensitive models show global warming in excess of 10 °C over the coming centuries, reaching temperatures not seen since the Eocene — an epoch when sea levels were 70 metres higher and warmth-loving reptiles roamed the Arctic. Meanwhile, the least sensitive show temperatures reaching one-third of this level. Is this range of predictions realistic? The recent literature suggests not: up-to-date global energy-budget observations[1,2] indicate a climate sensitivity below the modelled range, implying that future warming has been overestimated. Writing in *Nature Climate Change*, Mark Richardson and colleagues[3] show that much of this disagreement stems from apples-to-oranges definitions of historical surface temperature change. Combined with two other independent lines of research that also call for upward revisions, it appears that climate sensitivity estimates have now been reconciled and are consistent with the modelled range.

Observational estimates of climate sensitivity — a metric of how much the world warms from GHGs — are based on historical measurements of global warming; the climate forcing that has caused the warming; and the heat being stored in the world's oceans. High sensitivity is inferred when observed warming is high, climate forcing is small and heat storage is large. The widest range of climate sensitivity supported by recent observations[1,2] is 1.0–4.0 °C, with a best estimate at around 2.0 °C. At face value, this suggests that models, with a range[4] of 2.0–5.6 °C, are altogether too sensitive. A metric of near-term global warming, known as the transient climate response (TCR), can also be estimated from observed warming and climate forcing. As Richardson *et al.* report, this too suggests that models are overly sensitive, with a range of 1.2–2.4 °C compared to the observation-based range of 0.9–2.0 °C. But, are observations and models measuring the same thing?

Strictly speaking, climate sensitivity is defined as the global mean near-surface air temperature change that would eventually result from a sustained doubling of atmospheric CO_2. 'Global mean', 'near-surface air temperature', 'doubling of atmospheric CO_2', 'eventually' — encoded in these conceptual chunks[5] are the keys to understanding the challenges inherent to observation-based estimates of climate sensitivity.

A global mean is as it sounds — the area-weighted average of temperatures from all over the globe. And near-surface air temperature refers to air that is a couple of metres above the Earth's surface, whether over land, ocean or ice. We can easily calculate these from model output, but confront a daunting task from observations: temperature records are sparse (lacking global coverage) and from diverse sources (such as ships and weather stations).

Here is where the analysis by Richardson *et al.* bears interesting fruit: those ship-based measurements are actually of the ocean's surface layer, which has been warming at a slightly slower rate than the air just above. Guided by models, Richardson *et al.* show that accounting for this offset between sea-water and near-surface air temperatures leads to a 9% increase in global warming estimates. Furthermore, they consider the impact of incomplete geographical coverage on estimates of global-mean warming, finding that the most poorly measured regions on Earth have also warmed the most (the Arctic's temperature is inadequately sampled, yet sea-ice has disappeared before our eyes). This is a separate 15% effect[3], meaning that global near-surface air warming estimates should be revised upward by 24% in total. Consequently, observation-based estimates of climate sensitivity and TCR must also be revised upward by 24%, resolving much of the mismatch with modelled values.

The findings by Richardson *et al.* become even more powerful when combined with other recent work. Although the third term, doubling of atmospheric CO_2, is called for in the strict definition of climate sensitivity, the observed warming has been driven by a variety of climate forcing agents — primarily CO_2, but also other GHGs such as methane, sunlight-blocking particles called aerosols, changing land use (for example the shift from forests to farms) and more. Recently

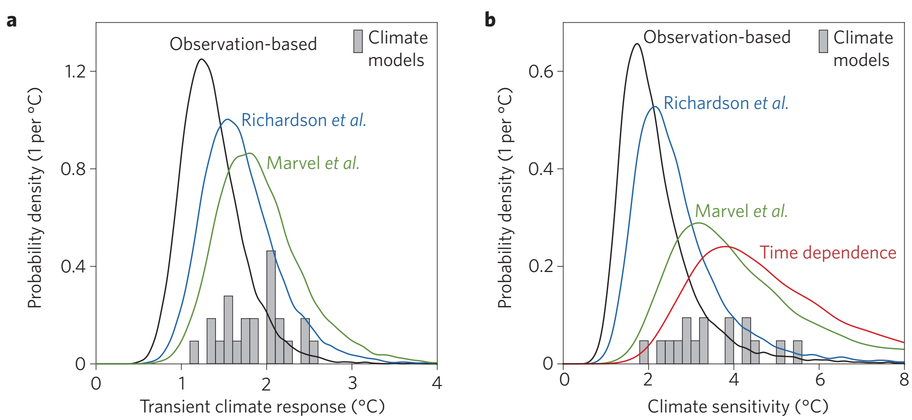

Figure 1 | Probability distribution of climate response to forcings. **a**, Transient climate response estimated from observations[1] (black), and its revision following Richardson *et al.*[3] (blue) then following Marvel *et al.*[6] (green). **b**, As with **a** but for climate sensitivity, with an additional revision for climate sensitivity appearing smaller than its true value[7–11] (red). Histogram of climate model values shown in grey.

in *Nature Climate Change*, Marvel *et al.*[6] showed that these non-CO_2 forcings have distinct effects on temperatures that are not directly equivalent to CO_2. These findings call for what amounts to a downward adjustment to the effective forcing on climate, and thus for an upward revision to observational estimates of climate sensitivity and TCR — another 30% (or so) that is multiplicative with the revision by Richardson *et al.*

The final term, eventually, refers to the time it takes Earth to fully respond to an imposed climate forcing — several thousand years, or more, due to the large heat capacity of the oceans. Thus, observations tell us about a comparatively early phase of warming. Although observation-based studies make the implicit assumption that climate sensitivity estimated today will still apply in the distant future, a recent line of research[7–11] calls this into question based on a robust behaviour of climate models — in the early warming phase, climate sensitivity appears smaller than its true value. This requires yet another upward revision to observation-based estimates (by around 25%, on average) in order to achieve an apples-to-apples comparison with models.

Although each of these independent revisions could stand to be better understood and more fully quantified, so far it seems that their tendencies are robust. In aggregate, the findings indicate that observation-based estimates of climate sensitivity and TCR may be substantially higher than previously reported, aligning them more closely with the range simulated by climate models and raising the spectre of a very warm future (Fig. 1). ❐

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HYDROLOGY

What brings rain to the Sahel?

The Sahel has suffered through severe droughts but recent years have seen increased rainfall. Now research suggests warming of the Mediterranean Sea surface may dictate future rainfall in the region.

Michela Biasutti

Squeezed between the hyper-arid Sahara desert to the north and the lush tropical forests of the Gulf of Guinea and Central Africa, is the Sahel: a ribbon of semi-arid land where summer brings heavy rain but the rest of the year is a prolonged dry season. Normal rains can sustain agriculture and pastoralism, but drought has horrific consequences, as was often the case in the 1970s and 1980s. However, the most recent decades have seen an upswing of rainfall, prompting many to hope that climate change is bringing the onset of another pluvial, and scientists to debate the causes of the recovery. Writing in *Nature Climate Change*, Park, Bader and Matei[1] suggest that increasingly warm temperatures in the Mediterranean Sea have brought anomalous moisture to Africa and have caused the recent trend towards a wetter Sahel. The moistening effect of a warm Mediterranean had been identified before[2,3], but this study suggests that anthropogenic warming of the West Pacific has changed the basic state of the tropical ocean in a way that has left extratropical influences — and the Mediterranean in particular — to dominate Sahel variability now and into the future. The analysis of multi-model ensemble simulations suggests that the degree of warming in the Mediterranean will thus determine the degree of wetting in the Sahel.

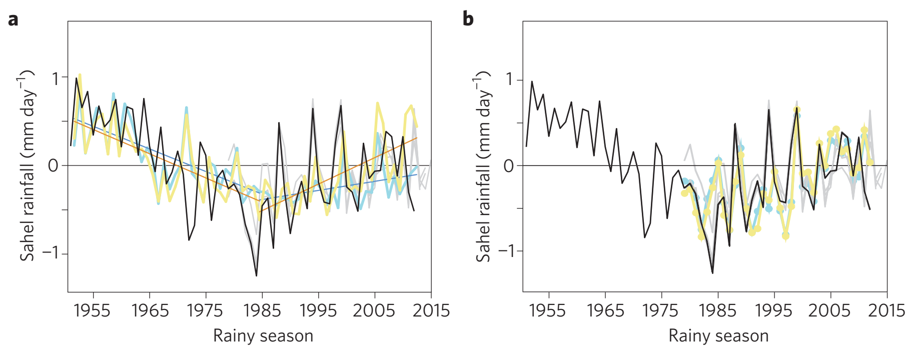

Figure 1 | Inclusion of Mediterranean SST or direct GHG forcing increases the simulated wetting trend in the Sahel, but does not improve the mismatch between models and observations. **a**, Observed Sahel summer rainfall anomalies in several datasets (TS3p2 in black; CHIRPS, TRMM3B42, GPCP and CMAP in grey) compared to AM3 simulations with (yellow) and without (blue) forcing from the Mediterranean. Figure adapted with permission from ref. 1, NPG. **b**, The same observations are compared to the ensemble average of 60 simulations forced by observed SST and observed radiative forcing by atmospheric composition changes (yellow) and 50 simulations by the same models, without the direct radiative forcing (blue). The CAM4, ECHAM5, and LBNL-CAM5-1-1degree simulations were obtained from ref. 16.

The mechanisms of Sahel rainfall variability are many, and not easily separable. It is now accepted that twentieth-century Sahel droughts were paced by variability in the global sea surface temperature (SST)[4,5]. Seminal early work[6] highlighted the connection of the drought with greater