Observations refute the idea that warming strongly reduces cloudiness

The response of cumulus clouds in trade-wind regions to warming is a large uncertainty in climate projections. Observations now indicate that the mechanism leading to the strongest cloud reductions in models does not occur in nature, suggesting that extreme sensitivity of Earth's temperatures to climate change is less likely than previously thought.

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The problem

A persistent problem in climate science is determining how clouds will respond to global warming. The response of small cumulus clouds in tropical trade-wind regions has been particularly difficult to predict. These 'trade cumulus' clouds are known to cool the planet by reflecting sunlight. It has long been feared that global warming would lead to a loss of these clouds, thereby amplifying warming and creating a positive-feedback loop.

According to a theory known as the 'mixing-desiccation hypothesis', when these clouds grow higher, they bring down dry air ('mixing'), which dries ('desiccates') the lower cloud layer and decreases cloudiness there[1]. The strength of this mixing-desiccation mechanism is thought to increase with global warming. As such, climate models that represent such mixing-desiccation behaviour predict higher climate sensitivity — that is, more global warming in response to increases in atmospheric carbon — than do other climate models. Despite being fundamental to our understanding of climate change, the strength of mixing and the extent of cloudiness at the base of the cloud layer have been challenging to observe, making it difficult to test this hypothesis.

The discovery

To collect data to test the mixing-desiccation hypothesis (Fig. 1a), we carried out the one-month EUREC^{4}A study anchored in Barbados[2]. We measured cloudiness at the base of the cloud layer by using horizontally looking radar and lidar sensors from an aircraft. We also dropped more than 800 atmospheric probes from a second aircraft that flew in circles about 200 km in diameter, to measure the slow, mesoscale vertical motion of air. Measures of this mesoscale vertical motion, made possible using a new flight strategy and estimation technique[3], were crucial for gauging vertical mixing.

Our observations indicate that the mixing-desiccation mechanism does not actually occur in nature. The mesoscale vertical air motion and the smaller-scale 'entrainment' mixing — whereby air from higher levels is drawn into low layers, below the base of the clouds — both contribute to variability in convective mixing. However, whereas small-scale entrainment mixing reduces humidity, mesoscale circulations (on scales of about 200 km) actually increase humidity (Fig. 1b). Thus, stronger convective mixing does not desiccate clouds at their base.

Our observations are at the scale of a typical grid cell in climate models, and therefore provide a test of models' abilities to represent the interplay of processes that regulate trade-cumulus clouds. Indeed, in most of the climate models we analysed, the relationship between mixing and cloudiness on a day-to-day timescale differs strongly from that supported by our observations. Models that predict a large positive-feedback effect of trade-cumulus clouds tend to represent a mixing-desiccation mechanism, counter to our observations. Our data render those models implausible, and instead provide physical evidence for these clouds having only a weak feedback effect on warming.

The implications

By showing that mesoscale overturning circulations prevent the mixing-desiccation mechanism, we refute a key line of evidence for high climate sensitivity. This is good news, as it shows that extreme climate sensitivities are less likely than previously predicted. The work also sheds light on the role of mesoscale circulations in buffering the responses of clouds to warming. Mesoscale circulations are ubiquitous in trade-wind regions, but their effect on humidity is poorly represented in high-resolution, limited-area simulations[4], and completely absent from climate models.

Using present-day observations of day-to-day weather variability to learn about cloud responses on climate timescales has some limitations. Trade-cumulus clouds are usually organized in distinct patterns. Although we sampled all the canonical cloud-organization patterns during the EUREC^{4}A study, it is unclear whether certain patterns (for example, those with greater cloud cover) will become more or less frequent with global warming[5]. Very little theory exists for how the strength of mixing in trade-wind regions will change with warming. Future research should investigate the processes that control mesoscale circulations and cloud organization, and show how they might change as the climate warms.

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EXPERT OPINION

"These timely conclusions contribute to the intense discussion of the potentially high sensitivity of global climate to carbon dioxide that has been predicted by climate-change models. As part of this discussion, a great deal of process-realism analysis has been done on mid-latitude clouds, but the equally or perhaps more important tropical shallow cumulus regime has received less attention. It is refreshing to see this important cloud type being addressed." (CC BY 4.0)

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FIGURE

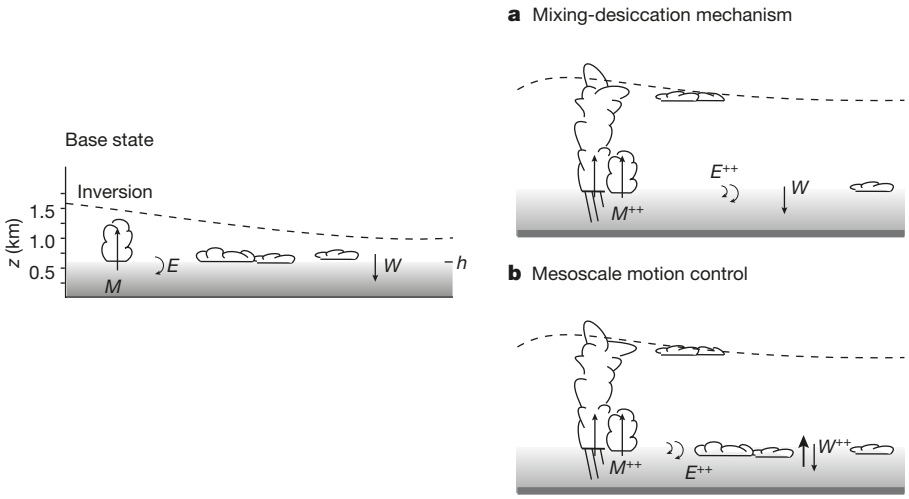


Figure 1 | Two hypotheses for the coupling of convective mixing and cloudiness. Schematic illustrations show the interplay of convective mixing, entrainment, mesoscale circulations, and coudiness at the cloud base. **a**, Observations from the EUREC^{4}A field study refute the mixing-desiccation hypothesis, which predicts that warming would strongly decrease cloudiness compared with the base state (left). According to this hypothesis, stronger mixing (M^{++}) leads to excessive drying through entrainment (E^{++}), whereby air from higher levels is drawn into the lower layers, below the base of the clouds. **b**, In the mesoscale-motion control mechanism, the contribution of mesoscale vertical air motion (W^{++}) prevents drying of the cloud layer and thus prevents decreases in cloudiness in response to stronger mixing. Climate models that predict high temperature increases in response to the climate change caused by carbon emissions simulate the first mechanism, but EUREC^{4}A observations reveal that the second mechanism operates in nature. *z*, distance above ground level. Vogel, R. *et al.*/*Nature* (CC BY 4.0).

BEHIND THE PAPER

It has been amazing for us, as young researchers, to be part of such a large international field experiment, from its preparation through its execution and data analysis. It has been eye-opening to follow the progression of a scientific idea to the point of testing a single hypothesis, and then developing new measurement techniques and designing a field campaign to collect the necessary data. Seeing these beautiful clouds in the field and up close from an aircraft, rather than on a computer screen, changed our perspective. Naturally, given the field campaign's name, we had our share of 'eureka' moments. We could not have imagined a better occupation during the COVID-19 lockdowns that started a few weeks after our return from Barbados. Working on this fascinating and important problem as a small team kept us strongly connected despite being physically isolated from each other during that time.

A.L.A. and **R.V.**

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FROM THE EDITOR

Do observations support or refute the specific physical processes that create 'hot' models — that is, Earth system models with high climate sensitivity? It turns out that this is an incredibly hard question to answer, because it almost inevitably involves clouds and the myriad processes and states controlling their formation and movement. Vogel *et al.*, though, have succeeded, using the results from an ambitious observational campaign to take one of the key processes off the table.

Michael White, Senior Editor, *Nature*