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CLIMATE

A moist model monsoon

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Received wisdom about the main driver of the South Asian monsoon comes into question with a report that tests the idea that the Himalayas, not the Tibetan plateau, are the essential topographic ingredient.

A substantial literature takes it for granted that the prime reason for the great strength of the South Asian monsoon is the heating effect of the Tibetan plateau. On page 218 of this issue, Boos and Kuang[1] show that what counts is the barrier posed by the mountains at the southern edge of the plateau, not the heating. This view has deep implications for our mechanistic understanding of this monsoon system, for our projections of how it might be altered in a warmer world, and for our understanding of Earth history.

The prevailing wisdom is based on plausible and venerable ideas. First, there is the idea of the monsoon as a giant sea-breeze (onshore) circulation. Land heats faster than the ocean: in summer, or on a diurnal basis, the temperature rises faster in the lower levels of the atmosphere above land, and so the pressure falls. The resulting pressure gradient drives the atmospheric flow onshore and, in the case of the monsoon, moisture-laden winds blow towards land and the rains begin. It is a reasonable expectation that enhancing the heating should increase the power of the monsoon — which brings us to the extra heating expected from the looming presence of the world's largest elevated region, the Tibetan plateau. The solar energy driving Earth's climate system is absorbed far better by land than by air. Hence, an elevated land surface should be warmer than the nearby atmosphere at the same height above sea level. So we should expect the presence of the plateau to put an extra charge into the heating differential driving the monsoon.

The previous paragraph set up a straw man, but one still esteemed in research papers and textbooks. It is perhaps adequate to explain monsoonal wind shifts, but not the rains. A heat low forms over land well before the monsoon begins, but still it does not rain. In fact, the land is hotter in May, before it rains, than at the height of the monsoon season in July. A more useful view, nicely presented by Gadgil[2], unifies monsoon rains with other tropical rainfall. In this view, tropical rainy seasons are largely a matter of when the Intertropical Convergence Zone, a near-global belt of deep atmospheric convection, passes overhead as it migrates north–south with the seasons.

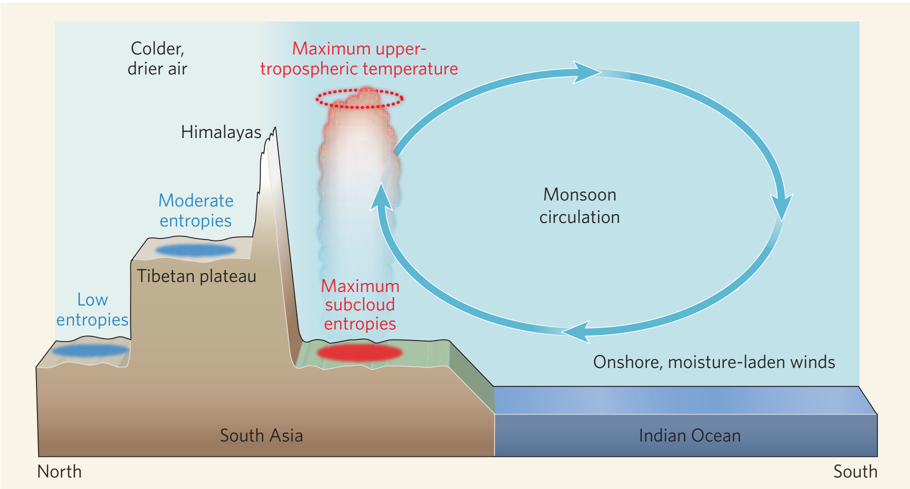

Figure 1 | A new model monsoon. Boos and Kuang's thinking[1] centres on the role of moisture convection rather than heat absorbed and radiated by the Tibetan plateau. Maximum subcloud moist entropy occurs south of the Himalayas, and the heat released as water vapour rises and condenses is reflected in peak temperatures in the overlying upper troposphere. The Himalayas keep the moist warm air over South Asia separated from the colder, drier air to the north, so the high energy of this air mass is undiluted, remains favourable for moisture-driven convection and underlies the strength of the South Asian monsoon.

This perspective brings moisture to the fore as a driver. Deep convection requires that surface air has enough buoyancy to rise to the top of the troposphere (the lowest 10–15 km of Earth's atmosphere). Water vapour is a crucial ingredient; a rising parcel of air can acquire additional buoyancy from the heat that is released as water vapour condenses. To see if a region is ripe for deep convection, we invoke a parameter called moist entropy, which tells us how the temperature of a parcel of air will change as it rises, accounting both for the decrease due to expansion as the pressure falls with height, and for the increase as the water vapour it contains condenses, releasing heat.Thus, we compare a measure of moist entropy at the surface, such as the equivalent potential temperature (θ_e), which is indicative of the density a parcel will have as it rises, with a measure of the density in the upper troposphere. In the tropics, we expect mean conditions to reflect a statistical equilibrium between convection and radiation[3,4]. Where a parcel of moist air is able to rise to great heights from near the surface, that is, where there is deep convection, it will pass a level at which it becomes saturated, because temperature decreases with height. Thereafter, its temperature is enhanced by the latent heat released as water vapour condenses. Thus, in convective regions, upper-level temperatures are largely determined by the temperature and humidity of near-surface air.

Boos and Kuang[1] show that, below cloud level, the maximum moist entropy is located south of the Himalayas, indicating that the important surface entropy supply is in the moist air over the Indian continent, not the Tibetan plateau to the north. The peak upper-tropospheric temperatures are over the continent, although direct heating of the Tibetan plateau is evident in a local dry boundary layer. It is telling that the straw-man reasoning above considered radiative processes, but not moist convection.

Noting the sharp gradients in θ_e at the Himalayas, Boos and Kuang hypothesize that the mountains enable a stronger monsoon by preventing the high-entropy warm and moist air to the south from being diluted by mixing with the low-entropy cold and dry air to the north

(Fig. 1). Without the topographic barrier, one would expect regions of such high θ_e gradients to be unstable, generating eddy mixing that would smooth the gradients.

Boos and Kuang[1] test their idea in experiments with an atmospheric general circulation model (GCM). There are many GCM experiments in the literature that remove all topography, but then one cannot tell whether the weakened monsoon that is obtained results from the loss of the Tibetan plateau as a heat source or from the lack of the mountains as a barrier. The literature generally assumes the former, which has reinforced its status as the prevailing wisdom. (A significant exception, cited by Boos and Kuang, is a paper by Chakraborty *et al.*[5].) Instead, Boos and Kuang do modelling experiments in which they remove the plateau, but leave the mountains in place as a narrow topographic barrier. The monsoon characteristics in this experiment — temperature, winds and precipitation — are very close to the model runs with full topography.

As ever, caveats are necessary. Although the GCM used by Boos and Kuang does a decent job of simulating the South Asian monsoon, it would be reassuring to see their results reproduced with other models, especially the nested high-resolution models[6] that produce rather different precipitation patterns from the best of the GCMs. Additional analyses would bolster the argument for the importance of the mountains as a barrier to mixing. By computing the mixing by eddies in these experiments, one could verify explicitly that the mountains do indeed reduce mixing. The authors' Figure 3 (centre column) on page 220 shows that although the θ_e gradients are weaker in the 'no mountains' experiment, they are still quite strong, and over the continent θ_e is not diminished (although temperature is; left column). Are these differences enough to account for the strength of the monsoon? The rainfall patterns in the experiments (right column of Fig. 3) are what would be expected when air is forced by high topography to rise and cool; it rains intensely on the windward side of the mountains. Is this effect more important than mixing?

Regardless of that, Boos and Kuang[1] decisively show that the heating of the Tibetan plateau is not responsible for the Indian monsoon's great strength. As documented in their references, that notion has motivated much work linking the origins of the monsoon to tectonic uplift. This new view of the South Asian monsoon does not obviate the value of the previous work, but it does refocus it on the Himalayas rather than the entire plateau.

Global warming will reduce the snow cover on the Tibetan plateau. The widely held idea that less snow would give a stronger monsoon, which goes back to at least 1886 (ref. 7), adds to the expectation of a stronger monsoon in a future where the land will be heated more. The view provided by Boos and Kuang raises questions about that expectation but does not settle the issue; the difference between a normal monsoon and a poor monsoon is a reduction in rainfall of only 10%, and we cannot yet rule out the Tibetan plateau as responsible for changes of that order. In any case, the greater concern about land heating in this region is the impact of glacier melting on the hydrology of rivers that originate on the plateau — rivers that are vital to almost half the world's population. ■

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