

# A review of recent progress on Tibet's role in the South Asian monsoon

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## Abstract

*The Tibetan Plateau exerts a profound influence on winds in boreal winter primarily through mechanical means, blocking flow to create waves in the jet stream that extend around Earth's full circumference (e.g. Held et al., 2002). In contrast, this plateau was thought to influence boreal summer winds primarily through its thermal effects, providing a heat source over 4 km high and 2,000 km wide that generates the interhemispheric flow of the South Asian monsoon. But recent work has shown that although orography greatly strengthens the South Asian summer monsoon, it operates via a different mechanism that requires only a relatively narrow but continuous chain of mountains around the northern edge of the monsoon, rather than a broad plateau. This review presents a brief history of research on the role of orography in the South Asian summer monsoon, with a focus on recent work that frames monsoon dynamics in terms of modern theories for precipitating large-scale circulations. This review does not address the mechanical forcing by orography that seems important for East Asian climate (e.g. Wu et al., 2007; Wang et al., 2008; Molnar et al., 2010; Park et al., 2012).*

## I. CLASSIC VIEW OF TIBET AS AN ELEVATED HEAT SOURCE

**T**HE rapid geographic expansion of Chinese meteorological observations in the 1950s provided the first view of the Tibetan Plateau as a heat source for the boreal summer troposphere. Estimates of the atmospheric heat budget showed that the plateau must emit abundant sensible heat in boreal summer, sufficient to warm much of the overlying troposphere by about  $2 \text{ K day}^{-1}$  (Yeh et al., 1957; Staff Members of Academia Sinica, 1958). Together with the existence of a warm upper-tropospheric anticyclone in the vicinity of Tibet, these estimates were taken as evidence that direct heating of the middle to upper troposphere by plateau surface fluxes forced a large part of the South Asian monsoon (e.g. Koteswaram, 1958).

However, it was soon realized that condensation and precipitation of water just south of the plateau instead constituted the dominant diabatic heat source for the South Asian monsoon; the plateau's sensible heat fluxes were

argued to indirectly drive the monsoon by causing this latent heating (Flohn, 1968). In other words, Tibet was claimed to be part of a "heat engine", with its sensible heating causing ascent and horizontal moisture convergence, that in turn produces the latent heating that drives monsoon flow. Decades later, Li and Yanai (1996) used gridded analyses of observations to confirm that diabatic heating by precipitation over the Bay of Bengal is the dominant heat source in the South Asian monsoon, and this diabatic heating is balanced by adiabatic cooling in the ascending branch of the monsoon circulation. This balance between moist convective heating and adiabatic cooling due to ascent is a general characteristic of tropical circulations (e.g. Sobel and Bretherton, 2000), and makes inferring the causal heat source difficult because any net temperature change results from the small residual of large opposing terms in the thermodynamic equation. Nevertheless, Li and Yanai (1996) argued that observations of large sensible heat fluxes over the plateau supported "the thermal influence of the Tibetan Plateau as a dominant factor driving the planetary-scale

monsoon system.”

Numerical modeling studies provided what seemed to be support for that conclusion by showing that the intensity and poleward extent of the South Asian summer monsoon were greatly diminished when Asian orography was removed (Hahn and Manabe, 1975; Ruddiman and Kutzbach, 1989; Prell and Kutzbach, 1992). These numerical results were taken as confirmation of the importance of sensible heat fluxes from the broad, elevated plateau surface, and the idea that plateau heating drives the South Asian monsoon became sufficiently widespread to make its way into textbooks (e.g. Hartmann, 1994).

## II. MODERN THEORIES OF CONVECTIVELY COUPLED MONSOON DYNAMICS

At the heart of the idea of Tibet as a dominant thermal forcing lies the realization that precipitation south of the plateau is the largest diabatic heat source, as mentioned above. In the classical view, this precipitation is assumed to be caused by moisture convergence induced by plateau sensible heating. This is essentially a moisture-convergence closure for monsoon convection, similar to moisture-convergence closures for convection that were used in early theories of tropical cyclones (e.g. Charney and Eliassen, 1964; Kuo, 1965).<sup>1</sup> The assumed positive feedback between large-scale moisture convergence and latent heating has been termed Conditional Instability of the Second Kind (CISK).

These ideas for the workings of moist convection in monsoons persist to this day, with CISK explicitly argued to be the mechanism by which elevated surface heat fluxes from orography produce a strong South Asian mon-

soon (e.g. Wu et al., 2007; Chen et al., 2014). However, moisture-convergence closures for convection are now rarely used in theories and numerical models of other tropical circulations (e.g. Arakawa, 2004). In a review of convectively coupled circulations, Emanuel et al. (1994) went so far as to call CISK “an influential and lengthy dead-end road in atmospheric science.” Theories of convective quasi-equilibrium (CQE) have taken its place. These theories posit that cumulus convection is a fast process that prevents large accumulations of convective available potential energy (CAPE), so that moist convection does not act as a heating that forces large-scale flow but instead maintains the vertical temperature structure of the troposphere near that of a moist adiabat. If convection does prevent large variations in CAPE, then tropospheric temperatures will covary with  $h_b$ , the moist static energy of air below the base of cumulus clouds.<sup>2</sup> In short,

$$\delta h_b \propto \delta T_u \quad (1)$$

where the  $b$  subscript denotes a property of air below cloud base, and  $u$  a property of the “upper” troposphere (i.e. the convecting layer above cloud base). The variations in  $h_b$  and  $T_u$  represented in (1) can occur in time or in space, as long as moist convection exists to couple the subcloud layer with the free troposphere.

Monsoon dynamics in a CQE framework were first explored in highly idealized models, and although almost none of these contained orography they nevertheless laid the foundation for new thinking about Tibet. Using a model of intermediate complexity with a CQE parameterization for convection, Chou et al. (2001) showed that advection of low- $h_b$  air from extratropical oceans into monsoon regions could suppress monsoon precipitation on the west side of continents and limit the

<sup>1</sup>Since monsoons and tropical cyclones can both be represented as idealized, warm-core axisymmetric vortices (e.g. Wirth and Dunkerton, 2006; Boos and Emanuel, 2008), one could imagine Tibet’s sensible heat fluxes producing the warm core in the “eye” of the monsoon vortex, which in turn causes radial (i.e. meridional) moisture convergence, precipitation, and amplified ascent in the “eyewall” just south of the plateau.

<sup>2</sup>The moist static energy  $h = c_p T + L_v q + gz$ , with  $c_p$  the specific heat of air at constant pressure,  $L_v$  the latent heat of vaporization,  $g$  the gravitational acceleration, and  $T$ ,  $q$ , and  $z$  representing temperature, specific humidity, and height, respectively. The equivalent potential temperature  $\theta_e$  is sometimes used in place of  $h$ ; the two have similar distributions and are for the present purpose interchangeable.

poleward extend of monsoons. This “ventilation” of warm and moist monsoon air by cold and dry extratropical air was shown to operate in the North American, South American, and Asian monsoons (e.g. Chou and Neelin, 2001, 2003; Neelin, 2007). However, the model used to demonstrate this did not have orography, so its relevance to Asia remained questionable. In a general circulation model (GCM) with idealized boundary conditions, Privé and Plumb (2007b) showed that thin vertical walls on the east and west coasts of a rectangular, off-equatorial continent could suppress ventilation, strengthening monsoon precipitation and allowing it to extend further poleward. They speculated that plateau orography could “have a very significant impact on the moist static energy distribution, by shielding India and Southeast Asia from inflow from the Asian midlatitudes.”

Even though this CQE literature laid the foundation for a new view of orography as an insulator that inhibits ventilation, the idea that Tibet acts as an elevated heat source persisted. This is not surprising, because even if one abandons the idea that sensible heat fluxes from the plateau drive the monsoon via CISK, free-tropospheric temperatures and  $h_b$  are known to equilibrate at values that increase with the elevation of the underlying surface. Molnar and Emanuel (1999) demonstrated this in idealized simulations of radiative-convective equilibrium over surfaces of different heights, so it would seem reasonable to assume that this effect of surface elevation could constitute a large forcing not represented in the idealized CQE studies discussed above. Furthermore, no estimates of the distribution of subcloud  $h_b$  over South Asia and Tibet were published until Boos and Emanuel (2009) conducted an observationally based analysis of South Asian monsoon onset in a CQE framework, and the upper-tropospheric temperature maximum was commonly assumed to lie directly over the Tibetan Plateau (e.g. see discussion in Privé and Plumb, 2007b).

### III. REEVALUATING THE ROLE OF TIBET

A year before Privé and Plumb speculated that Tibet might inhibit the penetration of cold mid-latitude air into the South Asian monsoon, Chakraborty et al. (2006) showed that Asian orography in a GCM with realistic boundary conditions did inhibit this ventilation. But there was a twist: Chakraborty et al. (2006) found that Indian monsoon onset was delayed more by removal of orography in southwestern Asia (including the western third of the Tibetan Plateau) than by removal of orography in southeastern Asia (including the remainder of the plateau). They showed via estimates of meridional temperature advection in their GCM that the orography “acts as a barrier for the cold winds from the upper-latitudes”. Although Chakraborty et al. (2006) did not refer to the previous literature on CQE monsoon dynamics, their work is essentially an application of the ventilation hypothesis of Chou and Neelin (2001) to the orography of Asia<sup>3</sup>.

A clearer assessment of the relative importance of plateau heating and orographic insulation was provided by Boos and Kuang (2010). Using reanalysis, radiosonde, and satellite data, they showed that peak  $h_b$  during boreal summer lies over the non-elevated Indo-Gangetic plain south of the Himalayas, and peak upper-tropospheric temperatures lie over this  $h_b$  maximum, as expected in a CQE state. These features are reproduced in the most recent reanalysis of the European Centre for Medium Range Weather Forecasts (ERA-Interim, Dee et al., 2011), as shown in Fig. 1. Furthermore, large horizontal gradients in  $h_b$  are coincident with orography, as one would expect if orography acts primarily as an insulator rather than a heat source. Horizontal gradients of  $h_b$  are weaker over Tibet than over the Hindu Kush range west of Tibet, suggesting that surface elevation may indeed enhance  $h_b$  but that this effect is not strong enough to make Tibet the thermal maximum. Boos and Kuang (2010) also conducted climate model integrations in

<sup>3</sup>It should be noted that Chakraborty et al. (2006) also argued for an absolute threshold in  $h_b$  over India, rather than the critical horizontal gradient of  $h_b$  shown to be relevant by Emanuel (1995)

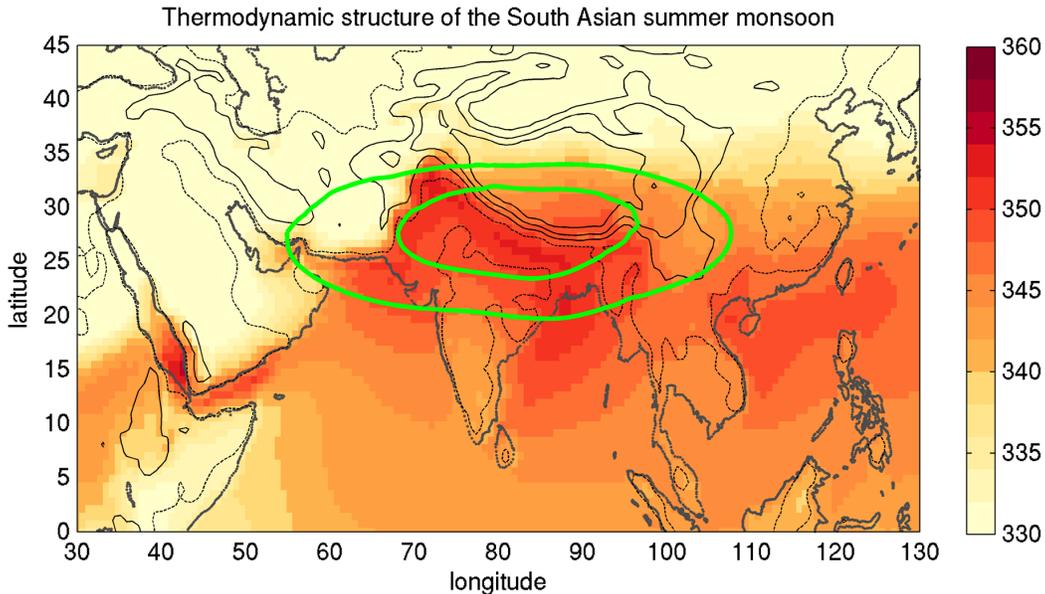
which the plateau was flattened while the comparatively thin orography south and west of the plateau was preserved. With only that thin orographic barrier, the model produced a monsoon of nearly the same strength and horizontal structure as with a full plateau. Monsoon strength was similarly perturbed little by setting the surface albedo of the plateau to unity, which eliminates the ability of the plateau to serve as a heat source. Removing the plateau or setting its albedo to unity did reduce precipitation along the Himalayas, but this is a highly local response distinct from the large reduction in cross-equatorial monsoon flow that occurred when all orography was removed.

Although the hypothesis that orography acts primarily as an insulator has met with some objections, proponents of the “elevated heating” idea no longer claim that the horizontally extensive Tibetan Plateau is the dominant heat source. Instead, Wu et al. (2007) argued that sensible heat fluxes from the plateau’s sloping boundaries (e.g. the Himalayas) constitute the dominant forcing for the South Asian monsoon, with these heat fluxes amplified through a CISK-like feedback. Wu et al. (2012) showed that the South Asian monsoon weakened in a climate model when surface sensible heat fluxes were eliminated from all Asian orography, and that precipitation along the Himalayas greatly diminished when sensible heat fluxes from the Himalayas were eliminated. Consistent with the shift away from the idea that elevated plateau heating drives the entire South Asian monsoon, Wu et al. (2012) concluded that a “striking feature of the present experiments is the insensitivity of the southern part of the SASM [South Asian Summer Monsoon] to IPTP [Iranian Plateau and Tibetan Plateau] forcing”. So any argument in the literature is between proponents of the idea that the northern “branch” of the South Asian monsoon is driven by surface heat fluxes from mountain slopes amplified by a CISK-like feedback (e.g. Wu et al., 2012) and proponents of the idea that the entire South Asian monsoon is greatly amplified by the suppression of ventilation by orography (e.g. Chakraborty et al., 2006;

Boos and Kuang, 2010). There may actually be little disagreement since Boos and Kuang (2010) did find that plateau heating enhanced precipitation along the Himalayas; they simply classified this as a relatively minor and local response to plateau heating distinct from the nonlocal response of the interhemispheric, large-scale South Asian monsoon to orographic insulation.

Any monsoon, even in regions without orography, is fundamentally caused by horizontal gradients in the energy supplied to the atmosphere by external sources such as radiation and surface heat fluxes (e.g. Neelin and Held, 1987). Suppressing land surface heat fluxes in the summer hemisphere of a climate model is thus expected to reduce monsoon strength whether or not the land surface is elevated, and the central question is whether the monsoon is more sensitive to heat fluxes from elevated or nonelevated surfaces. Boos and Kuang (2013) showed that South Asian monsoon strength in a climate model was more sensitive to surface heat fluxes emitted by nonelevated parts of northern India than to heat fluxes from Himalayan slopes. They argued that this is expected, because the maxima in  $h_b$  and upper-tropospheric temperature lie over the non-elevated parts of northern India, and a thermally direct circulation will respond most strongly to heating in coincident with its thermal maximum.

Other findings support the idea that Tibet’s thermal forcing is not especially important for the monsoon. Years of strong South Asian precipitation are accompanied by an enhanced land-sea contrast in  $h_b$ , with the largest  $h_b$  increase lying over the Indo-Gangetic plain and little signal seen over Tibet (Hurley and Boos, 2013). Rajagopalan and Molnar (2013) found that  $h_b$  over Tibet does covary with Indian rainfall, but only during the very early and late parts of the monsoon; they estimated that at most 20% of total summer rainfall might be explained by plateau heating. Finally, Boos and Hurley (2012) showed that the latest ensemble of global climate models has a negative bias in  $h_b$  over northern India that seems to be asso-



**Figure 1:** ERA-Interim June-August climatological mean (1979-2012) thermodynamic structure of the South Asian monsoon. Shading shows moist static energy about 40 hPa above the surface, represented in K by dividing by the specific heat of dry air at constant pressure. Green contours show temperature averaged 200-400 hPa (the 245.5 and 246.5 K isotherms). Dotted black line is the 300 m topographic contour and solid black lines are topographic contours starting at 1.5 km with a 1.5 km interval.

ciated with the orographic smoothing that is inevitable at the resolutions of those models. This underrepresentation of peak topographic heights seemed particularly important in the Hindu Kush just west of Tibet, consistent with Chakraborty et al. (2006) and with the importance of the orographic insulation mechanism (the lowest  $h_b$  in South Asia lies just west of the Hindu Kush, e.g. Fig. 1).

#### IV. AN UPDATED VIEW OF “VENTILATION”

A more comprehensive examination orography’s role was conducted by Ma et al. (2014), who applied surface height and surface heat flux perturbations to a global model having substantially finer resolution — 40 km in the horizontal — than used in any of the studies discussed above. Ma et al. (2014) confirmed that removal of the Tibetan Plateau had little effect on South Asian monsoon strength pro-

vided the Himalayas and adjacent mountain ranges were preserved. They confirmed that monsoon strength was most sensitive to heat fluxes from non-elevated surfaces just south of the Himalayas in the location of the  $h_b$  maximum, with heat fluxes from Himalayan slopes being less important for monsoon strength. But their most novel finding was that the proportionality constant implicit in the CQE relation (1) was larger when orography was flattened than when surface heat fluxes were eliminated. This seemed to occur because removing orography allowed dry extratropical air to intrude into the monsoonal free-troposphere where it was entrained into convective updrafts and increased the  $h_b$  needed to maintain a given amount of CAPE. This is an important modification of the CQE frameworks that have been applied to monsoon dynamics (e.g. Emanuel, 1995; Chou and Neelin, 2001; Privé and Plumb, 2007a; Boos and Emanuel, 2009). This modification, which merits further examination

and quantification, is consistent with previous work that shows moist convection is sensitive to free-tropospheric humidity in ways that cannot be captured by the form of CQE that assumes CAPE is a function only of  $h_b$  and free-tropospheric temperature (e.g. Derbyshire et al., 2004; Holloway and Neelin, 2009).

More generally, the concept of monsoon “ventilation” needs to be updated to emphasize the deleterious effect of dry desert air on monsoon strength. The original idea of ventilation posited that cold and dry air from extratropical oceans could inhibit the strength and poleward extent of monsoons (e.g. Chou and Neelin, 2001; Neelin, 2007; Privé and Plumb, 2007b; Boos and Kuang, 2010). However, the region with lowest  $h_b$  adjacent to the monsoon thermal maximum is the desert region of western Pakistan, Afghanistan, and Iran. Thus, orography prevents the *hot* and dry air of continental deserts from penetrating the monsoon thermal maximum, rather than the *cold* and dry air of extratropical oceans. This grants the greatest importance to orography west of Tibet (e.g. the Hindu Kush), consistent with the perturbed orography model experiments of Chakraborty et al. (2006) and Boos and Hurley (2012), although the former did not seem to recognize the importance of dry desert air intrusions. Perhaps if the Hindu Kush and Iranian Plateau ever attained elevations higher than those at present, this may have produced an especially intense South Asian monsoon.

## V. CONCLUDING REMARKS

Since the 1950s, the horizontally extensive surface of the Tibetan Plateau was thought to drive the South Asian summer monsoon. Although several competing hypotheses have been published in the past decade to explain the influence of orography on this monsoon, all agree that the monsoon instead owes its great strength to the comparatively narrow Himalayas, Hindu Kush, and adjacent mountain ranges. There is widespread agreement that Tibet is not the primary thermal forcing, as evidenced by numerical climate mod-

els (Chakraborty et al., 2006; Boos and Kuang, 2010; Wu et al., 2012; Ma et al., 2014), the observed thermodynamic structure of the mean summer monsoon (Boos and Emanuel, 2009; Boos and Kuang, 2010), and the spatial structure of interannual variations in monsoon rainfall and subcloud  $h_b$  (Hurley and Boos, 2013; Rajagopalan and Molnar, 2013).

Orography greatly strengthens the inter-hemispheric South Asian monsoon circulation by preventing ventilation of the convective maximum by dry extratropical air. This conclusion is the fairly natural extension of a series of studies on CQE monsoon dynamics (Chou and Neelin, 2001, 2003; Privé and Plumb, 2007b; Boos and Emanuel, 2009). Heat fluxes from the elevated slopes of the Himalayas contribute to local precipitation along those mountains, but this is a local effect limited to the northernmost part of the South Asian monsoon (Boos and Kuang, 2010; Wu et al., 2012). Theoretical progress on convectively coupled tropical dynamics shows that a misplaced emphasis on surface sensible heat fluxes formed the cornerstone of the “elevated plateau heating” idea and its requisite CISK feedback. Both sensible and latent heat fluxes are equally important to monsoon strength in a CQE framework, and the thermally direct monsoon circulation must export the energy that is fluxed into the atmospheric column by the sum of these surface enthalpy fluxes and the convergence of radiative fluxes.

Open questions on the role of orography in monsoons still abound. For example, can simple theoretical models of CQE monsoon dynamics be modified to incorporate the effects of free-tropospheric moisture? Since temperatures do increase with the elevation of the underlying surface in the theoretical state of radiative-convective equilibrium (e.g. Molnar and Emanuel, 1999), why doesn’t the thermal state of the Tibetan Plateau play a stronger role in the South Asian monsoon? What role is played by the north-south oriented mountains on the west coasts of southern India and Myanmar (e.g. do they simply organize precipitation or do they actually enhance the domain-mean

monsoon precipitation)? How does elevated topography alter the gross moist stability (e.g. Neelin and Held, 1987) of the South Asian monsoon? Modern theories of convectively coupled circulations are only beginning to be applied to domains with orography, so the coming decade could be a time of great progress in understanding the South Asian monsoon.

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