Monsoons as eddy-mediated regime transitions of the tropical overturning circulation

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Monsoons are generally viewed as planetary-scale sea-breeze circulations, caused by contrasts in the thermal properties between oceans and land surfaces that lead to thermal contrasts upon radiative heating[1,2]. But the radiative heating evolves gradually with the seasons, whereas the onset of monsoon precipitation, and the associated circulation changes such as reversal of surface winds, occur rapidly[3,4]. Here we use reanalysis data to show that the onset of the Asian monsoon marks a transition between two circulation regimes that are distinct in the degree to which eddy momentum fluxes control the strength of the tropical overturning circulation. Rapid transitions of the circulation between the two regimes can occur as a result of feedbacks between large-scale extratropical eddies and the tropical circulation[5]. Using simulations with an aquaplanet general circulation model, we demonstrate that rapid, eddy-mediated monsoon transitions occur even in the absence of surface inhomogeneities, provided the planet surface has sufficiently low thermal inertia. On the basis of these results, we propose a view of monsoons in which feedbacks between large-scale extratropical eddies and the tropical circulation are essential for the development of monsoons, whereas surface inhomogeneities such as land-sea contrasts are not.

Although monsoons are prominent features of the summertime circulation of the Earth's atmosphere, the mechanisms responsible for their occurrence and their rapid onset remain poorly understood. Numerous hypotheses have been proposed, but their relevance to observed monsoons is unclear. For example, transitions of axisymmetric circulations from linear to nonlinear regimes occur when subtropical heating exceeds a threshold, provided meridional temperature gradients at the equator vanish[6,7]; however, their relevance to monsoons is unclear because meridional temperature gradients at the equator are non-zero before monsoon onset (see refs 5,8,9 for a discussion of the literature).

Here, we focus on the most extensive and striking of Earth's monsoons, the Asian Monsoon. At the beginning of the warm season, the large-scale circulation in the Asian monsoon sector changes rapidly, resulting in poleward movement of the intertropical convergence zone[10] (ITCZ) and onset of intense precipitation in the subtropics; a reverse albeit less rapid transition occurs at the end of the warm season (Fig. 1a). The meridional overturning circulation zonally averaged over the Asian monsoon sector rearranges itself at monsoon onset from an equinox pattern, with two cells almost symmetric about the equator (Fig. 2a), to a monsoon pattern dominated by a single cross-equatorial cell, with ascent in the summer hemisphere subtropics and descent in the winter hemisphere (Fig. 2b). Strong upper-level easterlies develop in the tropics (Fig. 2d), and, consistent with gradient-wind balance[7], the near-surface temperature and moist static energy (MSE) gradients reverse at monsoon onset[11] (Fig. 2f). Equatorward of the near-surface MSE maximum at $\sim 26°$ N, precipitation and upward motion attain their largest values (Fig. 2b,f). Consistent with the Coriolis force on the meridional near-surface flow approximately balancing the drag on the zonal near-surface wind, the zonal near-surface wind in the northern hemisphere subtropics rapidly reverses at monsoon onset when the cross-equatorial near-surface flow reaches the subtropics (Fig. 3).

It has been argued that tropical meridional overturning circulations (global or local Hadley cells) are constrained by conservation of absolute angular momentum in their upper branches[6,8,12,13]. However, meridional momentum fluxes associated with large-scale eddies can lead to deviations from angular momentum conservation. If eddy momentum fluxes are strong, streamlines of an overturning circulation cross angular momentum contours; if an overturning circulation conserves angular momentum, streamlines and angular momentum contours coincide. In the southern cell in the Asian monsoon sector around equinox, eddy momentum fluxes of extratropical origin extend into the upper branch, angular momentum contours are only slightly distorted away from the vertical and streamlines cross angular momentum contours throughout the cell (Fig. 2a). When the southern cell has become the cross-equatorial cell during the monsoon, eddy momentum fluxes of extratropical origin are confined to the descending branch, angular momentum contours are more strongly distorted away from the vertical and streamlines in the upper branch are more closely aligned with angular momentum contours (Fig. 2b). More quantitatively, the local Rossby number $\mathrm{Ro} = -\bar{\zeta}/f$ (where $\bar{\zeta}$ is the mean relative vorticity and f is the planetary vorticity) in the upper branch of an overturning circulation is a non-dimensional measure of the proximity of the circulation to the angular-momentum-conserving limit because angular momentum conservation requires that the absolute vorticity $f + \bar{\zeta} = f(1 - \mathrm{Ro})$ vanishes in regions of divergent horizontal flow[8,14]. If $\mathrm{Ro} \to 0$, the circulation strength

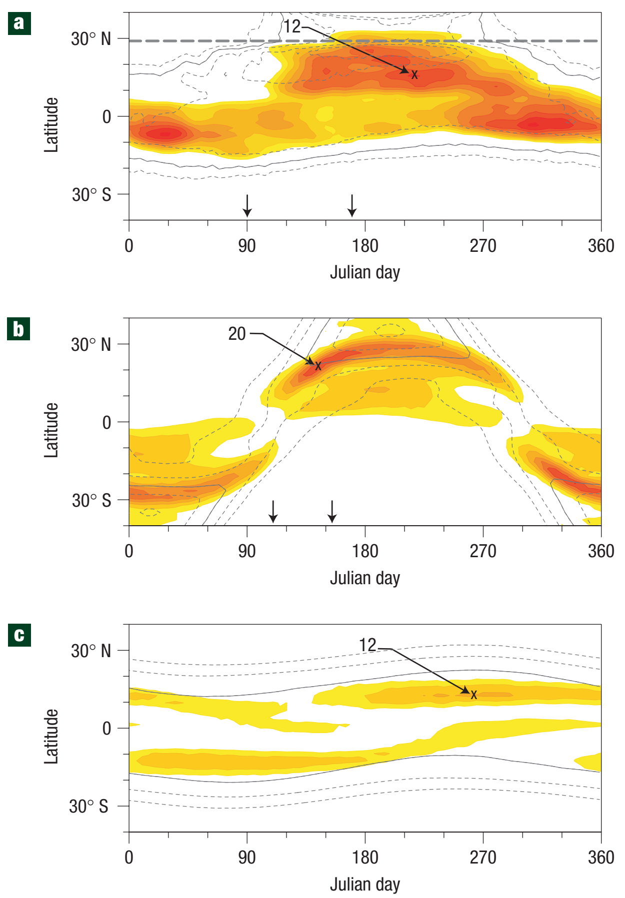

Figure 1 Rapid shifts of precipitation zones. a, Seasonal cycle of zonal- and pentad-mean precipitation (colour contours, mm day^{-1}) and sea-level air temperature (SAT; grey contours) from observations in the Asian monsoon sector. **b**,**c**, The same from aquaplanet simulations with ocean mixed-layer thickness of 1 m (**b**) and 100 m (**c**). SAT is evaluated at 1,000 hPa in the observations and at the lowest model level in the simulations. The contour interval for precipitation is 1 mm day^{-1} in **a** and 2 mm day^{-1} in **b**,**c**, with maxima identified by crosses. For SAT, the contour interval is 2 °C, with the solid grey line marking the 24 °C isoline. Precipitation rates in the simulations can exceed observed precipitation rates because the lower boundary in the simulations is entirely water-covered. The thick dashed line in **a** shows the latitude at which the zonal-mean topography in the Asian monsoon sector rises above 3 km. Arrows at the time axes in **a**,**b** indicate the centres of the 20-day periods for which circulations are shown in Figs 2 and 4. Observed precipitation is from Global Precipitation Climatology Project[29] data for the years 1999–2005. In this and subsequent figures, zonal means for the Asian monsoon sector are averages between 70° and 100° E. Results are robust to changes in the averaging sector and do not change substantially if southeast Asia is included in the averages.

is controlled by eddy momentum fluxes and can respond to variations in thermal driving only indirectly through changes in eddy momentum fluxes[15]. If $Ro \rightarrow 1$, the circulation approaches the angular-momentum-conserving limit, and its strength responds directly to variations in thermal driving[12]. Local Rossby numbers in the upper troposphere in the Asian monsoon sector change at monsoon onset, from $Ro \lesssim 0.4$ in the upper branch near the centre of the southern cell pre-onset to $Ro \gtrsim 0.7$ in the upper branch near the centre of the cross-equatorial cell post-onset. Therefore, at monsoon onset, the southern cell transitions from an equinox regime, in which its strength is primarily controlled by eddy momentum fluxes, to a monsoon regime, in which its strength is more directly controlled by the thermal driving. A reverse transition occurs at the end of the monsoon.

We have previously shown that when an overturning circulation undergoes such a regime transition, two dynamical feedback mechanisms act, rendering the transition and accompanying circulation changes rapid even in the absence of surface inhomogeneities and an active hydrological cycle[5]. First, upper-level easterlies and, by gradient-wind balance, poleward temperature and MSE gradients develop in the tropics in early summer as cross-equatorial flow develops (Fig. 2d,f). Because the local zonal wind determines the propagation characteristics of the energy-containing extratropical eddies[16], upper-level easterlies shield the cross-equatorial cell from the eddies, which are primarily confined to regions of westerlies (Fig. 2d). This allows the overturning cell to approach the angular-momentum-conserving limit more closely, leading to strengthening of the cell and strengthening and extension into the winter hemisphere of the upper-level easterlies[5]. Second, advection of cold (low MSE) air by the lower branch of the cross-equatorial cell pushes the MSE maximum poleward (Fig. 2b,f), leading to poleward movement of the ascending branch because the main ascent region is near the MSE maximum[9]. The poleward movement of the ascending branch implies strengthening of the cell and strengthening and extension into the winter hemisphere of the upper-level easterlies[5,13]. Together these mechanisms, discussed in ref. 5, render the regime transitions rapid compared with the timescale of variations in radiative heating.

Using an idealized general circulation model (GCM) with an active hydrological cycle and with a homogeneous lower boundary, we demonstrate that these feedback mechanisms can mediate rapid transitions of an overturning circulation with circulation and precipitation changes resembling those in the Asian monsoon. We simulate seasonal cycles by prescribing variations of mean daily insolation at the top of the atmosphere in an idealized GCM[17] in which the lower boundary is a mixed-layer (slab) ocean of constant depth, with a prescribed time-independent meridional heat transport estimated to match the observed annual-mean ocean heat transport in low latitudes[18,19]. We show results from two simulations, one with a thin (1 m) and one with a thick (100 m) mixed layer, respectively implying low and high surface thermal inertia.

Like the overturning circulation in the Asian monsoon sector, the overturning circulation in the simulation with a thin mixed layer undergoes a rapid transition from an equinox to a monsoon regime. In the equinox regime, upper-level westerlies and strong eddy momentum flux divergence extend into both circulation cells (here, Hadley cells because the simulated climate is statistically axisymmetric), leading to deviations from angular momentum conservation in the upper branches (Fig. 4a,c). Local Rossby numbers satisfy $Ro \lesssim 0.3$–0.4 in the upper branches and show that the circulation strength is primarily controlled by eddy momentum fluxes. In the monsoon regime, the streamfunction maximum is located near the equator, in a region of upper-level easterlies, where it is shielded from extratropical eddies and the eddy momentum flux divergence is small (Fig. 4b,d). Rossby numbers are poorly defined in the upper branch of the cross-equatorial cell close to its centre near the equator, but that the flow in the ascending and upper branches is closer to angular-momentum-conserving is manifest from the near-coincidence of angular momentum contours and streamlines there. Similar to what is seen during the Asian monsoon, westerly winds prevail near the surface in the summer subtropics. Strong easterlies prevail at upper levels throughout the tropics (Fig. 4d); by gradient-wind balance, the near-surface temperature and MSE gradients are reversed (Fig. 4f),

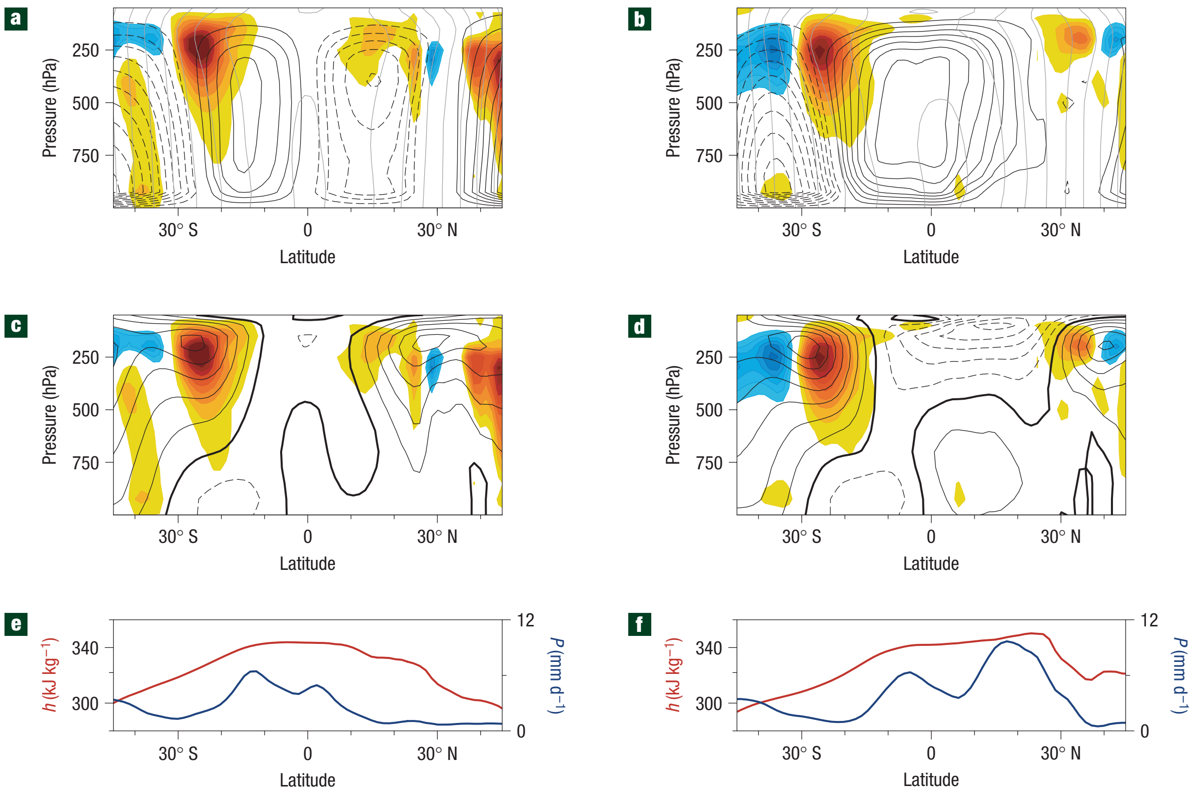

Figure 2 Observed monsoon onset over Asia. Zonal- and temporal-mean circulation in the Asian monsoon sector at two 20-day periods before (left panels, Julian Day 81–100) and after (right panels, Julian Day 161–180) monsoon onset. **a**,**b**, Streamfunction of meridional overturning circulation (black contours, contour interval 50×10^9 kg s^{-1}, with solid contours for anticlockwise rotation and dashed contours for clockwise rotation), angular momentum per unit mass (grey contours, contour interval $\Omega a^2/15$ with Earth's rotation rate Ω and radius a) and transient eddy momentum flux divergence div$([\overline{u'\mathbf{v}'}]\cos\phi)$, with horizontal velocity vector $\mathbf{v} = (u, v)$ (colour contours, contour interval 0.6×10^{-5} m s^{-2} in **a** and 1.2×10^{-5} m s^{-2} in **b**, with red tones for positive and blue tones for negative values). Here, $\overline{(\cdot)}$ denotes a temporal mean over the 20-day period and over all years of data, primes denote deviations from this mean and $[\cdot]$ denotes a zonal mean over the monsoon sector. **c**,**d**, Zonal wind (black contours, contour interval 6 m s^{-1}) and eddy momentum flux divergence (colour contours) as in **a**,**b**. **e**,**f**, Precipitation P (blue) and near-surface (850 hPa) MSE h (red). Except for precipitation, all quantities are obtained from the ERA-40 reanalysis[30] and are averaged over the years 1981–2000. In the latitude zones of the tropical overturning circulation, the horizontal eddy momentum flux divergence shown in the figure is the dominant term balancing the Coriolis force on the mean meridional flow and the mean meridional momentum advection in the zonal momentum budget; other terms, such as the stationary eddy momentum flux divergence and the zonal geopotential gradient across the monsoon sector, are smaller.

primarily as a result of MSE advection (which dominates the MSE budget in the boundary layer). The transition between the equinox and monsoon regimes in the simulation occurs rapidly compared with variations in radiative heating. This is manifest in the rapid intensification and relocation of the ITCZ into the summer subtropics (Fig. 1b) and the rapid changes in subtropical near-surface winds (Fig. 3). Overall, the transition in the simulation resembles the onset of the Asian monsoon. A reverse transition occurs at the end of the warm season; this transition occurs more rapidly than in the Asian monsoon, suggesting that processes not captured by our idealized GCM modulate the Asian monsoon retreat.

For the feedback mechanisms discussed above to be able to mediate rapid transitions of the overturning circulation, the surface thermal inertia must be sufficiently low for the near-surface MSE to be able to adjust rapidly. Only then can circulation changes occur rapidly because the near-surface MSE controls the location of the ascending branch of the cross-equatorial cell (and hence of the main precipitation zone) and, by gradient-wind balance, the upper-level zonal wind, both of which must be able to adjust

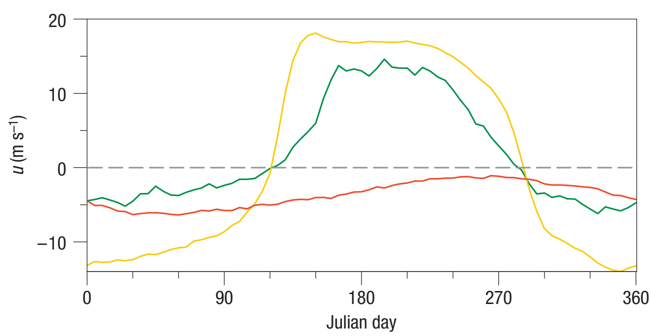

Figure 3 Rapid changes in near-surface zonal wind at 15° N. Seasonal cycle of zonal- and pentad-mean near-surface zonal wind at 15° N from observations in the Asian monsoon sector (green) and from aquaplanet simulations with ocean mixed-layer thickness 1 m (yellow) and 100 m (red). The near-surface zonal wind is evaluated at 850 hPa in the observations and at $\sigma = 0.85$ in the simulations, where $\sigma = p/p_s$ is pressure p normalized by surface pressure p_s.

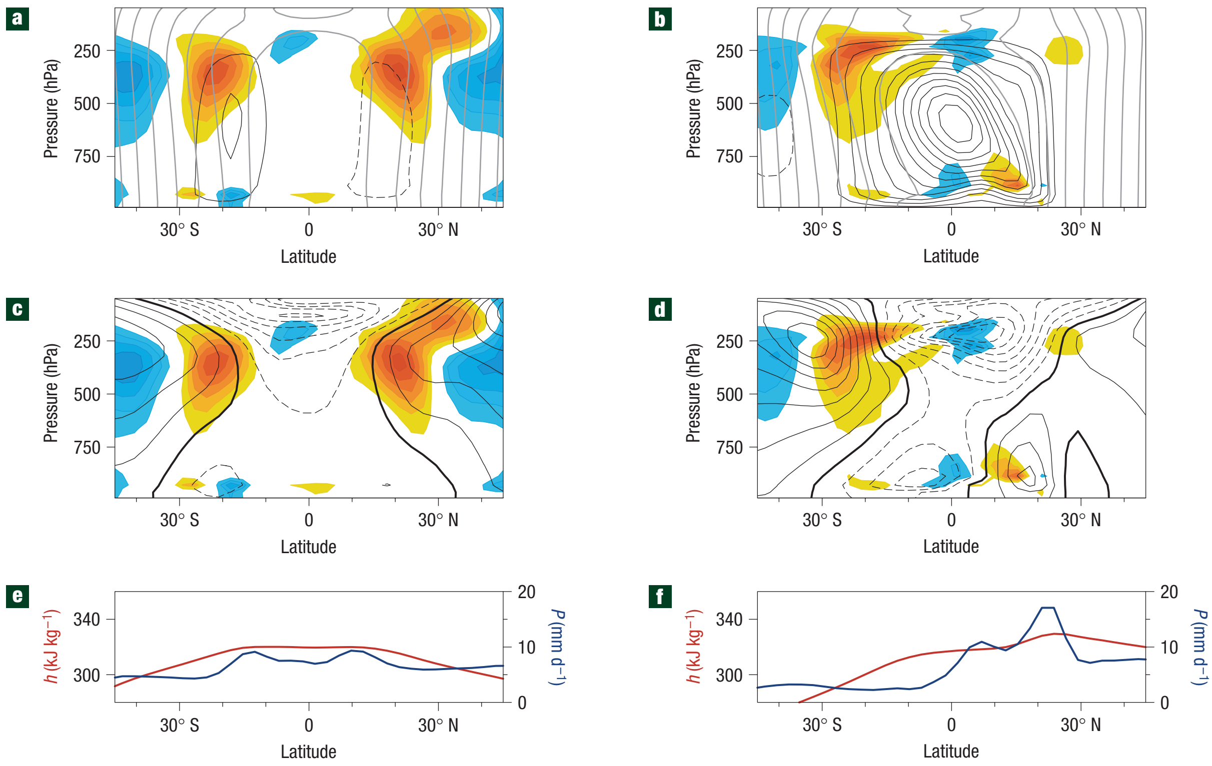

Figure 4 Simulated monsoon onset. Zonal- and temporal-mean circulation at two 20-day periods before (left panels, Julian Day 101–120) and after (right panels, Julian Day 145–165) monsoon onset in a simulation with a 1-m ocean mixed layer. Quantities shown and contour intervals are as in Fig. 2, except for the contour interval for eddy momentum flux divergence (3×10^{-6} m s^{-2} in **a**,**c** and 9×10^{-6} m s^{-2} in **b**,**d**). Mean fields are zonal and temporal means over the 20-day period and over the last 20 years of a 25-year simulation; (transient) eddy fields are deviations from this mean. The vertical coordinate of the GCM is σ, and eddy and mean fields in the figure are σ-coordinate analogues[15] of the pressure-coordinate fields in Fig. 2. The vertical σ-coordinate is expressed as an equivalent pressure by multiplication of σ with the global-mean surface pressure.

rapidly for the feedbacks to act rapidly. Indeed, in the simulation with a thick ocean mixed layer, precipitation is concentrated in a tropical double ITCZ (Fig. 1c), the intensity and location of which vary gradually; subtropical near-surface zonal winds do not exhibit rapid changes in strength and direction (Fig. 3).

That simulations with an aquaplanet GCM with a surface of sufficiently low thermal inertia exhibit rapid transitions of the tropical circulation, with all defining characteristics[1,10] of monsoon transitions, shows that monsoons can occur even in the absence of the surface inhomogeneities that are traditionally deemed necessary[1,2]. Subtropical continents are still needed for monsoons, but in the view proposed here, their primary role is not to create thermal contrasts through land–sea contrasts in surface properties but rather to provide a surface of sufficiently low thermal inertia for the outlined mechanisms to be able to act on intraseasonal timescales. Topography[20], land–sea contrasts[1,2] and other surface inhomogeneities[2,21,22] modify these mechanisms and account for the complex morphology of the Earth's monsoons, including the onset/end asymmetry of the Asian monsoon; however, monsoons can occur without them, for instance, over a homogeneous swamp surface. Consistent with the view of monsoons proposed here, the observed changes in precipitation (Fig. 1a) and zonal wind (Fig. 3) in the Asian monsoon sector seem to be a superposition of the corresponding changes in the simulations with a thin and a thick mixed layer, the first more closely capturing the dynamics in land-covered parts and the second in ocean-covered parts. Because the near-surface monsoon flow is directed towards the summer pole across the equator and turns eastward further poleward, where the near-surface meridional momentum balance becomes approximately geostrophic[5], monsoon precipitation requires moisture supply equatorward and westward of a surface of low thermal inertia. This seems to account for the presence of monsoon precipitation over western but not central Africa.

Aquaplanet monsoon transitions have been obtained in previous simulation studies. In those studies, however, sea surface temperatures were prescribed, preventing the mechanisms we described from acting, and either inhomogeneities in lower boundary conditions were imposed in lieu of land masses[23], or wind-induced surface heat exchange[24,25] (WISHE) was posited as responsible for the transitions[26,27]. In simulations in which we suppressed WISHE by prescribing a time-invariant near-surface wind speed in the evaporation parameterization, the monsoon transitions do not differ substantially from the ones reported here, showing that WISHE is not necessary for monsoons in our GCM. In addition, waves and instabilities excited at monsoon onset by the rapid rearrangement of the tropical circulation may accompany but do not necessarily cause monsoon transitions[22,28].

On the basis of these results, we propose a view of monsoons as eddy-mediated transitions in the tropical overturning circulation between regimes that are distinct in the degree to which eddy momentum fluxes control the strength of the circulation. This view accounts for the changes in atmospheric circulation and precipitation at the onset and end of monsoons as well as for the rapidity of the transitions. De-emphasizing the role of surface inhomogeneities, it posits interactions between extratropical eddies and the tropical meridional overturning circulation as essential for monsoons.

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