On the Role of the African Topography in the South Asian Monsoon

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ABSTRACT

The Somali jet, a strong low-level cross-equatorial flow concentrated in a narrow longitudinal band near the coast of Somalia, is a key feature of the South Asian monsoon (SAM) circulation. Previous work has emphasized the role of the East African Highlands in strengthening and concentrating the jet. However, the fundamental dynamics of the jet remains debated, as does its relation to the SAM precipitation.

In this study, numerical experiments with modified topography over Africa are conducted with the GFDL AM2.1 general circulation model (GCM), to examine the influence of topography on the Somali jet and the SAM precipitation. We find that when the African topography is removed, the SAM precipitation moderately increases in spite of a weakening of the cross-equatorial Somali jet. The counter-intuitive precipitation increase is related to lower-level cyclonic wind anomalies, and associated meridional moisture convergence, which develop over the Indian Ocean in the absence of the African topography. Potential Vorticity (PV) budget analyses along particle trajectories show that this cyclonic anomaly primarily arises because, in the absence of the blocking effect by the African topography and with weaker cross-equatorial flow, air particles originate from higher latitude with larger background planetary vorticity and thus larger PV.
1. Introduction

The South Asian Monsoon (SAM) is the southern part of the Asian monsoon system, the largest scale monsoon in the Earth’s atmosphere. The monsoon brings rain that is concentrated in the summer to densely populated and rapidly growing regions, such as India and neighboring countries. Traditionally, the SAM has been interpreted as a large-scale sea breeze circulation driven by contrast in thermal properties between the Indian subcontinent and the surrounding ocean. However, recent theoretical advances suggest that the SAM should be more generally viewed as the regional manifestation of the seasonal migration of the Intertropical Convergence Zone (ITCZ) into the summer subtropical continents (e.g., Gadgil 2003). The associated thermally direct circulation is characterized by ascending motion in the summer hemisphere subtropics, opposite cross-equatorial flows at lower and upper levels, and descending motion in the winter hemisphere (Nie et al. 2010), giving rise to a reversed meridional temperature gradient and, by thermal wind balance, an easterly vertical wind shear in the summer hemisphere (e.g., Li and Yanai 1996). At lower levels, westerly winds dominate in the summer hemisphere over the Indian Ocean, consistent with the Coriolis force on the cross-equatorial flow approximately balancing the drag in near-surface zonal winds (e.g., Bordini and Schneider 2008), while easterlies develop at upper levels. The strong precipitation, the displacement into the northern hemisphere (NH) of the upper-tropospheric temperature maximum, and reversal of lower-level winds from easterly to westerly over the Indian Ocean in the NH are all distinctive features of the SAM in the boreal summer.

Upstream of the lower-level westerlies, a strong cross-equatorial jet develops near the east coast of Africa. This jet, referred to in the literature as the Somali jet, flows along the East African Highlands (EAH), having a core located at about 1.5 km above sea level, equatorial mean wind speed of around 25 m s$^{-1}$, and maximum wind speed as large as 50 m s$^{-1}$ (Findlater 1969). The
Somali jet is estimated to contribute up to half of the mass flux crossing the equator during the Asian summer monsoon season. After crossing the equator and turning eastward in the Arabian Sea, the jet brings into the Indian subcontinent moisture from the warm ocean, with around 60 – 80% of the moisture estimated to originate from the Southern Hemisphere (SH) (Hoskins and Rodwell 1995).

The Somali jet results from cross-equatorial flow developing in response to the ITCZ displacement in the NH subtropics, and its dynamics has been described as analogous to those of western boundary currents in the ocean (e.g., Anderson 1976). The EAH have been argued to be essential for the spatial concentration and strength of the cross-equatorial flow. Krishnamurti et al. (1976) used a one-level primitive equation model to show that the East African and Madagascar mountains, the land-sea contrast, and the beta effect are all necessary to simulate a Somali jet similar to what is seen in observations. Subsequent studies have explored the response of linear models with prescribed diabatic heating and have argued that a western boundary (provided by the EAH) is necessary to develop a concentrated cross-equatorial flow (e.g., Paegle and Geisler 1986; Sashegyi and Geisler 1987). Rodwell and Hoskins (1995), hereafter RH95, extended these results to a non-linear, hydrostatic, primitive equation model with linear drag in the lowest two levels and specified orography and diabatic heating. Their analysis shows how the combination of high terrain over East Africa and greater friction there acts as a positive tendency to potential vorticity (PV) that partially cancels the negative PV of air crossing the equator from the SH and allows the flow to concentrate in a jet and remain in the NH, rather than curving back southward and returning into the SH.

Interest in the fundamental dynamics of the Somali jet is motivated by its possible impact on the SAM precipitation through the associated moisture transport. Some early observational studies do support a positive correlation between the strength of the Somali jet and the rainfall intensity
over western India (e.g., Findlater 1969; Halpern and Woiceshyn 2001). However, no comprehensive observational study has provided further support to the existence of such robust correlation on scales from intraseasonal to interannual using recent higher resolution data. The only multi-year study based on reanalysis (Boos and Emanuel 2009) indicates that the rapid onset of the SAM based on the square root of kinetic energy over the Arabian Sea is not associated with a rapid strengthening of the Somali jet. This suggests that the relationship between the lower-level flow near the SAM region and the monsoonal precipitation might be more subtle than generally thought. This is confirmed by recent modeling studies, which show that the removal of the African topography in fact results in an increase rather than a decrease of the monsoonal precipitation over India, despite a weakening of the Somali jet (Chakraborty et al. 2002, 2006, 2009; Slingo et al. 2005).

This discussion highlights how important questions on the impact of the African orography over the SAM remain outstanding: 1) How does topography over Africa affect the strength and spatial structure of the Somali jet? 2) What is the relationship between the cross-equatorial flow and its downstream westerly extension over the Arabian Sea? 3) How are topographically induced changes in lower-level meridional and zonal flow related to the SAM precipitation? In this paper, we will address these questions by performing simulations with a comprehensive general circulation model (GCM) with modified topography over Africa and the Arabian peninsula. The GCM experiments are described in Section 2. In Section 3, we explore how the Somali jet and the precipitation over India respond to the removal of the African topography. The dynamics of these changes is explored more in depth and linked to changes in the PV and the larger-scale circulation over the monsoon region in Section 4. In Section 5, we present results from an additional simulation, in which we remove both the African and Arabian topography, to understand how the absence
of an extended topographical wall from Africa into Arabia might affect the monsoon. Conclusions follow in Section 6.

2. Methods

The simulations in this study are performed with the Geophysical Fluid Dynamics Lab (GFDL) Atmospheric Model, version 2.1 (AM2.1, Anderson et al. 2004). AM2.1 uses a finite-volume dynamical core with horizontal resolution of 2.5 degrees in longitude and 2.0 degrees in latitude and 24 vertical levels. Climatologically fixed sea surface temperature (SST) derived from 2 degrees x 2 degrees 49 years (1950 to 1998) monthly mean of Reynolds reconstructed historical SST analysis (Smith et al. 1996) are used as the lower boundary condition. The convection scheme is the relaxed Arakawa-Schubert scheme.

In this study, we primarily discuss two simulations: A control (CTL) simulation where full global topography is retained (Fig. 1a) and an experiment simulation in which topography over Africa is removed (NoAf). In the NoAf experiment, topography is removed between 20°W – 35°E, 0°N – 35°N and between 10°E – 50°E, 40°S – 15°N. The topographic height of the grid points right outside the edge of these boxes is halved to allow for a smoother transition, as shown in Fig. 1b. In Section 5, we also briefly discuss an additional experiment, NoAfArab, in which together with topography over Africa we also remove the Arabian topography. More precisely, in the NoAfArab experiment, topography is removed between 20°W – 40°E, 0°N – 35°N; 10°E – 50°E, 40°S – 15°N; 40°E – 47°E, 15°N – 30°N; and 47°E – 55°E, 15°N – 25°N (Fig. 1c).

In all these experiments, the orographic gravity wave drag is modified accordingly to modified topography.

The initial conditions for all three experiments are derived from a one-year simulation with standard topography. After the topography height is changed following the one-year simulation,
the experiments are integrated for 19 years, and the analyses discussed below are based on the last
ten simulated years.

Large-scale budgets, such as the moisture and PV budgets, are analyzed to shed light into mech-
anisms that are implicated in the precipitation and circulation response to the topography. We also
perform trajectory analyses, to explore how topography, possibly through blocking, impacts the
trajectories of air parcels reaching the Indian region, and to more carefully analyze the PV budget
from a material perspective. Three-hour wind field data in pressure coordinates are used to com-
pute backward and forward trajectories. The integration time step is three hours as the data output.
For each integration, we use the wind fields at the time of calculation, so that the wind fields
used in the integration are updated at every calculated time step. Once the trajectories have been
computed, other variables, including the different terms in the PV analysis, as described in detail
in Section 4, are interpolated along the paths. Please note that trajectories are being computed
using the 3-dimensional (3D) wind field resolved by the GCM at the grid scale. In regions where
convection is active, the resolved mean vertical velocity might underestimate vertical motions due
to subgrid-scale convective processes.

In order to consider the conditions representative of the JJA average, eight different initial dates
are chosen within July and August (e.g., 7/15, 7/20, 7/25, 7/30, 8/5, 8/10, 8/15, 8/20) for the
trajectory analyses. In the PV budget analysis, we average the eight integrations from the same
initial location and for the different starting dates, to show average summertime trajectories. The
spread of the eight trajectories for different starting dates increases with integration time, but the
trajectories all have similar patterns (not shown).
3. Impact of the African topography on the Somali Jet and SAM precipitation

Here we analyze the CTL and NoAf experiments to assess the impact of the African topography on the strength and structure of the Somali jet and on the SAM precipitation. We find that the meridional cross-equatorial flow in the core of the Somali jet weakens when topography over Africa is removed, with a reduction of $\sim 30\%$ of the maximum jet strength (Fig. 2 and Fig. 3). While not explicitly discussed there, this weakening appears to be in agreement with the simulation results in previous studies (Chakraborty et al. 2002, 2006, 2009; Slingo et al. 2005). A height-longitude cross-section at the equator shows that the maximum reduction is at around 800 hPa (Fig. 3). Additionally, in the NoAf experiment, the cross equatorial flow spreads over the African continent, and the jet core moves to lower levels and weakens. This finding confirms that the African topography helps accelerate and spatially concentrate the Somali jet. Interestingly, we find that the removal of the African topography causes a positive meridional wind anomaly over the Arabian Sea north of the equator, where climatological winds are primarily westerlies. As discussed below, this positive anomaly has an unexpected and important impact on the SAM precipitation.

The weakening of the cross-equatorial flow in the Somali jet core region in the absence of topography over Africa might support the expectation of a similar decrease in monsoonal precipitation, possibly because of decreased moisture transport. Counter-intuitively, we find that precipitation increases almost everywhere in the Indian region, with largest anomalies just west of the Indian subcontinent and over the Bay of Bengal (Fig. 4b). The accumulated precipitation in a region representative of the larger-scale SAM ($7.07^\circ$N – $27.3^\circ$N, $63.75^\circ$E – $93.75^\circ$E, shown by the red rectangle in Fig. 4b) for the CTL and NoAf experiment is in Fig. 4a, which shows how in the NoAf experiment precipitation increases by $\sim 8.5\%$ compared to the CTL experiment.
These results therefore demonstrate how changes in the strength of the Somali jet in response to modified topography are not linearly correlated to changes in SAM precipitation. This is consistent with Boos and Emanuel (2009), who showed how in the annual cycle the rapid strengthening of the wind over the Arabian Sea at monsoon onset is not accompanied by similarly rapid changes in the cross-equatorial mass transport in the core of the jet near the EAH (between 38.75E and 48.75E). They found that these rapid SAM wind changes are instead accompanied by a rapid strengthening of the cross-equatorial mass transport in the periphery of the jet (between 48.75E and 71.25E). This suggests that the maximum speed of the cross-equatorial jet, which is influenced by the existence of the African topography, might not be directly related to the SAM precipitation.

Following the procedure in Boos and Emanuel (2009), we analyze separately changes in the cross-equatorial mass flux in the topographically-bound core cross-equatorial flow, and in its oceanic periphery region. As shown in Fig. 5, in the NoAf experiment, the cross-equatorial mass flux decreases solely in the core region, and remains largely unchanged in the periphery. This suggests that even in the absence of the African topography, the cross-equatorial mass flux in the periphery region transports sufficient moisture to sustain the monsoon and prevents significant decreases in its precipitation. It also suggests that the strength of the Somali jet alone might not be directly correlated to the wind and precipitation in the Indian region even on interannual and intraseasonal time scales, and that in fact its downstream might be a better predictor of monsoon precipitation intensity. This hypothesis will be further explored in future studies.

While the removal of the African topography seems to have only a marginal impact on the overall accumulated precipitation in the monsoon domain, it does lead to spatial changes that have non-negligible regional impacts. We interpret these regional changes using the moisture budget, which relates the net precipitation (P - E) to the vertically integrated moisture flux convergence. Calling $\delta$ the difference between the NoAf and the CTL simulations, and decomposing changes
in the moisture flux convergence into changes due to winds (the dynamic components, including convergence term and advection term) and changes due to moisture (the thermodynamic component) as done by a number of previous studies (e.g., Walker et al. 2015; Held and Soden 2006; Clement et al. 2004), we can write:

$$\delta P = \delta E - \langle \bar{q} \nabla \cdot \delta v \rangle - \langle \delta v \cdot \nabla \bar{q} \rangle - \langle \nabla \cdot [\langle \delta \bar{q} \rangle \nabla] \rangle,$$

(1)

where \(\langle \cdot \rangle\) represents a mass-weighted vertical integral [i.e., \(\int \langle \cdot \rangle dp / g\)] and \(\langle \cdot \rangle\) a time average. The first term in the right hand side is the change in evaporation, the second term the dynamic convergence term, the third term the dynamic advection term, and the last term the thermodynamic term.

Except for evaporation, which is negligible, the contribution of all terms in Eq. 1 to precipitation changes are shown in Fig. 6. The residual term is small relative to the other terms, especially compared to the \(\delta P\) term. This small residual also includes the quadratic term, due to covariations in changes of moisture and winds. Consistent with Chakraborty et al. (2002, 2006, 2009), we find that the largest contribution comes from the dynamic convergence component, that is, changes in precipitation are primarily accounted for by changes in wind convergence. Chakraborty et al. (2009) suggest that in the absence of blocking by the African topography, the westerly flow over Africa would extend eastward into the Arabian Sea and increase the westerlies there. This in turn would favor an increased wind and moisture convergence as the flow approaches the Indian subcontinent. We test this hypothesis by examining how both the westerly flow and air parcel trajectories are modified in the absence of the African topography. When comparing forward trajectories for particles originating over Africa at 850 hPa in the CTL (Fig. 7a) and NoAf (Fig. 7b) experiments, we see that in the absence of the African topography air particles can indeed flow past Africa and move into the Indian region. Also, in our simulations, the zonal wind does increase near the region.
in which topography is removed and over the equatorial Indian Ocean (Fig. 8). This suggests that indeed the African topography blocks air from Africa and weakens the westerlies. However, the stronger zonal wind does not extend into the Arabian Sea and the Indian subcontinent, where the precipitation response to the topography removal is the largest. After further decomposing the horizontal convergence in the dynamic convergence term into zonal and meridional components in the moisture budget (Eq. 1), as shown in Fig. 6(e, f), we find that the enhanced precipitation results primarily from increased meridional wind convergence, rather than stronger zonal wind convergence as proposed by Chakraborty et al. (2009). This stronger meridional moisture convergence is associated with the development of a larger-scale cyclonic circulation anomaly over the Arabian Sea (Figs. 4b and 9a). Mechanisms driving this cyclonic anomaly are explored more in detail in the next Section.

4. Impact of the African topography on the larger-scale circulation

a. Stationary wave pattern

The cyclonic anomaly developing over the Arabian Sea in response to the removal of the African topography and the anticyclonic anomalies in its upstream and downstream are indicative of a wave-like pattern. A similar wave-like pattern is also seen in the simulations of Slingo et al. (2005), who suggest a possible link between the stationary wave response to the African topography and changes in the SAM precipitation as the topography is removed. Mechanisms are however not discussed, and the origin of this wave pattern and possible influence on the monsoonal precipitation remain elusive. Here, we want to understand this anomalous wave train using simple theories of topographically forced stationary waves. Most of these theories have been developed for wintertime mid-latitude conditions, where stationary waves arise from the interaction between
a strong background westerly flow and topography. However, the co-existence over Africa of background westerlies, elevated topography and the strong meridional gradient of planetary vorticity raises the possibility that similar arguments might be applicable to near-equatorial dynamics in the Indian monsoon region.

As discussed in Holton 2004 (Ch. 4.3), the stationary wave response to topographical forcing can be qualitatively understood using barotropic PV conservation in a simple shallow water model. If barotropic PV [i.e., \((\zeta + f)/H\), where \(\zeta\) is the relative vorticity, \(f\) the planetary vorticity, and \(H\) the depth of the column between two isentropic surfaces] is to remain constant, an air column moving with the background westerly flow is first stretched upstream, as it approaches the barrier, and then squashed on its way to the top of the mountain. Thus, the air column must turn cyclonically to conserve PV as it approaches the mountain while being stretched. This cyclonic curvature causes a poleward drift, so that \(f\) also increases, reducing the relative vorticity change needed for PV conservation and the northward movement. As the column begins to climb the mountain, its depth decreases, and the relative vorticity becomes anticyclonic, with a southward meridional motion, and further changes in \(f\). This would bring the column back to the initial latitude with a southward velocity, with the column moving further south of its original location. Hence, the combination of the changes in the column depth, and the planetary and relative vorticity forces the parcel to follow a wave-like trajectory in the horizontal plane to conserve PV, with a flow pattern characterized by a cyclonic anomaly immediately east of the barrier and an alternating series of ridges and troughs in its downstream.

Analytical solutions for this lee wave can be obtained with a quasi-geostrophic (QG) barotropic model of forced Rossby waves with idealized bottom topography and upper rigid lid (Charney and Eliassen 1949). The steady-state solution of this model shows that the perturbation geopotential (or streamfunction) has a minimum at 1/4 wavelength to the east of the maximum topography.
(Holton 2004, Ch. 7.7.2 and Vallis 2006, Ch. 13.1.1). In our simulations, the shape of the topography is more complicated than the idealized one used in the simple models, and the background flow is non-uniform. Additionally, PV is not conserved, with source and sink terms arising from heating and frictional tendencies. Despite these caveats, the anomalous streamfunction that in our simulations can be attributed to the response to the African topography and computed from the difference between CTL and NoAf experiments (please note that this is opposite to the convention otherwise used through the rest of the manuscript) still features a minimum just downstream of the topography, followed by a wave pattern reminiscent of those seen in the simpler models discussed above (Fig. 10). The forward trajectory analysis introduced in the previous section for particles starting over Africa also confirms that particles move in similar wave-like trajectories as they interact with the topography (Fig. 7). Some of these particles move first to the north, and then curve back southward as they pass over the mountains. The wave like pattern, with associated meridional displacements, is clearly evident in the downstream of the mountain. As the topography is removed, trajectories are much more zonally oriented, with negligible excursions in the meridional direction.

One can use the results from the Charney-Eliassen model to estimate the stationary Rossby wavelength \( \lambda_s = \sqrt{\frac{\beta}{u}} \) and the expected eastward shift between the maximum topography height and the perturbation streamfunction minimum. While the background westerly flow varies with both latitude and longitude, we take as a representative value the mean zonal wind just upstream of the African mountain in the CTL simulation at 5°N, which is around 3.3 m s\(^{-1}\). We find a \( \lambda_s \approx 21.6 \) degrees (or \( \sim \)2396 km) based on the theory. This is somewhat smaller than the wavelength we see in our simulations, which is around 30 degrees (Fig. 10). From the theory, one would therefore expect a shift of the streamfunction minimum relative to the maximum topography of around 5.4 degrees (1/4 \( \lambda_s \)). The observed shift in our simulation is smaller, and around 3 degrees.
This shows that while qualitative consistency exists between our results and the simplified models of stationary wave dynamics, a more quantitative understanding of the cyclonic anomaly over the Arabian Sea requires consideration of the 3D full-physics PV dynamics. This is discussed in the following subsection.

**b. PV dynamics of the Somali jet and its relation with the SAM precipitation**

As discussed in detail in the previous subsection and as shown in Fig. 9a, a cyclonic circulation anomaly (i.e., the difference between NoAf and CTL experiments) exists to the west of India over the Arabian Sea. A region of positive PV anomaly is also located there. In Section 3, we have shown how, as topography is removed, precipitation increases mainly over the ocean just west of the Indian continent, primarily in association with anomalous meridional wind convergence (Figs. 4b and 9a). The increased meridional wind convergences is colocated and linked to the southerly flow on the eastern flank of the cyclonic anomaly over the Arabian sea. Hence, understanding dynamical mechanisms responsible for the anomalous lower-level circulation also provides insight into mechanisms for the anomalous precipitation. Here, we consider the full PV dynamics, which includes its sources and sinks, and perform a detailed analysis of its budget.

Ertel’s PV, \((1/\rho)\eta \cdot \nabla \theta\), is a scalar quantity that expresses both the rotational and stratification features of the fluid. Here, \(\eta\) is the 3D absolute vorticity vector, \(\theta\) the potential temperature, and \(\rho\) the density of the fluid. In z-coordinate, the PV budget is:

\[
\frac{DP}{Dt} = \frac{1}{\rho} F_\eta \cdot \nabla \theta + \frac{1}{\rho} \eta \cdot \nabla \dot{\theta},
\]  

(2)

where \(P\) is the PV, \(F_\eta\) the curl of the 3D frictional forcing \(F\), and \(\dot{\theta}\) the heating rate. The first term in the right-hand side of Eq. (2) is the frictional term and the second term is the heating term. This
conservation law clearly highlights how PV is materially conserved in the absence of friction and diabatic heating.

RH95 used the PV budget to analyze the dynamics of the Somali cross-equatorial flow. They argued that the change in sign of planetary rotation at the equator would prevent cross-equatorial flow in a stratified fluid, so much so that PV material tendencies are necessary for cross-equatorial flow to be achieved. Particles that retain their negative PV over the Arabian Sea would recirculate back into the SH, with a significant reduction of the moisture flux into the monsoon region. The combination of land-sea contrast in friction, which is enhanced by the African topography, and diabatic heating allows for sufficient positive PV modification and helps maintain the jet in the NH. Removal of topography in their dry model, forced by a prescribed diabatic heating, suggests that without the African topography, PV tendencies would decrease to a point that no significant cross-equatorial flow could be maintained into the Indian monsoon.

In our simulations, removing the African topography has a significantly less dramatic impact on the cross-equatorial flow than what discussed in RH95. In fact, the cross-equatorial flow weakens only in its core, close to the region of modified topography. However, we still find significant differences in the lower-level flow, and its curvature, downstream of the topography in the CTL and NoAf experiments. In the NoAf experiment, the flow has a stronger meridional component, with anomalous southerlies, compared to that in the CTL experiment, in which the flow is primarily zonally oriented when approaching the Indian subcontinent. This, as discussed above, has a non-negligible impact on the SAM precipitation. Here, we want to explore if and to what extent these lower-level flow changes can be understood through changes in the PV budget along flow trajectories. To this aim, we perform a PV budget analysis similar to the one done by RH95. One important difference is that in this work we use a full-physics GCM, where the impact of frictional and diabatic heating PV tendencies cannot be assessed separately. We analyze the overall impact
of these two terms on the PV budget of the cross-equatorial flow and its downstream extension. In particular, we want to unravel mechanisms responsible for the positive PV anomaly over the Arabian Sea when the African topography is removed.

Fig. 9b shows the difference of the JJA mean material PV tendency between NoAf and CTL experiments at 850 hPa (i.e., the sum of the frictional and heating terms). Caused by the mountain to the west of the cross-equatorial flow, lateral frictional forces induce positive material PV tendency in the CTL experiment along the particles moving near the African topography. When the African topography is removed, the frictional tendencies to its east decrease, which explains the negative anomalies there. Positive anomalies in PV tendencies are found over the Arabian Sea, in the same broad region of positive PV anomalies. One might therefore anticipate that larger PV over the Arabian Sea in the NoAf experiment is primarily due to these positive PV tendencies. However, the tendencies shown in Fig. 9 are material tendencies, which can be directly linked to PV changes only from a Lagrangian perspective, following particle trajectories. That is to say that to understand PV changes over the Arabian Sea, one also needs to consider where particles reaching this region originated from and passed by. To this aim, we analyze the PV budget along backward trajectories for particles with starting points in the Arabian Sea region with largest PV anomalies. In so doing, we account for all factors that can potentially influence PV in the target region, from the particle initial location, and hence initial planetary vorticity, initial relative vorticity, and material tendencies accumulated along specific paths.

The backward trajectory analysis is calculated in both experiments with particles starting from the region that has largest PV anomaly (Fig. 12). The backward trajectories highlight important differences in the flow between the CTL and the NoAf experiments: while in the former, the cross-equatorial flow is more coherent and organized, with most of the particles in the Arabian Sea originating from similar latitudes in the southern hemisphere, in the latter particles appear to
originates from different latitudes, from the SH Indian Ocean to near equatorial Africa. By integrating the material PV tendency along the paths, we can track the evolution of PV and compute the net PV change along the trajectories\(^1\). These are shown for the two GCM experiments in Figs. 13 and 14. At time 0 hr, the PV in the NoAf experiment is larger than that in the CTL experiment for every trajectory (Figs. 13). This is to be expected since we choose the region of positive PV anomaly as our starting region. However, the PV difference at the ending time of our backward calculation (-240 hrs) is even larger. This implies that the larger PV anomalies over the Arabian Sea in the NoAf experiment at time 0hr are primarily due to larger values in the initial PV. This can also be seen from Fig. 14, which shows the PV net change along the trajectories. The averaged total PV net change is larger in the CTL experiment than that in the NoAf experiment. If this were the dominant effect, the CTL rather than the NoAf experiment would have a cyclonic, more positive PV anomaly in the Arabian Sea. Our results show the opposite, which suggests that the primary difference lies in the initial PV values. More specifically, the positive PV anomaly between the NoAf and CTL experiments over Arabian Sea is due to the larger (or less negative) initial PV in the NoAf experiment compared to those in the CTL experiment. This is further confirmed in Fig. 15, which shows the time evolution of the latitude along the particle trajectories in the CTL and NoAf experiments and their difference. These significant differences in the latitude of the original particle locations is consistent with the changes in the simulated flow, discussed in previous sections. In particular, in the NoAf experiment, the weaker blocking effect by the African topography and the weaker cross-equatorial flow close to the coast allows for some of the particles to originate further west and closer to the equator in the SH than what seen in the CTL run. The particles, therefore, have a larger initial planetary vorticity value: this allows them to

\(^1\)The offset between real PV evolution and the accumulated PV evolution integrated from the total material PV tendency is small, so we only focus on the calculated PV evolution.
reach the Arabian Sea with more positive PV, even if the net material PV tendencies along their trajectories are less positive than the one experienced by particles reaching the same location in the CTL experiment.

5. The Influence of the Arabian Topography

Although our main goal is to focus on the impact of the African topography on the SAM, the Arabian topography is located right to the west of the Indian subcontinent and can be thought of as providing an extension to the African topography. This prompts us to examine further changes in the SAM when the Arabian topography is also removed (Fig. 1c). In the simulation when both African and Arabian topography are removed (NoAfArab), the precipitation in the larger-scale SAM domain increases relative to the CTL experiment (Fig. 16), but decreases slightly relative to the NoAf experiment (Fig. 17a). The decrease in precipitation relative the NoAf experiment is due to reduced precipitation over western, central India. A moisture budget analysis (Eq. 1) reveals that this precipitation decrease is associated with a reduction in the dynamic convergence term (Fig. 17c).

The reduction in precipitation when the Arabian topography is removed relative to the NoAf experiment, which is associated with decreased wind convergence over India, prompts us to analyze the dynamic response to the topography, as was done in the previous section. The anomalous (NoAf minus NoAfArab) vorticity shows a positive vorticity to the southeast of the Arabian topography, followed by a weak negative anomaly further downstream (Fig. 18). This is similar to the expected stationary wave response to a topographic barrier, in that the streamfunction minimum (i.e., positive vorticity anomaly) is located downhill of the topography. Since the background flow in this region is not purely westerly, but has a northerly component, the wave pattern has a slight northwest-to-southeast tilt.
Since the idealized theory of the stationary topographic Rossby waves only offers qualitative explanation for our simulations, we also conduct the full 3D PV budget along trajectories. While the PV anomaly over the Arabian Sea is stronger in the NoAfArab experiment than in the NoAf experiment (Figs. 9 and 19), the precipitation response has opposite sign (Fig. 17). That is, the precipitation increase relative to the CTL run on the eastern flank of the cyclonic anomaly over the Arabian Sea is smaller when both the Arabian and African topography are removed than when the African topography is removed in isolation. This appears to be due to the fact that the southerly flow on the eastern flank of the stronger PV anomaly, associated with anomalous meridional convergence relative to the CTL experiment, does not increase in the NoAfArab experiment relative to the NoAf experiment. This can occur because PV is not only influenced by the absolute vorticity, but also by the atmospheric stability. Changes in the latter can induce changes in the PV field, without changes in the absolute vorticity. Additionally, changes in relative vorticity are not necessarily correlated to changes in the southerly flow on the eastern flank of the PV positive anomaly. Therefore, the small changes in PV between the NoAf and NoAfArab experiments are not easily related to wind circulation patterns, and associated precipitation changes, near the Indian region. This highlights the complexity of the circulation response to changes in topography in a full physics GCM.

Despite not necessarily providing a direct link to understanding precipitation changes, it is still of interest to analyze mechanisms behind the PV increase over the Arabian Sea when the Arabian topography is removed. Therefore, we compute the PV budget following particle trajectories. The backward trajectories are similar to the ones in the NoAf experiment (not shown). The difference in the initial particle location, which was critical in explaining differences between the NoAf and CTL experiments, does not play a significant role here. This means that removing the Arabian topography does not modify substantially the trajectories of particles that reach the Arabian Sea in
the region of largest PV anomaly. This suggests that accumulated PV material tendencies have to be larger in the NoAfArab experiment than in the NoAf one, to explain the positive PV anomaly between the two experiments. This is confirmed in Fig. 20, which also shows that the largest material PV modification arises from the larger heating term, rather than changes in the frictional term.

In summary, these results show how the Arabian topography has a relative small impact on the SAM precipitation response and only slightly modifies the response to the removal of the African topography. This might due to the smaller height and range of this topographical feature, as well as its location: being further north than the African topography, the Arabian topography likely has a smaller interaction with the cross-equatorial flow.

6. Conclusions

The precise role that the African topography plays on the structure and intensity of the SAM cross-equatorial flow and the precipitation still remains debated. While it is widely accepted in the literature that the African topography helps to spatially confine the cross-equatorial flow and to enhance the SAM precipitation, recent studies show how the SAM precipitation increases rather than decreasing in numerical experiments when the African topography is removed. Here, we perform similar GCM experiments with modified topography and we provide a more comprehensive and quantitative discussion of the impact of the topography on the monsoonal lower-level flow and precipitation.

In simulations with a full-physics GCM, when the African topography is removed, the SAM precipitation increases even if the cross equatorial flow weakens. We find that in the absence of the blocking effect of the African topography, westerly winds strengthen over the Arabian Sea. Previous studies attributed the precipitation increase in the absence of African topography to
the strengthening of the westerly winds, and associated moisture convergence, as the zonal flow
approaches the Indian continent. In our simulations, however, stronger precipitation arises because
of stronger meridional, rather than zonal, convergence. This enhanced meridional convergence is
in turn associated with anomalous southerly flow on the eastern flank of a cyclonic wind anomaly
over the Arabian Sea.

PV budget analyses along particle trajectories are being conducted, to explain mechanisms giv-
ing rise to this cyclonic, or positive PV, anomaly. It is shown that particles over the Arabian Sea
have higher PV in the NoAf experiment relative to the CTL experiment not because they expe-
rience more positive material PV tendencies along their paths, but rather because they tend to
originate from higher latitudes, and therefore carry with them higher values of initial planetary
vorticity. Weaker cross-equatorial flow and weaker blocking effect (i.e., stronger westerly wind)
in the absence of the African topography allows for particles originating from near equatorial
Africa to reach the monsoon region. Because of the larger PV, the flow over the Arabian Sea has a
stronger southerly components to the west of India, and therefore stronger moisture convergence
and precipitation in the NoAf experiment.

We also conduct and discuss an experiment where the Arabian topography is removed in ad-
dition to the African topography. Despite inducing interesting and non-intuitive changes in the
circulation and precipitation fields, the Arabian topography is found to have only a very modest
influence on the monsoon, consistent with its smaller extent, height and northward position relative
to the African topography.

In our simulations, we do not consider the ocean response to the circulations changes, in that
SSTs are kept fixed and the same in all experiments. The ocean-atmosphere coupling can have
important impacts on the mechanisms here discussed. For instance, the reduction of the cross-
equatorial flow as the African topography is removed would reduce upwelling and increase SSTs.
Similarly, changes in wind strength could induce further SST changes through evaporation, which in turn would influence the precipitation response. These effects will be explored in future studies with experiments in a slab-ocean or fully coupled GCM.

Unlike more idealized work, which has attempted to consider the impact of topography and diabatic heating in isolation on the monsoonal flow, here we use a comprehensive GCM, where the distribution of diabatic heating is itself part of the response and dependent on the monsoonal circulation. Therefore, as the lower boundary is modified (here through changes in topography) the precipitation distribution can respond in ways not predicted by more idealized studies. As the topography is removed, changes in the resulting circulation will induce changes in the diabatic heating, which in turn will affect the PV of the monsoonal cross-equatorial flow and larger-scale circulation. While making causality harder to assess, this approach has the advantage of being energetically and dynamically consistent. In particular, it allows us to show how the Indian monsoon is significantly less sensitive to the presence of the African topography and a topographically confined Somali jet than what commonly thought: in fact, while having a quantitative impact on the structure of the Somali jet, the removal of the African topography does not modify in any significant way any of the major features of the simulated Indian monsoon, such as its position, strength and seasonality.

In this respect, this work is consistent with emerging theories of monsoons, which view these tropical circulations as regional manifestations of the seasonal cycle of the tropical Hadley circulation (e.g., Gadgil 2003; Bordoni and Schneider 2008) rather than large-scale sea-breeze circulations driven by local forcing. By shedding insight into the response of the Indian monsoon to modified topography, and resulting flow – precipitation interactions, this study might help to better constrain the influence of radiative and land surface forcing on the monsoon on different time scales.
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