Moist Dynamical Linkage between the Equatorial Indian Ocean and the South Asian Monsoon Trough*

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ABSTRACT

During boreal summer, both the monsoon trough and the equatorial Indian Ocean (EIO) receive intense climatological precipitation. At various time scales, EIO sea surface temperature (SST) and/or precipitation variations interact with rainfall along the trough. For instance, during July–August in strong Indian Ocean dipole/zonal mode (IODZM) years, EIO experiences below-normal rainfall while regions along the monsoon trough receive above-normal rainfall. A lack of spatial coherency between SST and precipitation variations is noted in both regions. This paper posits the hypothesis that interaction between equatorial waves and moist physics is important in determining precipitation anomalies over these regions and in setting up the teleconnection. The hypothesis is tested using a linear baroclinic model (LBM). IODZM-related SST anomalies derived from multicentury integrations of the Geophysical Fluid Dynamics Laboratory coupled model (GFDL CM2.1) are used to force the LBM. Consistent with observations and CM2.1 composites of strong IODZM events, steady-state LBM solutions simulate zonally oriented negative (positive) precipitation anomalies over the EIO (along the monsoon trough). To identify the processes simulated in the LBM, moisture and moist static energy budgets are examined. Over both regions, analyses reveal that moisture advection contributes the most to the LBM budget, with advection of climatological moisture by the anomalous wind being the principal factor. Specifically, in response to cold SST anomalies in the EIO, moist stability due to surface fluxes increases, giving rise to below-normal rainfall. These conditions produce anomalous anticyclonic circulation as a Rossby wave response in the lower troposphere. Over the central-eastern EIO, this anomalous circulation advects climatological air of lower moisture content from the subtropics. In addition, advection of anomalous moisture by both climatological and anomalous wind results in anomalous dry conditions over the entire EIO. In contrast, anomalous divergent circulations that emanate from the EIO advect climatological air of higher moisture content from the equatorial region, amplifying rainfall along the monsoon trough. Consequently, the two regions are connected by a thermally driven overturning meridional circulation. Budget diagnostics performed with CM2.1 composites and the ECMWF interim reanalysis for observed IODZM events support the hypothesis. The results here imply that in coupled models, realistic representation of the basic state and details of the moist processes are necessary for successful monsoon prediction.

1. Introduction

Over most parts of continental India, the seasonal mean (June–September) rainfall associated with the Asian summer monsoon (ASM) accounts for about 70%–80% of the total annual rainfall. During July–August, areas along and slightly to the south of the monsoon trough (a region of low pressure whose axis runs through central India, the Bay of Bengal, and the South China Sea) experience copious rainfall (Fig. 1a). The amount of this rainfall dictates agricultural output, water resources, and the livelihood of millions of people (Sikka 2006). Because of the unusual monsoon break in July 2002, the Indian Agriculture Department reported a 15% drop in food grains, which forced the India Meteorological Department to issue a midseason forecast update for July (Rajeevan et al. 2006). During this peak monsoon period the well-known suppressing effect of El Niño on the monsoon is not robust in certain decades (Annmalai and Liu 2005).

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FIG. 1. July–August averaged climatology, from (a)–(d) observations/ECMWF interim reanalysis and (e)–(h) CM2.1, showing (a),(e) precipitation (mm day$^{-1}$, shading) and SST ($^\circ$C, in contours; 28$^\circ$C isotherm is shown in dotted lines), (b),(f): sea level pressure (hPa), (c),(g) winds at 850 hPa (m s$^{-1}$), and (d),(h) divergent wind at 200 hPa (m s$^{-1}$). Scale vectors of (c),(g) 20 and (d),(h) 15 m s$^{-1}$ are also shown.
Therefore, elucidating the processes responsible for July–August rainfall variations is imperative. In the present study, we examine moist processes through which July–August sea surface temperature (SST) anomalies in the equatorial Indian Ocean induce anomalous monsoon rainfall.

a. Regional heat sources within the Asian summer monsoon domain

Figure 1a shows satellite-observed July–August averaged precipitation (shaded) and SST (contours) climatology. It is clear that regions experiencing intense rainfall (>6 mm day\(^{-1}\) or equivalently >2.5 K day\(^{-1}\) of column integrated heating) are over the Indo-Pacific warm pool, as detected in seasonal-mean climatology and in other conventional precipitation observations (Annamalai et al. 2007). We propose that the ASM actually consists of three regional heat sources: (i) the Indian summer monsoon (ISM; 10°–25°N, 70°–100°E), (ii) the western North Pacific monsoon (WNPM; 10°–20°N, 110°–150°E), and (iii) the equatorial Indian Ocean (EIO; 10°S–0°, 70°–100°E). The rationale for this hypothesis is as follows: a comparison of their variability at different time scales in both observational and modeling studies suggests that the three heat sources do not respond in unison. First, at intraseasonal time scales, rainfall anomalies depict a quadrupole structure: a north–south dipole with enhanced (suppressed) rainfall over the ISM (EIO) and a complementary dipole over the tropical western Pacific (Lau and Chan 1986; Annamalai and Slingo 2001). Second, at interannual time scales, during the developing phase of El Niño, the ISM (WNPM) is weaker (stronger) than normal and during years when eastern EIO experience cold SST anomalies, rainfall is weaker (stronger) than normal over EIO (ISM) (Annamalai and Liu 2005). Finally, global warming experiments using coupled models project precipitation increase (decrease) over the ISM and WNPM (EIO) (Stowasser et al. 2009).

In summary, at any time scale no forcing is strong enough to impact the heating over the entire ASM, equatorial and off-equatorial (Fig. 1a; 10°S–30°N, 70°–150°E), to produce a uniform single-signed anomaly. One hypothesis is that any forcing, local or remote, modifies one of the three proposed heat sources, and the circulation anomalies that develop as a response to anomalous heating interact with moist processes and subsequently influence other heat sources.

b. Present study

Figure 2 shows observed ocean–atmosphere variables during August 2006. Prominent signals include cold SST anomalies along the Java and Sumatra coasts (Fig. 2a), negative precipitation (Fig. 2b), and surface easterly wind anomalies (Fig. 2c) over the EIO. Positive feedback among the three variables intensified into the next season (not shown), a condition known as the Indian Ocean dipole/zonal mode (IODZM). Observations indicate that the IODZM develops in boreal summer, peaks in fall, and decays in December with relatively more...
frequent occurrences in the last two decades [Yamagata et al. (2004) and Schott et al. (2009) provide comprehensive reviews]. During the developing stages of strong IODZM events in July–August, above-normal rainfall is witnessed along the monsoon trough (Annamalai and Liu 2005), but the moist processes responsible for the monsoon rainfall increase have not been examined in detail.

Because future seasonal monsoon predictions will rely on coupled models, an examination of how moist processes are represented in them is of interest. Of the coupled models that participated in the Inter-governmental Panel on Climate Change Fourth Assessment Report (IPCC AR4), the latest version of the model developed at the Geophysical Fluid Dynamics Laboratory (GFDL CM2.1) realistically simulates monsoon precipitation climatology and its spectrum of variability (Annamalai et al. 2007; Sperber and Annamalai 2008; Stowasser et al. 2009), as well as IODZM (Song et al. 2007). Figure 3 shows July–August anomalous SST and rainfall composites based on CM2.1 IODZM events (section 2 provides details of data processing). In agreement with observations, the model simulates cold SST anomalies along the Java and Sumatra coasts (Fig. 3a) and below-normal rainfall over the eastern EIO (Fig. 3b).

Both observations and CM2.1 make two significant points: (i) rainfall increases over parts of central India, the northern Bay of Bengal, and the South China Sea in spite of the cold SST anomalies observed (Fig. 2a) or simulated (Fig. 3a) locally in those regions; and (ii) there is a lack of one-to-one spatial correspondence between anomalous SST and precipitation over the EIO (meridionally oriented SST anomalies versus zonally extended precipitation anomalies). Based on these points, our working hypothesis is that interaction between equatorial waves and moist processes determines precipitation anomalies both over the EIO and along the trough, and helps to establish the moist teleconnection.

Su and Neelin (2002) and Neelin and Su (2005) used a quasi-equilibrium tropical circulation model to identify moist processes that impact descent anomalies during El Niño. Their moisture and moist static energy (MSE) budget analyses show that the processes responsible for the descent anomalies vary. Here, we follow a similar procedure to examine the linkage between the EIO and monsoon trough; however, because many feedbacks in the fully coupled CM2.1 model make diagnosis of the processes impossible, we simplify the approach. First, we diagnose the budgets on solutions with a linear atmospheric model forced with IODZM-related SST anomalies; then we compare them to budget estimates with CM2.1 and the European Center for Medium-Range Weather Forecasts (ECMWF) interim reanalysis.

Although rainfall along the monsoon trough is influenced by EIO SST/precipitation variations at other time scales, SST leads precipitation by 10 days at an intraseasonal time scale (Kemball-Cook and Wang 2001) and EIO rainfall decreases despite in situ SST warming in global warming experiments (Stowasser et al. 2009). It is only during strong IODZM years that local SST variations have a simultaneous imprint on EIO precipitation (Fig. 2). Therefore, we force the model with IODZM SST anomalies to identify moist processes that may be operating in the EIO–monsoon trough teleconnection.

The remainder of the paper is organized as follows. Brief descriptions of the data, models, and experimental designs are presented in section 2. Diagnostics from CM2.1 and solutions from the linear baroclinic model (LBM) are discussed in section 3. Budget results are described, and the moist teleconnection mechanism is proposed in section 4. A summary of the results and their implications for monsoon seasonal prediction are presented in section 5.

2. Data, model, and experimental designs

a. Data and method

We have examined the three-member ensemble twentieth-century (20c3m) integrations performed with the GFDL CM2.1. The runs spanning the period 1861–2000 were conducted at GFDL as part of the IPCC AR4. Model details including the numerical and physical packages employed are described in Delworth et al. (2006); the forcing fields used for the 20c3m runs are discussed in Knutson et al. (2006).

In the model runs, monthly anomalies were created with respect to 30-yr climatology (1971–2000). Two SST indices—one averaged over the eastern EIO (90°–110°E, 10°S–0°) during June–November and another averaged over Niño-3.4 region (5°S–5°N, 120°–170°W) during December–February—were constructed to represent IODZM and ENSO, respectively. Since our aim is to isolate the processes that link EIO to the monsoon trough, a threshold cutoff of 1.0 standard deviation on these indices identifies years of independent IODZM. In total, 30 IODZM events occurred and the sample size is large enough to provide confidence in the results. Composites for selected variables are constructed and a t test is applied to assess their statistical significance.

CM2.1 basic state and composites are compared to satellite-based observations and the ECMWF interim reanalysis. Monthly values of precipitation from the Tropical Rainfall Measuring Mission (TRMM; version 3B43), SST from the TRMM Microwave Imager (TMI), and surface wind from QuikSCAT for the period 1998–2007.
are used. Moist processes identified in LBM and CM2.1 are also compared with the ECMWF interim analysis. This product covers the data-rich period of 1989–2007 and is considered to capture tropical precipitation and the hydrological cycle well based on a system that uses new humidity analysis and improved model physics. The horizontal resolution employed is 1.5° and there are 60 vertical levels. More details are available in Simmons et al. (2006).

b. Linear baroclinic model

A linear baroclinic atmosphere model described in Watanabe and Jin (2003) is used. This model is a global,
time-dependent, primitive equation model; for this study, we linearized it around CM2.1 climatology. Forcing fields are taken from IODZM composites constructed from CM2.1 output. The horizontal resolution is T42 and there are 20 vertical levels. Two versions are used: the “dry” version has prescribed heating (i.e., convective heating functions are derived from precipitation) and the “moist” version is forced by SST in order to incorporate the feedback between convection and dynamics inherent in monsoon variations (Annamalai and Sperber 2005). Surface heat fluxes generated by SST forcing in the moist version are parameterized as in Betts and Miller (1986). A linearized moisture equation for perturbation specific humidity is used, and heat and moisture sources associated with cumulus convection are also parameterized (Watanabe and Jin 2003). In summary, the moist version generates its own heating functions. While all equations in the LBM are linear with respect to perturbation, advection of moisture and temperature are allowed, and the relationship between evaporation and temperature depends on the basic state. Details of the LBM budget equations are provided in the appendix.

c. Experimental designs

To check if the enhanced monsoon trough and circulation in the northern Indian Ocean (Figs. 3c,d) are direct responses to EIO heating anomalies, the dry version is forced with an anomalous diabatic heating rate or convective heating function proportional to precipitation amplitude (boxed area in Fig. 3b). In this dry version, the vertical heating profile has a maximum at 400 hPa as in Rodwell and Hoskins (1996). The moist version is forced with an anomalous SST (boxed area in Fig. 3a). The forcing function imposed in the dry version and the one generated within the moist version are shown in Fig. 4a. While tropical dynamical response is sensitive to vertical heating gradients (Schumacher and Houze 2003), the agreement in the heating distributions’ shape in both versions suggests that the profile used in the dry version is reasonable. Table 1 lists the main components of the experiments; unless otherwise mentioned, LBM is integrated for 30 days with fixed forcing. With the dissipation terms adopted in the model, the tropics approach steady state in about 15 days (Fig. 5c) and the solutions averaged for days 20–25 are used for detailed analysis.

As in many linear modeling studies, the present experimental designs have neglected some processes. Unlike the model employed by Neelin and Su (2005) and Chou and Lo (2007), radiation physics and atmosphere–ocean–land interactions are not included in the LBM. While cloud radiative forcing plays a role in the MSE budget, it is not considered to be the dominant process (Neelin and Su 2005). Because of observational constraints, the analyzed circulation fields and the moist budgets from interim reanalysis are influenced by moist convective parameterization employed in the forecast model of the reanalysis system (Annamalai et al. 1999). Finally, the LBM is linearized with the CM2.1 and not with the observed basic state. Therefore, a direct quantitative comparison of LBM solutions with observations/reanalysis is not attempted here. However, as we show, moist processes identified in LBM are also prominent in CM2.1 and in the ECMWF interim reanalysis (section 4).

3. CM2.1 diagnostics and LBM solutions

a. CM2.1 basic state and composite structure

Figure 1 shows the basic state of the ASM from (left) observations and (right) CM2.1. Within the framework of our hypothesis, CM2.1 captures the three regional heat sources mentioned in section 1. At about 25°N, the monsoon trough is characterized by a minimum in sea level pressure (SLP). The 200-hPa divergent circulation suggests that the monsoon Hadley cell has ascent along the trough and descent over the Southern Hemisphere subtropics. At low levels, the cross-equatorial flow has a maximum along Somalia, and the westerlies in the northern Indian Ocean and South China Sea are along the geostrophic contours. Some model deficiencies include higher (lower) precipitation over the eastern EIO and plains of Indo-China (Bay of Bengal and west of the Philippines) and a stronger heat low over the Arabian Peninsula.

The IODZM composites shown in Figs. 3a,b suggest that the relationship between anomalous precipitation and SST is not local, as discussed earlier in section 1b. Here we examine the association between precipitation and circulation anomalies. At low levels, positive SLP anomalies and twin anticyclones straddling the equator are prominent (Figs. 3c,d). These features are likely a Rossby wave response to EIO heating anomalies. The divergent flow emanating from the eastern EIO converges along the monsoon trough (Fig. 3c). This convergence, in conjunction with cyclonic vorticity induced by anomalous westerlies in the northern Indian Ocean (Fig. 3d), promotes ascent along the trough (Fig. 3b). Unlike the basic state that shows ascent along the trough and descent over the Southern Hemisphere subtropics (Figs. 1d,h), the anomalous divergent circulations during IODZM years suggest that the EIO and monsoon trough are connected by a meridional circulation (Figs. 3c,e). These model features agree with observations shown in earlier studies (Annamalai and Liu 2005) as well as here (see Figs. 15g,h).
b. LBM solutions

1) DRY VERSION

From the above interpretations (section 3a), one wonders if the enhanced monsoon trough and circulation in the northern Indian Ocean are direct responses to EIO heating anomalies (i.e., without invoking interaction between convection and dynamics). To test this, LBM is forced with heating functions (solid line in Fig. 4a) proportional to EIO precipitation anomalies (box outlined with dark lines in Fig. 3b); this experiment is termed DRY_EIO (Table 1). Both in surface pressure $P_s$ and 850-hPa winds (m s$^{-1}$), the Rossby wave response to EIO heating anomalies are aptly captured (Fig. 4b). Owing to asymmetry in the basic state, the Northern Hemisphere anticyclone is stronger than its Southern Hemisphere counterpart. Over the plains of northern India and the Bay of Bengal, lack of cyclonic shear in the westerly
anomalies is unfavorable for strengthening the monsoon (Raghavan 1973; Annamalai and Sperber 2005). Therefore, only an east–west divergent circulation prevails along the EIO (Fig. 4c). Because of the proximity of positive and negative heating patterns over the EIO (Fig. 3b), the net Kelvin wave response cancels out over the equatorial western Pacific, an interpretation consistent with our study that focused on boreal fall (Annamalai et al. 2005). Many past studies have used dry versions of linear models to understand the teleconnection between these two regions (e.g., Krishnan et al. 2000; Annamalai and Sperber 2005). While the dry version shows the possible role of equatorial waves, it does not answer the monsoon trough’s modulation. Nevertheless, negative \( P_s \) anomalies around 20°–30°N are detectable within few days after the heating is switched on (not shown), and in an interactive model this weak signal may be instrumental in monsoon trough’s amplification.

2) MOIST VERSION

In MOIST_EIO, LBM is forced with EIO SST anomalies (box outlined with solid lines in Fig. 3a) and the solutions are shown in Fig. 5. The temporal evolution of \( P_s \) averaged along the monsoon trough (Fig. 5e) illustrates that steady state is reached within about 14 days after SST forcing is turned on. As in DRY_EIO (Fig. 4b), positive \( P_s \) and anticyclonic circulation anomalies over southeastern Indian Ocean are simulated (Fig. 5a). A conspicuous result is an amplified monsoon trough that has a northwest–southeast orientation with multiple negative \( P_s \) centers. The low-level westerly (easterly) wind anomalies to the south (north) of the minimum pressure axis are along the geostrophic contours. Anomalous cross-equatorial flow is evident across the Indian Ocean (40°–110°E), with the strongest signature along the Sumatran coast. This cross-isobaric flow suggests the importance of ageostrophic component. The solutions capture the regional meridional circulation with ascent along the monsoon trough and descent over the central-eastern EIO (Fig. 5b). Barring higher intensity, spatial patterns of the low-level wind components agree with both CM2.1 (Fig. 3) and reanalysis (Fig. 15).

Additional experiments (Table 1) show the importance of persistent regional SST anomalies on the monsoon rainfall. First, in MOIST_EIO_5DAY SST forcing (box outlined with solid lines in Fig. 3a) is turned off at day 5 of the integration. The simulated precipitation and low-level wind anomalies at selected days are shown in Figs. 6a–d. At day 5, precipitation decreases (increases) over the eastern EIO (Bay of Bengal and South China Sea) and the circulation anomalies resemble those in Fig. 5a. As time progresses, at day 10, the precipitation signal fades away over the eastern EIO and wind anomalies weaken over the South China Sea. These features further weaken by day 15, leading to the collapse of the monsoon trough at day 20 (note in Fig. 6d the scaling is different). Thus, even in an interactive model, if the EIO SST forcing does not persist then its impact on the monsoon is short lived.

Both in observations and CM2.1 composites, cold SST anomalies over the Indonesian Seas (Figs. 2a and 3a) closely follow the life cycle of IODZM (H. Annamalai et al. 2009, unpublished manuscript). To understand their effect on the monsoon, in the MOIST_IS experiment cold SST anomalies over the Indonesian Seas are imposed (box outlined with dotted lines in Fig. 3a). In contrast to EIO SST anomalies, whose influence is manifested over the entire monsoon trough (Fig. 5a), the impact of the Indonesian Seas is confined to the South China Sea region (Fig. 6e). The results suggest that the regional SST anomalies over the near-equatorial Indo-Pacific warm pool region redistribute rainfall over the monsoon domain.

4. Moisture and moist static energy budget analyses

The budget analyses are focused over two regions: the EIO (area outlined with solid lines) and the monsoon trough (area outlined with dotted lines in Fig. 7a). Budget analyses and all future discussions are confined to MOIST_EIO solutions only (sections 4a and 4b). In section 4c, the overarching results are synthesized and the moist mechanism is proposed. Diagnostics are presented for LBM solutions first, and then for CM2.1 and observations.

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**Table 1.** Details of various LBM experiments conducted, including the forcing region and forcing function.

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Forcing region</th>
<th>Forcing specifics</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRY_EIO</td>
<td>(10°S–10°N, 50°–110°E)</td>
<td>Precipitation anomalies</td>
</tr>
<tr>
<td>MOIST_EIO</td>
<td>(15°S–5°N, 80°–110°E)</td>
<td>SST anomalies</td>
</tr>
<tr>
<td>MOIST_EIO_5DAY</td>
<td>(15°S–5°N, 80°–110°E)</td>
<td>SST forcing as in MOIST_EIO but the forcing is switched off at day 5</td>
</tr>
<tr>
<td>MOIST_IS</td>
<td>(10°S–10°N, 120°–150°E)</td>
<td>SST anomalies over the Indonesian Seas</td>
</tr>
<tr>
<td>MOIST_EIO_NO_QADV</td>
<td>(15°S–5°N, 80°–110°E)</td>
<td>SST forcing as in MOIST_EIO but horizontal moisture advection is suppressed.</td>
</tr>
</tbody>
</table>
a. Moisture budget analysis

Figures 7a–d show the four terms of the moisture budget [Eq. (A5)], namely precipitation $P'$, moisture convergence $\omega \bar{\varphi} q'$, moisture advection $-\bar{D} q'$, and evaporation $E'$ [all expressed in energy units (W m$^{-2}$); see the appendix for explanation of the symbols]. It should be noted here that in Fig. 7b, a positive sign means net moisture convergence...
into the column and vice versa. Similarly, moist advection (Fig. 7c) into the column is positive and dry advection is negative. Budget diagnostics in the MOIST_EIO solutions is justified because the simulated precipitation over both target regions (Fig. 7a) agrees qualitatively with CM2.1 composites (Fig. 3b) and observations (Fig. 2b).

For the dry conditions over the eastern EIO, contributions to precipitation anomalies from moisture divergence, reduced evaporation, and dry advection are about 55%, 10%, and 35%, respectively. While moisture divergence and decrease in evaporation are germane to prescribed cold SST anomalies, the role of dry advection is discussed later in section 4c. For the wet conditions along the monsoon trough, about 65%–75% comes from moisture convergence while moist advection contributes about 20%–25% over regions of local precipitation convergence.
maximum. The enhanced westerlies in the northern Indian Ocean (Fig. 5a) lead to evaporation increase over the southern Bay of Bengal, but they contribute only ~5% to monsoon rainfall. Climatologically, the regions of northwest India and Pakistan that lie over the western end of the monsoon trough receive less climatological rainfall (Fig. 1a), but moist advection is capable of increasing precipitation during IODZM years.

As expected in the deep tropics, precipitation and moisture convergence are undoubtedly the dominant terms in the moisture budget, shadowing the contributions from moisture advection and evaporation. In reality, moisture convergence is a “feedback” and not a “cause” in the chain of moist convective response to SST forcing (Su and Neelin 2002). In an interactive system, the feedback among convective heating, moisture convergence, and adiabatic cooling determines convergence as a response to other physical processes. Neelin and Su (2005) suggested that the MSE budget analysis provides a better approach to understanding thermodynamic balance in the deep tropics because it combines physical processes influencing temperature and moisture. In MSE, the effect of other processes in determining convergence can be brought out because moisture convergence and adiabatic cooling associated with rising motions cancel out substantially.

b. Moist static energy budget analysis

In Fig. 8 the dominant terms of the MSE equation [Eq. (A4)]—namely, MSE convergence $\omega \partial_p q'$, temperature advection $-D_T T'$, and sensible heat flux $H'$—are shown. Note that evaporation $E'$ and moisture advection $-D_q q'$ are already shown in Fig. 7. The vertically integrated MSE has spatial pattern identical to that of moisture convergence (Fig. 7b) but with a reduced amplitude. This is consistent with the result obtained over the tropical Pacific (Su and Neelin 2002). The sensible heat flux, although small, has a close spatial correspondence to evaporation (Fig. 7d). The temperature advection has a wavy nature with large amplitudes in the subtropics and
midlatitudes, but the signal is nonexistent in the monsoon region. Therefore, three prominent terms—evaporation, sensible heat, and moisture advection—contribute to MSE convergence.

Over the eastern EIO, anomalous MSE convergence is negative (Fig. 8a) because dry static energy import into the region is larger because of relative descent. Although evaporative (10%–12%) and sensible heat (5%–7%) fluxes contribute, dry advection’s role (~70%) dominates this import of dry energy. All the three terms have a zonal structure over the eastern EIO.
Along the monsoon trough, anomalous MSE convergence associated with anomalous ascent is positive. Over the northern Indian Ocean and South China Sea sensible heat flux shows a warming tendency together with an increase in evaporation. However, their contributions to MSE are only 5%–10% (sensible), and 20% (evaporation). Moist advection (60%–70%), on the other hand, controls the MSE balance, particularly over regions of precipitation maxima. In summary, over both target regions moisture advection is the major factor in the MSE budget. Also, over the Arabian Sea (western EIO), dry (moist) advection plays an important role.

To underscore moisture advection, we performed an experiment (MOIST_EIO_NO_QADV) wherein the horizontal advection of moisture is turned off but the SST forcing used in MOIST_EIO experiment is preserved. Compared to solutions in which advection is allowed (Figs. 5a and 9c), in the no-advection experiment over both target regions, \( P_s \) perturbations (Fig. 9a) and midlevel heating (Fig. 9b) are substantially weaker.

c. Proposed mechanism

Our primary interest is to understand how precipitation anomalies are generated over the two target regions. Over the EIO, the immediate response to prescribed cold SST anomalies is a reduction in surface fluxes (Figs. 7d and 8c) that subsequently weaken the in situ precipitation. In situations where the tropical atmosphere is subject to diabatic heating or cooling, the pressure (mass) and wind fields will experience an adjustment process (Hoskins and Wang 2006). Figure 10 shows snapshots of \( P_s \) and 1000-hPa divergent wind. Within one day after the SST forcing is turned on, positive \( P_s \) anomalies develop over the eastern EIO (Fig. 10a) and continue to intensify and spatially extend until steady state is reached (Fig. 10d). While persistent cold SST anomalies are necessary to maintain dry conditions (Fig. 6),
we show next that low-level circulation anomalies associated with the $P_i$ perturbations (Fig. 5a) interact with moisture advection in causing zonally extended negative precipitation anomalies over the EIO.

To understand relative contributions from horizontal wind and moisture gradient, the moisture advection can be partitioned into

$$\frac{\partial}{\partial t} \left( \frac{h}{C_1} q \right) = \frac{\partial}{\partial t} \left( \frac{h}{C_1} q \right) + \frac{\partial}{\partial t} \left( \frac{h}{C_1} q \right) + \frac{\partial}{\partial t} \left( \frac{h}{C_1} q \right).$$  \hspace{1cm} (1)

In the above equation, the symbol $\langle \rangle$ represents vertical integration. The first term on the right-hand side, $\langle \nabla \cdot (Vq) \rangle$, denotes advection associated with anomalous wind acting on climatological moisture gradient, and the second term, $\langle \nabla \cdot (Vq) \rangle$, represents advection due to climatological wind acting on anomalous moisture gradient. The other terms, $\langle \nabla \cdot (Vq) \rangle$ and $\langle \nabla \cdot (Vq) \rangle$, represent anomalous wind acting on anomalous moisture gradient and the residual term due to transient variability, respectively.

Figures 11a–c show the moisture advection terms. To aid in their interpretation, Fig. 12 shows July–August averaged climatology of the vertically integrated moisture from CM2.1 together with low-level circulation anomalies from MOIST_EIO. In the basic state, the meridional gradient in climatological SST in the tropical Indian Ocean (Fig. 1a) leads to a similar signature in moisture distribution (Fig. 12a). The zonal extension of precipitation anomalies over the EIO, $\langle \nabla \cdot (Vq) \rangle$, is the principal contributor, while $\langle \nabla \cdot (Vq) \rangle$ and $\langle \nabla \cdot (Vq) \rangle$ also make substantial contributions. Their individual and collective roles over the EIO are interpreted as follows:
First, over the eastern EIO the anomalous low-level anticyclonic circulation advects climatological air of lower moisture content from southern subtropics to EIO, which causes dry advection. Second, cold SST anomalies over the EIO induce anomalous moisture gradient in the EIO. The near-equatorial climatological easterlies around $5^\circ$S (Fig. 1g) and the anomalous near-equatorial easterly winds (Fig. 12a) will then advect dry air into the central Indian Ocean. Third, descent due to anomalous regional meridional circulation (discussed below) advects dry air. Collectively, the advection terms determine the zonal extension of negative precipitation anomalies over the EIO despite the fact that the LBM is forced with meridionally oriented SST anomalies.

Now let us focus on the rainfall variations along the trough. By day 1, concentrated divergent wind anomalies
are noticeable from the EIO (Fig. 10a). At the same time, a region of weak negative $P_s$ anomalies is seen over central India. By day 4, the divergent wind anomalies amplify and converge along the trough where the negative $P_s$ anomalies strengthen and extend zonally. The amplification of the fields continues until steady state is reached (Fig. 10d; unit vector scale varies). Theoretical (Lau and Peng 1990), and modeling studies (Annamalai and Sperber 2005) demonstrate that in the presence of equatorial Kelvin waves, baroclinic Rossby waves develop along the monsoon trough, as noted at day 1 (Fig. 10a), and the boreal summer basic state favors the amplification of Northern Hemisphere Rossby waves (Wang and Xie 1997; Krishnan et al. 2000). Note that the LBM was also linearized with the same basic state in the dry version as in the moist version, but the initial Rossby wave–induced $P_s$ perturbations (Fig. 4b) did not amplify in the dry version. This suggests the role of moisture advection.

Along the monsoon trough, the anomalous divergent winds (Fig. 10) advect climatological air of higher moisture content from the near-equatorial region (Fig. 12a), resulting in moist advection. In the vicinity of the SST forcing region, the zonal scale of the low-level divergent winds is larger than the divergence itself, and their orientation toward the monsoon trough (Figs. 3c and 10) is favorable for advecting high climatological moisture that is abundant over the eastern EIO. Figure 11d shows that the tendency associated with anomalous meridional wind acting on climatological moisture plays a substantial role over both target regions. The EIO and the monsoon trough are likely to be connected by a meridional circulation (Figs. 3e and 5b). To discern this possibility, and following the methodology outlined in Trenberth et al. (2000), we estimated the meridional mass flux averaged over the longitudes 70$^\circ$–110$^\circ$E (Fig. 12b). A well-defined thermally direct overturning circulation with ascent along the monsoon trough (10$^\circ$–20$^\circ$N) and descent over the EIO (10$^\circ$S–0$^\circ$) is apparent. Theoretical studies (Plumb and Hou 1992) demonstrate that because of the vanishing of planetary vorticity near the equatorial latitudes even for a weak forcing, a meridional circulation can be sustained. In addition, low-level cyclonic circulation anomalies (Fig. 12a)

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**Fig. 13.** Terms related to moisture and MSE budgets from CM2.1 composites: (a) moisture convergence, (b) moisture advection, (c) evaporation, and (d) sensible heat flux. All values are anomalies and units are in W m$^{-2}$, but the scaling in each panel is different. In all panels, the region outlined in dotted (solid) lines represents the monsoon trough (eastern equatorial Indian Ocean).
can also advect climatological air of higher (lower) moisture content from low (high) latitudes resulting in moist (dry) advection along the trough (over the Arabian Sea). The contribution of climatological winds (Fig. 1g) advecting anomalous moisture from the EIO to the monsoon trough is nonnegligible (Fig. 11b).

d. Budget diagnostics in CM2.1 and ECMWF interim reanalysis

Figure 13 shows the leading terms related to moisture and MSE budgets estimated from CM2.1 composites. Precipitation anomalies are already shown in Fig. 3b (note...
that precipitation unit conversion is 1.00 mm day$^{-1}$ = 28 W m$^{-2}$; Chou and Lo 2007). Contribution from temperature advection is low (not shown). With the available CM2.1 outputs, it is difficult to determine radiative heating rates and diagnose their role in the MSE budget.

In the moisture budget, anomalous moisture convergence (Fig. 13a) and precipitation (Fig. 3b) are the dominant balancing terms. However, over the eastern EIO, dry advection contributes (20%–30%) to precipitation anomalies. Along the coasts of Java and Sumatra, the input from evaporation (5%–8%) is cancelled by moist advection. In the central EIO, excess evaporation is cancelled by dry advection, whereas over the western EIO (5$^\circ$S–5$^\circ$N, 50$^\circ$–70$^\circ$E) moist advection and local evaporation contribute to precipitation increase. Figures 14a–c show the leading three components of the moisture advection from CM2.1. As in MOIST_EIO (Fig. 11), in CM2.1 all the terms contribute to dry advection over the EIO. Over local maxima along the monsoon trough, both $\langle v \cdot v q' \rangle$ and $\langle w \cdot (w q') \rangle$ make up the total anomalous moist advection. Note that $\langle v \cdot v q' \rangle$ still dominates because the low-level divergent flow is strong and oriented poleward toward the monsoon trough. These features favor moist advection from the EIO toward the monsoon trough (Fig. 3c). A regional meridional circulation with ascent along the trough and descent over the EIO is manifested in CM2.1 (Fig. 14d). Given the fact that LBM is linearized with the CM2.1 basic state and that there is close correspondence between MOIST_EIO solutions (Fig. 5) and CM2.1 circulation composites (Figs. 3c,d), this strengthens the discussion presented in section 4c.

Figure 15 shows moisture budget and advection terms together with low-level circulation anomalies estimated from the ECMWF interim reanalysis. These results are based on three strong IODZM events (1994, 1997, and 2006) that occurred together with moderate to strong El Niño conditions (Schott et al. 2009). While the
influence of El Niño–related SST anomalies is expected to affect the budgets, especially over the western Pacific, rainfall decreases over the EIO and increases along the monsoon trough in response to IODZM (Fig. 15a). Again, moisture convergence and precipitation dominate moisture budget, but the contributions from both moisture advection (Fig. 15c) and evaporation (Fig. 15d) are not negligible. The input from sensible heat flux is low (not shown). As expected, evaporation decreases over the cold SST anomalies of the eastern EIO whereas it increases over most parts of the northern Indian Ocean. Dry (moist) advection contributes to negative (positive) precipitation anomalies over the EIO (along the monsoon trough). As in both the CM2.1 (Fig. 14) and LBM solutions (Fig. 13), both \( \mathbf{\nabla} \cdot \mathbf{v} \) and \( \mathbf{u} \cdot \mathbf{v} \) contribute to dry (moist) advection over the EIO (along the trough). The qualitative resemblance of the circulation anomalies from the ECMWF interim reanalysis (Figs. 15g,h) to those from the LBM solutions (Fig. 5) and CM2.1 composites (Fig. 3) implies that the interpretations offered in section 4c are also valid for observations.

5. Summary and discussion

a. Summary

During boreal summer both the equatorial Indian Ocean and the monsoon trough experience intense climatological precipitation (Fig. 1a). At various time scales, EIO SST and precipitation variations interact with rainfall along the trough. During July–August of strong IODZM years, the EIO experiences below-normal rainfall while regions along the monsoon trough receive above-normal rainfall (Figs. 2b and 3b). A lack of spatial coherence between anomalous SST and precipitation is noted in both regions (Figs. 2 and 3). We hypothesize that interaction between equatorial waves and moist physics is important in determining precipitation anomalies over these regions and in setting up the teleconnection between the EIO and monsoon trough.

To test the above hypothesis, we force a linear atmosphere model (LBM). The LBM is linearized around GFDL CM2.1 climatology. IODZM-related SST anomalies identified in multicentury integrations of CM2.1 are used for forcing the LBM. Qualitatively, the steady-state
LBM solutions (Figs. 5a,b) agree with CM2.1 composites (Fig. 3) and observations (Figs. 2 and 15g,h). In particular, the zonally elongated below-normal rainfall over the EIO and increased rainfall along the monsoon trough are aptly captured (Fig. 7a). This consensus allows us to diagnose moisture and moist static energy (MSE) budgets from LBM solutions and compare them with CM2.1 composites and observed IODZM events.

Moisture budget analysis indicates that over both target regions (Fig. 7), precipitation and moisture convergence are the dominant terms but contribution by moisture advection is substantial (~20%–30%). The reason for moisture convergence dominance is that it is a feedback rather than a cause in the chain of moist convective response to SST forcing (Neelin and Su 2005). MSE budget diagnostics shed light on the physical processes affecting moisture convergence and indicate that over both regions moisture advection actually contributes the most (Fig. 7). Quantitatively, about 60% of the MSE divergence over the eastern EIO comes from dry advection. Along the monsoon trough, particularly over regions of local maxima, about 50%–60% of the MSE convergence is accounted for by moist advection. Budget diagnostics with CM2.1 composites (Figs. 13 and 14) and ECMWF interim reanalysis for observed IODZM events (Fig. 15) support LBM results. The importance of moisture advection is highlighted in experiment MOIST_EIO_NO_QADV, in which the horizontal moisture advection is suppressed and the resulting precipitation over both target regions decreases substantially (Fig. 9).

The moist mechanism that links the EIO to the monsoon trough can be summarized as follows. In response to cold SST anomalies over the EIO, moist stability due to surface fluxes increases and rainfall decreases. In response to this anomalous cooling, an anomalous anticyclonic circulation develops in the lower troposphere as a Rossby wave response. Over the central-eastern EIO this circulation advects climatological air of lower moisture content from the subtropics (Fig. 12a). The anomalous moisture gradient due to the imposed cold SST anomalies is advected westward to the central EIO by the climatological and anomalous easterlies. The net result is a zonally elongated anomalous dry pattern over the EIO (Fig. 7a). The divergent circulation that stems from the EIO (Fig. 10) strengthens the monsoon trough through advection of climatological air of higher moisture content from the equatorial region (Fig. 12a). The two regional heat sources are then connected by a meridional circulation (Fig. 12b). This circulation is then instrumental in maintaining and amplifying the dry (moist) convective anomaly over the EIO (along the trough). Neelin and Su (2005) concluded that in the deep tropics, interaction of atmospheric wave dynamics with moist convective processes is important in any teleconnection. Over the Asian monsoon domain, our results support their findings.

b. Discussion

Successful prediction of seasonal mean monsoon rainfall determines the socioeconomic conditions of millions of people in India. While dynamical seasonal monsoon prediction is still in its infancy, the statistical models employed by the India Meteorological Department have their own limitations (Rajeevan et al. 2006). Almost all predictors in regression models reflect the imprints of slowly varying boundary conditions, global or regional, but SST variations over the tropical Indian Ocean are not included in statistical models. The main reason is that observational and modeling studies suggest that large-amplitude SST variations over the EIO occur only during strong IODZM years and are episodic in nature. Nevertheless, IODZM-related SST anomalies modify EIO, one of the three regional heat sources, and influence the monsoon trough through interaction between equatorial waves and moist physics. Because of the coupled nature of IODZM and the fact that it grows during the monsoon season, coupled models appear capable of predicting July–August monsoon rainfall. Since anomalous wind advection of the climatological moisture dominates the total anomalous moisture advection, climate models need to capture the basic state as well as details of moist physics that heavily depend on the physical parameterizations employed.

More than 130 years ago, Blanford (1877) envisioned that the tropical Indian Ocean not only supplies the moisture for the monsoon rains but also is vitally linked to the intensity of the monsoon as a coupled land–atmosphere–ocean phenomenon. To date, simulating the monsoon basic state in coupled models, particularly the intensity and spatial distribution of the three regional heat sources (Fig. 1a), has been a challenge. There are a number of reasons for the models’ poor performance. First and perhaps most relevant is the complexity of the monsoon, which results from the interaction of phenomena on a variety of time (intraseasonal to interannual and longer) and space (regional to global) scales. Second, key physical processes (e.g., the generation of clouds) are not adequately represented in the models. The third reason is simply our lack of the observation of the three-dimensional moisture distribution and understanding of air–sea interaction processes in the tropical Indian Ocean. For instance, it is unclear which oceanic processes shape the three regional heat sources. More intriguingly, why does deep convection occur over the EIO during boreal summer? We are presently addressing these issues and investigating
the mechanism that links the EIO to the monsoon trough identified in this study at interannual time scales on other time scales.

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APPENDIX

LBM Budget Equations

In the moist LBM, equations governing the moisture and moist static energy budgets are briefly presented here. The temperature and moisture perturbation equations are given by

\[ \partial_t T' + D_T T' + \omega \partial_p s' = (Q_v)' + H', \]  
\[ \partial_t q' + D_q q' + \omega \partial_p q' = (Q_q)' + E', \]  

where \( (Q_v)' \), \( (Q_q)' \), \( H' \), and \( E' \) are the anomalous convective heat source, moisture sink, and surface sensible heat and latent heat fluxes, respectively. Also, \( s' = T' + \phi' \) is the anomalous dry static energy, where \( T' \) is temperature perturbation, \( \phi' \) is anomalous geopotential, and \( q' \) anomalous moisture; \( \omega \partial_p s' \) and \( \omega \partial_p q' \) are the anomalous dry and moist convergence, respectively. The anomalies here are with respect to the CM2.1 basic state. The symbols (\textsuperscript{\wedge}) and (\textsuperscript{\rangle}) represent vertical integration over the troposphere. The operators \( D_T \) (for temperature) and \( D_q \) (for moisture) include horizontal advection and horizontal diffusion terms:

\[ D = \mathbf{v} \cdot \nabla - K_H \nabla^2. \]  

Combining (A1) and (A2), and under steady-state conditions, the vertically integrated anomalous MSE equation is

\[ \omega \partial_p H' = -D_T T' - D_q q' + \left( \frac{g}{P_T} \right) (E' + H'), \]  

where \( \omega \partial_p H' \) is the anomalous MSE convergence, \( P_T \) is the constant reference pressure depth of the troposphere, and \( g \) is acceleration due to gravity. Since \( (Q_v)' = -\langle Q_v \rangle' = (g/P_T)P' \), the moisture budget equation, with \( P' \) as anomalous precipitation, can be written as

\[ P' = \left( \frac{P_T}{g} \right) [\omega \partial_p q' - D_q q'] + E. \]  

REFERENCES


Lau, K.-M., and P. H. Chan, 1986: Aspects of the 40–50-day oscillation during the northern summer as inferred from


