Interannual Variability of Indian Summer Monsoon arising from Interactions between Seasonal Mean and Intraseasonal Oscillations

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ABSTRACT

A significant fraction of interannual variability (IAV) of the Indian summer monsoon (ISM) is known to be governed by “internal” dynamics arising from interactions between high-frequency fluctuations and the annual cycle. While several studies indicate that monsoon intraseasonal oscillations (MISOs) are at the heart of such internal IAV of the monsoon, the exact mechanism through which MISOs influence the seasonal mean monsoon IAV has remained elusive so far. Here it is proposed that exchange of kinetic energy (KE) between the seasonal mean and MISOs provides a conceptual framework for understanding the role of intraseasonal oscillations (ISOs) in causing IAV and interdecadal variability (IDV) of the ISM. The rate of KE exchange between seasonal mean and ISOs is calculated in frequency domain for each Northern Hemispheric summer season over the ISM domain, using 44 yr of the 40-yr ECMWF Re-Analysis (ERA-40) data. The seasonal mean KE and the rate of KE exchange between seasonal mean and ISO shows a significant relationship at both the 850- and 200-hPa pressure levels. Since the rate of KE exchange between seasonal mean and ISO is found to be independent of known external forcing, the variability in seasonal mean KE arising from this exchange process can be considered as an internal component explaining about 20% of IAV and about 50% of IDV. Contrary to the many modeling studies attributing the weakening of tropical circulation to the stabilization of the atmosphere by global warming, this paper provides an alternative view that internal dynamics arising from scale interactions might be playing a significant role in determining the decreasing strength of the monsoon circulation.

1. Introduction

The dependence of agriculture, drinking water, and energy production on the Indian summer monsoon (ISM) rainfall makes it the lifeline for a large fraction of the world’s population. The economy, life, and property in the region are vulnerable to significant variability of the ISM on intraseasonal, interannual, and interdecadal time scales (Webster et al. 1998; Krishnamurthy and Goswami 2000; Goswami et al. 2006b). Hence, predicting the seasonal mean ISM rainfall is of great socioeconomic importance and has been attempted for many decades, albeit with limited success (Gadgil et al. 2005; Kang and Shukla 2006). Recognizing the fact that the tropical climate is largely determined by changes in slowly varying boundary forcing, a physical basis for prediction of seasonal mean monsoon rainfall was proposed by Charney and Shukla (1981). This concept, supported by a large number of modeling studies (e.g., Shukla 1998), established the basis for seasonal prediction in the tropics. Such slowly varying forcing can be considered “external” for the atmosphere, and may be predictable as it arises from the slow oscillations of the coupled climate system. Some of the major external forcings—the El Niño–Southern Oscillation (ENSO), Indian Ocean dipole (IOD), Atlantic multidecadal oscillation (AMO), and Eurasian snow cover—are known to influence the interannual variability (IAV) and interdecadal variability (IDV) of the Indian monsoon and have been well documented. Initially identified from correlations, the physical mechanisms and different pathways through which these phenomena influence the Indian monsoon have been further elucidated through diagnostic studies and model simulations (Rasmussen and Carpenter 1983; Shukla and Paolino 1983; Webster et al. 1998; Krishnamurthy and Shukla 2008; Goswami et al. 2006a; Krishnamurthy and Goswami 2000; Krishna Kumar et al. 2006; Hahn and Shukla 1976).

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While some fraction of the IAV of the seasonal mean may be governed by such predictable external forcing, a fraction of the IAV of the seasonal mean may arise from interactions among different scales of motion, interaction between seasonal mean and ISOs, interaction between organized convection and large-scale circulation, interaction between flow and topography, and so on. The contribution to the IAV of seasonal mean arising from these processes is collectively called the “internal” component. It has been argued that the IAV of seasonal mean caused by the internal component is less predictable (Goswami 1998). Hence, the potential predictability of the seasonal mean would depend on the relative contribution of the external and internal components to the IAV. Recent studies using both observational analysis and model simulations (Ajaya Mohan and Goswami 2003; Kang et al. 2004; Goswami and Xavier 2005; Krishna Kumar et al. 2005) show that the Asian monsoon region is an exception in the tropics where the potential predictability is relatively low, underpinning the role of internal variability compared to external variability over this region. The seminal role of internal variability in determining the seasonal mean may be one reason for the current poor skill of almost all models in predicting the seasonal mean ISM rainfall (Kang and Shukla 2006). A clear understanding of the mechanism responsible for the internal IAV over the ISM domain may help us develop better initialization techniques for improving the seasonal forecast.

The intraseasonal oscillations are quasi-periodic fluctuations of atmospheric origin, which play a major role in determining the amplitude of seasonal mean of individual summer seasons by modulating the strength and duration of active/break spells of the ISM through the northward-propagating 30–60-day mode and the westward-propagating 10–20-day mode (Goswami 2005, and references therein). The ISOs are also found to exert an indirect control on the seasonal mean by modulating the synoptic-scale activity through clustering of lows and depressions along the monsoon trough (Goswami et al. 2003). Hence, the IAV of monsoons arising from interaction between seasonal mean and ISOs may be a major source for internal IAV. The internal IAV has received much attention recently and a few studies have proposed mechanisms for the generation of internal IAV involving summer ISOs (Sperber et al. 2000; Goswami and Ajaya Mohan 2001; Goswami et al. 2006b; Hoyos and Webster 2007). Since the dominant modes of IAV of the seasonal mean and the ISOs share a common spatial pattern, it is hypothesized that a shift in the probability density function of ISOs can give rise to some internal IAV (Ferranti et al. 1997; Sperber et al. 2000; Goswami and Ajaya Mohan 2001). It has also been argued that nonlinear interaction between the ISOs and the annual cycle could give rise to a biennial internal variability of the monsoon (Goswami 1995; Goswami et al. 2006b). While these studies demonstrated the proof of the concept using simple heuristic models, the quantitative contribution of such interactions to the observed IAV could not be estimated. Several studies showed the existence of significant correlation between the seasonal mean and the ISO over the ISM domain, indicating a physical relationship between these two scales (Lawrence and Webster 2001; Qi et al. 2008; Fujinami et al. 2011). Corroborative evidence in this direction is also obtained by estimating the correlation between area-averaged variance of ISO and seasonal mean rainfall over India for 104 yr (correlation coefficient = 0.53). The correlation is much higher during the recent 54-yr period (correlation coefficient = 0.64) (Fig. 1a). Although all these studies provide circumstantial evidence for the link between ISOs and seasonal mean over the ISM domain, no clear picture of how ISOs lead to internal IAV has emerged so far. Thus, a physical mechanism through which the ISOs influences the seasonal mean and introduces internal IAV still remains an open question.

Recently, Qi et al. (2008) made an attempt to quantify the role of ISO perturbations in determining the strength of the mean zonal wind, and thereby the strength of ISM, through a dynamical framework. The relationship between the mean zonal wind tendency and the eddy momentum transport was derived from the primitive equations of motion. It is shown that the eddy momentum transport can significantly affect the westerly tendency during strong and weak ISO years. However, since the eddy momentum transport term includes variability on all time scales, the role of ISO feedback in affecting the strength of the mean westerly is not clear. Moreover, the seasonal mean variability of ISM rainfall is more strongly related to the strength of the winds over the low-level jet (LLJ) and the upper-level tropical easterly jet (TEJ) regions (Figs. 1b,c). Besides, not only the zonal wind but also the meridional wind component is significant. Figure 2a shows the seasonal mean rainfall averaged over the Indian landmass (6.5°–27.5°N, 72.5°–85.5°E) and the seasonal mean kinetic energy (KE) at 850 hPa averaged over the LLJ core region (0°–20°N, 50°–70°E). A strong correlation of 0.61 significant at the 95% confidence level establishes the connection between the seasonal mean rainfall and the cross-equatorial flow. Figure 2b shows the seasonal mean rainfall averaged over the landmass and the seasonal mean KE at 200 hPa averaged over the TEJ region (0°–15°N, 50°–80°E). The moderately strong correlation coefficient (0.52, significant at the 95% confidence level) suggests a significant relationship between the strength of upper-level monsoon circulation and seasonal...
The strong relationship between the IAV of KE of LLJ and that of TEJ and monsoon rainfall implies that better insight into the IAV of monsoon rainfall can be obtained through understanding the mechanisms of IAV of LLJ KE and TEJ KE. To quantify the role of interaction between seasonal mean and ISOs in causing the IAV and IDV of the seasonal mean, the analysis scheme presented by Qi et al. (2008) is reframed using spectral energetic analysis. In the present study, we investigate how scale interactions between the seasonal mean monsoon and the ISOs can give rise to variability of kinetic energy of the monsoon flow on interannual and interdecadal time scales.

The data used in this study are described in section 2. A dynamical framework for the ISO–seasonal mean interaction in terms of atmospheric energetics is given in section 3. Details of the computation of KE exchange between the seasonal mean and ISO is presented in section 4. Section 5 describes the IAV and IDV of the exchange of KE between the seasonal mean and ISOs, and its relationship with the IAV and IDV of seasonal mean. The issue of sensitivity of temporal window length on the calculation of seasonal mean–ISO interaction is addressed in section 6. The dependence of the KE exchange on the reanalysis data used is discussed in section 7. Section 8 summarizes the important results.

2. Data

Our primary analysis is based on 44 yr (1958–2001) of the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analyses (ERA-40) daily wind data (Uppala et al. 2005) at the 850- and 200-hPa pressure levels for the ISM period [i.e., June–September (JJAS)]. The consistency of the analysis is tested with National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis daily wind data (Kalnay et al. 1996). We have also used high-resolution 1° × 1° daily rainfall data available for the period 1901–2004 (Rajeevan et al. 2008). Monthly Niño-3.4 data available from 1871 to 2007 are downloaded from the NCAR Earth System Laboratory (http://www.cgd.ucar.edu/cas/catalog/climind/TNI_N34/) and the JJAS mean was calculated. The Pacific decadal oscillation (PDO) index is downloaded (from
3. Dynamical framework for understanding the ISO–seasonal mean interaction

The dynamic effect of transient eddies on the time mean flow received considerable attention during the 1970s and 1980s (Holopainen 1978a; Hoskins et al. 1983; Hoskins and Pearce 1983). Most of these studies focused on the influence of transient disturbances on the local time mean flow over the midlatitude regions in terms of large-scale Reynolds stresses in a quasigeostrophic (QG) framework. The atmospheric flow at any time period can be partitioned as the sum of time mean and transient fluctuations, and this concept was used by Holopainen (1978b) to derive the growth or decay of time mean KE using the primitive equations of motion. The rate of change of time mean KE is the resultant of various physical processes. The abbreviated representation of the equation for the rate of change of KE is given below (the complete forms of the equations are given in the appendix):

\[
d(\overline{K})/dt = BC + CAK + WF + D, \tag{1}
\]

where \(\overline{K}\) represents the time mean KE, BC represents the barotropic energy conversion, CAK stands for conversion of available potential energy (APE) to KE, and WF and \(D\) indicate the wave energy flux and dissipation due to friction, respectively. The term CAK acts as the source for KE through conversion from APE generated by the diabatic heat sources in the tropics. The wave energy flux term includes the advection of KE as well as the work done by pressure. The BC term involves eddy–time mean interaction. The mechanism for the growth or decay of KE in the time mean scale can be summarized as follows.

The net radiation balance and the resultant equator-to-pole temperature gradient maintain a thermally direct large-scale circulation (Hadley circulation) in the tropics (Held and Hou 1980; Schneider and Lindzen 1977). Such a circulation in the presence of abundant moisture favors large-scale deep convection in the tropics. Deep convective activity generates APE that gets converted to KE in various scales. The time mean may gain KE through this direct conversion. Besides, the KE of the time mean scale over a local domain may result from barotropic energy conversion involving eddy–time mean interactions and from advection of KE by time mean and eddies. This is the basic principle behind the analysis used in this study.

This framework has been widely used by many studies to quantify the effect of transient eddies over different tropical regions (Lau and Lau 1992; Maloney and Hartmann 2001; Seiki and Takayabu 2007; Serra et al. 2008). The growth of barotropic eddy KE through eddy–time mean flow interaction over the eastern and western Pacific was studied by Maloney and Hartmann (2001), and this study noted the role of the Madden–Julian oscillation (MJO) in making favorable conditions for the formation of tropical cyclones over the Pacific. The eddy momentum transport term used in the study by Qi et al. (2008) can be viewed as an approximate form of the term BC. The interaction between transient eddies and time mean depends on the averaging period. The transient fluctuations include a collection of time scales whose maxima and minima depend on the time resolution and length of the averaging period. The goal of the present study is to quantify the feedback between the ISO and seasonal mean time scale over the ISM domain. Such a feedback involves interactions between the time mean and multiple frequencies in the ISO scale. Hence, in the place of eddy–time mean interaction framework, we study the scale interactions in the spectral framework.

The spectral energetic analysis method was originally introduced by Saltzman (1957) in the wavenumber domain for estimating the eddy KE contribution coming from different spatial scales. This formulation led to several case studies examining the role of KE exchange between zonal mean and waves, mostly the role of planetary-scale waves in the extreme behavior of the monsoon (Kanamitsu et al. 1972; Awade et al. 1982). However, the monsoon ISO is defined as the fluctuations whose time scale is greater than synoptic scale but less than the seasonal cycle; the energetic analysis in the wavenumber domain is not suitable for extracting the information about interactions between time mean and monsoon ISO over a region. Hayashi (1980) modified Saltzman’s scheme using a cross-spectral technique, and it can be used for studying the interactions between different scales of motion and the spectral transfer of energy in both wavenumber and frequency space.
Hayashi’s analysis scheme decomposes the KE equation in the frequency domain, and the energy conversions among different time scales can be studied through spectral windows of different frequency ranges. A comprehensive study of the spectral energetics of the atmospheric circulation in the frequency domain was carried out by Sheng and Hayashi (1990). Since then, this method has been extensively used for quantifying the interactions among different time scales ranging from synoptic to interannual over different tropical domains (Krishnamurti et al. 2000, 2003; Krishnamurti and Chakraborty 2005; Neena and Goswami 2010). In this study, we adopt an energetic analysis in the frequency domain to gain insight into the mechanism of interaction between ISO and seasonal mean of the ISM and the IAV caused by this process.

4. Kinetic energy exchange between seasonal mean and ISO

The growth or decay of KE in the frequency domain can be derived by applying Fourier analysis in time on the zonal and meridional momentum equations in spherical coordinate and by solving the resultant equations with the continuity equation. Analogous to Eq. (1) in the time domain, the time rate of change of KE in the frequency domain can be represented by Eq. (2):

$$\frac{\partial K^n}{\partial t} = \langle(K^n, K^p) \cdot K^n \rangle + \langle K \cdot K^n \rangle + \langle A^n \cdot K^n \rangle + E^n .$$

The rate of KE of a given scale $n$ $K^n$ involves four different physical processes. The first process represents the transfer of KE to the scale of frequency $n$ from a couple of other frequencies $m$ and $p$ that are governed by a trigonometric selection rule, namely $n = m + p$ or $n = |m - p|$ for an exchange. The second process is the growth (or decay) of KE of the given frequency $n$ when it interacts with $K$. The third process is the growth (or decay) of KE of a given frequency from the eddy available potential energy $A^n$ at the same scale. The last term $E^n$ represents the net loss or gain of KE of frequency $n$ by friction.

We adopt the method proposed by Hayashi (1980) for calculating the exchange of KE between the seasonal mean and individual frequencies. A positive (negative) sign for $\langle K, K^n \rangle$ implies that the seasonal mean loses (gains) energy to (from) the frequency $n$. The terms involved in the exchange calculation at a particular pressure level are given as follows:

$$\langle K \cdot K^n \rangle = -\left[ \frac{\partial P^n(u, u)}{\partial x} + \frac{\partial P^n(u, v)}{\partial y} \right]_{A} - \left[ \frac{\partial P^n(u, v)}{\partial y} + \frac{\partial P^n(v, v)}{\partial y} \right]_{B} - \frac{\tan \theta}{\alpha} \left[ \pi P^n(u, v) - \nu P^n(u, u) \right]_{C}$$

$$- \left[ \frac{\partial K^n}{\partial x} + \frac{\partial K^n}{\partial y} \right]_{D} - \left[ \frac{\partial P^n(u, v)}{\partial x} + \frac{\partial P^n(v, v)}{\partial x} \right]_{E} ,$$

where $u$, $v$, and $\omega$ respectively represent the zonal, meridional, and vertical wind components in pressure coordinates and $\pi$, $\nu$, and $\overline{\nu}$ are their seasonal mean counterparts. Also, $P^n$ and $K^n$ are the cross-spectral coefficient of frequency $n$ and KE of $n$th frequency, respectively; $\theta$ is the latitude and $\alpha$ is the radius of the earth.

It can be inferred from Eq. (3) that the calculation of the rate of KE exchange between seasonal mean and any scale $n$ involves five components (A–E). First, two terms involves the horizontal gradient of seasonal mean $u$ wind, seasonal mean $v$ wind, and the cross-spectral coefficients. The third term represents the product of the curvature term, seasonal mean $u$ and $v$ winds, and the cross-spectral coefficients. The fourth term is the convergence of KE of scale $n$ due to seasonal mean wind. The last term (E) implies the baroclinic processes through which the scale $n$ and the time mean interact. Since the order of magnitude of the terms involving the vertical derivative is very small, it is neglected. This formulation can be used for examining the rate of KE exchanges among different scales over a local domain, which would be helpful in understanding the fundamental dynamics of interactions between different scales over the region.

The rate of KE exchange between seasonal mean and each frequency during the 1958–2001 summer seasons is calculated using JJAS daily wind data of length 122 days. With 122-day data for each season, 61 frequencies are resolved. Grouping those frequencies that come under the ISO scale (10–60-day periodicity, 2–12 harmonics), the sum of KE exchange by all of these frequencies with the seasonal mean is considered as the net KE exchange by the ISOs with the seasonal mean. The harmonics representing 122-day periodicity is not considered as part of ISO since it is close to the seasonal cycle. The
rate of KE exchange between the seasonal mean and ISO for 44 summer seasons is calculated using ERA-40 wind data at 200 hPa over the region 0°–15°N, 50°–80°E, where a significant relationship exists between the wind strength and the seasonal mean Indian monsoon rainfall. Figure 3a shows the IAV of rate of KE exchange between the seasonal mean and ISO (thick black line) at 200 hPa and the contributions of different terms in Eq. (3) to this exchange. While during most years the ISOs take energy from the seasonal mean, the net exchange also exhibits considerable IAV. The convergence of ISO KE due to seasonal mean zonal wind dominates the net rate of KE exchange at 200 hPa. It explains about 43% of the total variability. Similar to the net rate of KE exchange, the convergence of ISO KE due to seasonal mean u wind also gives energy to the ISO scale. No notable trend is observed in this exchange. The convergence of ISO KE due to meridional wind is always negative, which means that energy is transferred to the seasonal mean scale. A decreasing trend is observed in this exchange, which implies that the seasonal mean is losing more energy to the ISO in recent decades. The sum of the first, second, third, and \(-d(V_0K_u)/dy\) terms cancel out each other, making the effective contribution of these terms nearly zero and leaving the last term \([-d(U_0K_u)/dy]\) to dominate the net KE exchange.

The same analysis is repeated at 850 hPa over the LLJ core region that shows a strong relationship with the Indian monsoon rainfall. Figure 3b shows the net rate of KE exchange between seasonal mean (thick black line) and ISO and the contributions from different terms in Eq. (3) to this exchange. One interesting fact to be noted in Figs. 3a and 3b is the opposite sign of the \(-d(U_0K_u)/dx\) and \(-d(V_0K_u)/dy\) components in the upper and lower atmosphere. It may be related to the opposing directions of circulation in the lower and upper levels. If the rate of KE exchange between seasonal mean and ISO were significant to make changes in the amplitude of seasonal mean KE, it would be reflected in the variability of seasonal mean KE and there would be a significant phase relationship between seasonal mean KE and the rate of KE exchange between seasonal mean and ISO. In the next section, evidences for significant internal interannual and interdecadal variability are presented.

5. Internal interannual and interdecadal variability of the ISM

To quantify the variability of the ISM IAV associated with the central Pacific SST anomaly, seasonal mean KE at 200 hPa over the TEJ region is correlated with the seasonal mean Niño-3.4 index for the 1958–2001 period. The Niño-3.4 index represents the area-averaged SST anomaly over the region 5°S–5°N, 120°–170°W. The correlation coefficient between the two is \(-0.53\), significant at the 95% confidence level. Thus, the ENSO can explain about 30% of the IAV of seasonal mean ISM (as represented by the KE of TEJ).

Although the ENSO is a dominant driver of IAV of most of the climate systems around the globe, about 70% of the IAV of the ISM arises from processes other than the ENSO. External forcing such as IOD and the North Atlantic SST anomaly could together explain another 30% of the ISM IAV (Table 1). Hence, it is suspected that the internal processes can account for some of the unexplained variability. The rate of KE exchange between the seasonal mean and ISO (10–60 day) at 200 hPa is calculated over the same region for the same time period using ERA-40 data. Figure 4a shows the IAV of seasonal mean KE at 200 hPa and the rate of KE exchange between seasonal mean and ISO over the TEJ region. It can be inferred from the figure that almost all of the years during which the seasonal mean KE shows a local maximum, ISO supplies energy to the seasonal
mean. At the same time, whenever the seasonal mean KE is low, either the ISO takes energy away from the seasonal mean or contributes little to the seasonal mean. Thus, it clearly demonstrates that internal processes (i.e., energy exchange among scales) can significantly affect the amplitude of seasonal mean and thereby cause its variability on interannual time scale (Hoyos and Webster 2007). The correlation coefficient between the KE of seasonal mean and the KE exchange between ISO and seasonal mean is 0.42, significant at the 95% confidence level. Despite exhibiting a significant relationship with the seasonal mean KE, the ENSO and other sources of external forcing do not exhibit any relationship with the energy exchange processes, indicating that the process is purely internal (Table 1). The ENSO effect is removed from the seasonal mean KE by regressing it with the Niño-3.4 index. The ENSO removed seasonal mean KE shows enhanced relationship (correlation coefficient = 0.48) with the energy exchange. Hence, it may be concluded that the internal process can explain about 20% of the IAV of seasonal mean of the ISM.

Since the South Asian monsoon is a result of baroclinic response of the atmosphere to deep tropospheric convective heating, the lower-level circulation is expected to be related to the upper-level circulation. Hence, a similar relationship can be expected to exist in the lower atmosphere between the KE of seasonal mean and its exchange with the ISO. The seasonal mean KE at 850 hPa over the LLJ core region and the rate of KE exchange between the seasonal mean and ISO are calculated for the 1958–2001 period using ERA-40 data. Figure 4b corroborates the finding at 200 hPa. It shows a correlation coefficient of −0.28. Even though it is not as strong as that in the upper atmosphere, the relationship improves (correlation coefficient = −0.31) when the ENSO effect is removed from the seasonal mean KE by linearly regressing it with the Niño-3.4 index (Table 1).

**TABLE 1.** Correlations at 850 and 200 hPa on interannual and interdecadal time scales. For the interannual time scale a correlation coefficient greater than 0.25 is significant at 95% confidence level for 42 degrees of freedom. For the interdecadal time scale the significance is also estimated at 95% confidence level. The significant correlations are in boldface.

<table>
<thead>
<tr>
<th>Correlation coefficient</th>
<th>Interannual time scale</th>
<th>Interdecadal time scale</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>850 hPa</td>
<td>200 hPa</td>
</tr>
<tr>
<td>Seasonal mean KE and seasonal mean rainfall</td>
<td>0.61</td>
<td>—</td>
</tr>
<tr>
<td>Seasonal mean KE and exchange</td>
<td>−0.28</td>
<td>−0.425</td>
</tr>
<tr>
<td>Seasonal mean KE and Niño-3.4</td>
<td>−0.33</td>
<td>−0.53</td>
</tr>
<tr>
<td>Exchange and Niño-3.4</td>
<td>−0.095</td>
<td>0.03</td>
</tr>
<tr>
<td>ENSO removed seasonal mean KE and exchange</td>
<td>−0.31</td>
<td>−0.48</td>
</tr>
<tr>
<td>Partial correlation coefficient between seasonal mean KE and exchange excluding the influence of Niño-3.4</td>
<td>−0.33</td>
<td>−0.483</td>
</tr>
<tr>
<td>Seasonal mean KE and IOD</td>
<td>−0.0574</td>
<td>−0.39</td>
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<tr>
<td>Exchange and IOD</td>
<td>0.0405</td>
<td>−0.0623</td>
</tr>
<tr>
<td>Seasonal mean KE and North Atlantic SST</td>
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<td>0.39</td>
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<tr>
<td>Exchange and North Atlantic SST</td>
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<td>−0.107</td>
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<tr>
<td>Seasonal mean KE and AMO</td>
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<tr>
<td>AMO removed seasonal mean KE and exchange</td>
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<td>Seasonal mean KE and PDO</td>
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<tr>
<td>Exchange and PDO</td>
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<tr>
<td>Partial correlation coefficient between seasonal mean KE and exchange excluding the influence of PDO</td>
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</table>

**FIG. 4.** Seasonal mean kinetic energy per unit mass (m² s⁻², solid line) and the rate of kinetic energy (per unit mass) exchange between the seasonal mean and 10–60-day time scale (×10⁻⁵ W kg⁻¹, dashed line) calculated using ERA-40 data (a) at 200 hPa over the region 0°–15°N, 50°E–80°E and (b) at 850 hPa over the region 0°–20°N, 50°–70°E. The corresponding correlation coefficients (CC) are given at the upper-left corner of each panel.
The moderate relationship between seasonal mean KE and the energy exchange process can be understood by considering the fact that the 850-hPa atmosphere is close enough to come under the influence of the planetary boundary layer and scale separation in the noisy atmosphere is difficult. In addition to that, the friction term and boundary fluxes are neglected while calculating the exchange over the ISM domain both in the upper and lower atmosphere. The boundary flux terms become zero when the equation is integrated over the globe, but it is nonzero if the calculation is restricted to a small area. The relationship between the seasonal mean KE at 850 hPa and the ENSO is also weak (it shows only a moderate correlation coefficient of $0.33$). Similar to the upper atmosphere, the exchange process shows no relationship with the ENSO. The exchange process and its phase relationship with the seasonal mean KE at 850 hPa validate our finding that the scale interaction is purely internal, and it can explain considerable amount of IAV of the ISM.

Since the KE exchange between ISO and seasonal mean is strongly related to the seasonal mean KE, any long-term tendency of this exchange may lead to longer-term variability of the ISM. The internal IDV of the ISM can be brought out by applying an 11-yr running mean on both the seasonal mean KE and the exchange. The running mean is the simplest available low-pass filter that removes fluctuation whose periodicity is less than its window size by preserving the low-frequency oscillation. However, when computing the correlation between two time series subject to low-frequency filtering, one has to be cautious about the reduced number of degrees of freedom. Filtering has the effect of smoothing the time series and thereby increasing the autocorrelations between the members of the time series. Here, following Chen (1982), we estimate the effective time between independent members $t_{	ext{eff}}$, and the effective degrees of freedom, using the autoregressive properties of both time series. All the correlations on interdecadal time scale discussed in the following sections are statistically checked for significance at 95% confidence level, using the corresponding effective degrees of freedom computed by this method.

Figure 5a shows the 11-yr running mean of the seasonal mean KE and the exchange at 200 hPa calculated using ERA-40 data. The low-frequency seasonal mean KE exhibits a linear decreasing trend with a multidecadal variability embedded in it. The low-frequency rate of KE exchange between the seasonal mean and ISO is always positive except for some part of 1960s, and it shows a linear increasing trend and multidecadal variability. The seasonal mean KE and the exchange are strongly linked with a correlation coefficient of $0.71$ (Table 1). The relationship is unaffected whether the linear trend is removed from both time series or not. Hence, the internal processes can explain nearly half of the interdecadal ISM variability. The weakening of upper-level ISM strength and its multidecadal variability can be explained in terms of energy exchange between the seasonal mean and ISO. During the initial periods, when seasonal mean KE was high, ISO supplied KE to the seasonal mean but later the seasonal mean started...
losing energy to the ISO. The fluctuations in the rate of KE exchange can account for the local maxima and minima in the seasonal mean KE. It can be deduced that ISO takes more and more energy from the seasonal mean and makes it lose its strength. Still, the question of modulation of interdecadal energy exchange process by external forcing may arise. The IDV of ENSO, IOD, PDO, and AMO was brought out by applying a 11-yr running mean on the JJAS mean Niño-3.4, IOD, PDO, and North Atlantic SST anomaly indices, respectively. Unlike the case of the interannual time scale, on the interdecadal scale the exchange process and external forcings are linked (Table 1). Figures 5b–d show the ENSO-, PDO-, and AMO-removed interdecadal seasonal mean KE and the rate of KE exchange between seasonal mean and ISO. The removal of external forcings not only preserved the linear trend and multidecadal variability in the seasonal mean KE and the exchange process but also improved the correlation coefficient between them (Table 1). It may be cautioned that in our analysis we removed only the linear relationship between the exchange and external forcing. There may still be some variability associated with complex nonlinear interaction among the different external forcing components.

The internal interdecadal variability is further examined at the lower level by applying an 11-yr running mean on seasonal mean KE and the energy exchange process at 850 hPa. Contrary to the observation of linear decreasing trend in the upper-atmospheric ISM strength, lower-atmospheric seasonal mean KE exhibits a linear increasing trend on interdecadal time scales (Fig. 6). It also shows a multidecadal variability. The exchange process is always negative; that is, the ISO always supplies energy to the seasonal mean. Analogous to the upper atmosphere, the long-term behavior and fluctuations can be explained in terms of energy exchange. The 11-yr running mean smooths out the high-frequency fluctuations and reveals a strong link between strength of the ISM and the energy exchange process on the interdecadal time scale. The relationship is unaltered whether the known quantifiable external forcing signal is removed or not. Consistent with the upper-atmospheric observation, the internal process can explain about 50% of the interdecadal variability of the ISM. In the next section, we discuss the sensitivity of our results to the temporal window length.

6. Temporal window length and the estimate of time mean–ISO interaction

Since the number of resolvable harmonics of a time series depends on the length of the time series, it is possible that the estimate of seasonal mean–ISO energy exchange may be influenced by the temporal window length. If the energy exchange is very much sensitive to the temporal window length, the estimation of IAV of seasonal mean due to the seasonal mean–ISO energy exchange may lead to unrealistic conclusions. To check the robustness of our results, we repeated our calculation by extending the length of the time series from 122 to 150 days, considering the data from 17 May to 14 October. The newly constructed time series not only brings in more harmonics in the ISO time scale but also extends the largest resolvable time scale from 60 to 75 days. Figure 7 compares the seasonal mean–ISO energy exchange estimated using 122- and 150-day windows at the 200- and 850-hPa pressure levels. Consistency in the estimation of energy exchange is observed at both levels at a correlation of 0.88 and 0.83, respectively (Figs. 7a,b), and it is reflected in the correlation coefficient of IAV of seasonal mean KE and the energy exchange between seasonal mean and 10–75-day KE ($R^2 = 0.47$ at 200 hPa and $R^2 = 0.41$ at 850 hPa). The inclusion of the 75-day scale and higher time scale resolution in the estimation of IAV of the seasonal mean due to feedback between seasonal mean and ISO brings about only a slight change, and the discrepancy is not significant.

7. Reanalysis data and rate of KE exchange calculation

The reliability of our results depends upon how well ERA-40 data capture the behavior of the true atmosphere. To quantify the interannual and interdecadal variability, long datasets are required. The changes in observing systems at the beginning of satellite era after the mid-1970s always raise a concern about the use of reanalysis products for analyzing long-term trends and multidecadal variability (Bengtsson et al. 2004). The consistency of our results is checked by repeating the analysis at 200 hPa with another independent dataset,
NCEP–NCAR reanalysis data, for the 1958–2001 JJAS months, and it is presented in Fig. 8. Consistent with the result obtained from the ERA-40 data, it also shows a moderate correlation of $0.42$, which is statistically significant at the 95% confidence level.

Although the amount of variability explained by the internal process is the same for both reanalysis products, the decreasing trend of seasonal mean KE at 200 hPa was more pronounced in the ERA-40 dataset. In addition, the nature of variability of the rate of KE exchange was different for both datasets. It can be noted from Figs. 9a and 9b that although the interannual seasonal mean KEs are in phase, NCEP–NCAR data overestimate the seasonal mean KE at 200 and 850 hPa. To examine this discrepancy, the seasonal mean KE is disintegrated into zonal and meridional components at 850 and 200 hPa and are presented in Fig. 10. It shows that there are differences in both amplitude and phases of meridional component of the seasonal mean KE at both levels. Also, there is no phase relationship between the zonal and meridional components of the seasonal mean KE of NCEP–NCAR dataset. For example, at 200 hPa, seasonal mean $U^2/2$ is decreasing but the seasonal mean $V^2/2$ shows a steady linear increasing trend. The cross-spectral method of estimation of KE exchange involves products of spectral coefficient and seasonal mean wind components. Hence, the difference in the phases of wind components can cause a discrepancy in the exchange estimation. The difference in the meridional KE between the two reanalyses may be related to the fact that the tropical divergent component of the wind is rather weak in the NCEP–NCAR reanalysis (Annamalai et al. 1999). Because of the biases in the meridional component of NCEP–NCAR reanalysis wind data, throughout our study we have used ERA-40 data, which show a coherent behavior of zonal and meridional wind at both 850 and 200 hPa.

8. Summary and conclusions

In this study, we have introduced a conceptual framework for quantifying the role of ISO in causing
interannual and interdecadal variability of the seasonal mean ISM. Although there have been some studies that indicated evidence for such an interaction over the ISM domain, such as the correlation between seasonal mean and ISO variance, a clear mechanism through which such an interaction takes place had remained elusive (Goswami and Ajaya Mohan 2001; Lawrence and Webster 2001; Qi et al. 2008). As the ISOs represent a dominant mode of summer monsoon variability, we hypothesize that the ISOs play a significant role in modulating the seasonal mean through scale interaction and causing internally generated interannual and interdecadal variability of the seasonal mean.

A cross-spectral method of estimation of KE exchange in the frequency domain (Hayashi 1980) is employed for quantifying the interannual and interdecadal seasonal mean–ISO interaction. The analysis is done using ERA-40 wind data at the 850- and 200-hPa pressure levels over the region where the seasonal mean KE shows a significant relationship with the seasonal mean ISM rainfall. It is found from the energy exchange calculation in both the upper and lower atmosphere that the amplitude and phases of the net rate of KE exchange between seasonal mean and ISO is determined by the convergence of ISO KE by seasonal mean zonal wind.

The internal interannual and interdecadal variabilities were quantified by correlating the seasonal mean KE phase variability with the rate of KE exchange between the seasonal mean and ISO at upper and lower levels. It is found that the long-term trend and much of the variability of the seasonal mean KE could be related to the exchange of energy between seasonal mean and ISO. The issue of sensitivity to choice of temporal window length on the energy exchange is addressed separately by extending the length of the time series. The KE energy exchange process at 200 hPa is less noisy and relatively free of boundary layer turbulence, hence its variability with the seasonal mean KE is considered for the quantification of internal variability of the ISM seasonal mean. Although contaminated by friction and boundary flux terms, the lower-level atmosphere also shows a statistically significant relationship, which is also independent of any known and quantifiable external boundary forcing. On the whole, the influence of external forcing on the exchange process is negligible on interannual time scale, while on interdecadal time scale external forcing does have some contribution. The internal IAV of the ISM could independently account for approximately 20% of the ISM seasonal mean variability. It is shown that in both the upper and lower atmosphere the energy exchange process could explain about 50% of the variability of the ISM seasonal mean on an interdecadal time scale. This conclusion was drawn on the assumption that the relationship between the exchange and the different external forcing components is linear. There may still exist some unaccounted external variability arising from nonlinearity and this may be a caveat in our analysis. Another issue that demands

Fig. 10. (a),(c) Seasonal mean (JJAS) $U^2/2$ (m$^2$ s$^{-2}$) calculated using NCEP–NCAR reanalysis (solid line) and ERA-40 data (dashed line), at (a) 200 and (c) 850 hPa. (b),(d) Seasonal mean (JJAS) $V^2/2$ (m$^2$ s$^{-2}$) calculated using NCEP–NCAR reanalysis (solid line) and ERA-40 data (dashed line) at (b) 200 and (d) 850 hPa.
a closer examination is the weakening of the relationship between seasonal mean and ISOs after the mid-1970s. At present, it is not clear whether this difference is due to the reported mid-1970s climate regime shift or is simply an artifact of reanalysis dataset.

The weakening of the monsoon circulation on interdecadal time scales as evidenced by a decreasing trend of seasonal mean KE of the TEJ is often attributed to global warming (Vecchi et al. 2006; Vecchi and Soden 2007). Based on a modeling study, Chou and Chen (2010) proposed that increase in global temperature would cause an uplifting of the tropopause, which may favor deeper convection and eventually lead to an increase in the stability and weakening of the tropical circulation. However, we speculate that this decreasing trend of seasonal mean KE could be partially explained through an internal dynamical process where the mean is losing increasingly more energy to the ISOs through scale interactions.

Concerns about the usage of reanalysis data for the study of multidecadal variability and long-term trend are also discussed separately. It is found that the zonal component of KE is slightly overestimated in NCEP–NCAR reanalysis but is well correlated on interannual time scale with that in the ERA-40 dataset. However, there are some notable differences in the meridional component of KE in the two products. Significant relationships between the ERA-40 wind data and rain gauge data add further confidence in using it. It is already known that the ISO can influence the synoptic activity through clustering of lows and depression along the monsoon trough (Goswami et al. 2003). In the present study, we demonstrate the role of ISO in modulating the ISM seasonal mean on interannual and interdecadal time scale. This emphasizes on the need for further research in improving the simulation of MISO in order to improve the prediction of monsoon on short, medium, and longer time scales, since it not only affects active and break spells but also affects the variability in other scales.

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APPENDIX

Derivation of Rate of Change of Time Mean Kinetic Energy

The rate of change of time mean kinetic energy in the transient eddy–time mean framework is represented by Eq. (1). The equation is derived in Cartesian coordinates from the momentum equations and the continuity equation by assuming that the large-scale atmosphere is in the state of hydrostatic balance. Variant forms of Eq. (1) were used by different researchers (Holopainen 1978b; Lau and Lau 1992; Maloney and Hartmann 2001, Serra et al. 2008) to quantify the eddy–time mean interactions. Here we again present Eq. (1):

$$d(K)/dt = BC + CAK + WF + D.$$  

Variables with an overbar represent the time mean and the primed quantities represent the transient eddies. The expansion of the components of Eq. (1) is given below:

$$\text{BC} = u'u'\partial u/\partial x + u'v'\left(\partial u/\partial y + \partial v/\partial x\right) + a'v'\partial p/\partial y, \quad \text{(A1)}$$

$$\text{CAK} = \overline{\alpha}\overline{\omega}, \quad \text{(A2)}$$

$$\text{WF} = \nabla \cdot \left[\phi \nabla + \overline{k \cdot V} + \left(\overline{V \cdot V'}\right) V'\right], \quad \text{(A3)}$$

$$D = \nabla \cdot f, \quad \text{(A4)}$$

where $V$ represents the horizontal velocity and $u$, $v$, and $\omega$ respectively represent the zonal, meridional, and vertical components of velocity. Also, $k$ stands for kinetic energy per unit mass [i.e., $(u \times u + v \times v)/2$], $\Phi$ and $\alpha$ represent the geopotential height and specific volume, respectively, and $f$ stands for friction.

REFERENCES


