The Dominant Modes of Recycled Monsoon Rainfall over India

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ABSTRACT

This study estimates the seasonal mean (June–September) recycled rainfall and investigates its dominant modes of variability over the continental regions of the Indian summer monsoon. A diagnostic method based on the basic atmospheric water vapor budget equation is employed in order to partition the observed rainfall into recycled and advected components. The global teleconnections with the recycled (advected) rainfall are found to be weak (strong), which is consistent with the basic assumptions of the sources of atmospheric water vapor. It is shown that the mean recycled rainfall over the Indo-Gangetic Plain, central India, and western Himalayas ranges between 10% and 40% of the total rainfall. While EOF1 (38.5%) of the recycled rainfall reveals covariability between the regional and external influences, EOF2 (14%) shows a mode independent to the external influences (i.e., advected rainfall), prevailing over the Indo-Gangetic Plain. Furthermore, a strong decreasing trend in PC2 over the last 36 years suggests a change in the local feedback (land, atmosphere), which in turn may have also contributed to the decreasing trend in the observed monsoon rainfall over central and northern India.

1. Introduction

The Indian summer monsoon is an interhemispheric circulation system, coupled with the land, atmosphere, and ocean, and contributes about 80% of the annual rainfall over India (Goswami 1998; Webster et al. 1998; Chakraborty et al. 2002; Gadgil and Kumar 2006; Ding and Sikka 2006). It is also a primary source of freshwater required for agriculture and industry. The interannual standard deviation of the Indian summer monsoon rainfall (ISMR) is about 10% of its climatological seasonal mean, which has a large impact on the agriculture and economy (e.g., Gadgil and Kumar 2006).

The variability of ISMR arises because of complex nonlinear interactions among land, atmosphere, and ocean. These interactions result in variability in the atmospheric water vapor flux and hence the rainfall. Some of these interactions are local and provide water vapor to the atmosphere through evapotranspiration (ET) from the land surface. A part of the water vapor from ET gets converted into rainfall and falls back over the same region, which is known as rainfall recycling (Brubaker et al. 1993; Eltahir and Bras 1994). The ratio of recycled rainfall to the total rainfall is defined as recycling ratio \( \rho \). However, it is generally accepted that the primary sources of atmospheric water vapor for the ISMR are the neighboring oceans. Once the monsoon circulation sets in, it brings moisture-laden air from the oceans, and that is converted into rainfall through complex atmospheric processes. A part of this rainfall is retained over land in the form of soil and canopy moisture and water bodies (lakes, rivers, etc.) and acts as a secondary source of atmospheric water vapor. Therefore, rainfall of a region can be attributed to local (i.e., ET from the regional land surface) and remote (e.g., advected evaporation from the oceans) sources of water vapor (Eltahir and Bras 1996; Trenberth 1999; Burde and Zangvil 2001).

ET is known to affect precipitation as well as the global circulation (e.g., Shukla and Mintz 1982). Furthermore, variability in the regional ET can be attributed to the regional land–atmosphere feedback on various time scales. Chang et al. (2009) have shown that wetness of land surfaces affects the lifetime and, to some extent, intensity of a monsoon depression. The memory of soil moisture can have effects on the regional land–atmospheric interactions (e.g., Koster et al. 2004).
the modulation of the amplitude of the monsoon intra-seasonal oscillations (ISOs; e.g., Saha et al. 2012), and the climatological ISO (CISO; Saha et al. 2011), which in turn affect the seasonal mean monsoon rainfall. In this context, the recycling ratio can be viewed as a partial measure of the strength of the soil moisture–precipitation feedback.

The regional land use–land cover (LULC) change can affect the local ET (e.g., Halder et al. 2016) and that may have an impact on the moisture recycling. Similarly, black carbon and other aerosols can also alter the net surface radiative heat flux (Ramanathan et al. 2005; Ramanathan and Carmichael 2008) and hence the energy available for ET. Therefore, recycled rainfall may be an indicator of variability (change) in the regional climate owing to natural/anthropogenic causes. The land–atmospheric feedback may also give rise to natural modes of variability in the recycled rainfall. Therefore, any change in the regional feedback and hence the recycled rainfall can also be viewed through the changes in these modes. However, these modes have not been explored so far.

Recycling is not necessarily always related to the local evapotranspiration, but is due to advection of evaporated moisture from a remote land area (Goessling and Reck 2011). However, this may not be the case for the Indian summer monsoon region because of its unique topography and monsoon circulation pattern. Here we employ the diagnostic method of Eltahir and Bras (1994) on reanalysis data to estimate the recycling ratio. Based on the estimated recycling ratio, total observed rainfall is divided into advected and recycled components. The dominant modes of variability in the recycled rainfall and global teleconnections are investigated. Section 2 describes the data and methods used in this study. Results are described in Section 3. Section 4 summarizes the results from this study.

2. Data and methodology

The basic principle of most of the recycling model is based on the conservation of atmospheric water mass (e.g., Eltahir and Bras 1996; Burde and Zangvil 2001). Following Burde and Zangvil (2001), the vertically integrated water vapor mass balance equation can be written as

\[
\frac{\partial m}{\partial t} = \left[ \frac{\partial (um)}{\partial x} + \frac{\partial (vm)}{\partial y} \right] + ET - P, \tag{1}
\]

where the left-hand side is the atmospheric water vapor storage term. The three terms on the right-hand side are horizontal advection of water vapor masses, ET, and precipitation \( P \), respectively. The terms \( m, um, \) and \( vm \) are the vertically integrated water vapor mass and zonal and meridional flux of vapor mass, respectively. The recycling model of Eltahir and Bras (1994), which is based on the water vapor mass conservation equation, uses the following two basic assumptions: (i) the rate of change in the storage term is negligible compared with other terms for the time scale the model has used, and (ii) the atmospheric water vapor is well mixed. The model calculates the recycling ratio at each grid point of a selected domain and considers species of water vapor molecules, which evaporate within the region (i.e., local) and outside the region (i.e., advection part).

For a finite control volume of the atmosphere, the mass conservation equation of the model is given by

\[
\frac{\partial N_w}{\partial t} = I_w + ET - O_w - P_w, \tag{2a}
\]

\[
\frac{\partial N_o}{\partial t} = I_o - O_o - P_o, \tag{2b}
\]

where \( N \) is proportional to the number of water vapor molecules and subscripts \( w \) and \( o \) denote the water vapor molecules, which evaporate within the region and outside the region, respectively. The variables \( I \) and \( O \) are inflow and outflow, respectively.

The storage term of Eq. (1) using ERA-Interim reanalysis (Dee et al. 2011) is very small as compared to each of the terms on the right-hand side. The area-averaged storage terms over India (16°–36°N, 70°–90°E) on the time scale of 30, 60, and 120 days are 0.097, 0.053, and 0.017 mm day\(^{-1}\), respectively. Therefore, the first assumption of the Eltahir and Bras (1994) model is also applicable over the Indian summer monsoon region on the seasonal time scale [i.e., storage term on the left-hand side of Eq. (2) is zero]. The assumption of well-mixed water vapor implies that water vapor molecules of both advected and local origins have equal probabilities of falling back as precipitation (Eltahir and Bras 1994). Hence, the recycling ratio is defined as

\[
\rho = \frac{P_w}{P_w + P_o} = \frac{O_w}{O_w + O_o} = \frac{N_w}{N_w + N_o}. \tag{3}
\]

Applying assumption (i) on Eq. (2) and using Eq. (3), the final form of the recycling ratio [after some rearrangement, see Eltahir and Bras (1994) for details] is given by

\[
\rho = \frac{(I_w + E)}{(I_w + E + I_o)}. \tag{4}
\]

The recycling model is used over the Indian summer monsoon domain (6°–38°N, 68°–97°E, only over land)
on the seasonal monsoon time scale [i.e., June–September (JJAS) average]. The seasonal mean (JJAS averaged) winds, specific humidity, and evapotranspiration data from ERA-Interim reanalysis (Dee et al. 2011) are used to estimate the recycling ratio. The observed seasonal monsoon rainfall or the total rainfall (TR) is partitioned into recycled rainfall (RR) and advected rainfall (AR) using the estimated ρ. The observed rainfall data used here are from the Climate Research Unit (CRU TS3.23; with 0.5° × 0.5° horizontal resolution) (Harris et al. 2014) and the India Meteorological Department (IMD; with 1° × 1° horizontal resolution) (Rajeevan et al. 2006) for the years 1979–2014. Rainfall from ERA-Interim reanalysis is also used. MERRA-2 reanalysis (Bosilovich et al. 2015) is used as an additional source of data to compare with the results based on ERA-Interim reanalysis.

The rainfall anomaly of a year at a grid point can be considered as the sum of the anomalous advected and recycled rainfall. Therefore, the interannual variance of rainfall $\sigma_T^2$ is due to a sum of variance in the advected rainfall $\sigma_A^2$ and recycled rainfall $\sigma_R^2$ and the covariance between advected and recycled rainfall $2\text{cov}(A', R')$: \[
\begin{align*}
\text{TR} + T' &= (\text{AR} + A') + (\text{RR} + R'), \\
T' &= A' + R', \\
\sigma_T^2 &= \sigma_A^2 + \sigma_R^2 + 2\text{cov}(A', R'),
\end{align*}
\]
where $\text{TR}$, $\text{AR}$, $\text{RR}$ $(T'$, $A'$, $R')$ are the climatological mean (anomaly) of total, advected, and recycled rainfall, respectively.

3. Results

a. Recycling ratio and recycled and advected rainfall

A large recycling ratio (by a maximum of 40%) over the Indo-Gangetic Plain, central India, and western Himalayas, including Tibet, is evident (Fig. 1d). The estimated values of ρ over these regions varies between 10% and 40%, which are within the ranges found in previous studies using different methods and on different time scales (e.g., van der Ent et al. 2010). Furthermore, the interannual standard deviation of ρ is about 2%–8% over the same regions. Van der Ent et al. (2010) have shown that values of ρ over the Indo-Gangetic Plain and central India (Tibet) are within 40%–50% (70%–80%) on the annual time scale. It may be noted that spatial pattern of ρ is very different from that of the seasonal mean monsoon rainfall. For example, western Tibet receives a little amount of rainfall (Fig. 1a), but it is a region of maximum recycling. Therefore, variability and spatial patterns of the recycled rainfall are expected to be different than that of ρ.

The seasonal mean pattern of ISMR (i.e., TR) consists of rainfall maxima over the Western Ghats, central India, and the western coast of Myanmar, extending toward the foothills of the Himalayas and northeastern states of India (9–15 mm day$^{-1}$; Fig. 1a). A similar spatial pattern in the mean advected rainfall (i.e., AR) supports the fact that oceanic moisture is the primary source of ISMR (Fig. 1b). On the other hand, the recycled rainfall (i.e., RR) shows maxima over central and north India, the foothills of the Himalayas, and southern Tibet region, which predominantly varies between 0.8 to 2.4 mm day$^{-1}$. It may be recalled that ET over land only is considered for estimating ρ. The meandering south-westerly wind (or cyclonic vorticity) along the monsoon trough advects water vapor available from local ET, toward the northwest and the foothills of the Himalayas. On the other hand, moisture from the local ET over the southern part of India primarily advects toward the ocean (Bay of Bengal) because of prevailing strong westerlies. Hence, the recycling of local moisture is rather small over the southern part of India as compared to that over central and northern India.

Total variance $\sigma_T^2$ of rainfall can be considered as the sum of individual contributions of external $\sigma_A^2$ and internal $\sigma_R^2$ influences and covariances between external and internal influences [Eq. (5)]. The global variability, which is outside of the monsoon region but affects the ISMR through teleconnection, is termed here as “external” influences [e.g., El Niño–Southern Oscillation (ENSO)]. On the other hand, the effects of regional feedback, which are independent of the “external” influences are termed as “internal” influences (e.g., soil moisture and ISO interactions). It turns out that $\sigma_T^2$ is about 5%–15% of $\sigma_T^2$ over central and northern India (Fig. 1e). On the other hand, the covariance part is quite large and explains about 10%–35% of the total variance (Fig. 1f). Furthermore, the covariance shows an east–west dipole structure. It may be recalled that this region (central and north India) is identified as one of the global hot spots, where soil moisture–rainfall feedback is quite strong (Koster et al. 2004). Therefore, variances of recycled rainfall are a quantitative measure of soil moisture–rainfall feedback.

As $\sigma$ is derived from ERA-Interim reanalysis and rainfall is used from CRU, the mean and variances of the recycled and advected rainfall may be affected because of inconsistency between these two datasets. Therefore, the above analysis is repeated using rainfall from ERA-Interim reanalysis. It turns out that the mean patterns of rainfall, particularly the recycled rainfall (Figs. 2a–c), are very similar to those using CRU data (i.e., Fig. 1a–c). Moreover, the variance and covariance using ERA-Interim rainfall (Figs. 2d,e) mirror the
structures, which are also similar to those using CRU rainfall (Figs. 1e,f).

The above analysis is repeated using $x$ based on MERRA-2 reanalysis. The remaining possible combinations of the mean advected and recycled rainfall and their variances and covariances are calculated (i.e., ERA-Interim $x \Rightarrow$ IMD rainfall; MERRA-2 $x \Rightarrow$ IMD, CRU, and ERA-Interim rainfall). The spatial pattern of the mean recycled rainfall is quite invariant (Fig. 3). Furthermore, variances and covariances also bear the same structures (figure not shown).

External influences may affect the regional feedback, but the regional land–atmosphere feedback may not be strong enough to affect the external influences. A deficit (excess) monsoon year is often linked with an external influence like ENSO, and that year may have less (more)
available soil moisture for ET. Hence, the external influence is likely to be a major source of variability of the recycled rainfall (e.g., Pathak et al. 2014). In other words, a strong covariance pattern (Fig. 1f) suggests a greater role played by the advected rainfall on the variability of the recycled rainfall (further discussed in section 3c).

b. Teleconnections

Now we examine the global teleconnections with the recycled, advected, and total rainfall. ENSO is known to be the single-largest natural source of variability, which explains about 20%–30% of the interannual ISMR variance (e.g., Kumar et al. 1999). Therefore, variability of advected (recycled) rainfall must have a stronger (weaker) teleconnection with ENSO. To verify this, area-averaged (box shown in Figs. 1b,c) total, advected, and recycled rainfall are regressed with sea surface temperature (SST) over ocean, 2-m air temperature over land, and winds at 850 hPa (Fig. 4). Regression of total and advected rainfall clearly reveals the ENSO pattern (Figs. 4c,b). The advected and total rainfall

FIG. 2. (a)–(c) As in Figs. 1a–c and (d),(e) as in Figs. 1e,f, but using only ERA-Interim reanalysis data (i.e., rainfall and recycling ratio).
are inversely related to the equatorial central and east Pacific SST. Meanwhile, both of them are directly related to land surface temperature north of 30°N. It may be noted that the ENSO teleconnection is stronger for advected rainfall than that of total rainfall. On the other hand, the regression pattern between SST and recycled rainfall reveals a rather weak ENSO teleconnection (Fig. 4a). Above all, this suggests that the technique used here for partitioning the total rainfall into recycled and advected components is robust.

The regressed 850-hPa wind shows prevailing easterlies over the western and central Pacific, anticyclonic circulation over the western North Pacific, and a mean monsoon wind pattern over the Indian summer monsoon region (Figs. 4b,c). This is consistent with the fact that a deficit (surplus) monsoon year is associated with the weakening (strengthening) of the mean circulation over the monsoon as well as the western Pacific region. However, for the recycled rainfall, easterly wind prevails mainly over the western Pacific, and the anticyclonic
circulation over the western North Pacific is weak (Fig. 4a). Furthermore, there exists a weak cyclonic (anticyclonic) circulation over western (northeastern) India, which is consistent with the covariance structure shown in Fig. 1f. It is also interesting to note that there are strong mid- and high-latitude influences. Apart from ENSO, the variability of the Indian summer monsoon is known to be associated with Eurasian snow (e.g., Bamzai and Shukla 1999; Saha et al. 2013), North Atlantic SST (e.g., Goswami et al. 2006), subtropical North Pacific SST (e.g., Chattopadhyay et al. 2015), etc. These teleconnections become more prominent in the non-ENSO years and hence show up as modes, which are orthogonal to ENSO (e.g., Saha et al. 2016).

A careful observation further reveals that the regressed 2-m air temperature over land in the northern latitudes and the SST over the equatorial central and east Pacific are stronger for the advected rainfall than those of the total as well as recycled rainfall. A stronger (weaker) teleconnection suggests a stronger (weaker) external influence on the flux of atmospheric water vapor. Using a similar analysis with Northern Hemisphere summer monsoon rainfall, Wang et al. (2013) have noted a strong positive regressed temperature anomaly over the northern-latitude land region. The north–south land–ocean temperature gradient has increased in the past few decades due to a rapid increase in land temperature caused by global warming. Increases in the surface temperature gradient may have increased the Northern Hemisphere monsoon rainfall (Wang et al. 2013), which is contrary to the observed decrease in the monsoon rainfall over India (Naidu et al. 2009; Kulkarni 2012). Nevertheless, the stronger regressed temperature anomaly (land and ocean)
suggests a greater role played by the external influences on the advected rainfall.

The above teleconnection patterns using recycled and advected rainfall based on MERRA-2 reanalysis ($\rho$ and 850-hPa winds from MERRA-2, rainfall and 2-m temperature from CRU, and SST from HadISST) are very similar to those using ERA-Interim reanalysis. Similar regression patterns are also evident when IMD rainfall (instead of CRU rainfall) with ERA-Interim and MERRA-2 reanalysis is used (figure not shown). However, the amplitudes of the regression patterns are weaker when IMD rainfall is used. This is partly related to the missing values in IMD data beyond the political boundary of India (particularly over the foothills of the Himalayas), which makes the area-averaged rainfall variability weaker.

c. Modes of variability of the recycled rainfall

It is plausible that regional land–atmosphere interactions may give rise to a variability in the recycled rainfall, which is quite independent of the external influences. The local ET is primarily constrained by soil moisture and available net surface radiation. Transpiration also depends on the vegetation type. Furthermore, ET is not a linear function of soil moisture. Regional variability/change in aerosol and black carbon can give rise to variability/change in the regional net available surface radiation and hence ET. Regional LULC change may also give rise to a change in the local supply of moisture to the atmosphere. Hence, for a given large-scale or external variability, the regional nonlinear feedback can give rise to a variability that is uncorrelated with the external variability. Therefore, sources of variability of the recycled rainfall may be broadly categorized into 1) the regional land–atmospheric feedback, which is independent of the external influences, and 2) the external influences, which controls the large-scale advection of moisture and hence the recycling.

To identify the modes of variability in the recycled rainfall, EOF analysis is carried out. The first two EOFs mimic the covariance and variance structure of Figs. 1f and 1e, which explain 38.5% and 14.2% of the variances, respectively (Figs. 5a,b). The third EOF explains 9.8% of the variance and shows a tripole structure along the northeast-to-southwest direction (Fig. 5e). While EOF1 corroborates the covariability between recycled and advected rainfall, EOF2 is likely to be an independent mode, replicating the structure of the individual contribution of the recycled rainfall.

The EOF structures themselves are not sufficient to confirm their sources of variability. If the advected rainfall (which is mostly an external influence) has any contributions on the above modes of variability, it can be seen through correlation/regression patterns between principal components (PCs) and the anomalous advected rainfall. It turns out that only EOF1 has some association with the advected rainfall (Fig. 5d), which is able to capture the east–west dipole structure to some extent (the correlation pattern is statistically significant over part of central India, northwest India, and Bangladesh). However, the correlation between PC2 and the advected rainfall anomaly is not statistically significant around the Indo-Gangetic Plain region, and neither it is able to replicate the pattern of EOF2 (Fig. 5e). Similarly, PC3 has a weak correlation with the advected rainfall (Fig. 5f). While PC1 has a strong and significant correlation with the Niño-3.4 SST, it is rather weak and insignificant for the case of PC2 (Table 1). This further confirms that EOF2 is a local mode and does not depend on external influences.

EOFs of the recycled rainfall from all remaining combinations of $\rho$ (ERA-Interim and MERRA-2 reanalysis) and rainfall (from CRU and IMD) are calculated (figure not shown). The first two EOF modes are very much consistent with Figs. 5a and 5b. The common features that emerge from these EOFs are 1) an east–west dipole pattern in the first EOF and 2) a positive maxima over the Indo-Gangetic Plain. Therefore, the found dominant mode of variability in the recycled rainfall is quite independent of the choice of data.

Several previous studies have identified a decreasing trend in the summer monsoon rainfall over central and north India over the past few decades (e.g., Naidu et al. 2009; Kulkarni 2012). The observed decrease in rainfall is attributed to LULC change (Krishnan et al. 2015; Halder et al. 2016) and warming trends in the ocean due to global warming (Kulkarni 2012), black carbon, and other aerosols (Ramanathan et al. 2005; Ramanathan and Carmichael 2008; Bollasina et al. 2014). Furthermore, a decreasing trend in pan evaporation is found using observations of 58 stations distributed all over the Indian land region (Padmakumari et al. 2013). A decreasing trend in ET from ERA-Interim and MERRA-2 reanalysis over central India (figure not shown) is also consistent with the observations. While PC1 shows a slight increasing trend, PC2 shows a strong decreasing trend (significant at 95%) in the last 36 years (Figs. 5g,h). Therefore, it is plausible that the observed decrease in monsoon rainfall is associated with the change in regional feedback (i.e., LULC, aerosol, etc.), which is primarily the second dominant mode in the recycled rainfall. The area-averaged recycled rainfall over a box around the maximum variance (i.e., EOF2 in Fig. 5b) indeed shows a strong decreasing trend (Fig. 5j). During the last 36 years, the recycled rainfall
has decreased by about 40 mm, and the decreasing trend is significant at 98.5% using the Mann–Kendall trend test. Similarly, the recycled rainfall calculated from ERA-Interim rainfall, MERRA-2 rainfall, and MERRA-2 IMD rainfall reveals decreasing trends of about 45, 20, and 38 mm, respectively, in the last 36 years. However, a similar decreasing trend is not realized in the total rainfall because of the relatively shorter time period and strong interannual variability of the monsoon rainfall. Nevertheless, a decreasing trend in the recycled rainfall indicates a decrease in local land–atmosphere feedback, and that may be related to the change in LULC, atmospheric aerosols, etc.

4. Conclusions

A part of the moisture from ET contributes to the rainfall of the same region, and that is known as the recycled rainfall. The ratio of recycled rainfall to the total precipitation is known as the recycling ratio $\rho$.

<table>
<thead>
<tr>
<th>Recycling ratio, rainfall</th>
<th>PC1</th>
<th>PC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA-Interim, CRU</td>
<td>−0.372</td>
<td>−0.226</td>
</tr>
<tr>
<td>MERRA-2, CRU</td>
<td>−0.468</td>
<td>0.034</td>
</tr>
<tr>
<td>ERA-Interim, IMD</td>
<td>−0.433</td>
<td>−0.277</td>
</tr>
<tr>
<td>MERRA-2, IMD</td>
<td>−0.521</td>
<td>−0.152</td>
</tr>
</tbody>
</table>
This study estimates the seasonal mean (JJAS) ρ using reanalysis data (ERA-Interim and MERRA-2). A diagnostic method based on the basic atmospheric water vapor budget equation is employed in order to estimate ρ, and that estimated value is used to partition the observed rainfall into advected and recycled components.

The seasonal mean recycled rainfall over the Indo-Gangetic Plain, part of central India, and the western Himalayas was found to be about 10%–40% of the total rainfall. The ENSO teleconnections with the recycled (advected) rainfall are found to be weak (strong), which is consistent with the basic facts that variability in the recycled (advected) rainfall arises primarily due to the local feedback (remote teleconnections). While the interannual variance of recycled rainfall explains about 5%–15% of the total variance, the covariance between advected and recycled rainfall explains about 10%–35% of the total variance over central and northern India and the western Himalayas. Furthermore, EOF1 (38.5%) of the recycled rainfall reveals covariability between the regional and external influences. A dominant local mode of variability in the recycled rainfall (i.e., EOF2, variance = 14.2%) over the Indo-Gangetic Plain is identified. The corresponding principal component (i.e., PC2) reveals a strong decreasing trend (significant at 95%) over the last 36 years, which indicates weakening of the local feedback (land and atmosphere). Furthermore, recycled rainfall over the Indo-Gangetic Plain region shows a strong decreasing trend (significant at 98.5% using the Mann–Kendall trend test). Therefore, changes in the regional physical processes (LULC, aerosol, etc.), may have significantly contributed to the observed decreasing trend in the monsoon rainfall over this region.

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