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Dynamics of east-west asymmetry of Indian summer monsoon rainfall trends in recent decades

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[1] Understanding the regional trends in Indian summer monsoon rainfall has important implications in developing appropriate adaptation strategies. Here, we provide a mechanistic explanation of the observed asymmetry in the trends of seasonal mean rainfall during past three decades over the eastern and western parts of the country. This asymmetry in trends of the seasonal mean rainfall is primarily contributed by a similar asymmetry in the trends of low and medium rainfall (R_{LMR}) events explaining 85% of the seasonal mean. As the R_{LMR} generally comes from mesoscale and synoptic systems, it is likely that the observed asymmetry may arise from some asymmetry in changes in large scale dynamic and thermodynamic parameters. We show that increasing vertically integrated moisture transport (VIMT) over the Arabian Sea (AS) is likely reason for the increasing trend of R_{LMR} in the western parts during recent decades. In contrast, over the eastern parts, the R_{LMR} is decreasing due to a decreasing trend of VIMT over the Bay of Bengal (BoB). The increasing trend of VIMT over AS arises primarily due to increasing trends of low level wind speed and moisture content while the decreasing trend of VIMT over the BoB seems to be due to decreasing trends of low level wind speed and moisture content. **Citation:** Konwar, M., A. Parekh, and B. N. Goswami (2012), Dynamics of east-west asymmetry of Indian summer monsoon rainfall trends in recent decades, *Geophys. Res. Lett.*, *39*, L10708, doi:10.1029/2012GL052018.

1. Introduction

[2] While the surface temperature averaged over the country (India) has a significant increasing trend during the past three decades [*Kothawale et al.*, 2010, Figure 2a], the trends of the seasonal mean (JJAS) Indian summer monsoon rainfall (ISMR) over different sub-divisions of the country are different [*Guhathakurta and Rajeevan*, 2008] with largely positive trends (with the exception of Kerala) to the west of 80° E while it is largely negative towards the eastern region (see Figure 7 of *Guhathakurta and Rajeevan* [2008] and Figure S1a in the auxiliary material).[1] This is further illustrated by the decreasing trend of area averaged seasonal rainfall east of 80° E and increasing trend of area averaged seasonal rainfall west of it (Figure S1b). As the agricultural productivity and freshwater resource of each region is strongly dependent on the monsoon rainfall, it is crucial to understand the causative mechanisms responsible for these regional trends of monsoon rainfall for planning of agricultural productivity, crop management and water resource management.

[3] The objective of this study is to try to unravel the underlying mechanism responsible for this asymmetry in trends of seasonal mean rainfall between eastern and western segments of the country during the past three decades. Although rainfall data over India is available for a long time, we focus on the recent three decades as the reanalysis data required to understand these trends is robust during this period and unlikely to have artificial trends. Anthropogenic aerosols are a potential driver for either increasing or decreasing monsoon rainfall. Some studies [*Ramanathan et al.*, 2005; *Chung and Ramanathan*, 2004] propose that cooling of Indian continent and northern part of Indian Ocean by certain aerosols is linked to weakening of the north-south surface temperature gradients and decrease in monsoon rainfall. During June–September (JJAS) over the monsoon region, however, the meridional gradient of surface temperature remains negative and cannot sustain the monsoon during JJAS. Rather, it is the tropospheric temperature (TT) gradient that drives the monsoon circulation and precipitation [*Goswami and Xavier*, 2005; *Xavier et al.*, 2007]. Yet other studies [*Lau and Kim*, 2006, 2010] indicate that heating of lower atmosphere over northern India by absorbing aerosols could enhance meridional thermal gradient and resultant convergence of moisture could enhance monsoon rainfall at least in the early part of the monsoon season. The veracity of this elevated heat pump hypothesis has been recently debated [*Bollasina et al.*, 2008; *Nigam and Bollasina*, 2010]. In a recent study, *Bollasina et al.* [2011] use a coupled ocean-atmosphere model with improved aerosol chemistry and cloud microphysics and attribute the decreasing trend of monsoon rainfall over central India to aerosol. It is interesting that the spatial distribution of trends of seasonal rainfall simulated by the model only with aerosol forcing (AERO run in Figure 2 of *Bollasina et al.* [2011]) is similar to those shown in Figure S1a. However, the focus of their study was not on this asymmetry in trends of rainfall but the decreasing trend of the large continental scale rainfall. While models may indicate increasing trend of aerosol loading even during the monsoon season, observations do not support it. Although on annual mean sense, the aerosol loading (as represented by aerosol optical depth, AOD) is increasing over India, it is due largely to increasing trend of AOD during winter and post monsoon months rather than during monsoon season [*Ramachandran et al.*, 2012; *Dey and Girolamo*, 2011]. Further, no significant asymmetry is seen in the trend of AOD during JJAS (Figure S2) with any

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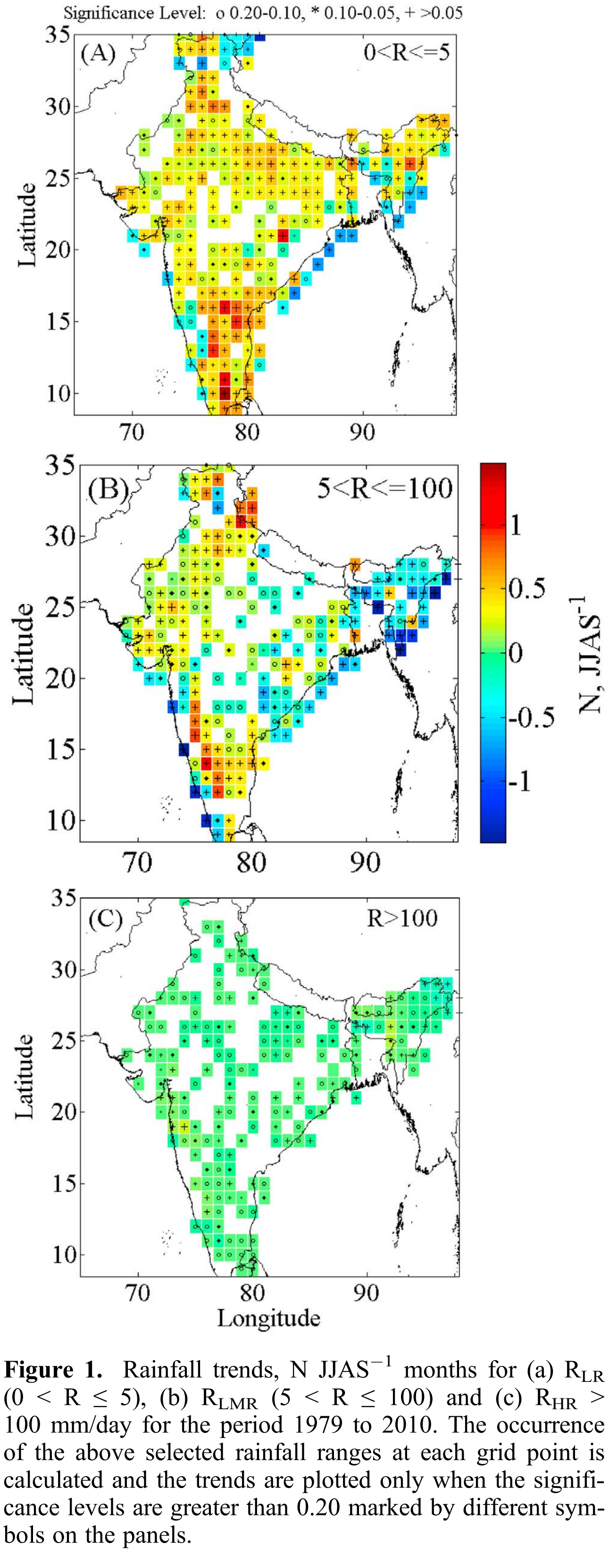

Figure 1. Rainfall trends, N JJAS^{-1} months for (a) R_{LR} ($0 < R \leq 5$), (b) R_{LMR} ($5 < R \leq 100$) and (c) $R_{HR} > 100$ mm/day for the period 1979 to 2010. The occurrence of the above selected rainfall ranges at each grid point is calculated and the trends are plotted only when the significance levels are greater than 0.20 marked by different symbols on the panels.

resemblance with the asymmetry seen in ISMR trend. As data for a longer period to calculate trends of aerosol loading over the whole country is not available, we assume that the trends obtained from the MODIS data can be considered representative of the longer period under consideration. In the absence of compelling evidences showing that aerosols are responsible for the observed asymmetry in the trends of monsoon rainfall, we argue that rather than aerosol, dynamics may be responsible for the observed asymmetric trend of ISMR. Therefore, here we explore whether other dynamical and thermodynamical processes could explain the asymmetry in the trends of ISMR.

2. Data and Methods

[4] Gridded (1° × 1°) rainfall (mm/day) data [*Rajeevan et al.*, 2006] from 1979 to 2010 (thirty two years) as obtained from India Meteorology Department (IMD) is considered to study the rainfall trends. Thirty two years of the ERA-40 interim products zonal (u, m/s) and meridional (v, m/s) wind components and specific humidity (q, Kg/Kg) are considered to study the vertically integrated moisture transport (VIMT) over the Arabian Sea (AS) and the Bay of Bengal (BoB) basin. The trends of VIMT obtained from ERA-40 are compared for consistency with Modern Era Retrospective analysis for Research and Applications (MERRA). We utilized effective radius of cloud droplets, R_e (μm), AOD, cloud top temperature (K) and surface water vapor (SWV) at 925 mb data obtained from Terra Moderate Resolution Imaging Spectroradiometer (MODIS) [*King et al.*, 1992] satellite from the year 2000 to 2010. By using above mentioned data sets we investigated what causes the recent trends in anomalies of ISMR.

[5] In order to delineate the type of rainfall that contributed to the asymmetry in the trends of seasonal rainfall discussed above, we divided the IMD gridded rainfall data for JJAS into the three different regimes based on rainfall magnitude, (1) very light rainfall (R_{LR}), $0 < R \leq 5$ mm/day, (2) low to moderate rainfall (R_{LMR}), $5 < R \leq 100$ mm/day, and (3) heavy rainfall (R_{HR}), $R > 100$ mm/day. While this classification is similar to the one adopted in *Goswami et al.* [2006], our goal is not to isolate 'extremes' but to isolate processes contributing to different types of rainfall. We do this classification keeping in mind that the different categories represent rainfall coming from different types of clouds. Very light rains largely come from stratiform clouds while low and moderate rains come from low and middle level convective clouds associated with synoptic and mesoscale disturbances. The heavy rains are associated with deep convective clouds. The trend for occurrence of rainfall type at each grid point is found out by counting the total number of such events in JJAS and then subjected to trend analysis.

[6] For trend analysis of R_e and AOD, the median value of R_e and AOD in each monsoon month is calculated in order to exclude the outliers and then mean of the median values of the JJAS seasons are considered for trend analysis. As we are interested in the R_e for the low and medium clouds contributing to the low and medium rain events, we exclude the very deep clouds from this analysis and the R_e values at each grid point is considered only when the cloud top temperature is warmer than 263 K. This criteria includes the super cooled clouds commonly occurred at temperature warmer than 263 K [*Pruppacher and Klett*, 1997].

[7] Confidence level is calculated at each grid point by performing standard one tail Student's t-test. Slope of the trend analysis is shown only when significance levels are greater than 0.2 marked by different symbols.

[8] The AS basin is considered within latitude of 5° to 21°N and longitude of 46° to 73°E while BoB basin is considered within 5° to 21°N and 80° to 100°E. The vertically integrated moisture transport (VIMT, Kg/ms) is computed using specific humidity, u and v components of wind integrated from 1000 mb to 300 mb as described in *Godfred-Spenning and Reason* [2002]. The VIMT is defined as,

$$VIMT = \frac{1}{g}\sum_{j=1}^{J} q_j\left(u_j, v_j\right)\Delta p_j$$

where, g is the acceleration due to gravity, q is the specific humidity (Kg/Kg), u_j is the zonal wind, v_j is the meridional wind, Δp_j is the thickness of jth pressure level.

3. Results

[9] Nearly 85% of net ISMR is contributed by R_{LMR} rainfall type, while 7.5% of net rainfall is contributed each by R_{LR} and R_{HR} respectively. The trends of rainfall at different categories along with significance levels (< 0.20) at different grid points are shown in Figures 1a–1c. Interestingly, both R_{LR} and R_{HR}, the trends are rather uniform over the whole country. Lack of a significant increasing trend of R_{HR} on individual grid points (Figure 1c) or as found in *Ghosh et al.* [2012] is not inconsistent with findings of *Goswami et al.* [2006] as the trend of aggregate number of extreme events can have an increasing trend even though the trends on individual grid points are not (see S3 in *Goswami et al.* [2006]). However, the trends of R_{LMR} over the south India (SI), north India (NI) and northwest India (NWI) are increasing as evident from Figure 1b. Over the central India (CI), trend of R_{LMR} is not significant. Importantly, R_{LMR} is decreasing over the eastern India (EI) and northeast India (NEI). These trends are greater than at significance level of 0.1. Thus, clearly there is east-west asymmetry in the trends in R_{LMR} similar to that in seasonal rainfall (Figure S1a). Based on these observations and keeping in mind that R_{LMR} contributes 85% to the seasonal rainfall, the east-west asymmetry in seasonal mean rainfall seems to come from the low and medium rainfall events.

[10] As the mesoscale and synoptic scale disturbances which depend on the instability of the background state, largely contribute to the R_{LMR}, the trends of R_{LMR} are likely to be linked to the changes in moisture availability. During the summer monsoon season, the EI and NEI receive moisture transported mainly by the northward branch of monsoon wind from the BoB (Figure 2a). The SI, NI and NWI regions receive moisture by the westerly and cross equatorial winds from the AS. Although the winds from AS may have some extension crossing the eastern coast of India (Figure 2a), the air over NEI during the monsoon months generally originate over the BoB (see Figure S3). The climatological JJAS mean VIMT (Kg/ms) over the north Indian Ocean are shown in Figure 2a from ERA-40. The trends of spatially averaged

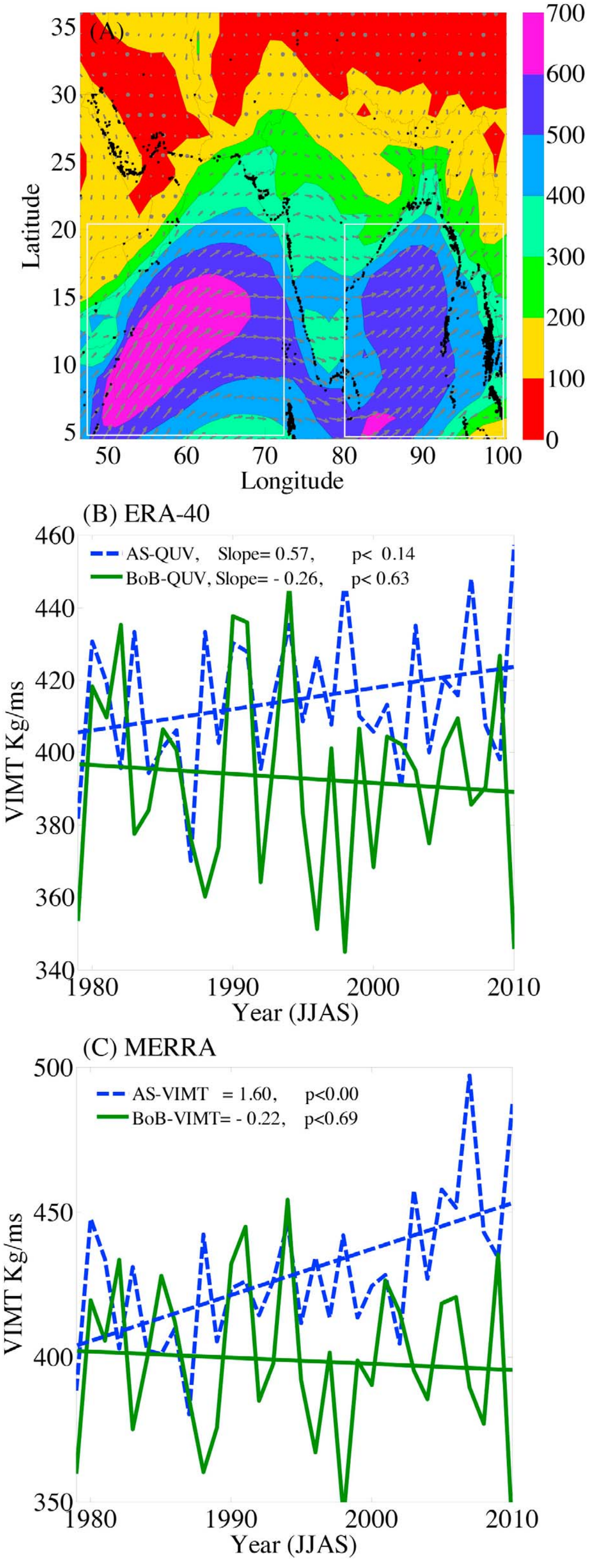

Figure 2. (a) Mean JJAS Vertically Integrated Moisture Transport (VIMT) as obtained from ERA40 interim over the Arabian Sea and Bay of Bengal from 1979 to 2010, the arrows shows the resultant of moisture components QU and QV. (b) Trend of spatially averaged moisture transport for both AS (46–73°E and 5–21°N) and BoB (80–100°E and 5–21°N). VIMT over the AS is increasing at 0.17 Kg/ms/JJAS and decreasing at −0.51 Kg/ms/JJAS over the BoB. (c) Same as Figure 2b but obtained from MERRA data. VIMT is increasing at 1.70 Kg/ms/JJAS over the AS basin while decreasing at −0.15 Kg/ms/JJAS over the BoB basin.

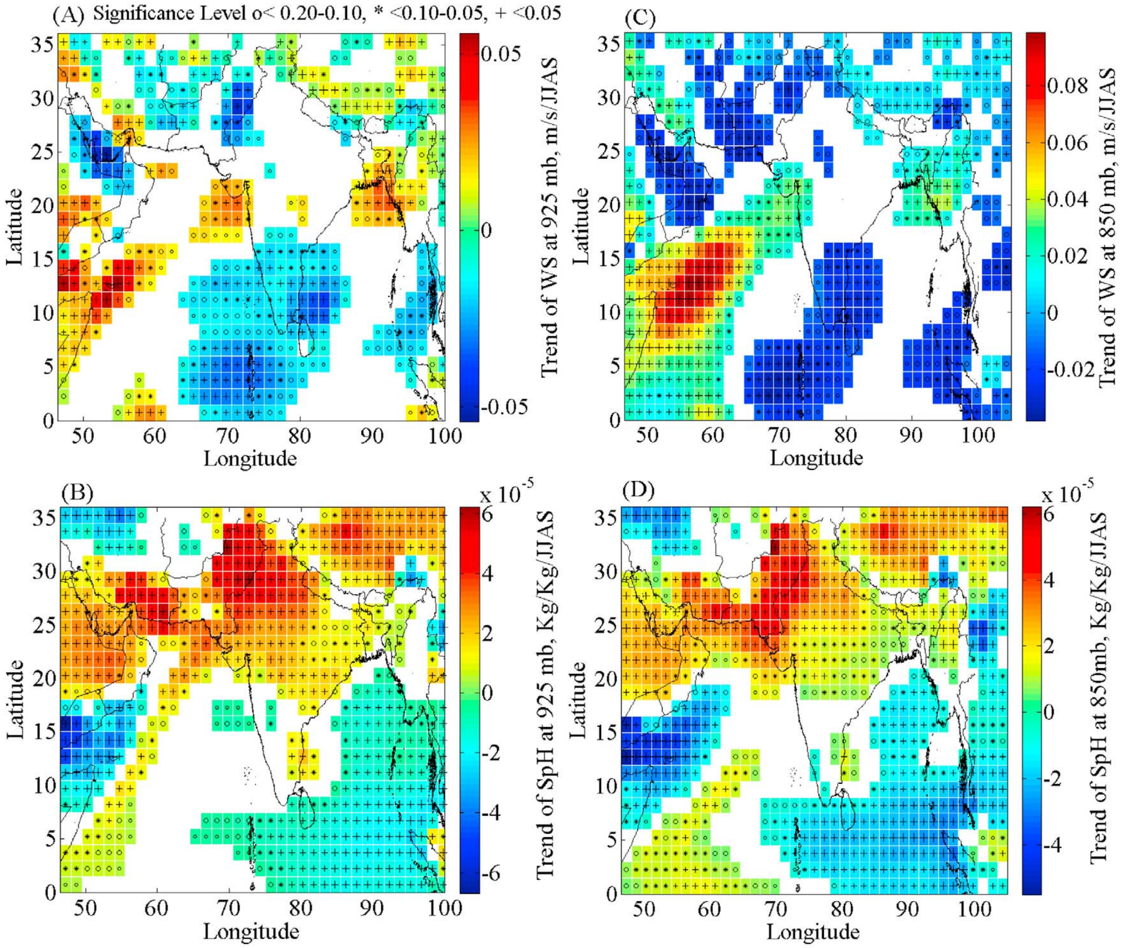

Figure 3. (a and c) Trend of wind speed at 925 and 850 mb as obtained from ERA-40 reanalysis data. The trend analysis is carried out for the period 1979 to 2010. Wind speed is increasing over AS while decreasing over BoB. The trends at different grid points indicated by separate symbols, e.g., circle for significant level 0.20–0.10, star for significant level 0.10–0.05 and plus for 0.05 significant level. (b and d) Trend of Specific Humidity at 925 and 850 mb as obtained from ERA-40 reanalysis data. The SH at 850 is increasing in some parts over AS while it is decreasing over the BoB basin. These trends are significant above 95% confidence level.

VIMT over the BoB and over the AS are shown in Figure 2b. The VIMT over the BoB averaged over (84–100°E, 5–21°N) is decreasing at −0.26 Kg/ms/JJAS while over the AS averaged over (50–73°E, 5–21°N), it is increasing at the pace of 0.57 Kg/ms/JJAS. Both the zonal and meridional moisture transport components contribute to the increasing trend of VIMT over the AS and decreasing trend over the BoB. The robustness of the increasing and decreasing trends of VIMT is examined by calculating the area averaged VIMT in another reanalysis, namely the MERRA (Figure 2c). Although the actual value of the trends may be debatable, the increasing trend of VIMT over the AS and decreasing trend over the BoB are robust features in both the reanalysis.

[11] What is responsible for the tends of VIMT over AS and BoB? As low level winds and moisture make maximum contribution to the VIMT, the trends of wind speed and specific humidity at 925 hPa and 850 hPa from ERA-40 are shown in Figure 3. Although there is some spatial inhomogeneity of the trends of wind speed and specific humidity at both levels, the trends are consistent with an increasing trend of VIMT in AS while a decreasing trend of VIMT in BoB. Thus, the increasing trend of VIMT over AS is contributed by both wind speed and low level moisture. Similarly, decreasing trends of both wind speed and low level moisture contribute to the decreasing trend of VIMT over the BoB. The trend of surface water vapour (SWV) at 925hPa from MODIS-TERRA provides another independent estimate of decreasing trend of low level moisture in the east and increasing trend in the west at least in the recent years (Figure S4).

[12] If the trends of VIMT is responsible for the trends of R_{LMR}, it is argued that VIMT and R_{LMR} over land regions of India should correlate positively on interannual time scale as well. It is interesting to note that indeed that is true with correlation 0.78 found between the AS-VIMT and R_{LMR} (west); while a weak correlation 0.1 found between BoB-VIMT and R_{LMR} (east) (Figure S5). It turns out that the weaker correlation between BoB-VIMT and R_{LMR} is largely contributed by ENSO (El Nino Southern Oscillation). If the El Nino years are excluded from the correlation analysis, while the correlation coefficient in the west increases to 0.79, it increases to 0.35 in the east. This implies that

increase in R_{LMR} in the west of 81°E is primarily due to the enhanced moisture transport from AS. However, the weaker correlation between BoB-VIMT and R_{LMR} (east) suggests that in addition to VIMT, there may be other factors contributing to the reduced R_{LMR} in the EI and NEI. Rather weak relationship between VIMT and seasonal mean rainfall is not surprising as the seasonal mean rainfall contains 'noise' arising from high frequency rainfall variability.

[13] For fixed moisture supply, increase in aerosol loading and hence that of Cloud Condensation Nuclei (CCN) leads to a decrease of the cloud effective radius (R_e) reduces collision-coalescence efficiency among the cloud droplets [*Gunn and Phillips*, 1957; *Rosenfeld*, 2000; *Konwar et al.*, 2010], delays warm rain process and results in reduction in rainfall. Reversing the scenario, if aerosol loading remain fixed (as there is no evidence of increasing trend of AOD during monsoon season), increase (decrease) in moisture supply is likely to increase (decrease) R_e, enhance (suppress) collision-coalescence efficiency and increase (decrease) rainfall. Therefore, it will be interesting to know if R_e has similar trend like R_{LMR} during the last decades over the Indian subcontinent. Unfortunately, such data is not available for the whole of the thirty two year period. The trends of R_e corresponding to R_{LMR} obtained from MODIS-TERRA satellite during the past decade is shown in Figure S6. Interestingly, significant decreasing trends of R_e at 0.20 micron/JJAS over the Tibetan plateau, EI, NEI and BoB are observed. Increasing trends of R_e over the SI, NI to NWI are also observed at greater than 0.1 significance level. It may be noted that the trend in R_e has similar asymmetry like that of R_{LMR} (Figure 1b) with decreasing trends east of 80°E and increasing trend west of it which in turn is also very similar to the trends of seasonal mean rainfall (Figure S1a). This observation is important as it illustrates a consistency between dynamical forcing and microphysical properties of clouds over this subcontinent.

4. Conclusions

[14] Barring few small pockets in EI, NEI and extreme southern tip of SI (see Figure S1a), the seasonal mean ISMR is decreasing in the eastern parts of India while it is increasing in the western parts of India during the past three to four decades. Here, we provide a mechanistic explanation for this intriguing observed asymmetry in trends of ISMR. With no asymmetry in trends of heavy rainfall events (R_{HR}) and light rainfall (R_{LR}), we show that asymmetry in the trends of seasonal mean arises from a similar asymmetry in the trends of low and moderate rainfall (R_{LMR}) events. As the R_{LMR} generally comes from mesoscale and synoptic systems, it is likely that the observed asymmetry may arise from some asymmetry in changes in large scale dynamic and thermodynamic parameters. We find that increasing moisture transport over AS is one of the plausible reasons why the CI, SI, NI and NWI are receiving more R_{LMR} in recent decades. In contrast, over the EI and NEI the R_{LMR} is decreasing due to the decrease of VIMT over the BoB. The increasing (decreasing) trend of VIMT over AS (BoB) is a result of combined influence of increasing (decreasing) trend of low level wind speed and moisture content.

[15] Assuming that the aerosol loading (and hence CCN concentration) remains roughly constant during the monsoon season, a decrease in atmospheric moisture would result in smaller R_e, while an increase in atmospheric moisture supply would favor large R_e. The contrasting trend in VIMT, therefore could influence the rainfall as size of cloud droplets affect the efficiency of the collision-coalescence processes within the cloud. A clear asymmetry in the trends of R_e with increasing trend in the western parts and a decreasing trend in the eastern parts during the past decade support our hypothesis that the asymmetry in the trends of monsoon rainfall is largely driven by dynamics.

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References

Bollasina, M., S. Nigam, and K. M. Lau (2008), Absorbing aerosols and summer monsoon evolution over South Asia: An observational portrayal, *J. Clim.*, *21*, 3221–3239, doi:10.1175/2007JCLI2094.1.

Bollasina, M. A., Y. Ming, and V. Ramaswamy (2011), Anthropogenic aerosols and the weakening of the South Asian summer monsoon, *Science*, *334*, 502–505, doi:10.1126/science.1204994.

Chung, C. E., and V. Ramanathan (2004), Aerosol loading over the Indian Ocean and its possible impact on regional climate, *Indian J. Mar. Sci.*, *33*(1), 40–55.

Dey, S., and L. D. Girolamo (2011), A decade of change in aerosol properties over the Indian subcontinent, *Geophys. Res. Lett.*, *38*, L14811, doi:10.1029/2011GL048153.

Ghosh, S., D. Das, S. C. Kao, and A. R. Ganguly (2012), Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes, *Nat. Clim. Change*, *2*(2), 86–91, doi:10.1038/nclimate1327.

Godfred-Spenning, C. R., and C. J. C. Reason (2002), Interannual variability of lower-tropospheric moisture transport during the Australian monsoon, *Int. J. Climatol.*, *22*, 509–532, doi:10.1002/joc.710.

Goswami, B. N., and P. K. Xavier (2005), ENSO control on the South Asian monsoon through the length of the rainy season, *Geophys. Res. Lett.*, *32*, L18717, doi:10.1029/2005GL023216.

Goswami, B. N., V. Venugopal, D. Sengupta, M. S. Madhusoodanan, and P. K. Xavier (2006), Increasing trend of extreme rain events over India in a warming environment, *Science*, *314*, 1442–1445, doi:10.1126/science.1132027.

Guhathakurta, P., and M. Rajeevan (2008), Trends in the rainfall pattern over India, *Int. J. Climatol.*, *28*, 1453–1469, doi:10.1002/joc.1640.

Gunn, R., and B. B. Phillips (1957), A experimental investigation of the effect of air pollution on the initiation of rain, *J. Meteorol.*, *14*, 272–280, doi:10.1175/1520-0469(1957)014<0272:AEIOTE>2.0.CO;2.

King, M. D., Y. J. Kaufman, W. P. Menzel, and D. Tané (1992), Remote sensing of cloud, aerosol, and water vapor properties from Moderate Resolution Imaging Spectrometer (MODIS), *IEEE Trans. Geosci. Remote Sens.*, *30*, 2–27, doi:10.1109/36.124212.

Konwar, M., R. S. Maheskumar, J. R. Kulkarni, E. Freud, B. N. Goswami, and D. Rosenfeld (2010), Suppression of warm rain by aerosols in rain-shadow areas of India, *Atmos. Chem. Phys. Discuss.*, *10*, 17,009–17,027, doi:10.5194/acpd-10-17009-2010.

Kothawale, D. R., A. A. Munot, and K. Krishna Kumar (2010), Surface air-temperature variability over India during 1901–2007 and its association with ENSO, *Clim. Res.*, *42*, 89–104, doi:10.3354/cr00857.

Lau, K. M., and K.-M. Kim (2006), Observational relationships between aerosol and Asian monsoon rainfall, and circulation, *Geophys. Res. Lett.*, *33*, L21810, doi:10.1029/2006GL027546.

Lau, K. M. W., and K.-M. Kim (2010), Fingerprinting the impacts of aerosols on long-term trends of the Indian summer monsoon regional rainfall, *Geophys. Res. Lett.*, *37*, L16705, doi:10.1029/2010GL043255.

Nigam, S., and M. Bollasina (2010), "Elevated heat pump" hypothesis for the aerosol-monsoon hydroclimate link: "Grounded" in observations?, *J. Geophys. Res.*, *115*, D16201, doi:10.1029/2009JD013800.

Pruppacher, H. R., and J. D. Klett (1997), *Microphysics of Clouds and Precipitation*, 2nd ed., 954 pp., Kluwer Acad., Dordrecht, Netherlands.

Rajeevan, M., J. Bhate, J. D. Kale, and B. Lal (2006), High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells, *Curr. Sci.*, *91*, 296–306.

Ramachandran, S., S. Kedia, and R. Srivastava (2012), Aerosol optical depth trends over different regions of India, *Atmos. Environ.*, *49*, 338–347, doi:10.1016/j.atmosenv.2011.11.017.

Ramanathan, V., C. Chung, D. Kim, T. Bettge, L. Buja, J. T. Kiehl, W. M. Washington, Q. Fu, D. R. Sikka, and M. Wild (2005), Atmospheric brown clouds: Impact on South Asian climate and hydrologic cycle, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 5326–5333, doi:10.1073/pnas.0500656102.

Rosenfeld, D. (2000), Suppression of rain and snow by urban and industrial air pollution, *Science*, *287*, 1793–1796, doi:10.1126/science.287.5459.1793.

Xavier, P. K., C. Marzin, and B. N. Goswami (2007), An objective definition of the Indian summer monsoon season and a new perspective on ENSO-monsoon relationship, *Q. J. R. Meteorol. Soc.*, *133*, 749–764, doi:10.1002/qj.45.