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Solar cycle effects on Indian summer monsoon dynamics

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Solar activity associated with sunspot number influences the atmospheric circulation on various time scales. As Indian summer monsoon (ISM) is the manifestation between warmer Asian continent and the cooler Indian Ocean, changes in the solar cycle are expected to influence the ISM characteristics. Among several elements of ISM, Tropical Easterly Jet (TEJ), Low Level Jet (LLJ), and rainfall are important features. As a part of CAWSES India Phase II theme 1 (solar influence on climate (0–100 km)) programme, we made an attempt to investigate the role of solar cycle variability on these ISM features using long-term data available from NECP/NCAR (1948–2010) and ERA-Interim (1979–2010) re-analysis products. To check the suitability of these data sets, ground based observations available over the Indian region are also considered. ISM characteristics are studied separately for the maximum and minimum as well as increasing and decreasing solar cycle conditions. Amplitudes corresponding to the solar cycle observed in TEJ, LLJ and rainfall are extracted using advanced statistical tool known as intrinsic mode function. Long-term trends in TEJ reveal decreasing trend at the rate of 0.13 m/s/yr (between 1948 and 2000) and no perceptible trend in LLJ. There exists inverse relation between TEJ strength and Central India rainfall. Large difference of 2 m/s (5 m/s) in the zonal winds of TEJ between solar maximum and minimum (increasing and decreasing trend) is noticed. There exists a difference of ~2 m/s in LLJ winds between solar maximum and minimum and increasing and decreasing trend of the solar cycle. However, no consistent relation between the ISM rainfall and solar cycle is noticed over Indian region unlike reported earlier but there exists a delayed effect around 13 years. We attribute the observed features as linear and non-linear relation between dynamics of ISM, rainfall and solar cycle, respectively.

1. Introduction

The Indian summer monsoon (ISM), which is a part of a large scale circulation pattern of Asian Summer monsoon (ASM), develops due to the differential heating between the warm Asian continent and cooler Indian Ocean. The strong southwesterly winds in the lower troposphere brings significant amount of moisture to the Indian subcontinent, which is released as precipitation. This rainfall plays a very important role in agricultural productions and economical conditions, thus its variability and long-term trends is of great interest. ISM is characterized by a few important features in the troposphere such as seasonal wind reversal Low Level Jet (LLJ) stream in the lower level and Tropical Easterly Jet stream (TEJ) in the upper level. TEJ is an important parameter of the ISM circulation which can be seen in the upper tropospheric levels (100–150 hPa) during the ISM months of June to September (Krishnamurti and Bhalme, 1976). This jet has wind speed of roughly 40–50 m/s with the strongest winds being found in northern hemispheric summer over the Arabian Sea (Reiter, 1961). The study of these features is important as they reveal the strength of the monsoon and its year-to-year variability.

To the present knowledge, many specific changes during the monsoon have been identified on long-term scales and based on these, forecasts are being made. However, many issues remain unexplained and monsoon is playing on its own way. Though the monsoon system is well understood at present, but it is evident that the effect of solar cycle on monsoon climate is least explored. Since many years the influence of solar activity on climate is on debate. Recent advances in reconstruction of the past climate with fine temporal resolution clarified the relationship between the solar cycles and the monsoon rainfall in South Oman with multiple time scales from decadal to millennial and the direct cause of higher rainfall in South Oman was explained by stronger northward surface winds (Neff et al., 2001; Burns et al., 2002; Fleitmann et al., 2003). The multidecade to century scale variations in the monsoon winds were much larger in the early Holocene

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coincident with increased sunspot numbers (Gupta et al., 2005). A possible association between Indian monsoon rainfall and solar activity was reported by Bhattacharyya and Narasimha (2005, 2007). Study by Agnihotri et al. (2011) indicates that anomalous dry periods of the Indian monsoon are coincident with negative total solar irradiance (TSI).

Note that understanding the influence of solar variability on the Earth's climate requires knowledge of solar variability, solar–terrestrial interactions, and the mechanisms determining the response of the Earth's climate system which can be associated with variations in ozone, temperatures, winds, clouds, and precipitation (Gray et al., 2010). Numerous studies have been established to identify the influence of solar cycle on various atmospheric parameters like sea surface temperature (SST), sea level pressure (SLP), rainfall and tropospheric temperatures (Reid, 1987, 1991; Haigh, 1996; Hiremath and Mandi, 2004; Gray et al., 2010; Roy and Haigh, 2010). Long term variations in Earth's temperature are closely associated with variations in the solar length, and it closely matches with the long term variations in the land temperatures in the Northern Hemisphere (Christensen et al., 1991). As the major source for the ISM to occur is the thermal gradient between the Asian continent and the Indian Ocean, changes in solar cycle are expected to influence the monsoon winds correspondingly.

Solar variability has to be carefully monitored in decadal to multi-decadal timescale, in conjunction with other greenhouse parameters, in order to achieve predictive capability of monsoon rainfall (Agnihotri and Dutta, 2003). Reddy et al. (1989) found that there is a correlation between rainfall and solar cycle with phase delay of 0.16 year (solar cycle leads). The spring and southwest monsoon rainfall variabilities are positively correlated with the sunspot activity (Hiremath and Mandi, 2004). It was also proposed that solar influence on monsoon activity is not due to a change in radiative heating in the troposphere but rather originates from the stratosphere through modulation of the upwelling in the equatorial troposphere, which produces a north–south see-saw of convective activity over the Indian Ocean sector during summer. Increase in solar activity resulting increased in precipitation over Arabia and India (Kodera, 2004). Larger precipitation is found along the western Pacific Ocean and reduced over equatorial Indian Ocean due to the high solar activity (Claud et al., 2008). Solar cycle influences the mean meridional circulations (Hadley and Brewer–Dobson circulations) in northern summer especially during the east phase of the Quasi-Biennial Oscillation (Labitzke, 2003). Although the observational data suggests that solar activity has influenced temperature on decadal, centennial and millennial timescales; however there could be some other sources co-exists which need to be differentiated from other factors such as volcanic eruptions and the El Niño Southern Oscillation (ENSO) (Haigh, 2003). Using a multiple linear regression analysis Roy and Haigh (2010) identified solar cycle signals in 155 years of global SLP and SST in the Northern Pacific and found a statistically significant weakening of the Aleutian Low and a northward shift of the Hawaiian High in response to higher solar activity in SLP and a weak El Niño like pattern in the tropics in SST. The solar response shows largest warming in the stratosphere and bands of warming of more than 0.4 K throughout the troposphere in the mid-latitudes.

In this present study we made an attempt to investigate the role of solar cycle variability on ISM features like TEJ, LLJ and rainfall. As mentioned earlier, the common feature that can be observed during ISM which occurs at 16 km ($\sim$100 hPa) is the TEJ and it affects the formation of storms during this season. By considering about 50 years data up to 1998, Sathiyamoorthy (2005) has shown that the strength of TEJ has decreased in the recent years. But recent results by Raman et al. (2009) and Venkat Ratnam et al. (2013) showed that there exists an increase in the strength of TEJ from 2000 onwards at about 1 m/s/year. We further extend the study made by them to explore the variability of TEJ characteristics and monsoon rainfall over India due to the solar cycle using advanced statistical tool like Intrinsic Mode Function (IMF). Similar analysis has been extended for the LLJ that occurs at $\sim$850 hPa during ISM months and on the rainfall.

2. Database

2.1. NCEP/NCAR and ERA-Interim reanalysis datasets

The 64 years (1948–2010) monthly mean zonal wind data from National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data available with 2.5° latitude × 2.5° longitude (Kalnay et al., 1996) grid on 17 pressure levels from 1000 hPa to 10 hPa has been used to study the spatial distribution and long-term trends in TEJ and LLJ strength. In addition, European Centre for Medium-Range Weather Forecasts (ECMWF) Interim (ERA-Interim) reanalysis data available with 1.5° latitude × 1.5° longitude with 37 vertical pressure levels from 1000 hPa to 1 hPa from 1979 onwards is also used to verify the results obtained by relatively less vertical and horizontal resolution NCEP/NCAR data. It is worth to mention here that there is a concern about the use of reanalysis data for calculating climate trends as they can overestimate/underestimate the true trends (Bengtsson et al., 2004). Note that in case of ERA-Interim, warming of the lower stratosphere by approximately 0.2 K in December 2006 with the introduction of GPS radio occultation data from the COSMIC constellation is being reported and slight excess warming of upper-tropospheric temperatures due to the assimilation of growing numbers of warm-biased temperature measurements from aircraft, beginning in 1999 (Dee and Uppala, 2009). After December 2006, this drift is somewhat reduced with the introduction of GPS radio occultation data from the COSMIC constellation. This might have some effect on the observed winds only in the latter half of the recent decade as gradient in temperature result in the winds. In the case of NCEP, the final product from this model again put through the quality check and assimilated with a data assimilation system kept unchanged over the reanalysis period. Thus, we are not expecting a big change except in the last decade as in the case of ERA-Interim. However, in the present study we restrict to variation in the winds from these reanalysis data which are more than two-sigma variations. Further we also validate the use of reanalysis from one of the location using high resolution ground based observations.

2.2. MST radar and GPS radiosonde observations

Data available from high vertical resolution MST Radar located at Gadanki (13.5°N, 79.2°E) since 1996 has also been considered to verify the accuracy of reanalysis data sets. The Indian MST radar is operated almost daily for about half-an-hour around 1730 LT (LT=UT+0530 h) with vertical resolution of 150 m and accuracy of 0.1 m/s (horizontal winds). MST radar located quite over the core of the TEJ grid provides an opportunity to observe the monsoon features like TEJ with high-vertical resolution (Narayana Rao et al., 2000; Ghosh et al., 2001; Vasantha et al., 2002; Raman et al., 2009; Venkat Ratnam et al., 2013). High-resolution radiosonde observations available daily from the same location during the period of April 2006 to December 2011 is also used to verify the LLJ variability observed in reanalysis data sets. Most of these radiosondes were launched around 1730 LT.

In addition to these data sets, we also make use of the gridded (1° × 1°) rainfall data obtained from India Meteorological

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