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On identifying the role of Sun and the El Niño Southern Oscillation on Indian Summer Monsoon Rainfall

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Abstract

A solar influence on Indian Summer Monsoon (ISM) rainfall, identified in previous studies using the method of solar peak year compositing, may not be robust and can be influenced by other factors such as the El Nino Southern Oscillation (ENSO) and trends. Regression analysis, which takes into account variations across the whole solar cycle rather than just the minimum /maximum solar years, fails to detect any direct solar influence on the ISM during June–August. Regression suggests that the spatial pattern of ENSO, as imprinted in the sea level pressure in the Indian Ocean region, covering parts of Australia, has changed during the second half of last century. Thus ENSO impacts via variations in the local Hadley circulation may have played a role in modulating the ISM during that period. Finally, we discuss a possible indirect connection between the solar cycle and monsoon rainfall, which are different since the 1950s.

Keywords: **ENSO; Indian Summer Monsoon; Solar cycle**

1. Introduction

The Indian Summer Monsoon (ISM) is one of the most important climate systems, having huge impact on India's socio-economic infrastructure. Studies have identified connections between the ISM and the El Niño Southern Oscillation (ENSO) (e.g. Turner *et al.*, 2005; Maity and Kumar, 2006), though ENSO is not the sole driver of variations in monsoon rainfall. Analysis suggested that warm events of ENSO are usually associated with less rainfall and cold events are associated with more rainfall. However, this 'rule' is not universal and there are many exceptions (Kumar *et al.*, 2006; Maity and Kumar, 2006) suggesting that other factors may also play a role. In addition, the ISM exists in a global climate system that is influenced by both natural and anthropogenic factors. It is a major challenge to predict natural and anthropogenic variations of Indo-Pacific modes (AchutaRao and Sperber, 2006; Collins *et al.*, 2010) and hence their interaction with monsoon must be a problem of even greater complexity.

The sun, being the major driving factor of earth's climate, is clearly a prime factor in establishing the mean ISM conditions. Van Loon and Meehl (2012) (hereafter, vLM12) discuss a connection between variations in the ISM and variations in the energy output of the sun. They showed that peak years of the solar sunspot cycle are related to sea level pressure (SLP) anomalies which, in turn, are related to more rainfall in India during summer. Balachandran *et al.* (1999) and Meehl *et al.* (2008) show that there is an intensification of the Inter Tropical Convergence Zone (ITCZ) during high solar years. White *et al.* (1997) have suggested that SST anomalies in the tropical Pacific follow the 11 year solar cycle. Kodera *et al.* (2007) showed ENSO-related signals are confined in the Pacific sector during higher solar (HS) years and extend into the Indian Ocean only during periods of low solar (LS) activity. They examined 79 years of data from 1920 to 1998, among which 48 years were of LS and 31 years of HS years. They defined HS (LS) years according to whether the solar index (measured as SSN) was higher (lower) than the long-term mean value. Their study suggested that such changes in intensity results from a shift in the location of the descending branch of anomalous Walker Circulation. This result, that the ENSO influence extends into the Indian Ocean through a modification of the Walker Circulation, is quite consistent with a model study using an atmosphere-ocean coupled general circulation model (CGCM) by Behera *et al.* (2006).

2. Methodology and data

The two main methods that are used here are the method of solar maximum/minimum year compositing and the method of multiple regression analysis with AR(1) noise model. Compositing is described in detail by Van Loon *et al.* (2007), Meehl *et al.* (2008), Van Loon and Meehl (2011) and Van Loon and Mehl (2011, 2012) and the regression by Roy and Haigh (2010, 2011, 2012) and Roy (2013). We also present simple scatter plots including various factors to enhance understanding of the ISM variations. Variables used in this analysis are SLP, monthly Sun Spot Number (SSN), Nino3.4 index, Stratospheric Aerosol Optical Depth (OD, indicative of volcanic eruptions) and monsoon precipitation in India.

For SLP, the in-filled HadSLP2 dataset from Allan and Ansell (2006), which covers the whole of the globe and available as monthly means from 1850 to

2004, is used. It can also be found from http://www.metoffice.gov.uk/hadobs/hadslp2.

Monthly Sun Spot Number (SSN) is used to represent solar cyclic variability, as available from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL/monthly/MONTHLY.PLT. It is also available from Waldmeier (1987) and Solar Indices Bulletin, issued by National Geophysical Data Centre, Solar-Terrestrial Physics Division (E/GC2), Boulder Colorado. The main advantage of using SSN as a solar index is that the measurement is taken directly and also available for a longer time period. It is free from the influence of longer term trends [as seen in various reconstructions of Total Solar Irradiance (TSI)] and only captures the cyclic variability of the Sun. It is the most commonly used solar index, for representing decadal variability and for the purpose of analysing long-term climate data.

For ENSO, the Niño 3.4 index, obtained from Kaplan *et al.* (1998) is used, which is available since 1856 and can also be found from http://climexp.knmi.nl. Niño 3.4 is defined as the three month running mean of SST departures in the region (5°N–5°S, 120–170°W), calculated with respect to the 1971–2000 base period. The SST reconstruction methodology is described in Smith *et al.* (2008).

Stratospheric aerosol optical depth (OD) has been used in regression analysis to represent climatically important volcano. The Sato *et al.* (1993) series is available up to 1999. It can also be found from http://data.giss.nasa.gov/modelforce/strataer/tau_line.txt. Here we extend to 2005 with near zero values to include those years in the regression. Indian precipitation data is collected from Parthasarathy *et al.* (1994, 1995)and is available from 1871 to 2011. It can also be found at: ftp://www.tropmet.res.in/pub/data/rain/iitm-regionrf.txt. It covers an area with a network of 306 stations over 30 meteorological subdivisions covering about 90% of the total area of the country.

3. Results and discussion

3.1. Solar signal in SLP using the method of compositing

vLM12 use 14 peak solar years from the 11 year solar cycle variability during the period 1850 to 2004 to detect a solar signal in the ISM. Roy and Haigh (2010) show that solar peak years, as used by Van Loon *et al.* (2007) and Meehl *et al.* (2008) in their analyses have been associated with cold events of ENSO (−ve ENSO index). Haam and Tung (2012) showed that solar peak years can coincide with cold events of ENSO by chance, even if the two time series are independent, and such coincidence can continue for many cycles. In their study, using two sinusoidal series one with 11 year cycle and the other with 3.7 year cycle, they clearly demonstrated such coincidence and discussed their findings in details. Thus, for these pair of two auto-correlated time series, solar and ENSO, there can be zero correlation for the longer term period but statistically significant chance correlations may be achieved for some periods if the time series are subsampled. Hence it is possible that, when using the solar peak year compositing method, the ENSO signal is convolved with the solar signal. ISM precipitation is generally enhanced during the negative phase of ENSO, so it is possible that the enhancement of monsoon precipitation during the negative phase of ENSO is falsely attributed to peak solar activity.

However, there are also possibilities that a solar signal in the ISM is robust. For example, Roy and Haigh (2010, 2012) showed that a strong, significant solar influence around the location of Aleutian low during DJF. Though captured by maximum compositing, the influence is not sensitive to the methodology used. It is also detected using other methods including multiple regression, suggesting the robustness of that signal.

To investigate the possibility of the convolution of signals we perform solar peak year as well as solar trough year compositing of SLP during June–July–August (JJA) using the HADSLP2 data. Covering 14 solar peak/trough years during the 155 year period (1850–2004), we particularly focus around the regions of the Indian subcontinent (Figure 1(a)–(f)). Here we additionally perform solar-trough year compositing alongside peak year compositing to test the sensitivity of these choices of solar years. The purpose is to verify whether such choices reverse or change the detected signal. We use the same solar peak years as used by vLM12 and follow a similar technique in determining minimum years. For clarity, the peak years and trough years considered in this analysis are also shown in Table 1 with corresponding SSN values and concurrent Nino3.4 values. The right hand panel of Figure 1 shows the result using maximum (peak) year compositing, whereas the left hand panel uses minimum (trough) year compositing.

The period from the 1950s to 1997 was identified by several authors (e.g. Vecchi and Soden, 2007) as the period of weakening of both the Walker and Hadley Circulations; more in the Walker Circulation than the Hadley. Moreover, during the same period the shallow ocean Meridional Overturning Circulation in the tropical Pacific also weakened (Zhang and McPhaden, 2006) suggesting that both the atmosphere and the ocean system was in an anomalous state. In the upper panels of Figure 1, the climatological baseline period is considered as 1956–1997. We impose an arbitrary shift in baseline climatology from 1956 to 1997 (upper panels) to 1936–1975 (middle panels) to also highlight the sensitivity of the analysis to this choice. To have a general overview relating to climatological SLP of these two baseline periods, we have also drawn Figure 1(e) and f in the bottom panels. Figure 1(e) shows climatological SLP in hPa during (1956–1997), whereas Figure 1(f) shows difference in climatological SLP during period 1956–1997 to that in 1936–1975. The land and ocean SLP gradient is likely to play a role in regulating ISM rainfall through moisture transport (Krishnamurthy and

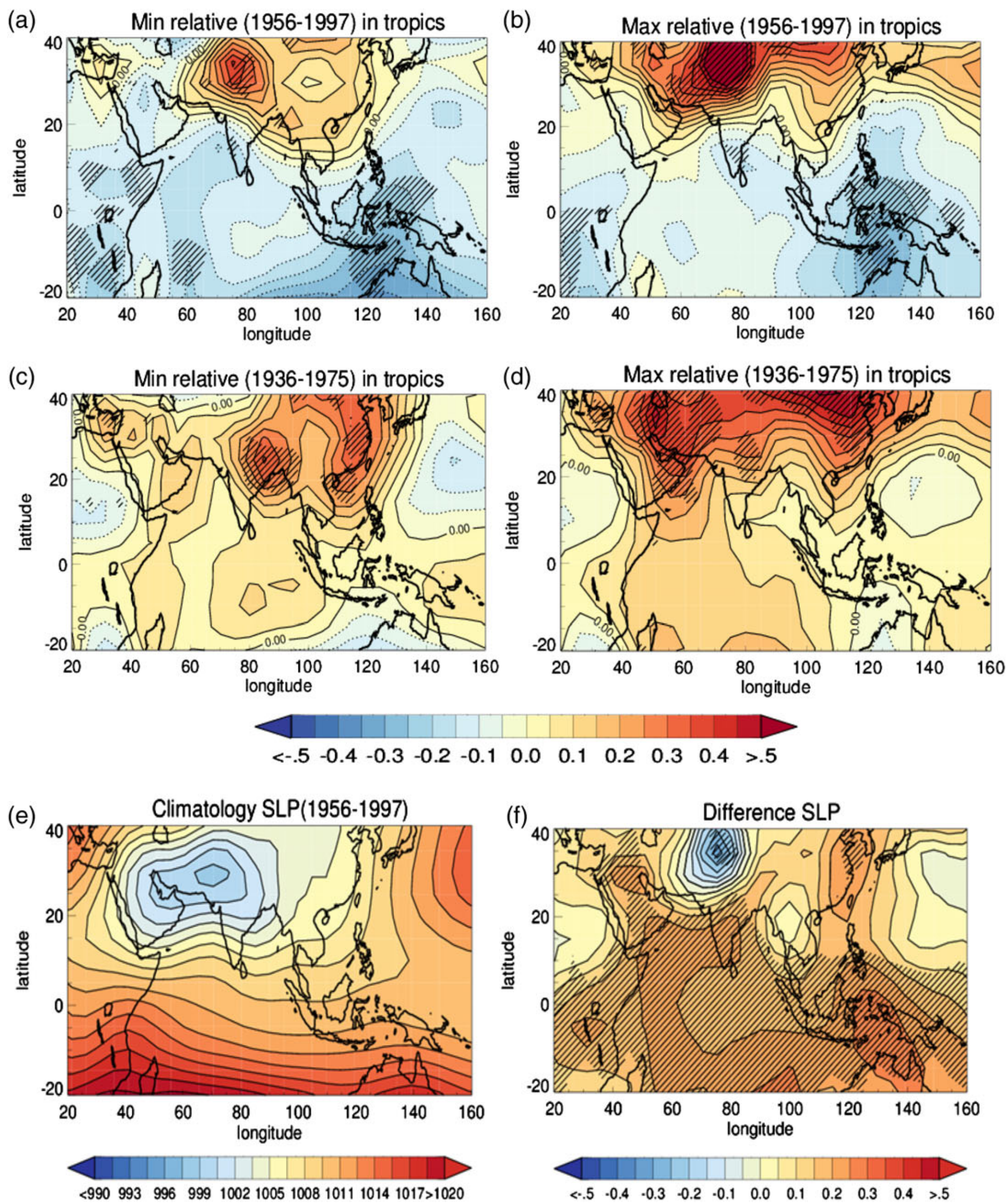

Figure 1. Solar signal in June–July–August (JJA) SLP data (HADSLP2 in hPa) using SSN minimum/peak years compositing for 14 solar cycles during 1850 to 2004, focusing on the Indian subcontinent. In Figure (a), the climatology from 1956–1997 is removed from the 1850–2004 period and the composite is for solar minimum years. In Figure (b) the solar peak year composite is shown using the same climatology period. Figure (c) and (d) are same as (a) and (b), respectively, but with the 1936–1975 climatology removed. Figure (e) shows climatological SLP in hPa during (1956–1997); whereas, Figure (f) shows difference in climatological SLP during period 1956–1997 to that from 1936–1975. Shaded regions are estimated significant at the 95% level using a *t*-test.

Kinter, 2002). Acknowledging the fact that mechanism of ISM variability involves several other factors, but also that the SLP plays very important role in regulating the ITCZ that also takes into account other processes, we particularly focused on SLP to test the robustness of the detected solar signal when using compositing. If we separately consider the top and middle panels, it is clear that the land-sea SLP contrast suggests similar patterns, irrespective of peak and minimum year compositing. For Figure 1(a) and (b), there is a significant signal around Darwin, with an opposite signal (which is significant) around the land region of India. Such climatological features play role in influencing the ITCZ and moisture convergence. Figure 1(a) and (b) clearly suggests that, irrespective of peak years or trough years, there should be more monsoon precipitation in general during the period 1956–1997 (following the sign convention, as the anomaly is calculated with respect to that period) if other factors are not taken into account. If we focus on the zero line of the figures in middle panels around the Indian Ocean, we observe the influence on the ITCZ, via the land–sea SLP contrast, is weaker in Figure 1(c) and (d), though the gradient is of similar sign. Moreover, there is no significant signal around Darwin, Australia. Figure 1 (upper and middle panels) suggests,

Table 1. Niño 3.4 index (DJF) at the peak year and trough year of SSN for the 14 solar cycles 1856–2007.

Solar cycle no	Year	Peak year	SSN	ENSO (DJF)	Trough Year	SSN	ENSO (DJF)
10	1856–1867	1860	95.8	−0.44	1856	4.3	1.01
11	1867–1878	1870	138.9	−0.82	1867	7.3	0.09
12	1878–1889	1883	63.6	−0.36	1878	3.4	2.20
13	1889–1901	1893	85.1	−1.43	1889	6.2	1.85
14	1901–1913	1905	63.5	1.24	1901	2.7	.57
15	1913–1923	1917	103.9	−1.33	1913	1.4	0.12
16	1923–1933	1928	77.8	0.14	1923	5.8	−0.45
17	1934–1944	1937	114.4	−0.01	1934	8.7	−1.08
18	1944–1954	1947	151.5	0.013	1944	9.6	−0.45
19	1955–1964	1957	189.8	−0.15	1955	37.9	−0.92
20	1964–1976	1968	105.9	−0.64	1964	10.2	0.82
21	1976–1986	1979	155.3	0.02	1976	12.5	−1.53
22	1986–1996	1989	157.8	−1.83	1986	13.4	−0.61
23	1996–2007	2000	119.5	−1.65	1996	8.6	−0.84
Total number	Solar cycle 14			C-9, W-2, N-3			C-7, W-7

C/W indicates the number of occurrences of index values of 0.02 °C lower/higher than its average value, while *N* indicates a near neutral state.

the deviation from the climatology (Figure 1(a) and (b)) is the deviation from the climatological period 1956–1997, whereas Figure 1(c) and (d) is the same from the period 1936–1975. The reverse signature in SLP around the ITCZ thus suggests the trend of the climatological period is playing dominating role. If the intensification of ITCZ is due to solar variations, the peak year compositing would have been completely opposite (or at least different) to that from the minimum year compositing.

Figure 1(e) shows climatology of SLP (in hPa) during the period (1956–1997), which suggests high SLP values around Indian Ocean covering Australia and low SLP around Indian subcontinent. Following the usual sign convention, such a feature suggests moisture convergence towards the ITCZ. However, when the deviation of SLP from that period is compared to that from 1936 to 1975 (Figure 1(f)), it clearly indicates an intensification of the ITCZ and more moisture convergence. Thus, from this discussion, it is suggested that trend is having a strong influence in enhancing the ISM precipitation during period 1956–1997. Moreover, it can also be considered as a potential factor in influencing the solar signal as detected by vLM12 using the compositing method.

Moving from the discussion of the influence of the mean climate state, we next focus on the composites relative to 'each other', i.e. peak years to minimum years. This is done by comparing right hand panels to that with left panels in Figure 1. The interesting point here is that the significant region shows as intensification of SLP during peak year compositing when compared to minimum-year compositing (Figure 1(b) to that from Figure 1(a) and 1(d) to that from Figure 1(c)). Such a feature might be associated with the preferential alignment of ENSO events (cold phase) with peak solar years as observed by Roy and Haigh (2010) and also shown in Table 1. It is clear from the difference between the right and left panels of Figure 1(a)–(d), that solar max compositing favours more intensification of the ITCZ and thus more rainfall, which is the same as the usual ENSO and ISM relationship (more rainfall during cold events of ENSO). Thus, apart from the trend, the ENSO signal in the compositing method is also related to the ISM precipitation, which is attributed by vL12 as solely due to solar. The overall analyses presented here indicate that caution should be taken in identifying a solar signal in the ISM using the method of compositing.

3.2. Signal in SLP using regression

The main advantage of the multiple regression technique to the compositing method is that it captures the signal over the whole solar cycle (all high and low solar years), so is not restricted to peak or trough years. It can also separate other factors that have potential to contaminate the results (provided they are orthogonal). Roy and Haigh (2010) showed that, if ENSO is not taken into account with care, that a signal might be misinterpreted as a solar effect. Table 1 also clearly indicates how solar peak year compositing can capture the cold phase of ENSO signals. It is also possible, when looking for a solar signal, to perform regression analysis over shorter time periods than compositing, to better isolate the impact of long-term changes, in contrast to the compositing technique of removing different climatological periods from the whole record. However, the compositing method also has certain advantages over regression, e.g. when performing regression analysis over shorter time periods, the role of outlying events may be exaggerated.

Based on Vecchi and Soden (2007) and Zhang and McPhaden (2006), we separate the data into a short 40-year period, 1956–1997 (one of the reference period chosen for the compositing above), and a longer 100-year period, 1856–1955, when the mean states of the atmosphere-ocean system are assumed to be different. The compositing method suggests that a trend might have played important role during that period and hence we do multiple regression analysis on SLP using a linear trend as one of the regressors. Other independent parameters used in the regression are the time series of the Volcanic Aerosol Optical Depth (OD), ENSO (Nino 3.4) and the sunspot number (SSN).

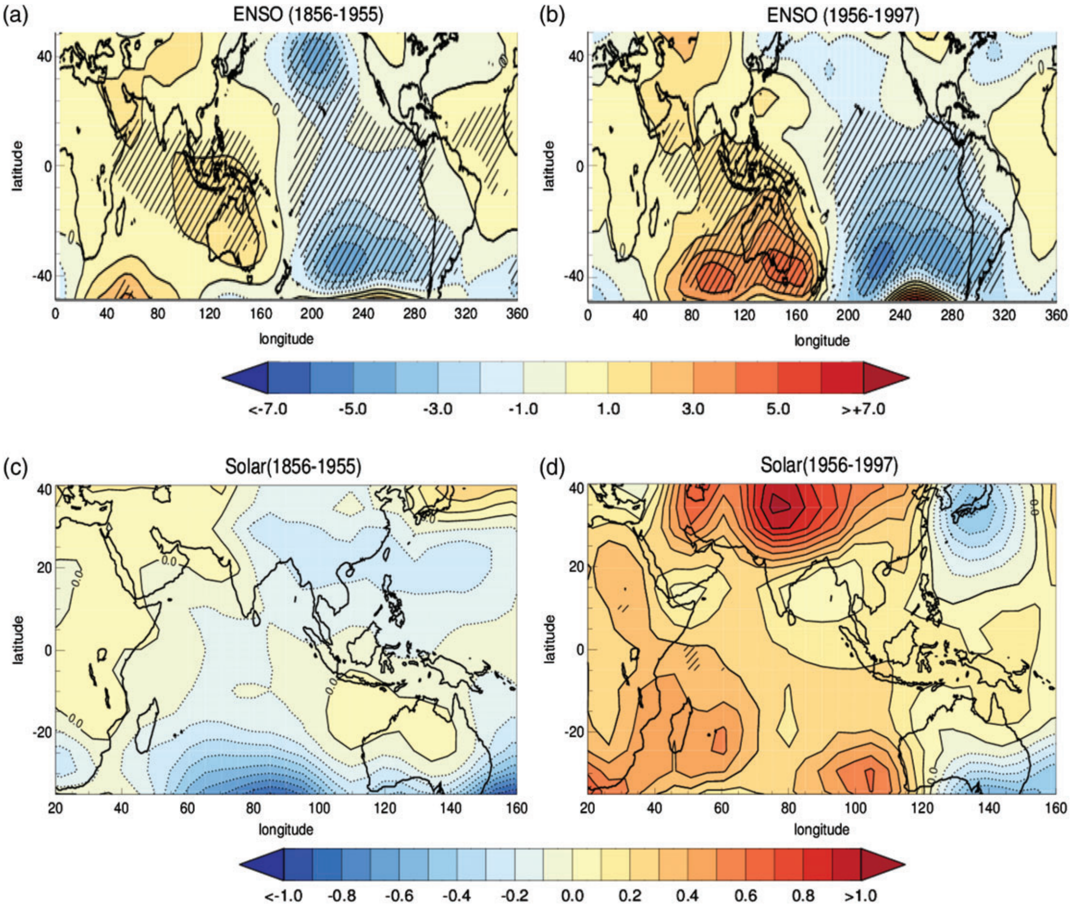

Figure 2. The signal (max−min, hPa) in JJA HADSLP2 data obtained from a multiple linear regression analysis on Nino 3.4 (top) and the solar cycle signal (bottom), covering regions of Indian subcontinent; (a) and (c) for period 1856–1955; (b) and (d) for 1956–1997. Other independent parameters used in the regression are the trend, the OD and the SSN for top and the trend, the OD and the ENSO for bottom. Excluding SSN as an independent parameter from the top, and ENSO from the bottom, does not affect these results. Negative contours are shown by dotted lines. Shaded regions are estimated significant at the 95% level using a *t*-test.

The top panels (a, b) in Figure 2 show the regression coefficients related to ENSO (max−min) projected onto SLP, when the other independent parameters used are the trend, the OD and the SSN. The ENSO signal is same with or without the SSN used as a regressors. The bottom panels (c and d) are the regression coefficients for the solar signal (max−min) for SLP when the other independent parameters are the trend, OD and ENSO. Here again, the results of the solar signal is the same with or without ENSO as one of the regressors. No significant solar signal around the Indian subcontinent is detected in either period during JJA using this regression analysis (Figure 2, bottom panels). Variations are larger during the later period, but amplitude-wise they are still small and insignificant. We also consider the full ∼150-year period (1856–2004) but could not detect a significant solar signal (Figure S1). Thus we conclude that the solar signal in the ISM, as detected by vLM12, is not robust but sensitive to their methodology.

Recent studies suggest that monsoon precipitation and ENSO show a weaker correlation during the 2nd half of last century, with the Indian monsoon occurring with normal levels of rainfall despite the occurrence of El Niños (Kumar *et al.,* 1999; Ashok *et al.,* 2001; Ashrit *et al.,* 2001). Other studies suggested the importance of separating the east Pacific ENSO and central Pacific ENSO events in terms of their influence on the ISM separately (Keshavamurty, 1982; Navarra *et al.,* 1999; Kumar *et al.,* 2006; Ashok *et al.,* 2007). However, here we mainly focus on ENSO in general rather than on those specific events. Recent observations indicated that the ENSO monsoon relationship in general has changed again since late 1990s.

Vecchi and Soden (2007) discussed that, during the last half of the 20th century, there was a weakening of tropical circulation which were more in the Walker cell than that in the Hadley cell. Here, in Figure 2 (top panels), we note that the spatial pattern of SLP around both the lobes of the SO is similar during two different periods considered. However, for Figure 2(b), the strongest rise in the variability of ENSO is noticed around the Indian Ocean including in the region of Australia. Such a change in the behaviour around Australia may also have some bearing on the changing behaviour of the Monsoon through the local north south Hadley circulation. Following the above discussion, and comparing Figure 2(a) and (b), it is suggested that the ENSO signal, transmitted via the Indian Ocean around region of

Australia, may have played a role in changing influence of ENSO and the ISM during that period, but was subdued by the stronger Walker circulation influence during the earlier period. A stronger SLP gradient from Australia to the Indian subcontinent in the later period, in comparison to that in the earlier period, can be one of the likely causes of more ISM rainfall (through more moisture convergence) in the warm phase of ENSO, in contrast to the normal ENSO–ISM relationship.

The ENSO signal in SLP around Australia is also important as it coincidentally projects onto the Indian Ocean Dipole (IOD), which in turn may also have more impact on the ISM rainfall in recent decades. Ashok *et al.* (2001) showed, using data covering similar period (1958–1997), that the IOD and ENSO have complementarily affected the ISM during that period. They showed that when the correlation between ENSO and ISM is low, the correlation between IOD and ISM is high, and vice versa. Using an Atmospheric Global Climate Model (AGCM), they found that the ENSO-induced anomalous circulation over the Indian region is either supported or countered by the IOD-induced anomalous meridional circulation cell.

3.3. The role of Sun on the ISM in earlier and later periods

As the regression method is unable to detect any significant solar influence on the ISM, here we explore further by considering different phases of ENSO. We plot a scatter diagram (Figure 3) with the ISM precipitation anomaly (JJA) versus annual average SSN. Figure 3(a) is for the period before the weakening tropical circulations, 1871–1955, from our available data series, while Figure 3(b) is for the later period, 1956–1997. The precipitation anomalies are presented in a normalised form to eliminate issues relating to the data range with the normalisation performed using the mean value for each period separately. The threshold of high or low solar index values sometimes plays a role in influencing various meteorological factors, as shown in several studies (e.g. Labitzke and van Loon, 1992, Kar and Bondyopadhaya, 1996, Roy and Haigh, 2012, among others). For that reason, we do not normalise the SSN here, in order to have a clearer overview about any possible threshold for SSN in influencing the ISM. There is a clear indication that ISM rainfall deficit years are usually associated with the warm phase of ENSO; whereas, years with excessive rain are allied with that of the cold phase. Though all the low precipitation years occur during the positive phase of ENSO, excessive rainfall during positive ENSO years is also possible. This indicates that, though ENSO is one important regulatory factor of ISM variability, it is not the sole driver. Rainfall during the positive phase of ENSO years is quite widely spread in comparison to that from negative ENSO years suggesting that the mechanism relating to the ENSO and ISM teleconnection is different in the positive phase when compared to the negative phase.

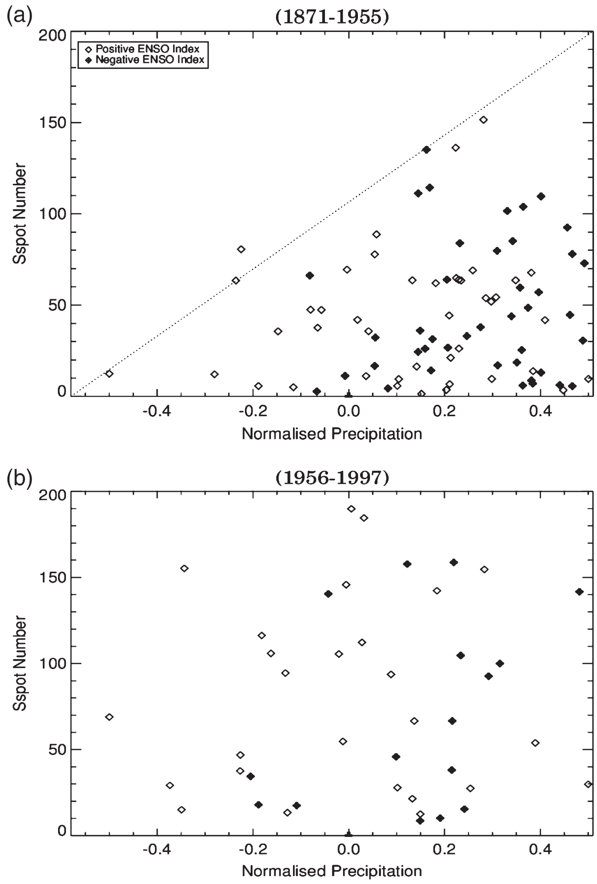

Figure 3. Scatterplot of SSN verses ISM precipitation anomalies (normalised) during JJA in two different time-periods: (a) 1871–1955; (b) 1956–1997. A positive ENSO index is shown with empty diamond and negative with black filled diamond. Dotted lines in Figure (a) have drawn to show that points are mostly confined to the bottom corner of the plot.

If we particularly focus on the earlier period (Figure 3(a)), we observe that those points are positively skewed with almost all the points are located in bottom half of the rectangle below the diagonal. On the other hand, points in Figure 3(b) show no such clear bias, with points in all parts of the diagram and no positive skewness. When all 150 years data are considered, no obvious connection between the ISM and SSN can be detected with points equally scattered over the diagram (hence that plot is not shown). This is in line with earlier studies (Mehta and Lau, 1997; Krishnamurthy and Goswami, 2000) which failed to detect a consistent relationship between the ISM, the solar cycle and ENSO over a long time period. Here we also note that we were unable to identify any threshold value for SSN that results in a detectable influence on the ISM in either period.

One possible explanation of why the points in Figure 3(a) are more confined below the diagonal is suggested by the studies of Meehl *et al.* (2008) and Roy and Haigh (2010, 2012). Meehl *et al.* (2008) proposed a mechanism whereby the variations in solar output, through the cloud-free subtropics of the Pacific, can influence the trade winds around tropical Pacific. Roy and Haigh (2010, Fig. 1) detected an intensification of the trade winds around the tropical Pacific during December–January–February (DJF) of higher solar years. Stronger trade winds in the Pacific during high solar years (and vice-versa) may act alongside usual inter-annual ENSO behaviour. Such a decadal solar signature is separate to that from the inter-annual ENSO signature, though they may be linked. Thus, high solar activity, through this indirect pathway, favours more ISM rainfall and suggests the reverse for low solar activity, following the usual ENSO–ISM behaviour. Moreover, Roy and Haigh (2012, Fig. 4) also noted that the significant decadal signature in the trade winds (though small in magnitude) is only observed during the earlier period and is missing since the 1950s. This might be one of the causes for a different solar/ISM behaviour during the latter period, as seen in Figure 3(b).

4. Summary

The solar signal influence reported by vLM12 on the ISM can be a result of the influence of ENSO and the trend when using composite analysis. Compositing suggests that during a period of weakened tropical circulations, the Indian Ocean plays role in the enhancement of monsoon rainfall. Regression that covers whole of the solar cycle, cannot detect any solar influence on the ISM. Regression, however, detects a strong signal of ENSO in SLP around the Indian Ocean. It also suggests that the influence of ENSO on SLP around regions of Australia have changed during the latter half of the last century. Following Vecchi and Soden (2007), it is suggested that, during that period, the weakening of the Walker circulation due to climate change may be overtaken by the local Hadley circulation and influence the ENSO–ISM teleconnection via ENSO changes in the region of Australia.

Before the 1950s we identify a connection between the sun and the ISM, which is not clear during the later period. We speculate that decadal solar forcing of the trade winds, that acts alongside usual inter-annual ENSO variability, may be one factor. Through this indirect route, high solar years favour more rainfall and low solar years favour less rainfall, following the usual ISM-ENSO behaviour during the earlier period.

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Supporting information

The following supporting information is available:

Figure S1. The solar cycle signal (max−min, hPa) in JJA HADSLP2 data from a multiple linear regression analysis for period 1856–2004 covering regions of Indian subcontinent. Other independent parameters used are the trend and the OD. Shaded regions are estimated significant at the 95% level using a *t*-test.

References

AchutaRao KM, Sperber KR. 2006. ENSO simulation in coupled ocean-atmosphere models: are the current models better? *Climate Dynamics* **27**: 1–15, doi: 10.1007/s00382-006-0119-7.

Allan R, Ansell T. 2006. A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850-2004. *Journal of Climate* **19**(22): 5816–5842.

Ashok K, Guan Z, Yamagata T. 2001. Impact of Indian Ocean dipole on the relationship between the Indian Monsoon Rainfall and ENSO. *Geophysical Research Letters* **28**(23): 4499–4502.

Ashok K, Behera SK, Rao SA, Weng H, Yamagata T. 2007. El Niño Modoki and its possible teleconnection. *Journal of Geophysical Research* **112**: C11007, doi: 10.1029/2006JC003798.

Ashrit RG, Rupa Kumar K, Krishna Kumar K. 2001. ENSO-monsoon relationships in a greenhouse warming scenario. *Geophysical Research Letters* **28**(9): 1727–1730.

Balachandran NK, Rind D, Lonergan P, Shindell DT. 1999. Effects of solar cycle variability on the lower stratosphere and the troposphere. *Journal of Geophysical Research* **104**: 27321–27339, doi: 10.1029/1999JD900924.

Behera SK, Luo JJ, Masson S, Rao SA, Sakuma H, Yamagata T. 2006. A CGCM study on the interaction between IOD and ENSO. *Journal of Climate* **19**: 1688–1705.

Collins M, An S-I, Cai W, Ganachaud A, Guilyardi E, Jin F-F, Jochum M, Lengaigne M, Power S, Timmermann A, Vecchi G, Wittenberg A. 2010. The impact of global warming on the tropical Pacific Ocean and El Nĩno. *Nature Geoscience* **3**(6): 391–397.

Haam E, Tung KK. 2012. Statistics of Solar Cycle–La Ninã connection: correlation of two auto-correlated time series (2012). *Journal of the Atmospheric Sciences* **69**: 2934–2939.

Kaplan A, Cane M, Kushnir Y, Clement A, Blumenthal M, Rajagopalan B. 1998. Analyses of global sea surface temperature 1856–1991. *Journal of Geophysical Research* **103**: 18567–18589.

Kar I, Bondyopadhaya R. 1996. Analysis of pre-monsoon thunderstorm frequency over Sriniketan, Alipore and Kalaikunda- The possible association with solar activity. *MAUSAM* **47**: 383–394.

Keshavamurty RN. 1982. Response of the atmosphere to sea surface temperature anomalies over the equatorial Pacific and the teleconnections of the Southern Oscillation. *Journal of Atmospheric Science* **39**: 1241–1259.

Kodera K, Coughlin K, Arakawa O. 2007. Possible modulation of the connection between the Pacific and Indian Ocean variability by the solar cycle. *Geophysical Research Letters* **34**: L03710, doi: 10.1029/2006GL027827.

Krishnamurthy V, Goswami BN. 2000. Indian monsoon-ENSO relationship on inter-decadal timescale. *Journal of Climate* **13**: 579–595.

Krishnamurthy V, Kinter JL. 2002. The Indian monsoon and its relation to global climate variability. In *Global Climate – Current Research and Uncertainties in the Climate System*, Rodo X, Comin FA (eds). Springer-Verlag: Berlin; 186–236.

Kumar KK, Rajagopalan B, Cane MA. 1999. On the weakening relationship between the Indian Monsoon and ENSO. *Science* **284**(5423): 2156–2159.

Kumar KK, Rajagopalan B, Hoerling M, Bates G, Cane M. 2006. Unraveling the mystery of Indian Monsoon failure during El Niño. *Science* **314**: 115–119.

Labitzke K, van Loon H. 1992. On the association between the QBO and the extratropical stratosphere. *Journal of Atmospheric and Terrestrial Physics* **54**(11/12): 1453–1463.

Maity R, Kumar DN. 2006. Bayesian dynamic modelling for monthly Indian summer monsoon rainfall using El Niño–Southern Oscillation (ENSO) and Equatorial Indian Ocean Oscillation (EQUINOO). *Journal of Geophysical Research* **111**: D07104.

Meehl GA, Arblaster JM, Branstator G, van Loon H. 2008. A coupled air-sea response mechanism to solar forcing in the Pacific region. *Journal of Climate* **21**(12): 2883–2897.

Mehta VM, Lau K -M. 1997. Influence of solar irradiance on the Indian monsoon-ENSO relationship at decadal-multidecadal time scales. *Geophysical Research Letters* **24**: 159–162.

Navarra A, Ward MN, Miyakoda K. 1999. Tropical-wide teleconnections and oscillation. I: teleconnection indices and type I/II states. *Quarterly Journal of the Royal Meteorological Society* **125**: 2909–2935, doi: 10.1256/smsqj.56006.

Parthasarathy B, Munot AA, Kothawale DR. 1994. All India monthly and seasonal rainfall series: 1871–1993. *Theoretical and Applied Climatology* **49**: 217–224.

Parthasarathy B, Munot AA, Kothawale DR. 1995. Monthly and seasonal rainfall series for all India, homogeneous regions and meteorological subdivisions: 1871–1994. Research Report No.RR-065, 113pp. Available from Indian Institute of Tropical Meteorology, Homi Bhabha Road, Pune 411008, India.

Roy I. 2013. The role of the sun in atmosphere–ocean coupling. *International Journal of Climatology* **34**: 655–677, doi: 10.1002/joc.3713.

Roy I, Haigh JD. 2010. Solar cycle signals in sea level pressure and sea surface temperature. *Atmospheric Chemistry and Physics* **10**(6): 3147–3153.

Roy I, Haigh JD. 2011. The influence of solar variability and the quasi-biennial oscillation on lower atmospheric temperatures and sea level pressure. *Atmospheric Chemistry and Physics* **11**: 11679–11687, doi: 10.5194/acp-11-11679-2011.

Roy I, Haigh JD. 2012. Solar cycle signals in the Pacific and the issue of timings. *Journal of Atmospheric Science* **69**(4): 1446–1451, doi: 10.1175/JAS-D-11-0277.1.

Sato M, Hansen JE, McCormick MP, Pollack JB. 1993. Stratospheric aerosol optical depths (1850–1990). *Journal of Geophysical Research* **98**: 22987–22994.

Smith TM, Reynolds RW, Peterson TC, Lawrimore J. 2008. Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). *Journal of Climate* **21**(10): 2283–2296.

Turner AG, Inness PM, Slingo JM. 2005. The role of the basic state in the ENSO-Monsoon relationship and implications for predictability. *Quarterly Journal of the Royal Meteorological Society* **131**(607): 781–804.

Van Loon H, Meehl GA. 2011. The Average influence of decadal solar forcing on the atmosphere in the South Pacific region. *Geophysical Research Letters* **38**: 12, doi: 10.1029/2011GL047794.

Van Loon H, Meehl GA. 2012. The Indian Summer Monsoon during peaks in the 11 year sunspot cycle. *Geophysical Research Letters* **39**: L13701.

Van Loon H, Meehl GA, Shea DJ. 2007. Coupled air-sea response to solar forcing in the Pacific region during northern winter. *Journal of Geophysical Research-Atmospheres* **112**: D02108, doi: 10.1029/2006JD007378.

Vecchi GA, Soden BJ. 2007. Global warming and the weakening of the tropical circulation. *Journal of Climate* **20**: 4316–4340.

Waldmeier M. 1987. Sunspot numbers, 1610–1985, World Data Centre A for Solar-Terrestrial Physics, Report UAG, 0579-7144, 95, based on "The sunspot activity in the years 1610–1960," by McKinnon, J.A.

White WB, Lean J, Cayan DR, Dettinger MD. 1997. Response of global upper ocean temperature to changing solar irradiance. *Journal of Geophysical Research: Oceans* **102**(C2): 3255–3266.

Zhang D, McPhaden MJ. 2006. Decadal variability of the shallow Pacific meridional overturning circulation: relation to tropical sea surface temperatures in observations and climate change models. *Ocean Modelling* **15**(3-4): 250–273.

