



The role of natural factors (part 1): addressing on mechanism of different types of ENSO, related teleconnections and solar influence

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Abstract

The role of natural factors, mainly the sun, is explored on major tropospheric modes of variability in a holistic way. It formulates a flow chart, depicting coupling in the ocean-atmosphere system, initiated by solar decadal variability that involves El Niño Southern Oscillation (ENSO). Possible mechanisms for Canonic ENSO, Modoki ENSO and Canonic-Modoki ENSO are proposed considering their relevance to the decadal variation of Hadley, Walker circulation and mid-latitude jets. The upper stratospheric feature of the polar vortex is included too. Teleconnections by the ENSO on Indian Summer Monsoon (ISM) with a special emphasis on the later two decades of the last century is discussed. The disruption of usual ENSO-ISM teleconnection during that period is also attended. Subsequent analyses presented some results of solar signature which could possibly trigger different types of ENSO, agreeing with proposed mechanisms of the flow chart. It addressed the changing pattern of ENSO behaviour since the 1970s. The overall study can benefit the modelling community by an improved representation of ENSO in models and a better representation of ISM teleconnection via regional Hadley cell.

1 Introduction

The El Niño Southern Oscillation (ENSO) is one of the most important modes of variability in the troposphere that influences most parts of the world through teleconnection. It has significant impacts on precipitation at seasonal time scale in several places around the world. Different types of ENSO, based on spatial patterns of sea surface temperature (SST) around tropical Pacific have been detected and discussed in recent studies. One type is dominated by variability around East Pacific (EP), known as Canonical ENSO or EP type and the other dominated by variability around Central Pacific (CP), known as Modoki or CP type (Trenberth et al. 2002;

Larkin and Harrison 2005; Ashok et al. 2007; Hill et al. 2009; Kug et al. 2009).

Studies suggest there are differences in global and local influences between Canonical and Modoki ENSO (Global (Weng et al. 2007; Ashok et al. 2007). Pacific Rim (Weng et al. 2009). India (Roy and Tedeschi 2016; Roy et al. 2017). South China Sea (Chang et al. 2008). Australia (Brown et al. 2009; Taschetto and England 2009; Cai and Cowan 2009)). It indicates the importance of understanding the underlying mechanism of these two types of ENSO to improve prediction skill.

Kao and Yu (2009), in a review, compared these two types of ENSO, regarding their evolution and structure. They showed for CP ENSO, atmospheric forcing plays the dominant role while for EP ENSO it is mainly regulated by thermocline shifting (also discussed by Ashok et al. 2007). Thermocline uplifting for El Niño (EN), while deepening down for La Niña (LN) is related to oceanic Kelvin and Rossby wave movement. That is the reason, the signal of phase reversal is detected only in EP ENSO, but CP ENSO occurs more as epochs or events rather than a cycle. For two types of ENSO, Yu and Kao (2007) indicated the different origins of formation mechanisms. For CP ENSO, its phase transition (barrier, onset, etc.) happens in the spring and it is phase locked with season; while for EP ENSO, though it is mainly regulated by the thermocline shifting, the phase shift

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and barrier varies decade to decade. Considering different times of onset of two types of ENSO, Kao and Yu (2009) indicated it could be related to the timing of mechanisms responsible for triggering particular events. Two mechanisms for extratropical connections for CP ENSO are proposed, Equatorial Ocean Advection Theory (Kug et al. 2009) and Extratropical Forcing Theory (Yu et al. 2010; Yu and Kim 2011; Kao and Yu 2009). Based on the first theory, anomalous SST along the equatorial Pacific is grown by the zonal ocean advection, while the second theory suggests that it is initially excited by forcing from extratropics and then developed by the advection from the tropical ocean. Various studies proposed about a decadal connection of ENSO (Hegyi and Deng 2011; McPhaden et al. 2011; Meehl et al. 2008, 2009; Roy 2014). An underlying quasi-decadal variability in the interannual ENSO is noted in many research (Chen et al. 2004; Zhang et al. 1997; White et al. 1997; Zhao and Dirmeyer 2003).

The sun is the principal source of energy for the climate of the earth, but the level of scientific understanding relating to its effects on the climate is still very low. Though regarding terms of energy output, there is only a 0.1% variation (Lean and Rind 2001) between minimum to maximum years of the 11-year cycle, too negligible to influence climate but studies identified significant regional impacts which are often seasonally dependent (Gray et al. 2010; Roy and Haigh 2010; Roy 2018a, b). The signal also fluctuates based on the chosen period of reference (Roy and Haigh 2012). Nowadays, there is a general agreement about solar-related mechanism involving the UV part of the spectrum in the stratosphere. It suggests that the variations in the UV spectrum between solar maxima and minima (6 to 8%) lead to more warming and ozone during solar maxima in the upper region of the stratosphere (Crooks and Gray 2005; Hood 2004). Following thermal wind balance relationship, it is responsible for stronger (weaker) upper stratospheric jet for maximum (minimum) years. There are changes in various dynamical features also linked to such variability. The work of Gray et al. (2010) and Roy (2018a) nicely discussed various solar influences on an 11-year time scale in the climate even excluding the effects of climate change signal, represented by the longer-term trend. Specific locations Aleutian Low (Roy and Haigh 2010) and Arctic (Roy 2018b) during northern winter were also focused, which detected a very significant influence of solar 11-year cyclic variability even segregating the influence of the longer-term trend, ENSO, volcano and Quasi-Biennial Oscillation (QBO). Decadal signature of solar variability changes is noted in various atmospheric and oceanic fields. In terms of atmospheric fields, it is detected in tropospheric circulations (Hadley Circulation (Haigh 1999, 1996; Haigh et al. 2005). Walker Circulation (Meehl et al. 2008, 2009), Polar Vortex (Kodera and Kuroda 2002), Mid-latitude Jet (Haigh et al. 2005; Brönnimann et al. 2006), and Intertropical Convergence

Zone (ITCZ) (Lee et al. 2009). The signal of decadal nature is also distinguished in various oceanic parameters (thermocline (Zhang and McPhaden 2006). North Pacific gyre circulation (Lorenzo et al. 2010)) and shallow Meridional Overturning Circulation (MOC) in Pacific (Zhang and McPhaden 2006)).

The ENSO through teleconnection can affect various regions around the world (Roy et al 2018). It also influences seasonal precipitation in several places, among which the Indian Summer Monsoon (ISM) is an important one. The ISM has enormous impacts on the country's economy as it provides up to 80% of the annual mean precipitation. Indian economy is mainly dominated by agriculture and associated industries and being one of the most populated countries in the world, ISM variability also impacts global economy. In terms of the global-scale atmospheric circulation, the ISM plays an important part, as it dominates the local Hadley circulation and the boreal summer tropical meridional overturning (Trenberth et al. 2006).

Studies have shown that the ENSO strongly modulates the ISM (e.g. Kripalani and Kulkarni 1997; Maity and Kumar 2006; Roy 2017), where EN years are usually associated with less rainfall, though LN experiences more rain. The ISM-ENSO teleconnection was also captured by Coupled Model Intercomparison Project Phase 5 (CMIP5) models matching with observations in parts of the central north east (CNE) region of India around ITCZ (Roy et al. 2017). This is the location where the coupling mechanism of atmosphere and ocean via ENSO through the Walker circulation could be communicated strongly (Gill 1980). According to that mechanism (Gill 1980), the ISM represents a large-scale source of heat around the CNE region and following the linear theory it could be related to both Walker and regional Hadley cell.

The regional monsoon-ENSO relationship is shown having common changing points around the 1970s. There was an enhancement of the relations for the western North Pacific, North American, Northern African and South American summer monsoons, with a recovery in the late 1990s. Interestingly, for the ISM, it weakened over the same period (Yim et al. 2013). Such a changing pattern of monsoon under global warming scenario is also discussed by Huang et al. (2013) in a recent study. The direction of anomalous change in circulation, both the Walker and Hadley circulation, and their relative strength around the Indian subcontinent, mainly in the CNE region, under climate change scenario, needs additional attention (Bollasina et al. 2011). Interestingly, observation indicates that the nature of ENSO also changed over the similar period; ENSO Modoki became more persistent and frequent since the 1970s (Ashok and Yamagata 2009; Yeh et al. 2009). Research suggests that the increase of ENSO Modoki during the latter decades of the last century could also be due to parts of decadal nature variability (McPhaden et al. 2011).

This part of work focuses on the role of natural factors, mainly the sun. It will discuss in a holistic way, how various influences on different types of ENSO are generated especially via the solar cyclic variability. The related teleconnections with the ISM will also be attended giving special emphasis on the so-called climate change period when the mean state of climate suffered certain deviations.

2 Methodology and data

This study discussed various established research to formulate a flow chart to depict a holistic representation of atmosphere-ocean coupling. Later, it applied the method of multiple linear regression (MLR) analysis with AR(1) noise model to test a few of the pathways. In this methodology, with the components of variability, noise coefficients are calculated simultaneously. It is done in such a way that the residual is consistent with a red noise model of order one and thus it is possible to minimise noise to be interpreted as a signature. Finally, measures of the significant levels are calculated, using Student's *t* test. This model is developed by Myles Allen, the University of Oxford and this methodology was widely used in various climate studies. Of late, Roy and Haigh (2012), Roy and Collins, (2015), Roy and Haigh (2011), Roy et. al (2016), and Roy (2018b) also applied this technique to analyse solar signals on various climate data.

Variables and climate indices employed in the regression are sea level pressure (SLP), monthly sun spot number (SSN), Niño3.4 (to represent ENSO), stratospheric aerosol optical depth (AOD) (indicative of volcanic eruptions) and longer-term trends. The ENSO data used here are anomaly value and all the data are normalised before an analysis. For SLP, the in-filled HadSLP2 dataset, which covers the whole globe (Allan and Ansell 2006) and available as monthly means from 1850 to 2004, are used. It can also be found at <http://www.metoffice.gov.uk/hadobs/hadslp2>. Error estimates are mentioned for HadSLP2 (unlike HadSLP1), to have ideas about the regions of little confidence. It has been updated up to 2012 using HadSLP2r_lowvar data (<http://www.metoffice.gov.uk/hadobs/hadslp2/data/download.html>). It is a version of HadSLP2r and consistent with HadSLP2. The global monthly HadSLP2r data that covers 2005 to 2012 is the NCEP-NCAR reanalysis data (Kistler et al. 2001), which is adjusted as its average for period 1961–1990 matches with HadSLP2. In the recent version of HadSLP2r_lowvardata, the deficiency concerning the difference in invariance between HadSLP2 and HadSLP2r is adjusted. Monthly SSN is used to represent solar cyclic variability and obtained from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/INTERNATIONAL/monthly/MONTHLY.PLT. For the ENSO, Niño 3.4 index, obtained from Kaplan et al. (1998) is used which is available since 1856 and can also be found at <http://climexp.knmi.nl>. In the regression, AOD has

been used to represent volcanic eruptions and collected from Sato et al. (1993) and available from https://data.giss.nasa.gov/modelforce/strataer/tau_line.txt (up to 1999). It is then extended up to 2005 with near zero value. It can also be obtained from KNMI Climate Explorer (<http://climexp.knmi.nl>). Longer-term trend is a rising linear line that represents increasing anthropogenic influence.

3 Formulation of flow chart—proposed mechanism

We develop a flowchart (Fig. 1) depicting a consolidated overview of ocean-atmosphere coupling, supported by highly cited established research. Initiated by solar decadal variability, how coupling in atmosphere-ocean is taking place is presented. The major climate variabilities; viz. ENSO and solar are shown with oval outlines; whereas, the major circulations (Walker, Hadley and Ferrel cell), responsible for modulating the influence of major variabilities are shown by non-rectangular parallelograms. Pathways of the signature are shown by labels that start from 'A', which is initiated by solar variability and the direction of behaviour change during the steps by '−' (for decrease) and '+' (for increase). The flow chart depicts the role of the sun and how the atmosphere and ocean coupling regulates the formation of various types of ENSO, viz. the Canonic ENSO, Modoki ENSO and Canonic-Modoki ENSO. The related teleconnection with ISM is also presented. Dash-dotted lines mark the pathways those are affected by so-called climate change signal. During this period, the mean state of climate suffered certain deviations. A similar flowchart was also formulated in the study of Roy (2014); however, that did neither consider different forms of ENSO nor included the part of ISM.

3.1 Solar 'top-down' vs. 'bottom-up' mechanism

Two fundamentally different routes for a solar influence on the troposphere have been proposed: one is the 'Bottom-Up' mechanism (Meehl et al. 2008, 2009) and the other, the 'Top-Down' mechanism (Haigh 1996; Haigh et al. 2005; Haigh and Blackburn 2006; Kodera and Kuroda 2002; Baldwin and Dunkerton 2001). In the 'Bottom-Up' pathway, the Sun can directly affect SST without stratospheric feedback; whereas, the 'Top-Down' influence of the sun is originated through the stratosphere. Roy (2014) elaborately documented more detailed discussions.

Frame and Gray (2009) showed using the observation that there is a cooling (warming) in the lower equatorial stratosphere during solar minimum (maximum) years (A, Fig. 1). The results from Haigh (2003) also showed that there is a positive solar response in the tropical lower stratosphere. It extends in vertical bands throughout the troposphere via

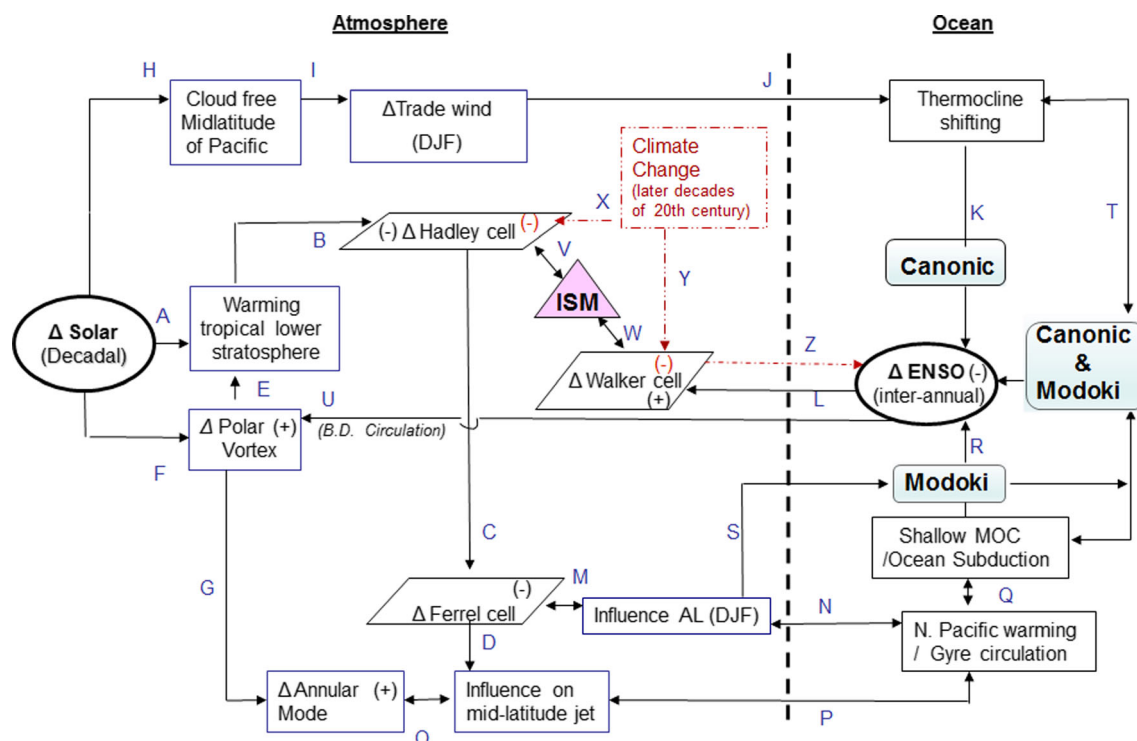


Fig. 1 Flow chart showing the role of the sun in an atmosphere and ocean coupling mainly during DJF and the possible mechanism for Canonic ENSO, Modoki ENSO and Canonic-Modoki ENSO. ENSO-related teleconnection (e.g. ISM) affected by climate change period is shown by the dash-dotted line

mid-latitudes (with a maximum amplitude of 0.5 K around 40–50° N) in both the hemispheres. Haigh et al. (2005; Haigh and Blackburn 2006; Haigh 1996) noted, an impact on tropospheric mean meridional circulation, characterising a weakening and expansion of the tropical Hadley cells, along with a shift of the Ferrel cells poleward (A–C, Fig. 1). It leads to coherent changes in the width and latitudinal location of the mid-latitude jet stream (D). Their studies established opposing solar influence in the tropospheric circulation fields in maximum years to those from minimum years in either models or observation. Those did not even involve the complex interaction of upper stratospheric polar vortex to detect that influence. Observational work of Brönnimann et al. (2006) also supports such findings. A possible mechanism was proposed by Kodera and Kuroda (2002), whereby the solar influence can change the equatorial stratospheric region through changes in the meridional circulation, which also involve polar vortex (E). According to them, the sun can influence the path of upward propagating planetary waves because the sun's heating anomalies can alter the strength of polar upper stratospheric jet. These planetary waves weaken the Brewer-Dobson Circulation (BDC) via depositing their zonal momentum on the poleward side of the jet in solar maximum years and subsequently warm the tropical lower stratosphere. Solar decadal variability regulates the strength of polar vortex by normal thermal wind balance relationship as labelled here by F. Baldwin and Dunkerton (2001) showed perturbations in the polar vortex, are related to polar annular modes (G). They

discussed a dynamical mechanism that might communicate stratospheric circulation anomalies downward to the tropospheric surface via polar modes.

Meehl et al. (2008, 2009) discussed the bottom-up route of solar influence and presented a mechanism related to sea-air-radiative coupling involving the sun. According to them, the spatial asymmetries of solar forcing, induced by cloud distributions, can cause greater evaporation in the subtropics. It consequently causes more moisture transport and intensification of the tropical convergence zone and strengthens the trade winds around the tropical Pacific (H, I).

3.2 Ocean coupling and atmosphere-ocean interactions

First, we will discuss the mechanism of ENSO that involves thermocline, Walker circulation and trade wind. In normal ENSO mechanism, triggering of the trade wind can cause uplifting of the thermocline (J, K), and subsequently can intensify the Walker circulation (L). Shifting of the thermocline is regulated by Oceanic Rossby and Kelvin wave movements which control the interannual nature of ENSO. It is consistent with studies that detected decadal signature in thermocline (Zhang and McPhaden 2006). Some wind triggering mechanism around tropical Pacific responsible for initiation of Kelvin and Rossby wave is needed, though source being still unclear (Vecchi and Soden 2007). The proposed flowchart suggests the sun could be a possible candidate. Roy and

Haigh (2010) also captured similar decadal signature in trade wind (I) in an observational analysis. The proposed pathway (K) matches to that with EP ENSO. Ashok et al. (2007) and Kao and Yu (2009) suggested that thermocline shifting is known to be the main driver for EP ENSO. A signature of phase reversal is also identified in EP type of ENSO with its major phase transition and the barrier was found to change decade to decade (Kao and Yu 2009).

The semi-permanent pressure systems in the troposphere are an integral part of the tropospheric circulations and play an important role in controlling their behaviour. Christoforou and Hameed (1997) studied the variations of semi-permanent pressure systems, the Aleutian Low (AL) and the Pacific High (PH) and found that solar variability influences their locations. Those can cause changes in storm tracks and large anomalies in regional climatic conditions. That study emphasised the location of AL and showed that solar variability not only shifts its location but also causes a significant difference in intensity (M). Observational analysis by Roy and Haigh (2010) and Van Loon et al. (2007) is also consistent with such findings. The weakening of Ferrel cell as noted by Haigh (1996; Haigh et al. 2005; Haigh and Blackburn 2006) and Brönnimann et al. (2006) can also be associated with the weakening of AL. Decadal variability around AL could be responsible for North Pacific warming (N) during high solar years. Such decadal signature around mid-latitude was captured in observation by Frame and Gray (2009) and Haigh (2003). North Pacific Gyre circulation in the ocean, which is wind driven, is also likely to be affected by the modulation of AL system. Decadal signature in North Pacific Gyre was observed by Lorenzo et al. (2010).

Warming around North Pacific is connected to the shallow conveyor belt of the ocean which has a rising branch around North Pacific near AL. That shallow ocean conveyor belt is flowing through tropical Pacific and links tropics to North Pacific via ocean pathway (Q). That tropical Pacific part can sometimes be termed as shallow meridional ocean circulation (MOC) in the Pacific. It characterises the equatorward convergence of the pycnocline volume transport across 9° S and 9° N. Using historical hydrographic data, Zhang and McPhaden (2006) observed decadal variability in the Pacific shallow MOC. Ocean subduction pathways could also act as links between North Pacific to tropics mass exchanges.

The strength of annular mode has the potential to change the intensity and location of tropospheric jets via usual mechanism and can influence North Pacific (O, P) (double-ended arrow show the two-way interactions). It can subsequently modulate mid-latitude ocean gyre through wind stress. The decadal signal around North Pacific could be transported to tropical Pacific via ocean pathway (P–R) to trigger Modoki ENSO feature (R). Lorenzo et al. (2010) showed decadal variations in the North Pacific gyre circulation are characterised by a pattern of SST anomalies resembling the CP type ENSO.

Sullivan et al. (2016) discussed that CP ENSO shows a dominant spectral peak at a decadal timescale, which on an inter-annual period possess a comparatively weaker variance. They showed there is a significant reduction in the frequency of the CP ENSO in observation and also in CMIP5 simulations of historical, preindustrial, and future scenario if that decadal component is removed.

The decadal signature in CP ENSO has a complex mechanism. Apart from oceanic connections, changes in the mid-latitude jets and AL can also directly impact CP ENSO through dynamic variability of the Hadley circulation. For CP ENSO, as seen in the flowchart, atmospheric forcing plays the dominant role as proposed by (Kao and Yu 2009) and it has extratropical connections. AL could play one dominant role as shown by S. Two mechanisms for CP ENSO for extratropical connections were discussed earlier, e.g. Equatorial Ocean Advection Theory (Kug et al. 2009) and Extratropical Forcing Theory (Yu and Kim 2011; Yu et al. 2010; Kao and Yu 2009) which are in agreement with those proposed pathways. The first theory suggests anomalous SST along the equatorial Pacific is grown by the zonal ocean advection, while the second indicates it is initially excited by extratropical forcing and then developed by the advection from the tropical ocean. It is also consistent with the observation that the CP ENSO occurs more as events or epochs than as a cycle (Kao and Yu 2009), which is noted for EP type. The phase locking of CP ENSO with the season, having phase transition in spring (Yu and Kao 2007) also supports a solar connection. Mantua and Hare (2002) indicated that Pacific in the mid-latitude and tropics is connected via ocean pathway. The pathway that establishes the linkage between tropics (via thermocline shift) and extratropics as shown by T, governs ENSO Canonical and Modoki (CM) combined feature.

Overall, the flowchart is consistent with studies those detected an underlying quasi-decadal variability in the interannual ENSO (White et al. 1997; Zhang et al. 1997; Zhao and Dirmeyer 2003; Chen et al. 2004), even if different types of ENSO are considered.

3.3 ISM teleconnection

Now, we present discussions that also involve the ISM. The ISM represents a large-scale heat source on the equator located at a mean position of about 20–30° N (around ITCZ) covering the region of CNE. Following the linear theory, the response to such a heat source suggests that it will be related to Walker circulation as well as regional Hadley circulation (Gill 1980). The Walker cell is related to equatorial heat sources and is regulated remotely by tropical Pacific; whereas, the local Hadley cell shows a direct response to the off-equatorial heat source. The location and strength of the monsoon heat source can also impact Walker and regional Hadley cell. Lee et al. (2009) studied decadal variability on ITCZ and found during

active solar periods there is an enhancement of the strength. Pathways V and W indicate about such relationship with ISM and tropical circulations involving ITCZ.

3.4 ENSO via polar vortex or troposphere

The influence of ENSO, in reverse direction, to various atmospheric fields, is also noted in many studies. The ENSO through Brewer–Dobson circulation can influence polar vortex (U) and subsequently to extratropics in an inverse pathway, as shown in the flowchart. During winter, Camp and Tung (2007) showed that warm-ENSO years are significantly warmer at the Northern Hemisphere polar and mid-latitudes in the stratosphere than the cold-ENSO years. Taguchi and Hartmann (2006) and Sassi et al. (2004), using a GCM showed that the warming difference between La Niña and El Niño years is statistically significant. They showed in the El Niño winters, stratospheric sudden warming (SSW) are twice as likely to occur than La Niña years. It indicates a possible connection between the ENSO and polar stratosphere. The ENSO can also influence tropospheric jets and polar annular modes were shown by Carvalho et al. (2005) and Haigh and Roscoe (2006) (O, P in a reverse direction). Carvalho et al. (2005), using data analysis for the period 1979 to 2000, observed that during the austral summer (December, January, February (DJF)), cold events of the ENSO are linked with dominant positive Antarctic Oscillation (AAO) and vice versa. Positive AAO phases are associated with the poleward shift and weakening of the subtropical feature accompanied by an intensification of the high-latitude feature. Following usual annular mode behaviour, such signature is also expected in the surface NAM/SAM. The analysis of Haigh and Roscoe (2006) is also in agreement, who, using data from the latter half of the twentieth century, showed in their MLR technique that there is an anti-correlation between the ENSO and polar modes in the lower troposphere.

Observations, as well as model simulations, suggested that it could be two-way interactions and both types of ENSO also have potentials to modulate the extratropics. CP ENSO influence is mainly seen around the Southern Hemisphere (SH), though EP in the NH. For CP ENSO, the variations in wind etc. are mainly localised around the central Pacific (Kao and Yu 2009). It enhances convective activity in the South Pacific Convergence Zone in austral spring and affects Antarctic surface temperatures and sea ice concentrations (Song et al. 2011; Schneider et al. 2012). The mechanism how EP ENSO could influence extratropics of NH is also discussed (Randel et al. 2009; Manzini et al. 2006; Garcia-Herrera et al. 2006). As EP ENSO is mainly regulated by thermocline shifting and shows basin wide variation of several features (Kao and Yu 2009; Ashok et al. 2007), it possesses the potential to perturb planetary-scale Rossby waves, which are mainly generated in the NH due to ocean land contrast. The enhanced planetary

wave driving leads to a weakening of the Arctic vortex and warms the polar stratosphere in boreal winter. It subsequently, deepens the north Pacific AL. In the absence of land-ocean contrast, planetary wave activity in the SH plays a nominal role and hence EP ENSO does not impact the extratropics in SH (Hurwitz et al. 2011).

3.5 Disruption of ISM teleconnection in climate change period

McPhaden and Zhang (2004), Vecchi and Soden (2007) and Held and Soden (2006) suggested there is a substantial decrease in the strength of both Walker and Hadley circulation since the 1950s as marked here by X and Y. It is likely to be reflected simultaneously in ISM as well as ENSO (Z). Roy and Haigh (2012) showed over the similar period, decadal signature around trade wind as demonstrated by J is missing, probably due to change in mean state. It indicates a weakening of the EP ENSO-related mechanism that involves thermocline. A recent study suggests, ENSO Modoki has become more frequent and persistent than Canonic ENSO since the later period of last century (Yeh et al. 2009; Ashok and Yamagata 2009). The change in ISM over a similar period is also well documented in various studies (Ashrit et al. 2001; Ashok et al. 2001). The climate change signal via X–Z subsequently affects ISM, using pathways V and W.

In the flowchart (Fig. 1), there could be various other pathways for, e.g. including major variability of QBO (shown in Roy 2014); but for clarity, we avoided enough complexities. Also, for presenting climate change signals (shown by the dotted-dash line) we avoided complicated pathways. More related discussions on so-called climate change are covered in a subsequent analysis, the part 2 of this study.

Labels agreeing on various pathways/studies as discussed here in (Fig. 1) are listed underneath to improve clarity:

- A: Haigh (2003), Frame and Gray (2009),
- A–D: Haigh et al. (2005), Brönnimann et al. (2006), Haigh (1996, 1999).
- E: Kodera and Kuroda (2002).
- F: Usual mechanism following thermal wind balance.
- G: Baldwin and Dunkerton (2001).
- H, I: Meehl et al. (2008, 2009).
- I: Roy and Haigh (2010).
- J–L: Normal ENSO (interannual) mechanism.
- K: Kao and Yu (2009), Ashok et al. (2007), Zhang and McPhaden (2006).
- M: Christoforou and Hameed (1997), Roy and Haigh (2010), van Loon et al. (2007).
- N, P: Haigh (2003), Frame and Gray (2009).
- N–Q: Usual ocean-atmosphere interaction involving wind stress.
- O, P: Carvalho et al. (2005), Haigh and Roscoe (2006).

- R: Kao and Yu (2009), Yu and Kao (2007), Sullivan et al. (2016).
- S: Kao and Yu (2009).
- T: Mantua and Hare (2002).
- U: Camp and Tung (2007), Sassi et al. (2004), Taguchi and Hartmann (2006).
- V, W: Gill (1980).
- X, Y: Held and Soden (2006), Vecchi and Soden (2007), McPhaden and Zhang (2004).
- Z: Ashok and Yamagata (2009), Yeh et al. (2009).

Table 1 indicates how each link is explained by a mechanism, evidenced by observation, or be viewed as a hypothesis at this stage. All pathways we used are either explained by a mechanism or evidenced by observation. However, some pathways are kept as hypothesis stage (Lower Stratosphere: H, M and Atmosphere-Ocean coupling: N, P, Q, S) partly because understanding in those directions may be improved.

Some model-based analyses also explored areas that need attention and pointed directly or indirectly towards lack of understanding of solar influences. A very recent study (Zheng and Yu 2017) indicated that further improvements in CP ENSO prediction skill should be a key and high-priority task for the climate prediction community. The feedback from shortwave has a key role in explaining the spread of ENSO characteristics among models as noted in new research (Dufresne et al. 2013; Lloyd et al. 2012). Thus, modelling communities, in general, will be greatly benefited from the analyses of Fig. 1.

The current weaker solar cycle may also have contributions on recent warming hiatus, but detailed analyses and mechanisms are yet to be proposed and established. In the model, the solar direct influence (0.1% variability) part is included; whereas, indirect effects through the dynamical coupling, which are playing major roles to influence climate are not so well represented. Hedemann et al. (2017), discussed the concern about our inability to explain the reason for the so-called hiatus in global mean temperature. Using energy budget for the

ocean surface layer in their model revealed that hiatus can be produced by deviations of energy-flux as low as 0.08 W m^{-2} . It can originate in the ocean, at the top of the atmosphere or both. According to them, unless the uncertainty of observational estimates can be considerably reduced, the true origin of the recent hiatus may never be determined. Our analyses through the flowchart could, however, also address the hiatus from a different angle. It suggests that the current weaker solar cycle with reduced energy-flux and through mechanisms of indirect dynamical coupling could also be likely candidates.

Though we focused on ISM, such flowchart is also relevant for other teleconnections that involve different types of ENSO. There are differences in global (Weng et al. 2007; Ashok et al. 2007) and local influences (Pacific Rim (Weng et al. 2009). South China Sea (Chang et al. 2008). Australia (Brown et al. 2009; Taschetto and England 2009; Cai and Cowan 2009)) between Canonical and Modoki ENSO as widely discussed in various studies. Incorporating the knowledge of solar variability on various types of ENSO, our understanding of various global and regional teleconnection features are likely to be improved. Thus, this study has implications which are not only limited to the local scale of India but also applicable to the wider context of the globe and different regional climatic scenarios.

4 Results of MLR: signature due to the sun on various ENSO phases

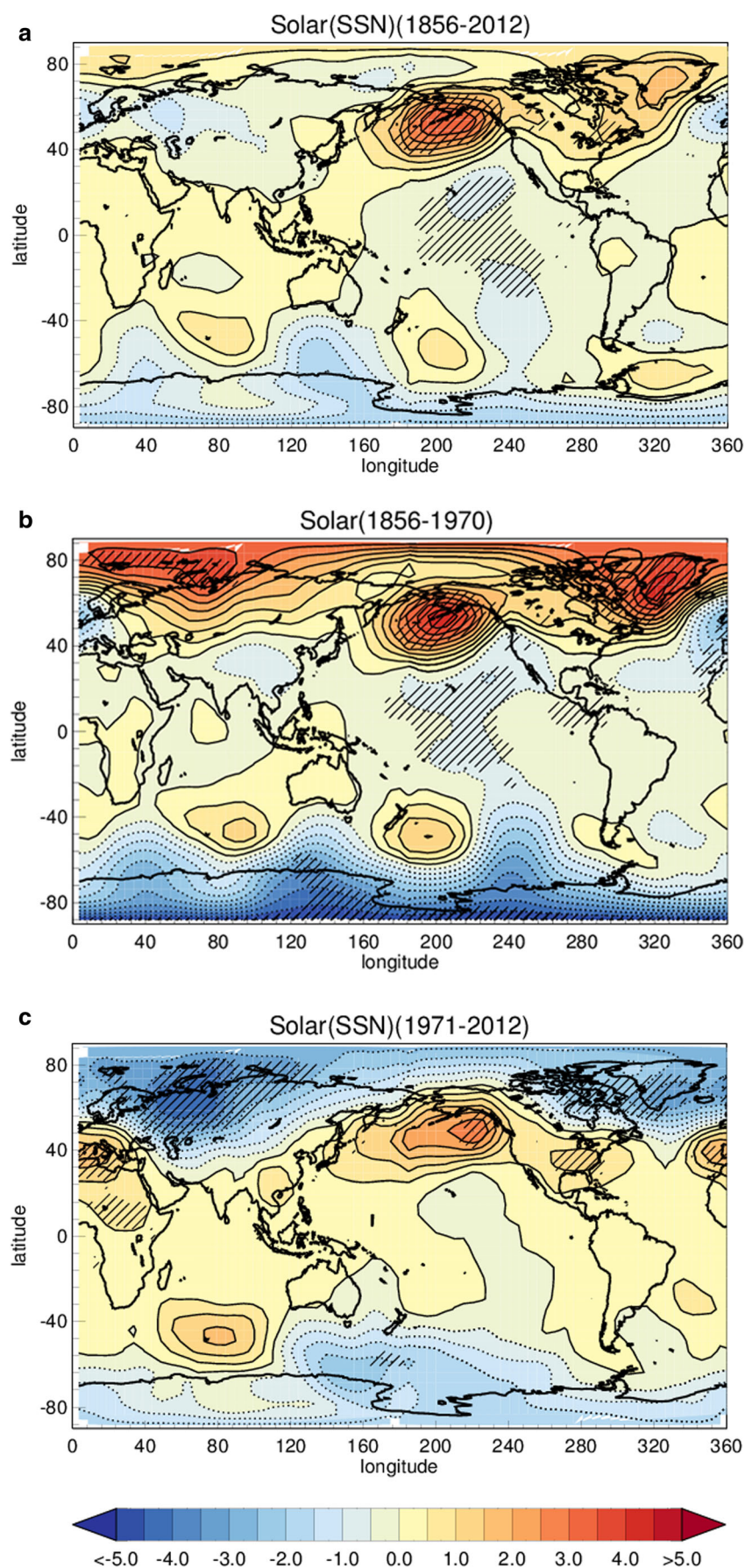
We further analysed the solar signature on SLP and studied the effect of a change in mean state. It is similar to the MLR analyses of Roy and Haigh (2012) but considered SLP data up to 2012 instead of 2004. The previous study also did not consider different types of ENSO, neither did it separate out period from the 1970s, as we did in the current study.

First, we addressed why ENSO Modoki has become more persistent and frequent than Canonic ENSO since the 1970s (Yeh et al. 2009; Ashok and Yamagata 2009). Three separate

Table 1 Indicate whether the pathways are evidenced or hypothesised.

		Observation	Mechanism	
			Explained	Hypothesised
Atmosphere (A-I, M, O)	Lower stratosphere (A-D, H, I, M)	A-D, H, I, M	A-D, I	H, M
	Upper stratosphere (E-G, O)	F, G	E, F, O	
	Atmosphere-ocean coupling (J-L, N, P-T, U-W)	J-L, U, S, P, R	J-L, N, T, V, W, Q	N, P, Q, S
Climate change (X-Z)		X-Z	Z	

Fig. 2 The solar cycle signal (max–min, hPa) in DJF HADSLP2 data obtained from a multiple linear regression analysis using monthly SSN. Other indices used are ENSO, AOD (volcano) and trend. Different periods are used: **a** Result for the entire period (1856–2012), **b** for an earlier period (1856–1970) and **c** a latter period (1971–2012). Significant regions at the 95% level using a two-sided Student's *t* test are shaded and dotted lines indicate negative contours



MLR analyses on SLP data (DJF) are carried: one for the whole period (Fig. 2a) and the other two before and after 1970 (Fig. 2b, c, respectively). Strong signal around AL is noticed in all plots. Interestingly, such strong solar signature in SLP around AL during northern winter is robust and found insensitive to various methodologies and time periods (van Loon et al. 2007; Christoforou and Hameed 1997). Roy et al. (2016) did seasonal analysis too and showed that solar signature around AL is only present during DJF. That signal is seen to be reduced in Fig. 2c to that from Fig. 2b.

Now, the focus is around central tropical Pacific and it is observed that the signature of the sun is also different in two periods (Fig. 2b, c). A small but significant decadal signature is present in SLP before 1970 (Fig. 2b), which could play a role in triggering trade wind. Figure 2a for the whole period also indicates significant signal though weaker in magnitude than Fig. 2b. Such solar signal on trade wind could be responsible for initiating ENSO through an indirect dynamical coupling. Instigating Oceanic Rossby and Kelvin waves it has a potential in shifting thermocline and subsequently trigger EP ENSO features. Such signature, decadal in nature, could be present in EP ENSO in addition to its interannual variability, which is regulated by oceanic Kelvin and Rossby wave movements. A decadal signal on thermocline is noted in various studies (Zhang and McPhaden, 2006 among others). It is also consistent with the earlier discussion, (Yu and Kao 2007) who indicated that for EP type, the phase transition and barrier change decade to decade and it is mainly regulated by thermocline shifting. That solar signature in trade wind is absent since 1971 (Fig. 2c) and could be one possible cause for dominance of CP ENSO over EP (Ashok and Yamagata 2009; Yeh et al. 2009).

Positive North Atlantic Oscillation (NAO) pattern for the sun is clearly distinguished in the later period (Fig. 2c), which is different during an earlier period (Fig. 2b). Perturbations around North Atlantic was found as a precursor of CP ENSO (Ham et al. 2013a, b) and the mechanism involves atmospheric Rossby wave. Positive NAO via triggering Rossby wave around mid-latitudes could influence north Pacific (AL is likely to be modulated) and subsequently has the potential to initiate CP ENSO through the atmospheric and oceanic bridge (for e.g. Extratropical Forcing Theory (Yu et al. 2010; Yu and Kim 2011; Kao and Yu 2009)). It was noted that the change in CP ENSO in recent decades could also partly be due to decadal nature variability (McPhaden et al. 2011). Sullivan et al. (2016) discussed that CP ENSO shows a dominant spectral peak at a decadal timescale, which on an interannual period possess a comparatively weaker variance. Over the last few decades, that decadal variations have an important contribution to the occurrence of

CP ENSO (Sullivan et al. 2016). Regression results suggest the Sun-NAO changing behaviour (Fig. 2c) could also be a responsible factor.

Regional Hadley circulation plays a role too. Bjerknæs (1966) showed that the major warming along the central and equatorial Pacific during boreal winter is often accompanied by an anomalous strength of the mid-latitude westerlies. There is a two-sided interaction. The anomalously great heat from the equatorial ocean to the rising branch of the Hadley circulation would strengthen the cell. It will generate above normal flux of angular momentum to the westerly winds around mid-latitude belt. Thus, warming in the tropical Pacific can also strengthen the mid-latitude westerly jets during boreal winter and subsequently can favour positive phase of the NAO. Following the similar mechanism—which can be a two-sided interaction—a positive NAO can also favour positive phase of CP ENSO.

Earlier studies showed that winter NAO can have an impact on ISM (Chang et al. 2001). Thus, the shift in a solar decadal signal via the winter NAO (Fig. 2b vs. Fig. 2c) and through regional Hadley circulation can also alter ISM features (Fig. 1).

5 Discussion

The flowchart is a holistic way of presenting ocean and atmosphere coupling. The role of natural factors mainly the solar 11-year cycle is investigated to understand how that decadal-scale variability can modulate stratosphere-troposphere-ocean coupling. Based on highly cited established research, possible mechanisms for Canonic ENSO, Modoki ENSO, and Canonic-Modoki ENSO are proposed. Different mechanisms for three different types of ENSO are explored attending their decadal connections. Initiated by solar variability how mid-latitude jets and tropospheric circulations (Walker and Hadley circulation) are affected and in turn, influence the ENSO is discussed. In terms of the atmospheric part, it considered the routes in both the troposphere as well as the stratosphere. In the stratosphere, the possible pathway of the polar vortex is also attended. Such flowchart will help improve the understanding of different types of ENSO and benefit the modeling community by better representations in models. The subsequent teleconnections by ENSO (for e.g.) on ISM is also presented. Focusing on the later two decades of the last century, we analysed how such connection could have been disrupted.

Some results of solar signature those could possibly trigger different types of ENSO are presented applying the technique of multiple linear regression. Such analyses help in addressing the changing pattern of ENSO and ISM behaviour since the 1970s, as noted in previous studies.

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