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The Role of Natural Factors on Major Climate Variability in Northern Winter

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Abstract. The role of natural factors mainly solar eleven-year cycle variability, and volcanic eruptions on two major modes of climate variability the North Atlantic Oscillation (NAO) and El Niño Southern Oscillation (ENSO) are studied for around last 150 years period. The NAO is the primary factor to regulate Central England Temperature (CET) during winter throughout the period, though NAO is impacted differently by other factors in various time periods. Solar variability indicates a strong positive influence on NAO during 1978-1997, though suggests opposite in earlier period. Solar NAO lag relationship is also shown sensitive to the chosen times of reference and thus points towards the previously proposed mechanism/ relationship related to the sun and NAO. The ENSO is influenced strongly by solar variability and volcanic eruptions in certain periods. This study observes a strong negative association between the sun and ENSO before the 1950s, which is even opposite during the second half of 20th century. The period 1978-1997, when two strong eruptions coincided with active years of strong solar cycles, the ENSO, and volcano suggested a stronger association, and we discussed the important role played by ENSO. That period showed warming in central tropical Pacific while cooling in the North Atlantic with reference to the later period (1999-2017) and also from chosen earlier period. Here we show that the mean atmospheric state is important for understanding the connection between solar variability, the NAO and ENSO and associated mechanism. It presents a critical analysis to improve knowledge about major modes of variability and their role in climate. We also discussed the importance of detecting the robust signal of natural variability, mainly the sun.

Keywords: solar variability; NAO; ENSO; volcanic eruptions; multiple regression

1. Introduction:

The Sun is the main source of energy of the earth, but the level of scientific understanding relating to its influences on climate is still low (IPCC, 2013). Regarding energy output, only a 0.1 % change between maximum to minimum of the solar 11-year cycle [Lean and Rind, 2001], which is too negligible to influence climate. However, studies identified significant regional impacts which are felt seasonally (Gray et al. 2010; Roy and Haigh, 2010; van Loon and Meehl, 2007) and also depend on overall period chosen (Roy and Haigh, 2012; Roy, 2014). In understanding climate variability and in interpreting signals of climate change it is important to ascertain the actual role of natural factors so that any human influence may be more accurately identified. More caution is also required to detect signal relating to natural variability (mainly the sun) and the robustness of identified signature need to be tested with a critical view point.

Nowadays, there is general agreement that the direct effect of the changes in the ultraviolet (UV) part of the spectrum (6 to 8% between maxima and minima years of 11-year cycle) leads to more ozone and warming in the upper stratosphere in solar maxima (Gray et al. (2010)). The variation of ozone, through absorption of solar UV spectrum around upper stratosphere, is one responsible factor for controlling temperature gradient between summer and winter hemisphere. Subsequently, through the well-known thermal wind balance variability in, the solar cycle can regulate the strength of polar vortex, suggesting a stronger stratospheric polar jet in active solar years and vice versa. Baldwin and Dunkerton [2001] showed perturbation in the polar vortex can affect the polar troposphere during the same season. Kodera and Kuroda [2002] proposed a mechanism, whereby active solar years have the potential to influence the polar vortex and subsequently down to the lower tropical stratosphere, which also involves upward propagating planetary waves. The solar signal from lower tropical stratosphere was shown to impact troposphere by modulating Hadley circulation and Ferrel cell (Haigh [1996] and Haigh et al. [2005]). All these mechanisms, by which, solar variability that affects the stratosphere are transported downwards and subsequently influences tropospheric climate is known as solar ‘Top-Down’ mechanism. Ineson et al. [2011] analysed the regional impact of the solar 11-year cycle on North Atlantic Oscillation (NAO) (the dominant mode of climate variability during boreal winter around the North Atlantic) by using UK Met Office Unified Model and found an in-phase relationship. They imposed a vast change in solar UV irradiance to produce their observed response. According to them, in years of low (high) UV activity, easterly (westerly) winds and cold (warm) winters are favoured to northern Europe indicating a negative (positive) NAO pattern. It is interesting to study the robustness of such proposed association between the sun and NAO (Ineson et al. 2011), and one of the focus of the current study is to explore that area.

Apart from variations in the sun, another major natural variability is volcanic eruptions (discussed in details by Robock [2003]). Major eruptions can eject short-lived ash and gases (sulphur dioxide etc.) high into the atmosphere. Sulphur dioxide converted to sulphate aerosols can remain in the air for few years blocking incoming solar radiation. Thus, the radiative effect of a volcano is global cooling irrespective of the period considered, but its actual influence around continents of the Northern Hemisphere (NH) suggests winter warming [Robock and Mao, 1992] and needs attention. Using reanalysis data of the 20th Century version 2 (20CRv2), [Compo et al., 2011], a significant surface warming over northern Europe and Asia was detected by Driscoll et al. [2012]. They showed that the surface temperature in the Arctic appeared anomalously warm during post-volcanic winter. Results from Coupled Model Inter-comparison Project 5 (CMIP5) simulations [Driscoll et al. 2012], concluded that the models fail to capture the NH dynamical response following eruptions. It indicates more study is required to explore the connection/mechanism relating to volcano and NAO.

Volcanic aerosols also have the potential to change stratospheric chemistry with most necessary chemical changes in the stratosphere related to ozone [Robock, 2003]. After the 1991 Pinatubo eruption, ozone column reduction of about 5% was noticed in between mid-latitudes of both the NH and Southern Hemisphere (SH). Considering ozone depletion in the aerosol cloud, it was much larger (20%). Thus, if intense volcano and atmospheric dynamics come together with the right timing, they could reinforce one another with different drastic results. During 1978–1997, the two strong eruptions (El Chichón and Pinatubo) coincided with the near peak years of very active solar cycles. It is interesting to study the role of last two eruptions, considering the phase of solar cycles. This study shows separating the period 1978–1997 is important for better understanding some climate features. Though it was pointed out earlier (Roy, I (a, b) 2016), but interestingly very recent studies (Polvani et al. 2017, Oliva et al. 2017) also indicated that it is indeed true.

El Niño Southern Oscillation (ENSO) is a major climate phenomenon of the atmosphere and ocean and through different teleconnections, affects almost all parts of the globe. Various ENSO index time series is formulated, based on slight different geographical considerations of tropical Pacific sea surface temperature (SST), among those, the most widely used one is the Niño 3.4 Index, which has a geographic coverage of (5N-5S, 170W-120W).

There is a growing body of evidence that suggests the low-frequency variability of ENSO is primarily modulated by decadal variability originated in the North Pacific [Gu and Philander 1997; Latif et al. 1997]. The decadal mode of ENSO might be related to solar 11-year cycle. Applying Empirical Orthogonal Function (EOF) technique on SST, White et al. [1997, in their Fig 6, Top] using data from the latter period of the 20th century showed that tropical Pacific

SSTs resemble positive phase of the ENSO. It is also in phase with the 11-year solar cycle. Whereas using the Method of Solar Maximum Compositing van Loon et al. [2007], and Meehl et al. [2008] detected an enormous negative signature in tropical Pacific SST for 150 years period, matching that of the negative phase of ENSO. Using the same dataset, over a similar time Roy and Haigh [2010] could not detect negative solar signal around tropical Pacific using Regression Technique. Haam and Tung [2012], Roy and Haigh [2010, 2012], Roy [2010, 2014] addressed those contradictory findings in details and reconciled some of the contradictions and discussed few mechanisms. Discussions still suggest that the solar-ENSO behaviour is a major area of dispute in climate science. More critical analyses and thorough investigations are highly required to understand the exact nature of that connections and its implication to global scale climate responses.

Emily-Geay et al. [2008] showed, regardless of solar forcing explosive volcanos, with a radiative forcing greater than 3.3 to 4 Wm-2 (roughly the magnitude of the El Chichón and Pinatubo eruptions), noticeably influence the modelled ENSO. Those can even significantly raise the likelihood of an El Niño event above the model's internal variability level. The response of ENSO from explosive volcanism was studied by Adams et al. [2003] by using two different paleoclimate reconstructions and two independent, proxy-based chronologies from AD 1649. They found a significant, multi-year, El Niño-like response over the past several centuries and nearly twice the probability of an El Niño occurrence in the winter following a volcano. Ohba et al., [2013] also studied the effect of massive eruptions in Model for Interdisciplinary Research on Climate (MIROC5). It suggested about excitation of the anomalous west Pacific westerly which subsequently causes an increase in the probability of El Niño that agrees with observational data of longer-term paleoclimate records [Adams et al. 2003, McGregor et al. 2011]. A similar response is also noticed by Stenchikov et al. [2009] that used Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model. The model result of Ohba et al. [2013] suggests that explosive volcanos during El Niño phase contribute to the duration of El Niño, whereas the same during La Niña counteract to its duration, shortening its period. The effect of strong volcanos on El Niño is more substantial than that in La Niña due to the amplification by the air-sea coupled feedback [Stenchikov et al., 2009]. A modelling study [Iles et al., 2013] suggested, in boreal winter, the magnitude of global hydrological responses under volcanism is significantly underestimated. The difference arises from the wet tropical regions and shows improvements after removing ENSO. All these indicate studies relating to the effect of explosive volcanism on ENSO needs further exploration.

The ENSO plays an important role in regulating global temperature. The warming of the tropical Pacific from 1990 to mid-1995 was unprecedented in the observational record for more than a century [Trenberth and Hore, 1996]. Wang and Fiedler [2006] discussed that there was a failure to recognize the 1982–1983 El Niño (the strongest one over a hundred year period) until it was well developed. They also discussed the unusual nature of warm events of ENSO during 1990–1995 in the context of an observed trend for fewer La Niña and more El Niño after the late 1970s. The mean SO index for the post-1976 period is statistically different (<0.05%) from the overall mean and also the period 1990–mid-1995 [Trenberth, 1997]. There is a good correspondence between the ENSO and temperature of troposphere [Sobel et al., 2002], with warm periods coincide with El Niño's whereas, the cold with La Niña's. At the warm phase of ENSO, the troposphere is capable of carrying more water vapour. In a clear sky, water vapour is the most important greenhouse gas that constitutes 60% of total radiative forcing [Kiehl and Trenberth, 1997]. Ranked by their direct contribution, the largest greenhouse gas compounds are water vapour, and clouds (36-72%) which have far higher contribution than that of CO2 (9-26%). Using satellite data, Laken et al. (2012) showed that ENSO is also the most accountable factor for changes in cloud cover. All these studies indicate the role of water vapour and cloud, associated with the ENSO has important role and needs attention.

Svensmark et al. (2009) discussed a link between Galactic Cosmic Ray (GCR) and cloud cover. GCR is strongly anticorrelated with SSN (SSN can also be served as a proxy for GCR) as during active solar years massive coronal mass ejections from the sun block the passage of GCR towards earth. Lockwood and Froehlich (2007) concluded that the rise in global temperature since last two decades of last century correlates poorly with solar variability although it suggests to the contrary during an earlier period. Those suggest improved knowledge on the connection among ENSO, cloud cover and SSN could be a step forward in climate studies.

Interestingly, the SST trend along the equator in the final 50 years of the 20th century shows an El Niño-like pattern which is robust for *all observations* even using different datasets. However, there are controversies for the trend pattern of the longer time historical SST observations, as it differs substantially among datasets and time periods [Liu et al., 2005]. Qiong, et al. [2008] showed the standard deviation of Niño-3 SST increased to around 0.9 °C - 1.0°C during the last two decades of 20th century and showed a nearly 50%- 60% rise in the ENSO variability (significant at the 95% confidence level). Though the decadal variation of the tropical climate has a considerable contribution to the ENSO variability [Fedorov and Philander, 2000], the amplitude of the ENSO variability still suggested a robust, rising trend during that period, even removing that contribution [Zhang, et al. 2008].

It is of considerable importance to determine how ENSO responds to natural climate forcing. Because this is a necessary step to project its evolution under rising amounts of greenhouse gasses [Cane, 2005]. Numerous studies discussed the evolution of ENSO in the Representative Concentration Pathway (RCP) scenario runs [Guilyardi et al., 2012 and Stevenson et al., 2012], though the uniform consensus is yet to be reached.

This paper addresses many of these issues relating to various modes of climate variability and discusses mechanisms, by using observational data. It reconciles some of the contradictory findings and presents a critical viewpoint to advance our understanding relating to major modes of variability and their role in climate. It will help improve future prediction skill, and next generation Coupled General Circulation Model (CGCM) group will greatly benefit out of it.

The structure of this study is as follows. Section 2 discusses Methodology and Data. Results detailed in section 3, which also addresses on the existing known mechanism in support and has four sub-sections. The first sub-section (3.1) covers analyses using time series of various factors. The first part discusses the general behaviour of different indices and their combined effect while the second part focuses on results of regression using various indices. Section 3.2 analyses data to identify the spatial signature. Few questions on Sun NAO lag relationship is raised in section 3.3, and the results are summarised in section 4.

2. Methodology and Data.

The method we used here is the method of Multiple Linear Regression (MLR) analysis with AR(1) noise model. Here noise coefficients are calculated simultaneously with the components of variability such as the residual matches with an order one red noise model. Following this methodology, it is possible to minimise noise being interpreted as a signal. The method is discussed in details by Roy and Haigh [2010, 2011], Roy and Collins [2015] and Roy [2010, 2014] and previously used by many other studies (Gray et al, 2010 among others).

Variables and climate indices used in this analysis are Sea Level Pressure (SLP), Sea Surface Temperature (SST), monthly Sun Spot Number (SSN), Niño3.4, Stratospheric Aerosol Optical Depth (AOD), (indicative of volcanic eruptions), longer term trends, Central England Temperature (CET) and North Atlantic Oscillation (NAO). For SLP, the in-filled HadSLP2 dataset from Allan et al. [2006], that covers the whole globe and available as monthly means from 1850 to 2004 are used. It can also be found from http://www.metoffice.gov.uk/hadobs/hadslp2. Unlike HadSLP1, error estimates are mentioned for HadSLP2, to have ideas about the regions of little confidence. Measurement and sampling errors are large in the high southern latitude due to the lesser number of observations, though it is small in other areas. The estimates lie between the observational error estimates of Kent et al. (1997) of 2.3 ±0.2 hPa and those of Ingleby (2001) of 1 hPa over most of the ocean basins. For SST, NOAA extended SST v4 (ERSST) data is used [Liu et al, 2014]. It is available from NOAA, Boulder, from their Web site at http://www.esrl.noaa.gov/psd/ and also from https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v4/.

SSN is used to represent solar cyclic variability, which is available from http://www.sidc.be/silso/versionarchive (version 1). The main advantage of using SSN is that it is free from the influence of trends and only captures the cyclic variability of the Sun. SSN is strongly correlated with various solar related parameters e.g., UV variability, visible solar irradiance and solar F10.7 (which is solar flux that can be measured in the ground and have bandwidth of 10.7 cm (2800 MHz)), while anti-correlated with GCR and hence can be considered as a proxy for all those indices. It is the most commonly used solar index for analysing long-term climate data. Moreover, the eleven-year cyclic nature of SSN can also be very useful feature for future prediction purposes. For ENSO, Niño 3.4 index, obtained from Kaplan et al. [1997] is used which is available since 1856 and can also be found at http://climexp.knmi.nl. In the regression, AOD has been employed to represent volcanic eruptions and available from http://data.giss.nasa.gov/modelforce/strataer/. It is also available from KNMI Climate Explorer (http://climexp.knmi.nl). Longer term trend is a rising linear line that represents increasing anthropogenic influence of the 20th century. In this analysis, NAO index from Climate Research Unit (CRU), University of East Anglia is used which is accessable since 1823. It is developed by Jones et al., (1997) that considered instrumental pressure observations from Gibraltar and southwest Iceland and also available from http://www.cru.uea.ac.uk /~timo/projpages/nao_update.htm.

The CET data is the longest record of station data and described in various publications [Manley et al. (1974), Parker et al. (1992), Parker and Horton (2005)]. It is available since 1659, and can be downloaded from http://www.metoffice.gov.uk /hadobs/hadcet/data/ download.html.

3. Results:

3.1. Analyses using time series of various factors:

3.1.1. General behaviour of different indices and their combined effect:

The Fig. 1 is time series plot of various parameters. Fig. 1(i) shows global surface air temperature anomalies and Fig. 1(ii) shows time series of various independent factors those are likely to influence surface temperature. First plot (Fig. 1(ii)) on top (a) is the linear trend that represents longer term climate change and mainly arises due to anthropogenic influence. The second plot from top (b) is due to AOD, and the third (c) and fourth (d) are due to solar eleven-year cycle variability (here SSN) and Niño3.4 index (representing ENSO) respectively.

Due to a large specific heat of ocean, it can retain heat for longer time scale and thus longer term variation of solar output is captured and detected mainly in the oceans. The Atlantic Multi-decadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO) are two primary modes of variability in the Northern Hemisphere (NH) which are generated due to atmosphere and ocean coupling and substantially regulate global temperature. In the current study, the primary interest is on the role of climate variability on time scales of decades and less and thus, PDO and AMO, which have a longer-term variability of ~20-30 years are not included. Moreover, those are not considered as an independent variable, rather they are the regional manifestation of longer-term SST variability.

Here is a brief discussion about global surface temperature variation as it corresponds to Fig.1(i). An apparent rise in temperature during 1917 to 1944 is noticed with a cooling trend prior to that. A sharp increase in temperature since 1978 is again continued till 1997. Three phases (I, II and III) are marked in Fig 1(ii) based on various combinations of the strength of volcanic activity and SSN that also follow the variation of surface temperature. Period (I) suggests cooling of surface temperature, period (II) suggests a rise in surface temperature; whereas, period (III) shows an abrupt increase in surface temperature.

The sun and volcano:

During the latter half of 20th century, the period dominated by the sudden rise in surface temperature, the solar cycles are also seen to be stronger as noticed in Fig. 1(ii). In addition, three major volcanos erupted during 1963, 1982 and 1991 and last two even coincided with the near peak of active solar cycles. Though the solar peaks and volcanic eruptions occurring simultaneously are a pure coincidence, but if it happens, it changes the mean state of stratosphere and troposphere. It has the potential for different dynamical effects including altering the strength and nature of solar so-called 'Top-Down' mechanism. Moreover, ocean-atmosphere coupling system is also disturbed. Thus, both the direct (radiative) and indirect (dynamical) effects of the intense eruptions need to be taken into account to actually judge its contribution in surface climate. It is also likely that actual anthropogenic influence is underestimated due to the offsetting effect of combined natural variability that needs to be investigated.

The late 1800s to the early 1900s was a very active period of volcanic eruptions and those also coincided with minimum/near minimum years of solar 11 year cycles. Together with a quiet sun that period (marked by 'I', Fig. 1(ii)) was cold as seen in Fig. 1(i). While the period during 1917 to 1944 (marked by 'II') was a period of very little volcanic activity that coincided with an increase in solar irradiance experienced a warming of global temperatures. However, the primary focus here is during the time with a steep rise in temperature at last two decades of the 20th century (Fig 1(i)) and the role of natural variability. There was an abrupt increase in surface temperature during 1978–1997 [IPCC, 2013]. It coincidentally happened when two very active volcanos erupted during near peak of active solar cycles (Fig. 1(ii), period III).

We speculate that not only the strength of eruption and the power of solar cycle necessary but also their combined behaviour that includes the timing of eruption relating to the phase of solar cycle are important in controlling the climate. It is interesting to investigate the role played by major variability individually and in combination, considering the dynamical and radiative influences with attention.

The role of ENSO:

The bottom plot of Fig.1(ii) is for ENSO, which shows the inter-annual variability of 2-7 years. It was usually of 2-3 years cycle during the earlier period and even 5-7 years cycle during the latter period of 20th century. In that figure, the period 1978–1997 is marked (III, Fig. 1(ii)) when ENSO showed some differences and discussed below. We only focused period III, as earlier period shows usual ENSO behaviour.

Using five months running mean of Niño3.4 SST index, to represent ENSO, Trenberth and Hoar [1997, Fig 1] clearly identified highest ENSO signal during 1982 and that with the longest duration during 1992. They mentioned that from March 1991 to March 1995, the average ENSO did not change sign suggesting those peaks were clearly linked. Last two decades of 20th century, experienced nearly 50%- 60% increase in the ENSO variability [Qiong, et al, 2008]. Fig 1(ii) bottom panel agrees with such observations and also supports Adam et al, (2003) and Ohba et al (2013), that indicates volcanic forcing drives the coupled ocean-atmosphere system more subtly towards a preferential direction, where multi-year El Niño-like situations are favoured, which is subsequently followed by a weaker rebound into a La Niña-like condition. As the number of El Niño outnumbers to that of La Niña during 1978–1997 (Fig. 1(ii), period III) with a significant rise of its variability and duration [Qiong, et al, [2008]; Trenberth and Hore [1996]], explains why SST trend along the equator in the final 50 years of 20th century shows a robust El Niño-like pattern for all observations using different datasets [Liu et al., 2005].

Considering water vapour as the most important greenhouse gas that constitutes 60% of total radiative forcing [Kiehl and Trenberth, 1997] and noting the fact of fewer La Niña and more El Niño events after the late 1970s (also seen in Fig.1(ii), bottom panel, period III), the rise in global temperature during that period, the different behaviour of El Niño that includes increase in amplitude and time period (Trenberth, 1997; Trenberth and Hore ,1996; Wang and Fiedler,

2006) could be one interesting area which needs to be revisited. More research is needed in that direction to advance future prediction skill. The focus here is mainly on natural forcing and it can also be noted that radiative cooling due to volcanic eruptions may override El Niño warming.

The overall analyses presented are indicative of studying the importance of combined behaviour of ENSO, volcanic eruptions, and solar variability. In addition to their individual influences, such combination is important to understand the overall climate impact regionally as well as globally.

Fig 2 shows a deviation of SST during 1978–1997 (where two explosive volcanos erupted in active solar phases) to that from two different periods 1920-1940 and 1999-2017 respectively, when there are no massive volcanos. Surprisingly an El Nino like pattern is noticed in both plots where central tropical Pacific SST has risen by around .4º to .8º C during 1978-1997. On the contrary, over the same period, there is a cooling around North Atlantic where SST cooled even more than 1 ºC. It is interesting to note such consistency in spite of two reference periods are considered (one is even so called recent 'Hiatus period'). Even with the presence of longer-term global warming trend throughout the period, (clearly seen around other parts of oceans), central tropical Pacific and North Atlantic shows deviations. Considering various arbitrary reference periods (Fig. S1), similarly signed signals are still noticed during 1978–1997, which are opposite in central tropical Pacific (warm) to that from North Atlantic (cold). This period (1978–1997) only differs from rest other reference periods regarding explosive volcanos matching with high years of active solar cycles. Hence in subsequent analyses we focus on those regions and make a little elaborate study on ENSO and NAO, considering solar variability and volcanos.

3.1.2 Results of regression using various indices:

This section presents discussion based on MLR technique. MLR technique is applied to three different parameters CET, NAO and ENSO in three subsequent columns (I, II and III) and presented in Table 1. The first column (I) shows the value of regression coefficients using CET as the dependent parameter, with the independent factors as the NAO, SSN, AOD, ENSO, and trend. The second column (II) is the result due to SSN, AOD, ENSO and trend as independent parameters with NAO being the dependent factor. Whereas, the third column (III) calculates regression coefficients for ENSO as the dependent variable with SSN, AOD, and trend as independent factors.

The period from the 1950s to 1997 was identified by several authors [e.g. Vecchi and Soden, 2007] as the period of a weakening of both the Walker and Hadley circulations; more in the Walker than the Hadley circulation. On the other hand, over the same time, the shallow ocean Meridional Overturning Circulation in the Tropical Pacific was also weakened [Zhang and McPhaden, 2006], suggesting that both the atmosphere and the ocean system was in an anomalous state. Hence, that period is separated to that from the earlier period to find the influence of different factors.

Various studies indicated the year 1976/77 as climatic ‘regime shift’ [Miller et al. 1994, Meehl and Teng, 2014] because many physical conditions in the atmosphere and ocean including surface temperature changed abruptly during that period. Substantial evidence also supports the idea that physical conditions changed around atmosphere [Minobe 2000; Bond et al. 2003] and ocean [McPhaden and Zhang, 2004; Vecchi and Soden, 2007] during 1998. Moreover, last two very active volcanos erupted during that intervening period (1978–1997) coinciding the active phase of strong solar cycles. Hence, those two decades are also separated.

In Table 1, period ‘A’ is for the entire period of consideration up to 1997 which is (1856–1997); whereas, ‘B’ only considers the time before 1957; ‘C’ is after 1958, while period ‘D’ focuses the time 1978–1997. There could be issues related to lesser data points hence we also repeated the analysis of period ‘D’ up to 2004 that covers 26 years period but the main findings did not change. The results of significance in different degrees (90 %, 95%, and 99%) are marked by various symbols (*, ** and *** respectively). However, the major results are based only on the significant level of 95% and 99%.

Influence on CET (column I):

In column I of Table 1, it is clearly seen that the NAO explains most of the variance for CET and the result is 99% significant in all the periods (A–D). Interestingly, during period D, volcano suggests cooling (95% significant) in central England, while linear trend indicates warming (90% significant). Irrespective of time periods considered, NAO plays a dominant role in regulating the temperature of England. Though the influence of NAO on CET is robust, but NAO is seen to be influenced by other independent factors differently during different periods considered.

Influence on NAO (column II):

Identifying the importance of NAO in controlling the temperature of Europe, Central England being one of the representative regions, it is now interesting to identify how NAO can be influenced by other factors and shown in column II. Studies suggested that there are preferences of positive phases of NAO in climate change scenarios [Visbeck, 2001]. This is consistent with the observation for trend during period C and D, though only significant at 80% level. Volcano though shows positive connection with NAO throughout the period (A–D), but only significant at 90% level for period A. It is likely that the number of total occurrence of volcanos in period A might have a role. The regression coefficient in period D (+1.29) is seen to be higher than that in period A (+1.18), but because of lesser data points, it fails to indicate the significant result. Such positive connection between volcano and NAO is also noted by Gray et al [2013, their Fig. 3] using MLR technique for over a 150 years of observational data.

Now the focus is on solar NAO behaviour. During the post 1957 period, the relationship between SSN and NAO has strengthened. From column II, Table 1, it is seen that the NAO is influenced positively by SSN during period D (level of significance 90 %) and C (only 80%, hence not marked) and the nature of this signature is consistent with the recent study by Ineson et al [2011]. Considering the period of latter half of 20th century Roy [2010, 2014] also detected such signal in observation. Interestingly, when the focus is on period A and B, column II, it is clear that the NAO solar relationship not only weakened but sometimes reversed in sign. Gray et al [2013, their Fig 3, 4] using data from longer time period found a reverse association between the sun and NAO in zero lag case. Furthermore, Roy and Haigh [2010, their Fig 1] also detected similar features for longer time period. In both those studies, sun and NAO suggested a negative (insignificant) association matching to that of Period B, Table 1. Such opposing nature of sun and NAO during different periods though was shown in various popular papers, but to my knowledge was never discussed before. Our analysis points towards the study of Ineson et al. [2011] that suggested an inactive phase of the sun (as represented by solar UV variability in their model) is linked with the negative phase of NAO and vice versa. It indicates the robustness of such association requires further exploration. The mean atmospheric state also needs to be taken into account with additional care in detecting the role of the sun on major climate variability and proposing a mechanism based on any detected signals. ENSO, however, does not show any significant influence on NAO in any of the periods.

Influence of ENSO (column III):

Now the attention is on the major dominant variability in tropics, the ENSO and it is interesting to identify whether ENSO is also influenced by other dominant factors. Possible candidates considered are longer term trend, to represent a linear rise in temperature, which is associated with anthropogenic influence and natural variability represented by volcanic eruptions and SSN. The discussion mainly follows on ENSO and natural variability.

The results using ENSO as the dependent parameter (column III) gives one interesting finding about the role of volcanic eruptions on ENSO. A volcanic eruption is seen to strongly favour positive phase of ENSO, but only true during last half of the 20th century. The signal is strongest during period D (99% significant), while it is weak in period B. Such result during period B (1856-1957) is probably dominated by lesser/weaker volcanos during the first half of the 20th century. During that half, without many volcanic eruptions, ENSO still followed its own inter-annual variability. When considering the overall period of analysis in period A, volcano and ENSO relationship is found to be dominated by period D and suggests a level of significance up to 95%, which is consistent with various works as discussed earlier [Emily-Geay et al., 2008; Ohba et al., 2013; McGregor et al., 2011; Stenchikov et al., 2009 and Adams et al, 2003]. Those discussed ENSO is noticeably influenced (in preference of its positive phase) by active volcanic eruptions. It is also consistent with the observation of Fig. 1 (ii), bottom panel and explains why SST trend along the equator in the final 50 years of 20th century shows a robust El Niño-like pattern for all observations using different datasets [Liu et al., 2005].

A little discussion about possible mechanism is added here (schematics are in Fig. 3). Warming in the central equatorial Pacific in response to explosive volcanos (Table 1, column III) can be explained by a hypothesis known as the dynamical thermostat hypothesis (Clement et al. 1996). It states for a uniform reduction of incoming surface solar radiation to a large degree, (which is associated here with explosive volcanos) the response of SST is different on two sides of the tropical Pacific. Due to ocean advection theory, the western Pacific cools faster than the east. It initially reduces the climatological zonal SST gradient, which subsequently influences trade winds in the central Pacific. The resultant positive SST gradient can activate El Nino phase reversing trade winds. McGregor et al. (2011) proposed another theory that states, the anomalous westerly in tropical Pacific could be attributed to the rapid response over the maritime continent, in response to uniform reduction of incoming surface solar radiation. It is mainly linked to the land-sea contrast, where the surface cooling around equatorial Pacific and its time-scale for adjustment are leading responsible factor. It is the fast cooling around the maritime continent that contribute to the positive zonal SST gradient. However, the role of a dynamical thermostat (Clement et al. 1996) and the proposition of McGregor et al. (2011) both can act together to reinforce the mechanism relating to volcano and ENSO.

Another interesting finding from column III is about solar-ENSO behaviour. In period C, there is a positive solar signal detected in ENSO, which is only significant up to 80 % level. Though it is less significant but the sign of such signature is in agreement with White et al. [1997, their Fig 6] who using data of second half of the 20th century detected a similar in-phase relationship between the sun and ENSO. However, when the focus is on Period B, the relationship not only reversed but even showed significant up to 95% level. It is noteworthy that Roy and Haigh [2012], focusing on a similar period of analysis, also observed the preferential alignment of the negative phase of ENSO during active phases of the solar cycle (i.e., when SSN >80) during northern winter. Updating that record with current data (upto 2015) also confirmed such observation (Fig. 4). The recent two years of 2016 and 2017, being low solar years, does not make any difference to our result. Considering spatial pattern, Roy [2010, 2014] however could not identify a detectable signature in tropical Pacific Sea Surface Temperature (SST) using Hadley Sea Surface Temperature version 2 (HadSST2) data during the same period, possibly because that accounted every month of the year rather than only boreal winter. Van Loon et al. [2007] and Meehl et al. [2008] using the method of a solar peak year compositing detected similarly signed signature during December January February (DJF), though it only focused on solar peak years rather than active/inactive phases of the solar cycle. Due to two opposite nature of signature in period B and C, it is difficult to discern any solar-ENSO relationship for the entire period of analysis as also noted in period A. Such study indicates the importance of mean state and the purpose of separating time periods to resolve various conflicting findings.

During earlier period (DJF), the significant negative association between the sun and ENSO can also be explained by the hypothesis of a dynamical thermostat (Clement et al. 1996) and the proposition of McGregor et al. (2011) (discussed in Fig 3, Mechanism I). Interestingly, during inactive phase of the sun, there is a uniform reduction of surface heat fluxes and hence, the same principle as discussed for the volcano is equally applicable. It could trigger El Niño like situation, while active solar years will trigger La Niña like situation following reverse mechanism. The decadal solar signature for inciting trade wind is clearly detected in Fig. 5a (left) (and discussed in section 3.2), which is though small in magnitude, but significant up to 95% level. Such association is also seen in Table 1, Period B, column III, as reflected by sun ENSO connection (β= - 0.84, significant at 95% level). In general, such analysis indicates that solar cycle drives the coupled ocean-atmosphere system more subtly towards a state in which La Niña conditions are usually favoured for active solar years; whereas, El Niños are usually favoured for low solar years. At low solar years, the usual interannual variability of ENSO (governed by Kelvin and Rossby wave movement) dominates, but during high solar years the solar signature overpower as seen in Fig. 4. The ENSO suggested cold phase not only during peak solar years of active cycles, but that also followed 1 to 2 years after the peak (Roy, 2014, Roy and Haigh, 2012). Overruling all speculations, the last solar peak year of 2014 again suggested the cold phase of ENSO (Roy et al. 2016). The three other solar peak years from later decades of last century (bottom plot, Fig 4) which are not influenced by volcanos (year 1968,1979, 1989) are also showing preference towards cold event side. It is noteworthy that the sun ENSO connection was reverted back again like earlier period since 1998 (Roy and Haigh, 2012, also seen in Fig 4).

3.2. Identifying spatial signature:

Focusing attention on the spatial pattern, a MLR technique is applied on SLP with independent parameters as AOD, linear trend, ENSO, and SSN (Fig.5). Shaded regions are estimated significant at the 95% level using a t-test. The major findings are discussed below.

Signature due to the Sun:

Fig. 5a shows solar signature in SLP (spatial pattern) excluding other major factors (volcano, ENSO, and trend), those are very likely to influence results. The right panel is for 1978–1997; whereas, left panel for the earlier period of available data series. In both the figures (Fig. 5a), a strong positive signal around Aleutian Low (AL) is clearly detected suggesting the robustness of that signal as noticed by Roy and Haigh [2010]. Right panel of Fig. 5a (also in Fig. S2) suggests a positive Arctic Oscillation (AO) pattern; whereas, a clear dissimilarity is noticed around the far North Atlantic in the left panel. A positive NAO-like signature is clearly distinguished in the right panel which is in accordance with the results of Table-1 (Period D, column II) and the study of Ineson et al [2011]. Surprisingly, that signature is opposite in nature in the left panel (Fig. 5a) with significant region mainly localised around the places of Greenland. Such opposite signature is also noticed in Roy [2010, 2014], that used earlier and latter periods (though different years than this study) of observational data. In those two works, however, it did not discuss solar NAO connections, neither did it consider/compare various time periods over 150 years. Current analyses also explain why Roy and Haigh [2010, their Fig 1] could not identify any NAO-like pattern using data of longer time period as is also seen and discussed in Table 1, (Period A, column II). All such analyses reconcile some contradictions and raise doubt about proposed relationship as discussed in Ineson et al [2011] and other related studies based on similar mechanism. It indicates that the robustness of solar NAO known connection needs exploring further and it could be a step forward for the climate community.

A brief discussion is also presented on one possible mechanism relating to the Sun and NAO connection, which can be explained by the proposition of Bjerknes (Bjerknes 1966). During latter decades, the broader maxima of solar cycles (1-2 year after peak solar years) are inclined to warm events of ENSO (Roy and Haigh, 2012, Roy 2014). Following Bjerknes (1966), (also discussed in details in Fig. 3, Mechanism II), the anomalously great heat of warm equatorial ocean enters into the rising branch of the regional Hadley circulation and strengthens the cell. It generates above normal flux of angular momentum to the westerly winds around mid-latitude. Thus warming in tropical Pacific can strengthen mid-latitude westerly jets during boreal winter and subsequently can favour a positive phase of NAO. Such response is strongest in the winter hemisphere due to greater baroclinicity. During the earlier period (DJF), the sun showed preferences towards La Niña phases (Roy and Haigh, 2012, also Table 1, Column III) in all active solar years. Following similar mechanism (Bjerknes, 1966), it can suggest a weakening of mid-latitude westerlies in boreal winter, indicating a negative association between the sun and NAO (Fig. 5a, left).

In Fig. 5a, apart from north Atlantic, the solar signal around tropical Pacific is also seen to be different in the left panel to that from the right. In the left panel, the significant signal observed in the tropics (though small in amplitude but 95% significant) might be responsible to incite trade wind and thus can favour cold event like situations of ENSO via indirect dynamical coupling (Roy, 2014). Such signature is missing in the right panel, which suggests it might be one of the several factors that could also be responsible for different sun and ENSO connection, positive during the 2nd half of 20th century to that of the earlier period of the data, which is negative and significant up to 95 % level (Table, 1, period B, column III). It supports Mechanism I (Fig. 3) in connection with the sun and ENSO, involving anomalous westerly in the tropical Pacific.

Different sun ENSO behaviour during the later period of last century (Fig. 4) suggests consistency among earlier discussed conflicting findings relating to the sun, global temperature, ENSO, cloud cover and GCR (Lockwood and Froehlich (2007), Laken et al. (2012) and Svensmark et al. (2009)). .

Signature due to the ENSO:

Fig. 5b shows the spatial signature of ENSO on SLP around north polar region, excluding SSN, AOD, and linear trend. The right-hand panel is for 1978–1997 and left hand for 1856–1977. Both the panels of Fig. 5b identifies negative NAO pattern for ENSO around pole. For solar signature (Fig. 5a), tropical Pacific trade wind was involved and hence the plot that covered tropical Pacific was shown. However, for ENSO signature, the focus of present discussion is mainly around polar region of NH and hence a stereographic map centered on the north pole is presented (Fig. 5b). The positive phase of ENSO is responsible for the warming of polar vortex during northern winter, as detected in observation [Thompson, Baldwin and Wallace, 2002] and model [Toniazzo and Scaife, [2006]]. It subsequently suggests a negative phase of polar annular modes in troposphere [Baldwin and Dunkerton, 2001]. One possible route how the ENSO influences polar vortex and then down to Arctic region can be through well-known Brewer-Dobson circulation. There are another mechanism that suggests, during warm phase of ENSO more planetary waves are generated and interact with polar vortex. Significant signature is noticed around the Arctic in Fig. 5b left-panel, but variability of SLP is increased in the right panel (but not significant). The change in the mean state due to combined different influence of active volcanos and high sun around the place of polar vortex (mainly due to variation of ozone) during the later period might cause reduction of significant level. The increased amplitude of signals around Arctic however could be linked to the fact that ENSO variability has increased (Fig 1(ii), bottom) and unevenly high number of warm events occurred to that from cold events during the period 1978–1997, as discussed earlier.

All these studies indicate that due to change in mean state of the atmosphere, the influence of major climate factors is felt differently in different parts of the globe.

3.3. Question on Sun NAO lag relationship:

A recent study by Gray et al. [2013] and Scaife et al. [2013] noted solar lag relationship around places of the Azores high and discussed mechanism based on their results. Here, MLR technique is applied during same two different time periods as considered in Fig. 5 and solar lag relationship (lag year 1 to lag year 3, Fig.6a–c) is performed. The results are also compared with the overall 150 years of data (in the bottom panel of each figure) as is done in Gray et al. [2013].

Fig. 6a shows results for lag year 1. The top two figures show a clear difference between the north pole which are similar in nature like Fig.5a respectively, though much weaker here. Signature in Fig. 6a, bottom panel, matches to that of the top left panel in places of North Atlantic probably due to longer data records of the earlier period. The result of the bottom panel is similar to that of Gray et al. [2013].

Fig 6b and c are for lag year 2 and 3 respectively. For North Atlantic region in lag year 2 (Fig, 6b), the bottom panel is dominated by strong signal during the period 1978–1997; whereas, for Fig. 6c it is overpowered by an earlier period (1856–1977). Strong positive solar signature for 150 years record is around Azores high for lag year 2 and 3 (strongest for lag year 3) which is consistent with the study by Gray et al. [2013]. The main findings in Fig. 6, bottom panel (all plots) concerning longer record is in agreement with Gray et al. [2013]. The little deviation, if noticed, might be related to a slight difference in the period considered.

The key observation from these analyses is that the lag relationship is also not robust but sensitive to the period chosen. The result of the overall 150 years is mainly dominated by a period that has stronger signals. Hence, caution should be taken in proposing any mechanism based on any detected signal unless that signal is very robust. It also points towards the complexity in relating major variabilities like a solar 11-year cycle, ENSO, and NAO without taking proper account of active volcanic eruptions and related dynamical coupling.

There could be an argument about the SLP data qualities. However, in support of robustness of current analyses, it may be stated that various popular research used the same data around polar region, including papers that we compared here [Ineson et al., (2011); Van Loon et al. (2007) and Gray et al. (2013), etc.]. The signal in this study as noted though detected using MLR technique as described, but it shows consistency throughout with earlier detected signals. It is mainly a critical piece of discussion that can serve resolving various contradictions and lead forward towards detecting robust signals of natural variability.

4. Discussion and Summary:

This paper addresses issues to improve understanding of the role of natural factors by using observational data and discusses some existing mechanisms in support. It also indicates that caution is required to detect signal relating to natural variability (mainly the sun) and the robustness of identified signature need to be tested with a critical view point.

We discussed SST during period 1979-1997 was different, but of similar nature, to that from two other periods (earlier and later) around central tropical Pacific and North Atlantic (Fig. 2). In spite of a longer term global warming signal, there is a warming in central pacific though cooling in north Atlantic during that particular period. We focused those areas and discussed the importance of ENSO in regulating global temperature.

We showed the NAO mainly explains the variability of CET, and this is true irrespective of chosen periods of reference (Table 1, column I). However, NAO is influenced by other factors differently at different times (Table 1, column II).

The last two solar cycles of previous century suggest a strong positive connection between the volcanic eruptions and ENSO (Table 1, column III). Various modelling and observational results also support such connection (Ohba et al., (2013); Adams et al. 2003; McGregor et al. 2011; Stenchikov et al., 2009). We discussed mechanisms (Mechanism I, Fig.3) to explain possible association between volcano and ENSO as observed.

Prior to period (1856–1957), a significant inverse relationship between the SSN and ENSO is identified during DJF. The signal is even opposite in sign and less significant during the second half of 20th century (Table 1, column III). We discussed mechanism (Mechanism I, Fig 3) to explain cooling in the central tropical Pacific during earlier period, which is mainly related to more solar radiative forcing in active solar years.

It is also seen in the observation that explosive volcanos are often associated with the positive phase of NAO (Table 1, Period A). It thus agrees with winter polar warming (Robock and Mao, 1992). Mechanism II (Fig. 3) can explain why warming along the central and equatorial Pacific during DJF (here it is related to ENSO due to the volcano) could favour a positive phase of NAO, following a non-linear alignment.

The in-phase relationship between the NAO and the sun as identified by other studies, though observed during last two decades of 20th century, is missing in earlier periods (Table 1, column II and Fig. 5a). The connection is strongest during later decades (Table 1, period D and Fig. 5a) when explosive volcanos coincidentally matched with the active phase of solar cycles and can be explained by a known mechanism (Mechanism II, Fig 3). During latter decades, the broader maxima of solar cycles (1-2 year after peak solar years) are inclined to warm events of ENSO (Roy and Haigh, 2012, Roy 2014). Such warming via regional Hadley cell is often accompanied by strengthening the midlatitude westerlies and subsequently, responsible for positive sun NAO connection. Following similar mechanism, active sun and cold ENSO, as it the case for the earlier period, will suggest a weakening of midlatitude westerlies in boreal winter, indicating a negative association between the sun and NAO (Fig. 5a, left).

Apart from issues concerning the robustness of earlier proposed connection on the Sun and NAO, it also questioned on their lag relationship. Massive volcanic eruption that matched near a peak of active solar cycles can have an enormous impact on the mean state of the atmosphere, (both the stratosphere and ocean) and thus the solar, NAO and ENSO relationship needs to be investigated with additional care.

Such critical overall analysis will be helpful for an improved understanding of various modes of variability and their role on climate. It is an essential step forward to improve future prediction skill and advance model performance.

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Table Caption:

TABLE-1: Regression Coefficients for various indices during DJF in different time periods. Values significant at 90%, 95% and 99% level derived using a Student-t test are shown by *, ** and *** respectively.

Figure Captions:

Fig. 1: Time series of various independent parameters (Fig. 1(ii)), those affect global surface air temperature (Fig. 1(i)). Fig. 1(i) presents global surface air temperature anomalies relative to 1951-1980 base period (after, Hansen et al., 2010, Fig. 9). Fig. 1(ii) shows time series of a) normalised linear trend (top), b) Stratospheric Aerosol Optical Depth (AOD) (2nd row), c) Sunspot number (SSN) (3rd row) and d) ENSO, represented by Niño 3.4 Index (ºC) (bottom). Three periods (I, II and III) are marked based on various combinations of strength of volcanic activity and solar irradiance for: I) cooling of surface temperature; II) rise in surface temperature and III) abrupt rise in surface temperature.

Fig.2: SST anomaly (DJF) from NOAA Extended SST V4 (ERSST), left for 1978–1997 minus 1999–2017, and right 1978–1997 minus 1920–1940.

Fig.3. Schematic describing the role of the sun for around last 150 years period. Particular emphasis is on the period 1978–1997 and the role of explosive volcanos. More details on Mechanism I and II are discussed in the Supplementary text.

Fig.4. Scatter plot of ENSO(DJF) against annual average SSN from 1856 to 2015 inclusive. Red squares mark the peak years of solar cycles. All years during 1856–1957 and 1998–2015 are aligned to the negative phase of ENSO during active phases of the solar cycle (i.e., when SSN >80), while intervening periods (1958–1997) show no such preferences for a high sun.

Fig. 5: Amplitudes of the components of variability for SLP (in hPa) during DJF. The top panel (a) is due to SSN using different independent factors as longer term trend, AOD and ENSO; whereas, the bottom panel(b) is due to ENSO using independent factors as trend, AOD and SSN. The bottom panel is an equatorial stereographic map centered on the north pole, as it mainly focuses on Arctic. The right panel is for period (1978–1997) and the left panel for (1856–1977). Shaded regions are estimated significant at the 95% level using a t-test.

Fig. 6: Amplitudes of the components of variability for SLP due to solar cycle variability (max-min), in hPa during DJF for a) lag of one year, b) lag of two years and c) lag of three years.

Independent factors used are longer term trend, AOD and ENSO. Shaded regions are estimated significant at the 95% level using a t-test.

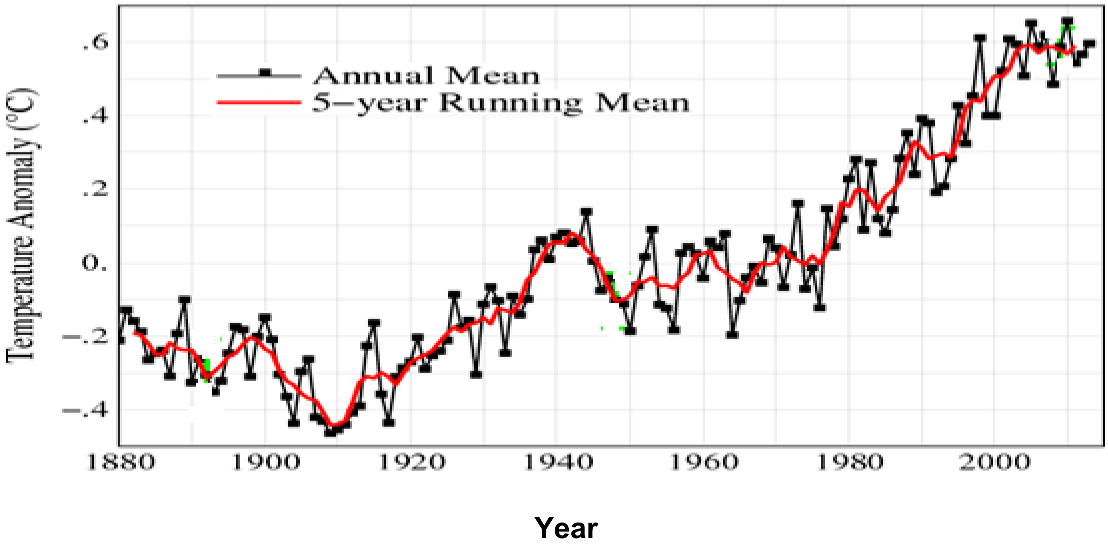
Fig.S1: SST anomaly (DJF) from NOAA Extended SST V4 (ERSST), top for 1978-1997 minus 1941-1977 and bottom for 1978-1997 minus 1860-1919.

Fig. S2. Same as Fig 5a, but period covered is (1978-2004). The signal around north Atlantic indicates similarly. It considered an additional seven years as HadSLP2 data used is available upto 2004.

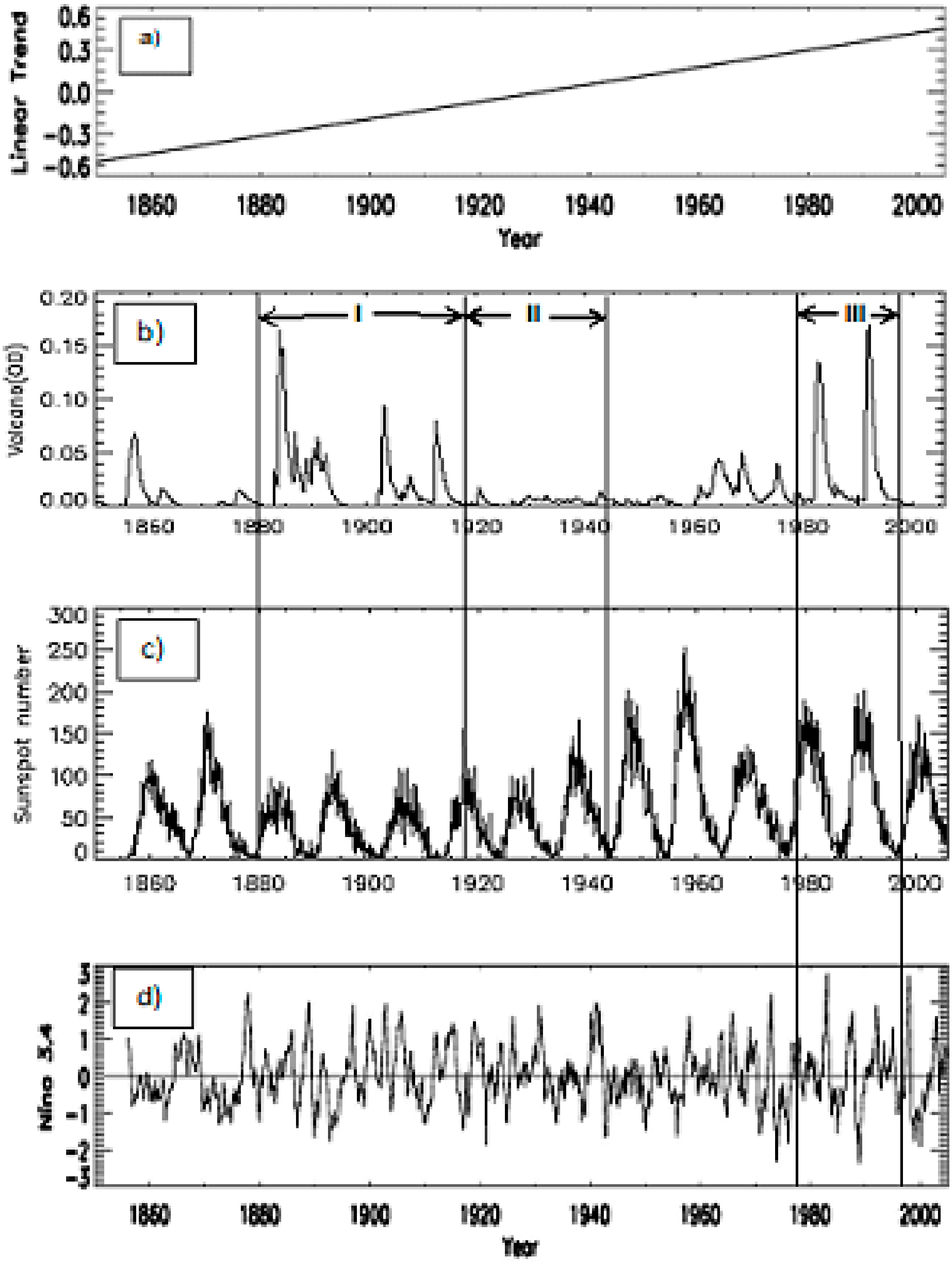
TABLE-1: Regression Coefficients for various indices during DJF in different time periods. Values significant at 90%, 95% and 99% level derived using a Student-t test are shown by *, ** and *** respectively.

	Independent Parameter	Dependent Parameter		
		(I) CET	(II) NAO	(III) ENSO
Period A **(1856–1997)**	Trend	0.76	-0.67	0.14
	AOD	-0.46	1.18 *	1.07**
	Sunspot Number	-.28	0.39	-0.20
	ENSO	0.06	-0.17	
	NAO	4.57***		
Period B **(1856–1957)**	Trend	0.31	-0.11	0.13
	AOD	-0.39	0.86	0.15
	Sunspot Number	-0.12	-0.04	-0.84**
	ENSO	0.22	-0.11	
	NAO	4.7***		
Period C **(1958–1997)**	Trend	-0.05	1.12	-0.24
	AOD	-0.38	1.07	2.01**
	Sunspot Number	-0.34	1.03	0.62
	ENSO	-0.27	0.28	
	NAO	4.01***		
Period D **(1978–1997)**	Trend	1.04 *	1.74	-.57
	AOD	-1.50 **	1.29	2.18***
	Sunspot Number	.15	1.70 *	-0.13
	ENSO	-0.02	.52	
	NAO	3.93***		

(i)


Annual Mean
5−year Running Mean
Temperature Anomaly (°C)
.6
.4
.2
0.
−.2
−.4
1880
1900
1920
1940
1960
1980
2000
Year

(ii)



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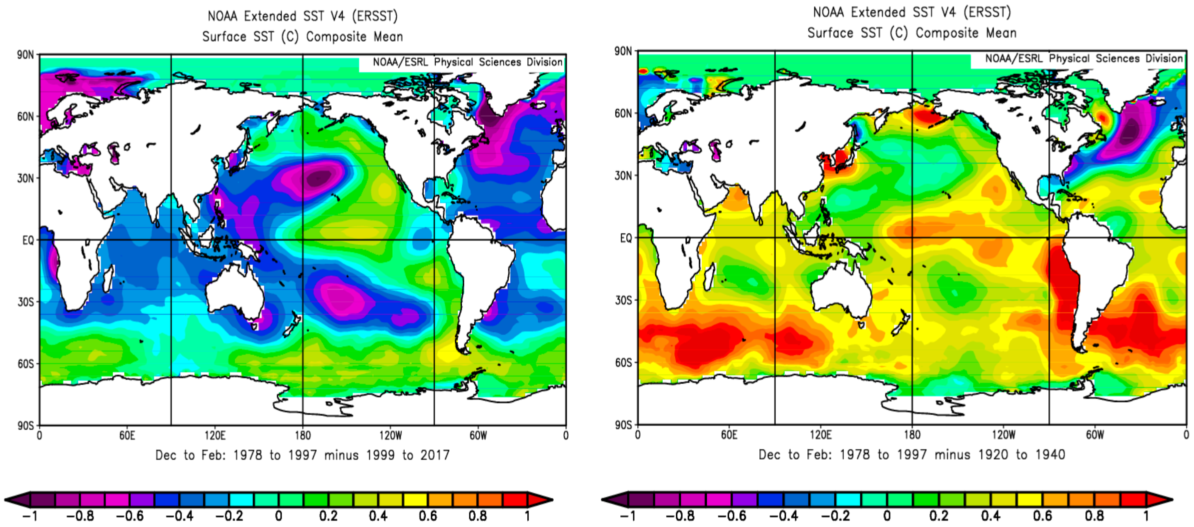
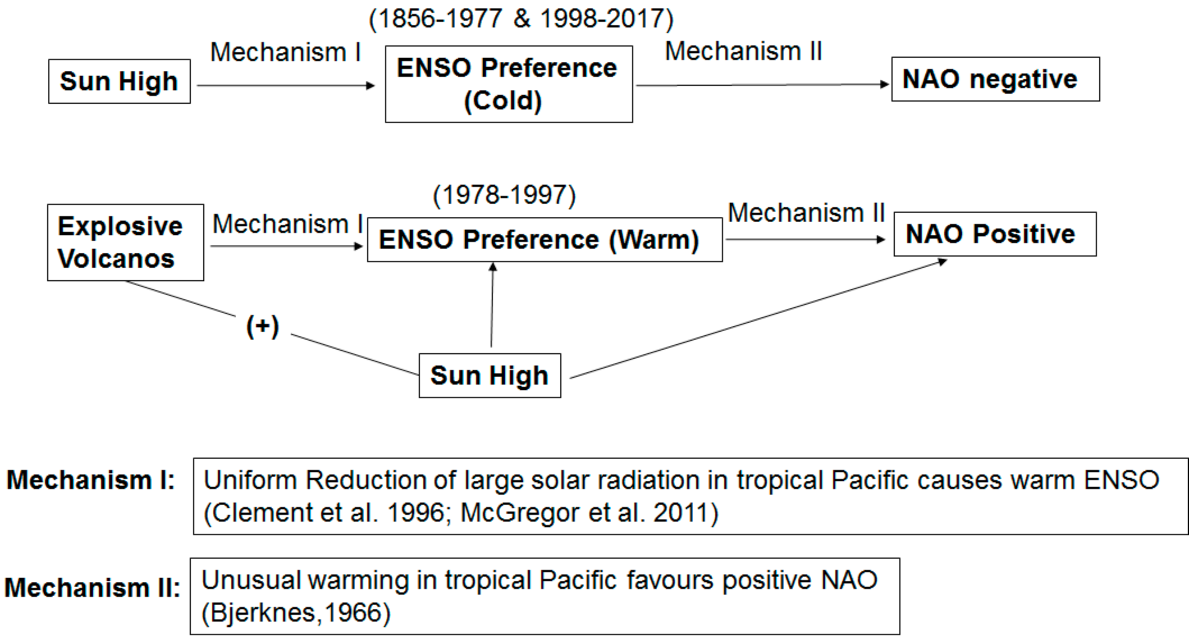


Fig.2. SST anomaly (DJF) from NOAA Extended SST V4 (ERSST), left for 1978-1997 minus 1999-2017, and right 1978-1997 minus 1920-1940.

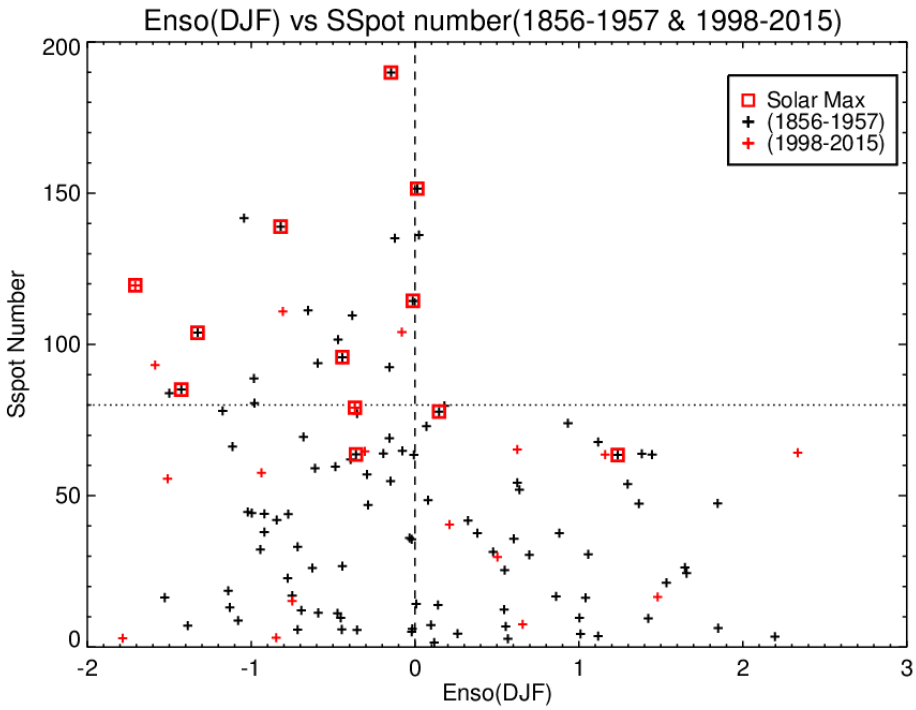
doi:10.20944/preprints201608.0025.v2

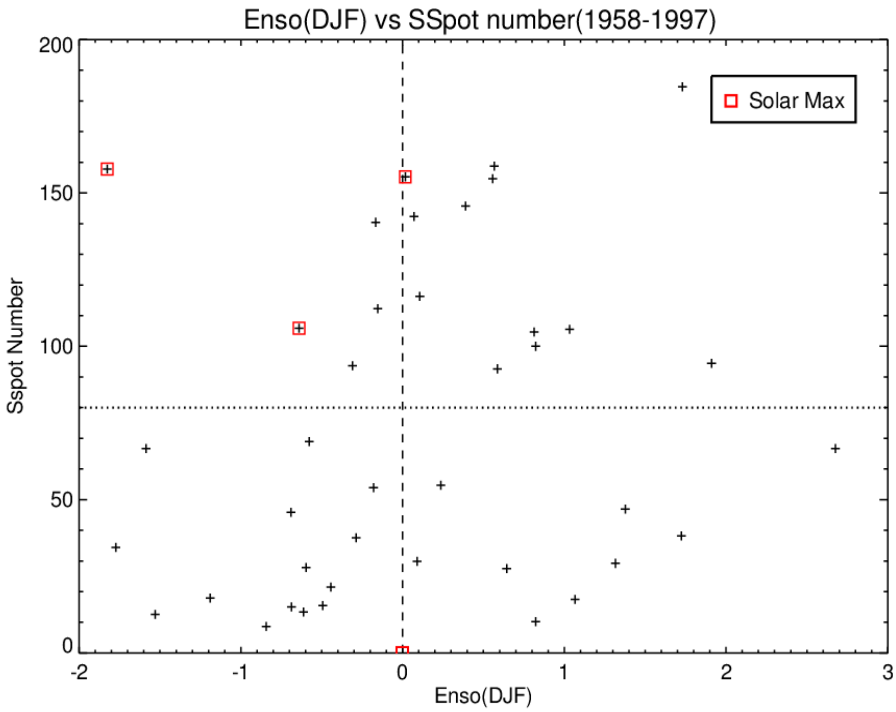


Mechanism I: Uniform Reduction of large solar radiation in tropical Pacific causes warm ENSO (Clement et al. 1996; McGregor et al. 2011)

Mechanism II: Unusual warming in tropical Pacific favours positive NAO (Bjerknes,1966)

Fig.3. Schematic describing the role of the sun for around last 150 years period. Particular emphasis is on the period 1978–1997 and the role of explosive volcanos. More details on Mechanism I and II are discussed in the Supplementary text.





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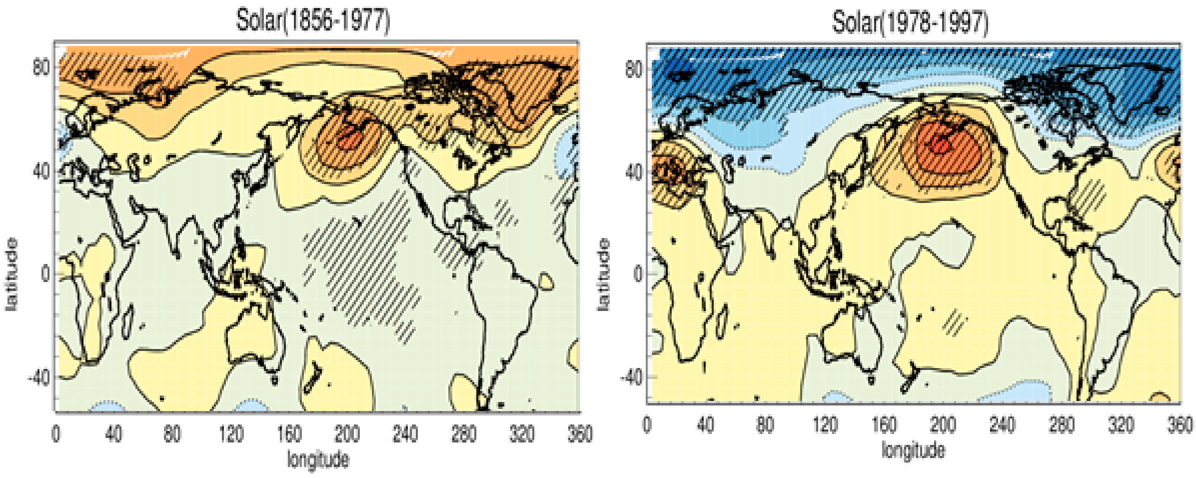
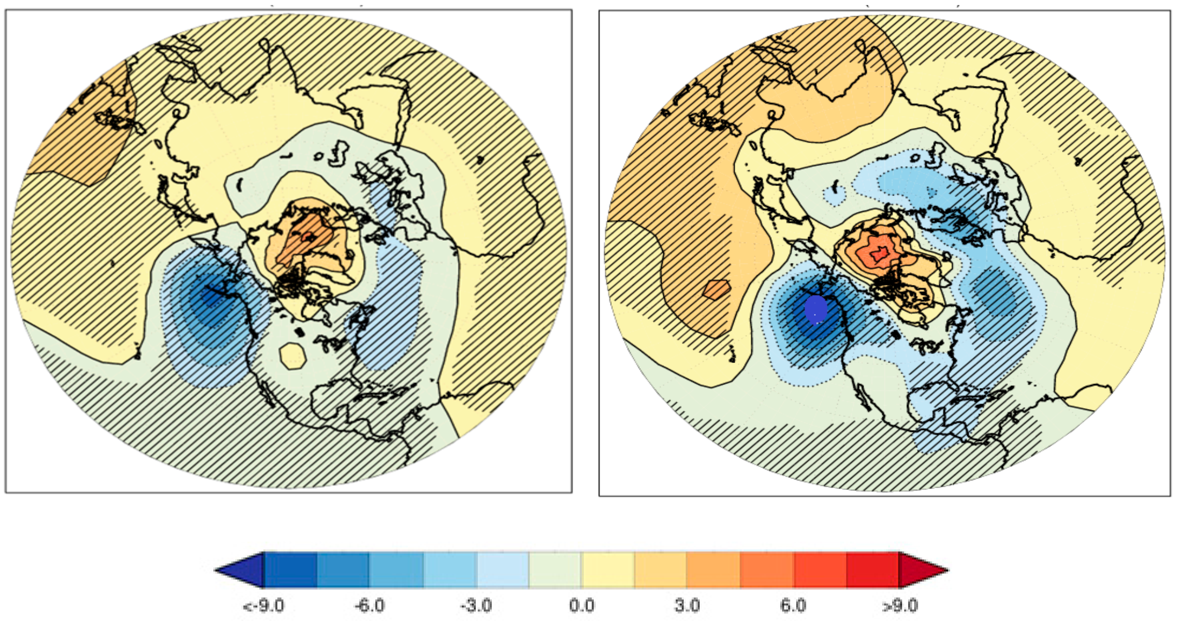
a) Solar



b) ENSO

ENSO(1856-1977) **ENSO(1978-1997)**



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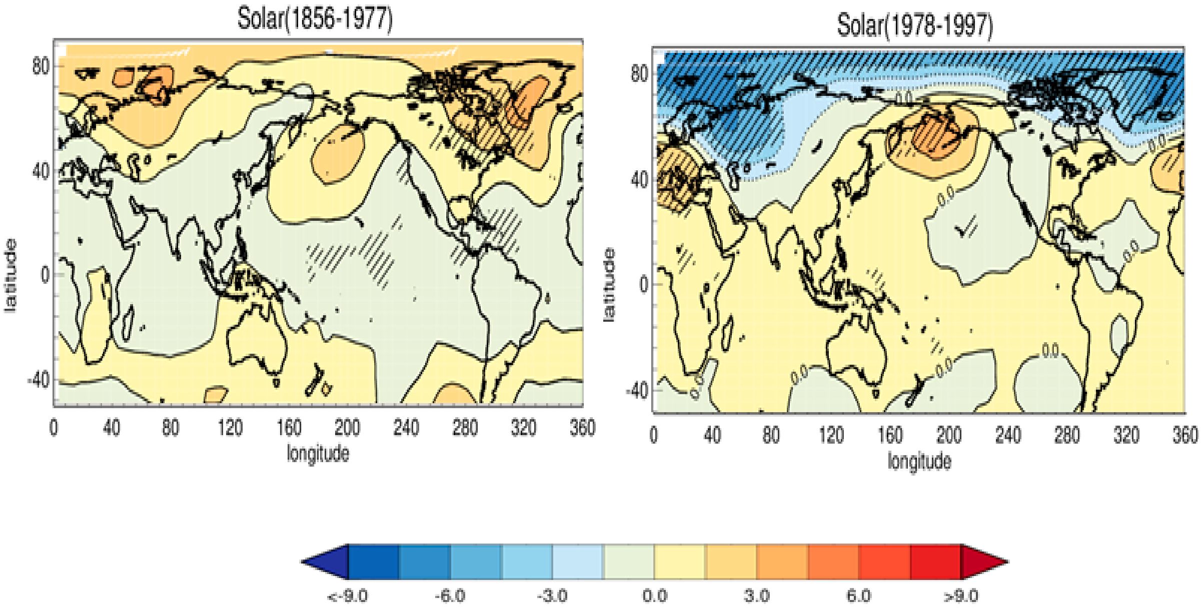
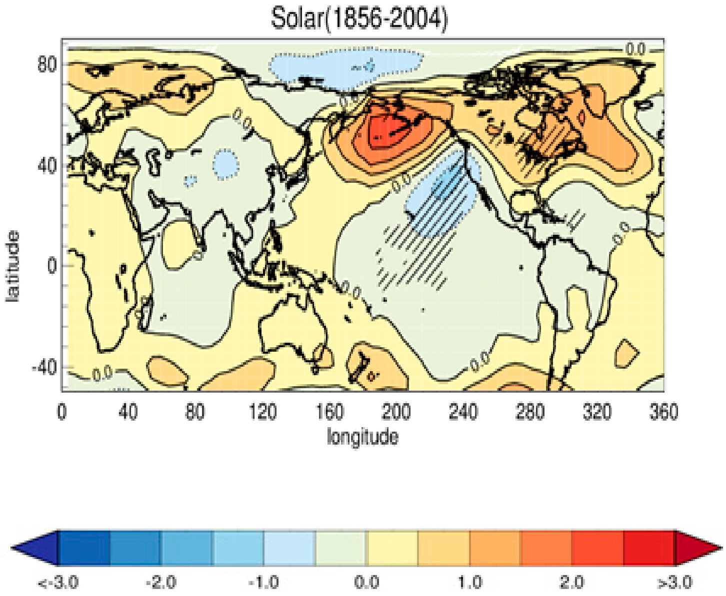
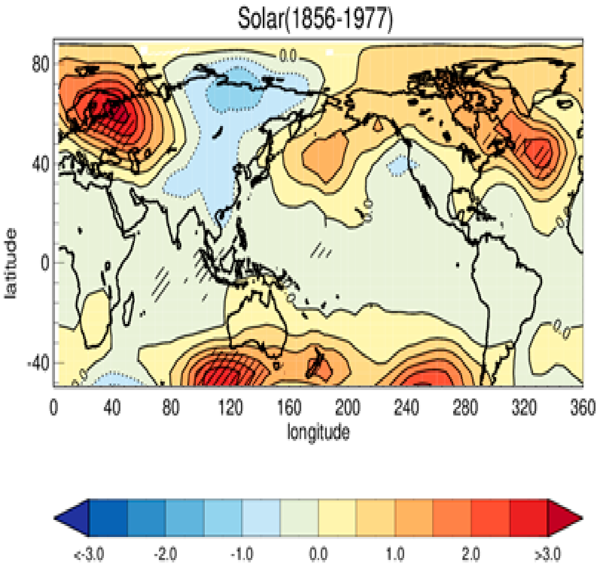
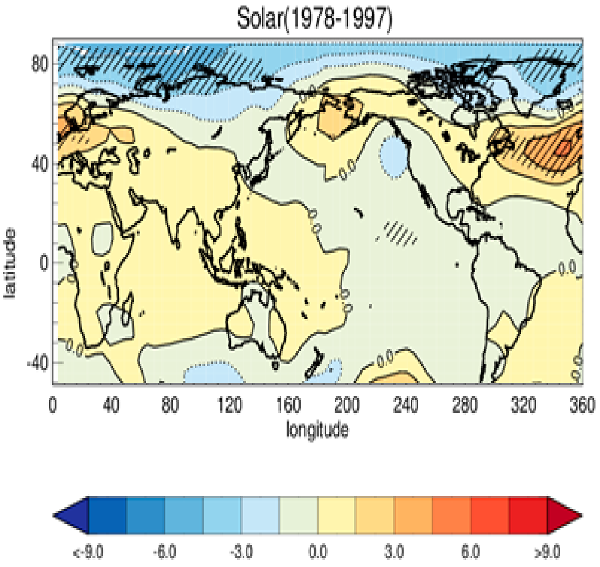
a) Lag1:

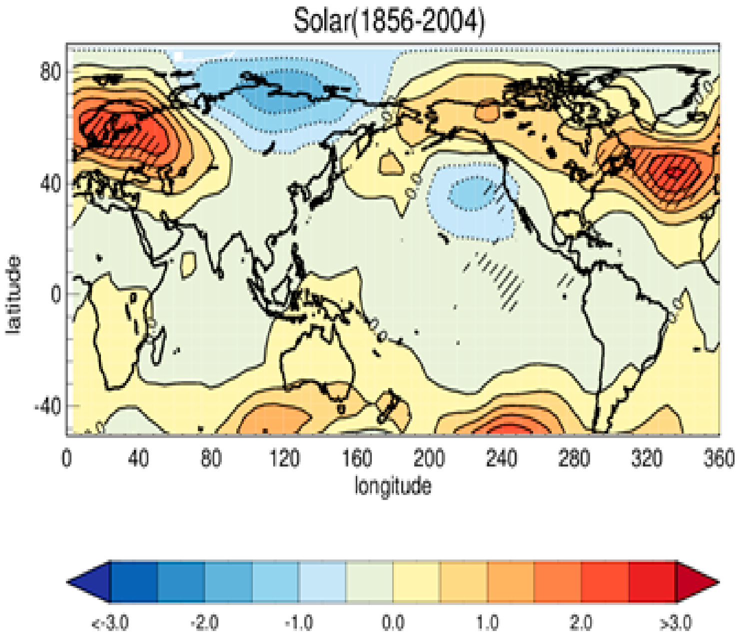

Solar(1856-1977)
Solar(1978-1997)
latitude
longitude
80
40
0
-40
0
40
80
120
160
200
240
280
320
360
0.0
<-9.0
-6.0
-3.0
0.0
3.0
6.0
>9.0


Solar(1856-2004)
latitude
longitude
80
40
0
-40
0
40
80
120
160
200
240
280
320
360
0.0
<-3.0
-2.0
-1.0
0.0
1.0
2.0
>3.0

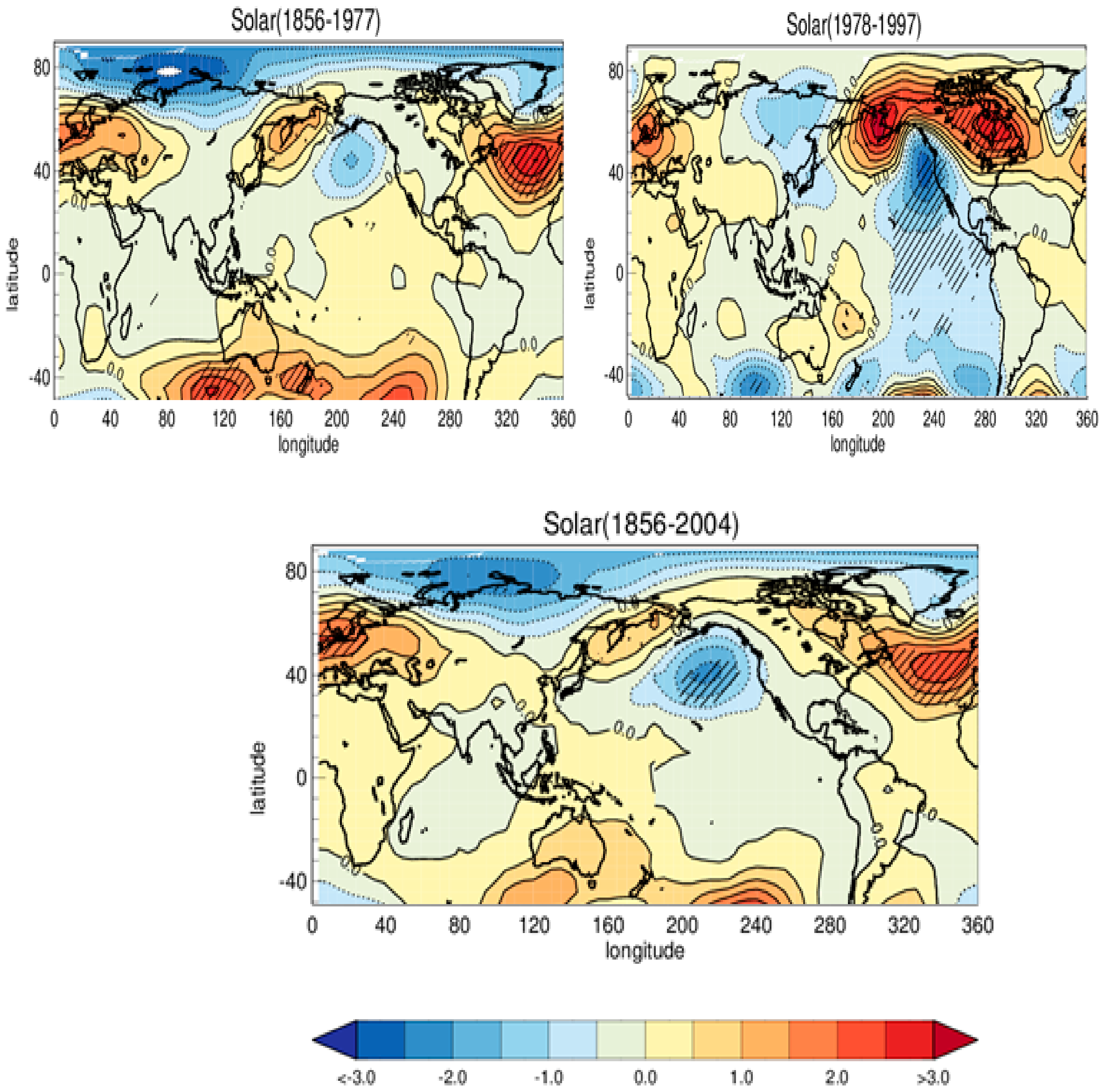
b) Lag 2:


Solar(1856-1977)


Solar(1978-1997)


Solar(1856-2004)

c) Lag 3:



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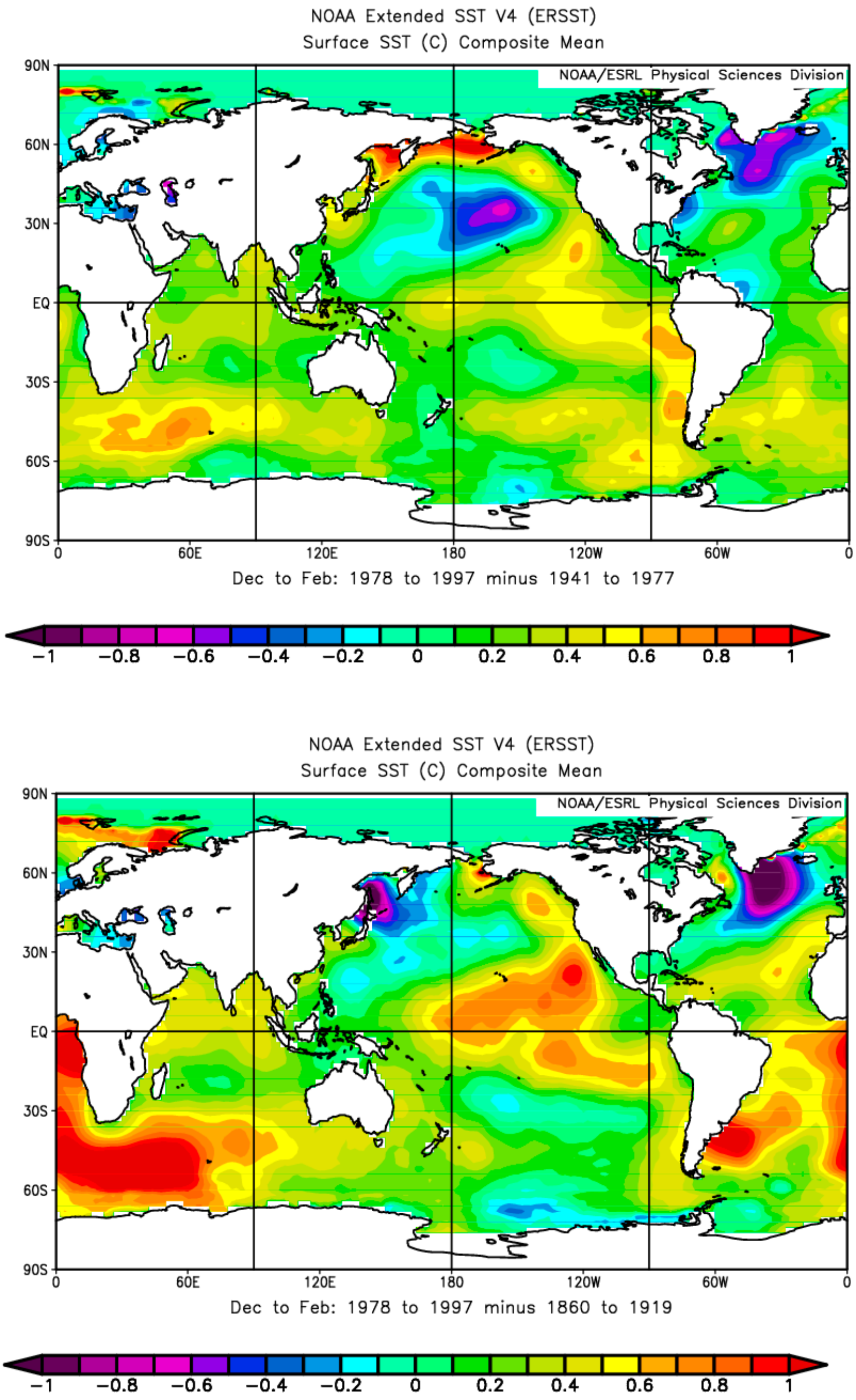

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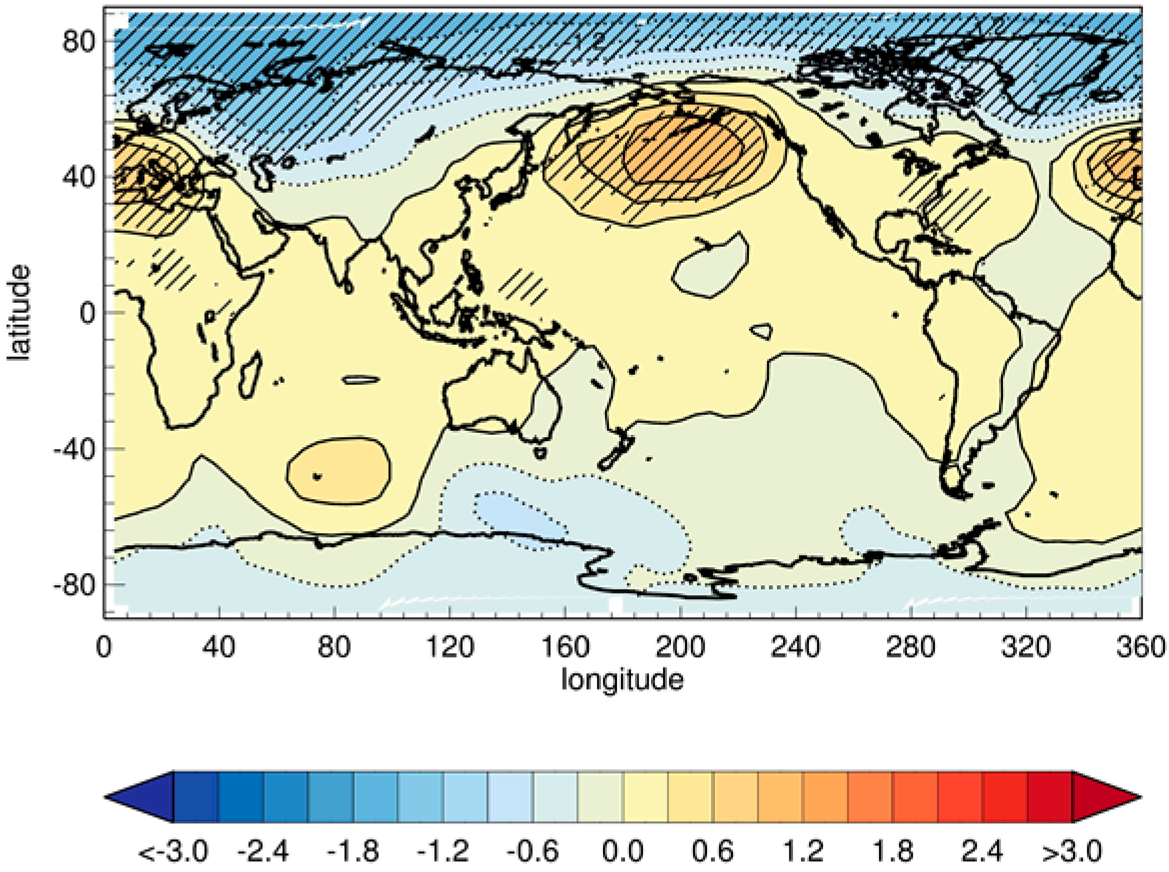

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Supplementary Text.

Mechanism I: Uniform Reduction of large solar radiation in tropical Pacific causes warm ENSO (Clement et al. 1996; McGregor et al. 2011)

Dynamical thermostat hypothesis (**Clement et al. 1996**): For a uniform reduction of incoming surface solar radiation to a large degree, (which could be associated with explosive volcanos or inactive solar years) the response of SST is different on two sides of the tropical Pacific. Due to ocean advection theory, the western Pacific cools faster than the east. It initially reduces the climatological zonal SST gradient, which subsequently influences trade winds in the central Pacific. The resultant positive SST gradient can activate El Nino phase reversing trade winds.

Hypothesis of **McGregor et al. (2011)**: The anomalous westerly in tropical Pacific could be attributed to the rapid response over the maritime continent, in response to uniform reduction of incoming surface solar radiation. It is linked to the land-sea contrast, where the surface cooling around equatorial Pacific and its time-scale for adjustment are leading responsible factor. It is the fast cooling around the maritime continent that contribute to the positive zonal SST gradient.

The role of a dynamical thermostat (Clement et al. 1996) and the proposition of McGregor et al. (2011) both can act together to reinforce the mechanism. It can explain volcano and ENSO connection and also applicable for sun (uniform reduction/increase of incoming surface solar radiation) ENSO association.

Mechanism II: Unusual warming in tropical Pacific favours positive NAO (Bjerknes,1966)

Proposition of **Bjerknes (1966)**: the anomalously great heat of warm equatorial ocean enters into the rising branch of the Hadley circulation and strengthens the cell. It generates above normal flux of angular momentum to the westerly winds around mid-latitude. Thus warming in tropical Pacific can strengthen mid-latitude westerly jets during boreal winter and subsequently can favour a positive phase of NAO. Such response is strongest in the winter hemisphere due to greater baroclinicity.