INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **34**: 655–677 (2014)
Published online 10 August 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3713

RMetS
Royal Meteorological Society

The role of the Sun in atmosphere–ocean coupling

Indrani Roy*†

Department of Physics, Blackett Laboratory, Imperial College London, UK

ABSTRACT: An overview of the processes involved in determining the Sun's influence on climate is presented in the form of a flow chart. Evidence and hypotheses concerning the combined influences of the El Niño-Southern Oscillation, the Quasi-Biennial Oscillation and the Solar Cycle on the Hadley and Walker circulations are discussed in the context of atmosphere–ocean coupling, focussing on the Pacific region. It is shown that the Sun plays a crucial role in ocean–atmosphere coupling but that this coupling appears to be disturbed during the latter half of the 20th century, probably related to climate change. The identification of a solar influence can lead to improved skill in prediction so as to better inform communities to address/mitigate some of the crucial issues that are associated with climate change.

KEY WORDS sun; ENSO; atmosphere–ocean coupling; QBO

Received 26 April 2011; Revised 5 March 2013; Accepted 30 March 2013

1. Introduction

A decadal scale solar signal was detected in the troposphere (Haigh, 1996, 1999, 2003; Lean and Rind, 2001, 2008; Rind, 2002; Lean *et al.*, 2005; van Loon and Labitzke, 1998; van Loon and Shea, 2000; Frame and Gray, 2010) and in the ocean (White *et al.*, 1997, 2003a, 2003b; Weng, 2005), specifically in the Indo-Pacific region (van Loon *et al.*, 2004, 2007, 2008). Meehl *et al.* (2008, 2009) posed the question of whether the effect of solar variability in the troposphere is '*bottom-up*', i.e. forced by solar heating of the surface or '*top-down*', i.e. primarily driven from the stratosphere. Different mechanisms were proposed to support both the views and are briefly described below with some potential routes for amplification.

On the basis of a modelling study, Meehl *et al.* (2003) proposed a mechanism related to air-sea-radiative coupling at the surface in the tropics, whereby the spatial asymmetries of solar forcing, induced by cloud distributions, result in greater evaporation in the subtropics and consequent moisture transport into the tropical convergence zones, thus producing higher precipitation through dynamically coupled ocean–atmosphere interaction.

Using the method of solar max compositing of nearly 150 years of data, Meehl *et al.* in multiple papers (2007, 2008, 2009) have shown that for an increase in solar forcing, there is a cold event like pattern in the Pacific during December-January-February (DJF). van Loon and Meehl (2008) also observed that, although the cold event-like pattern strongest during DJF, it is also apparent in June-July-August (JJA). Results from two different global-coupled models [Parallel Climate Model (PCM) and Community Climate System Model, version3 (CCSM3)], shown by Meehl *et al.* (2008), using multiple ensemble members from 20th century simulations, showed a similar pattern to the shorter observational record, and Meehl *et al.* (2008, 2009) suggested mechanisms. They also discussed a peak in irradiance at the peak of the decadal solar oscillation (DSO) producing the La-Niña-like response and this is lagged after a year or two by an El-Niño-like event.

According to the 'top-down' mechanism, direct variations in irradiance and indirect variations in stratospheric ozone in response to solar ultraviolet (UV) variability, change the vertical and horizontal temperature structure, resulting in dynamical responses in the stratosphere and troposphere (Haigh, 1996; Balachandran *et al.*, 1999; Shindell *et al.*, 1999). Such changes in the thermal gradients and thus in the wind systems, lead to changes in the vertical propagation of the planetary waves that drive the global circulation. Moreover, the relatively weak, direct radiative forcing of the solar cycle in the upper stratosphere can possibly lead to a large indirect dynamical response in the lower atmosphere through a modulation of the polar night jet, as well as through a change in the Brewer Dobson Circulation (BDC) (Kodera and Kuroda, 2002; Matthes *et al.*, 2004).

Kodera and Kuroda (2002) proposed a possible mechanism whereby the solar influence in the equatorial troposphere can originate from the equatorial stratosphere through changes in the meridional circulation. According to them, the solar heating anomalies that change the strength of polar stratospheric jet can influence the path of upward propagating planetary waves. These waves,

* Correspondence to: I. Roy, College of Engineering, Mathematics and Physical Sciences, Harrison Building, Streatham Campus, University of Exeter, North Park Road, Exeter EX4 4QF, UK. E-mail: i.roy@exeter.ac.uk

†Current address: University of Exeter, College of Engineering, Mathematics and Physical Sciences, Exeter EX4 4QF, UK.

© 2013 Royal Meteorological Society

depositing their zonal momentum on the poleward side of the jet, weaken the BDC and warm the tropical lower stratosphere in solar maximum years. Gray *et al.* (2006) have shown that perturbations to the equatorial upper stratosphere can perturb the polar lower stratosphere and thus provide a route for Quasi-Biennial Oscillation (QBO)-solar modulation of the tropical middle atmosphere to influence the lower stratosphere via a so-called 'polar route' during winter.

Haigh *et al.* (2005) proposed through simplified global circulation model (GCM), (without ocean) that moist feedbacks as suggested by Meehl *et al.* (2003) are not a crucial component of the observed response in troposphere due to the Sun; it is eddy/mean flow wind feedbacks that are the primary mechanism. Despite the presence of a uniform stratosphere, the lack of a stratospheric polar vortex, and the use of broad latitudinal-scale perturbations, they found it possible to reproduce the tropospheric patterns. Such a study suggests that a detailed representation of the stratosphere is not necessary for understanding the tropospheric aspects of solar influence, although the source of the stratospheric heating remains an important factor. In their simplified atmospheric general circulation model (AGCM) Haigh and Blackburn (2006) showed that imposed changes in the lower stratospheric temperature forcing lead to coherent changes in the latitudinal location and width of the mid-latitude jet stream and its associated storm-track, and that eddy/mean-flow feedbacks are crucial to these changes.

Haigh (1999) presented atmospheric circulation model results for the influence of the 11-year solar cycle on the climate of the lower atmosphere. In her model, solar forcing is represented by changes in both stratospheric ozone concentrations and incident irradiance, where the former has the stronger impact. A pattern of response was found, in which the subtropical jets and mid-latitude Ferrel cells move poleward and the tropical Hadley cells broaden and weaken for high irradiance. Such a pattern, as also seen in the modelling study by Haigh (1996), is very similar to the observational results. The changes in dynamics cause subtropical warming and a characteristic vertical band structure of mid-latitude temperature changes. Despite the presence of a uniform stratosphere, (without the stratospheric polar vortex) and absence of an ocean, the simplified GCM studies of the solar influence, also showed an impact on tropospheric mean meridional circulation, characterizing a weakening and expansion of the tropical Hadley cells, along with a pole ward shift of the Ferrel cells (Haigh, 1996; Haigh *et al.*, 2005), Haigh and Blackburn (2006). Recently, Simpson *et al.* (2009), using a simple model, were also able to capture the tropospheric features and indicate the role of synoptic scale eddies.

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. Studying the variations of semi-permanent pressure systems, the Aleutian Low (AL) and the Pacific High (PH), Christoforou and Hameed (1997) found that solar variability influences the location of these Centre of Actions (COAs), thus causing changes in storm tracks and large anomalies in regional climatic conditions. Apart from shifting the position, the AL also exhibits significant differences in intensity. van Loon *et al.* (2007) (vL07), using the method of solar max compositing also confirmed this observation.

Perturbations in the polar vortex, which appear to be related to the downward propagation via the Northern and Southern Annular Modes (NAM and SAM), were shown by Baldwin and Dunkerton (2001) in observational analysis. They discussed dynamical mechanisms that might communicate stratospheric circulation anomalies downward to the troposphere and surface via polar modes of variability. Thompson and Wallace (2000) also identified such downward propagation of both the polar modes. There are strong similarities between the meridional structures of the annular modes in Northern and Southern Hemisphere (Thompson *et al.*, 2005), despite the sharply contrasting land–sea distributions and stationary wave climatology of the two hemispheres; which supports some robust influence leading from the top. Such a pathway can provide a possible route of amplifying solar variability in the surface from the top.

Baldwin and Dunkerton (2001) mentioned that the pathway for solar influence via the polar modes of variability, appears to involve interactions with the QBO, but the details are not yet understood. Studies indicate that during the Northern Hemisphere (NH) winter, it is necessary to group the meteorological data according to the phase of QBO, in order to find a clear signal of the 11-year solar cycle in the stratosphere. For example, Labitzke and van Loon (1992), using data for the years 1956–1991, show that warm polar temperatures tend to occur during the west phase of the QBO at solar maximum and east phase at solar minimum. Moreover, Haigh and Roscoe (2006), through multiple regression analysis (using NCEP data during the second half of last century), showed no statistically significant solar signal in either the NAM or SAM; but that when a new index, the product of the solar and QBO indices, was used there is a good correlation throughout the atmosphere in the SAM, and at the lower levels in the winter NAM. Thus, they pointed out that solar stratospheric influence on the troposphere may well be through two different routes. The first of these is the influence of low latitude lower stratosphere heating on the Hadley circulation and mid-latitude eddies, which stimulate the NAO; the second is modulation, by a combination of solar and QBO forcing, of the polar stratosphere which influences the annular modes in both the Northern and Southern Hemispheres and provides another potential route for the transfer of a solar stratospheric influence down to the troposphere. Recent reviews by Gray *et al.* (2010) and Lockwood (2012) provide more detailed discussion of studies relating to the 'top-down' influence of the sun.

Dima *et al.* (2005), using different Sea Surface Temperature (SST) datasets and applying different statistical

© 2013 Royal Meteorological Society

techniques, identified two distinct modes of climate variability: one mode is associated with the sunspot cycle and defined by them as 'the solar mode'; whereas the other is linked to atmosphere–ocean interaction and defined as 'the internal mode'. They used the term 'mode' to refer a set of physical processes that are part of a large-scale coherent spatial structure and that have a quasi-periodic time evolution. According to them, the solar mode dominates Sea Level Pressure (SLP) and upper atmospheric levels; whereas, in the oceanic surface temperature, 'the internal mode' explains about three times more variance than that of the solar mode. For the purpose of quantifying the effect of Sun on climate, it is necessary to segregate the contribution resulting from internal climate variability as it may mask the signals of the sun (Rind, 2002). Hence, it is really important to understand more about that internal mode, associated with the oceanic surface temperature, where the El Niño-Southern Oscillation (ENSO), no doubt plays an important role.

Although, apparently, correlation/regression analysis could not establish any direct connection between the 11-year solar cycle and the ENSO, recent works have also detected some solar signature on the ENSO. Defining higher solar (HS) activity or lower solar (LS) activity according to whether the solar index was higher or lower than the long-term mean value (Kodera, 2004, 2005; Kodera *et al.*, 2007). Kodera *et al.* (2007) found that the ENSO-related signal is confined in the Pacific sector during HS years. They also showed that ENSO-related variability extends into the Indian Ocean during period of LS activity, which is not the case during HS activity. They suggested that such changes in intensity result from the shift in the location of the descending branch of the anomalous Walker circulation. This result, that the ENSO influence extends into the Indian Ocean through a modification of the Walker circulation, is quite consistent with a model study using an atmosphere–ocean coupled general circulation model (CGCM) by Behera *et al.* (2006). In continuation of the study of Barnett (1989), who reported that tropospheric biennial oscillation (TBO) is modulated by an 11-year solar cycle, Kodera (2004) suggested that this modulation of the TBO is derived from a difference in the extension of ENSO-related variation into the Indian Ocean. TBO is the tendency for a relatively strong monsoon to be followed by a weaker one and vice versa, for the Asian–Australian monsoon system. (Meehl, 1997; Chang and Li, 2000). Kodera (2002, 2003) found that during solar minimum conditions, the NAO signal is confined to the North Atlantic, while during solar maximum it extends over the NH. Toniazzo and Scaife (2006) also detected some footprint of the NAO in the ENSO. According to them, warm events of the ENSO are associated with negative phase of the NAO and vice versa. More recently, Ineson and Scaife (2009), using a GCM of the atmosphere, showed that there is a clear response of the ENSO in European climate via the stratosphere. This mechanism is restricted to years when Stratospheric Sudden Warming (SSW) occurs, leading to a transition to cold conditions in the northern Europe and mild conditions in the southern Europe in late winter during El Niño years. Thus, all these studies are indicative of a global scale teleconnection pattern involving the ENSO, where the role of sun cannot be ignored.

Gleisner and Thejll (2003), using a regression analysis with F10.7 as a measure of solar activity, found that there is a significant response of the troposphere to the 11-year solar cycle, and that the apparent solar signals are not merely due to chance co-variations with the El Niño or major volcanic eruptions. Their study revealed that solar forcing is strongest in the tropics and at mid-latitudes and the tropical meridional overturning of the atmosphere is somewhat weaker and broader in latitudinal extent during HS years. According to them, solar signals in vertical velocity indicate a spatially heterogeneous modulation of both the Hadley and Walker-type circulation together with a modulation of the Ferrel circulation. Their findings have implications on the issue of how and where the sun exerts its influences in the climate system.

The quasi-decadal oscillation (QDO) of 9- to 13-year period in the Earth's climate system has been found in the tropical Pacific Ocean similar to that governing the ENSO of 3- to 5-year period. This global SST and SLP patterns of variability of this QDO, and associated tropical warming, have been found fluctuating in phase with the approximately 11-year period signal in the sun's total irradiance during the 20th century (White *et al.*, 1997, 1998; Allan, 2000; White and Tourre, 2003a). White *et al.* (2003a) found that the tropical global-average temperature of the upper ocean (0.1 °C) is not driven by the approximately 11-year period signal in surface solar radiative forcing, but rather indirectly (via variable sensible-plus-latent heat flux) by a greater warming of the tropical troposphere temperature (0.2–0.5 °C) in response to the approximately 11-year period signal in the Sun's UV radiative forcing of the lower stratosphere temperature (1.0 °C) via absorption by ozone. The recent study of White and Liu (2008) using the method of compositing and Singular Value Decomposition (SVD) of nine solar cycles, covering period 1900–2000, even detected the phase-locking of harmonics of the ENSO time series with the solar cycle resulting in a warm event-like signal for about 3 years around the peak of the DSO with cold events approximately 2 years either side of the peak, and stronger warm events peaking 3–4 years before and after it.

All these previous studies demonstrate that the extent to which the effect of solar variability in the troposphere is primarily driven from the stratosphere or forced by solar heating of the surface is a subject of major importance. As outlined by Brönnimann *et al.* (2006), stratosphere–troposphere coupling may be a two way interaction and the possible downward propagation is normally preceded by an upward coupling and these two mechanisms may have different impacts on the tropical circulation. A number of works have been devoted in the past few years to understand these coupling mechanisms,

© 2013 Royal Meteorological Society

but they have tended to raise more questions than they answer.

Meehl *et al.* (2009) investigated two mechanisms, the top-down stratospheric response and the bottom-up coupled ocean–atmosphere surface response, in versions of three global climate models [CCSM3, Whole Atmosphere Community Climate Model (WACCM)-fixed-SST, WACCM-coupled], with mechanisms acting together or alone and compared results with their observations. The CCSM3 only includes the bottom-up coupled air–sea mechanism with coupled components of atmosphere, ocean, land and sea ice but without a resolved stratosphere or interactive ozone chemistry. While, a version of the WACCM, only includes the top-down mechanism. Here, solar variability is changed and the model is run with climatological SSTs keeping other external forcing constant. It has resolved a stratosphere with fully interactive ozone chemistry, but no dynamically coupled air–sea interaction. Neither these two models, on their own were able to reproduce the observed pattern of temperature on the decadal solar cycle time scale. However, when a new hybrid model was developed, using dynamical ocean, land and ice modules from CCSM3 coupled with atmospheric component from WACCM, it produced a much closer result to the observations in the Pacific. According to them, each mechanism acting alone can produce a weaker signature, but when the two mechanisms, act together it produces a response in the tropical Pacific that agrees closely to their observations. It indicates that the combination of mechanisms is much more appropriate than the sum of their individual effects.

The modelling experiments of Rind *et al.* (2008) suggest that both the proposed mechanisms for solar influence on the troposphere, i.e. forcing from above (stratospherically driven) and from below (with an SST influence) are operative; although the tropospheric and stratospheric dynamic responses are likely to be affected by the atmospheric background state. According to them, the use of a coupled atmosphere–ocean model, capable of realistically simulating ENSO phenomena is necessary to assess the solar impact on the tropical Pacific circulation.

Here, I will discuss how the Sun, ENSO and QBO all play important roles in regulating the climate of the troposphere. I seek to thread a chain of causalities, involved in the coupled atmosphere–ocean system (mainly involving the Pacific ocean) based on evidences and hypotheses, in a holistic context. I will show how the Sun plays a crucial role in ocean–atmosphere coupling, but that this coupling appears to be disturbed during the latter half of the 20th century.

2. Methodology and data

Here, data analysis is largely carried out through the technique of multiple regression. The main advantage of this technique is that it can separate other factors that might influence/contaminate the results of solar signal. In the regression, the multiple regression code of Myles Allen (University of Oxford, UK, personal communication) has been utilized.

Multiple linear regression may be represented as:

$$\mathbf{y} = \beta\mathbf{X} + \mathbf{u} \tag{1}$$

where, '**y**' is a vector of rank n containing the time series of the data. '**X**' is a matrix of order $n \times m$, comprising time series of m indices, which are thought to influence the data. 'β' is a vector of rank m that contains amplitudes of the indices, that we intend to estimate. '**u**' is the noise term which is unobserved and may arise due to various sources (e g. internal noise, all sources of observational error, un-modelled variability, etc.). Autocorrelation in the time series, and its effects on the derived regression coefficients and significance levels, are estimated using an autoregressive noise model order one [AR(1)]. Using a noise model of higher order does not significantly affect the results. Finally, using the Student's t-test the level of confidence in the value of β derived for each index is estimated.

In this methodology, noise coefficients are calculated simultaneously with the components of variability so that the residual is consistent with a red noise model of order one. To elaborate, first the autocorrelation and variance of the noise are estimated from the residual (**y**-b**X**, where 'b' is an estimate of 'β'); then a red noise function assumed to be of order one is fitted to the residual; afterwards, the values of 'b' and noise parameters are iterated until the noise model fits within a pre-specified threshold. By this process, it is possible to minimize noise being interpreted as a signal. It also produces, using Student's t-test, measures of the confidence intervals of the resultant 'b' values taking into account any covariance between the indices.

Multiple regression analysis of SLP and SST data is performed. For SLP, I used the HadSLP2 dataset from http://www.metoffice.gov.uk/hadobs/hadslp2. This is an upgraded version of the Hadley Centre's monthly historical mean sea level pressure (MSLP) dataset which is based on a compilation of numerous terrestrial and marine data and has been described in detail by Allan and Ansell (2006). It covers the whole of the globe and the available time period is from 1850 to 2004. Unlike HadSLP1, error estimates are available with HadSLP2 to advise the user about regions of low confidence.

In the regression analysis for SST, I used two different sets of data, one is from the Hadley Centre and the other is from National Oceanic and Atmospheric Administration (NOAA). The Hadley Centre Sea Surface Temperature 2 (HadSST2), obtained from http://hadobs.metoffice.com/hadsst2/, is a new SST dataset, based on the data contained within the recently created International Comprehensive Ocean Atmosphere Data Set (ICOADS) and has been described in detail by Rayner *et al.* (2006). The available time period is from 1850 to 2005.

The NOAA data are from the extended reconstructed SST dataset ERSST.v2 which is an improved extended reconstruction. Compared to version 1, the new reconstruction better resolves variations in weak-variance

© 2013 Royal Meteorological Society

regions. It also uses sea-ice concentrations to improve the high-latitude SST analysis, a modified historical bias correction for the 1939–1941 period, and it includes an improved error estimate. This is available from http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html with more details on http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.html. The available time period is from 1854 to 2007.

The independent parameters used in the regression are a linear trend, optical depth (OD), solar cycle variability, ENSO and sometimes QBO.

The linear trend is used to represent long-term climate change. The focus of our work is on 11-year cycle variability and the choice of long-term trend has little effect on the derived signal.

Monthly SunSpot Number (SSN) is mainly used to represent solar cycle variability, as available from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/MONTHLY.

Apart from SSN, two other Total Solar Irradiance (TSI) datasets are used. The Solanki and Krivova dataset is mainly based on facular brightening and relative SSN (Solanki *et al.*, 2003). Foster's TSI is mainly based on observation on sunspots (Foster, 2004).

Volcanic aerosols have been important in global climate forcing over the past century. Here stratospheric aerosol OD has been used as one of the independent indices in this analysis. The data used, based on the method described by Sato *et al.* (1993), are available from http://data.giss.nasa.gov/modelforce/strataer/tau_line.txt. up to 1999, extended to 2005 with near zero values.

For ENSO, we used the Niño 3.4 index, obtained from http://climexp.knmi.nl, defined as the 3-month running mean of SST departures in the Niño 3.4 region (5°N-5°S, 120-170°W), relative to the 1971–2000 base period.

QBO data, between 3 hPa and 90 hPa, are available from http://www.pa.op.dlr.de/CCMVal/Forcings/qbo_data_ccmval/u_profile_195301-00412.html for the period 1953 onward. Recent reconstructions of the QBO by Brönnimann extending back to 1900 are also available now (Brönnimann *et al.*, 2007).

3. Formulation of flow chart

Here, I develop a flow chart, depicting a consolidated overview of atmosphere–ocean coupling, supported by observations and mechanisms. Results from

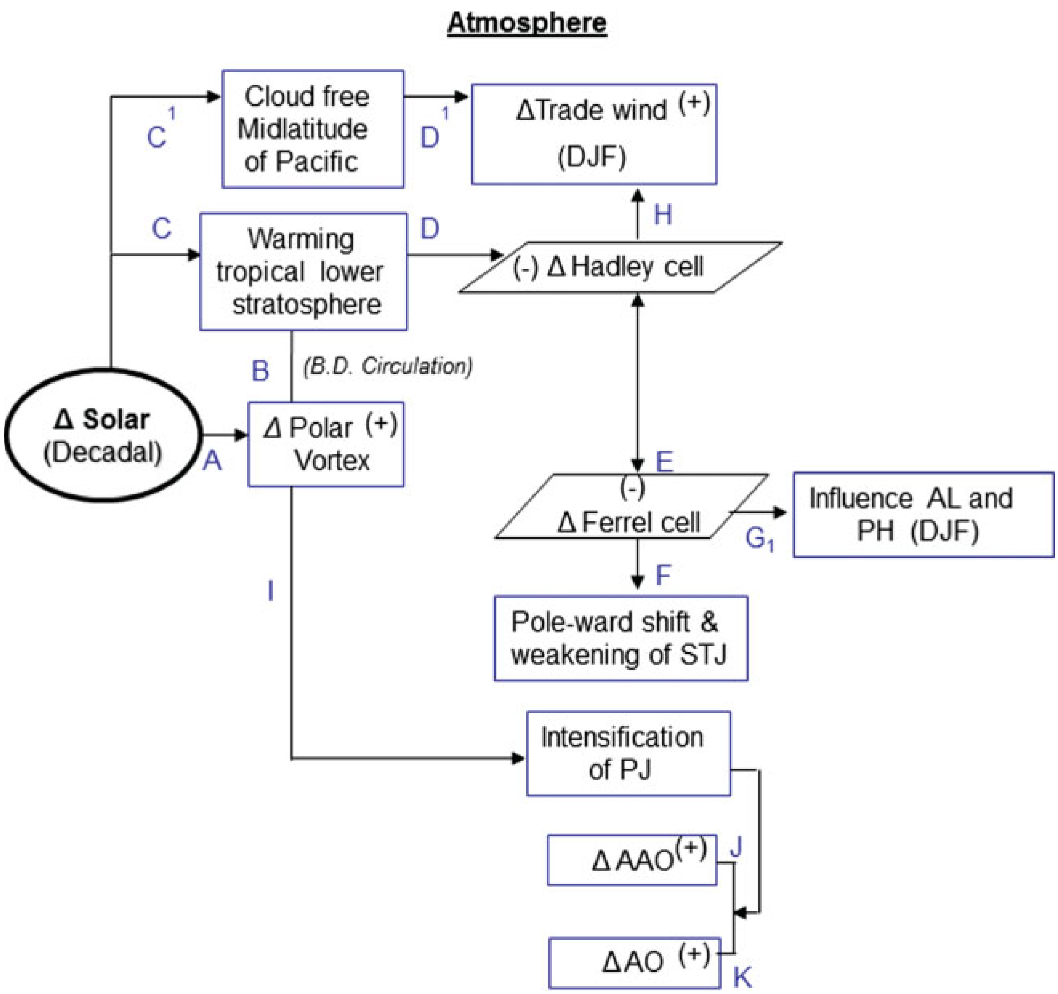

Figure 1. Flow chart showing solar signal in the atmosphere.

© 2013 Royal Meteorological Society

the regression study have been incorporated in formulating this flowchart. The three major climate variabilities; viz. solar, QBO and ENSO are shown with oval outlines; whereas, the major circulations, responsible for modulating the effect of major variabilities are shown by non-rectangular parallelograms. The pathways of the signals are marked by labels starting from 'A', initiated by solar variability and the direction of change in behaviour during the steps are shown by '+' (for increase) or '−' (for decrease). Subscripts in a label are introduced to indicate steps in a process.

3.1. Atmosphere only: Sun via lower stratosphere, cloud free mid-latitude and polar vortex (A–K)

How the solar signal is transmitted to the troposphere via the stratosphere and mid-latitude of Pacific is covered by 'A–K' in Figure 1 and shown with the heading '**atmosphere**'. Here, two pathways are indicated: one via the **lower stratosphere** (equatorial region) to the troposphere through circulation alongside cloud free **mid-latitude** of Pacific (A–H); the other, from the **stratospheric polar vortex** to the troposphere via polar modes (A, I–K). In the first pathway, superscripts are introduced to represent solar radiative forcing (C^1 and D^1) through the cloud-free region of mid-latitude of Pacific that act alongside solar dynamical forcing shown by C and D. Both the forcings have potential to influence the trade wind around Pacific.

Enhanced solar activity is liable to increase the strength of the polar vortex, which is designated by 'A'. The hypothesis that solar cycle/ozone interactions create temperature and wind anomalies in the upper stratosphere near 1 hPa (around 50 km), which is subsequently responsible for developing/modulating the polar stratospheric jet, has been evidenced in observations and also explained by modelling studies. A stronger stratospheric polar jet is associated with a stronger and colder polar vortex. Since HS years generate a stronger stratospheric jet, it can be said that the solar influence around stratospheric polar vortex, which is marked by 'A', is well explained by mechanisms with observational evidence.

Atmosphere only: sun via Lower stratosphere and mid-latitude of Pacific (A–H)

How the perturbation in the polar vortex is communicated to the tropical lower stratospheric region is marked by 'B'. Kodera and Kuroda (2002) proposed a mechanism (described in Section 1), whereby solar heating around the polar stratosphere may influence the atmosphere below. 'B' in the flow chart is explained via this mechanism. Moreover, the observational results of Frame and Gray (2010) and Haigh (2003) also suggest that the tropical lower stratosphere is warmer during solar maximum than from minimum and provide observational evidence for 'B'.

Warming (a small proportion of observed amplitudes) in the tropical lower stratosphere can also be due to UV absorption by ozone in the lower stratosphere, during solar max – which is shown by 'C'. Haigh (1996) using an AGCM with fixed SSTs (without ocean) first showed that despite the presence of a uniform stratosphere, the lack of the stratospheric polar vortex and use of broad latitudinal-scale perturbations, the model was able to reproduce the tropospheric patterns but with lower amplitude. Thus, 'C' gives some indication of the mechanism but cannot be the whole picture.

In the flow chart (Figure 1), 'D' indicates that warming in the equatorial lower stratospheric region can be responsible for a weakening and expansion of the Hadley cell (shown with '−'); a weakening of the Ferrel cell (shown by 'E' with '−') and a shift in the sub tropical jet (STJ) pole-ward, alongside weakening it (shown by 'F'). Results from both modelling and observational studies, confirm the proposed pathways.

The work of Haigh (1999, 1996), Haigh *et al.* (2005), Haigh and Blackburn (2006), Simpson *et al.* (2009), as described in Section 1, are all consistent with 'C–F'. Thus, all these studies not only agree with 'C', but also offer mechanisms to explain 'D–F'.

'D–F' are also evidenced in a number of observational studies. Haigh *et al.* (2005), using multiple regression analysis of NCEP Reanalysis data for zonal mean zonal wind, showed when the Sun is more active, the STJs are weaker and positioned further pole-wards. Brönnimann *et al.* (2006), using upper air data, also observed pole-ward shift of the STJ and Ferrel cell with increasing solar irradiance.

The weakening and shifting of the Ferrel cell is associated with subsequent changes in the AL and PH around the Pacific and is marked by 'G_1'. Supporting previous results of Christoforou and Hameed (1997), vL07 as described in Section 1, multiple regression studies also identify changes in intensity around the AL due to 11-year solar cyclic variability (Figure 2, also shown in Roy and Haigh (2010) as Figure 1.3). Such a solar

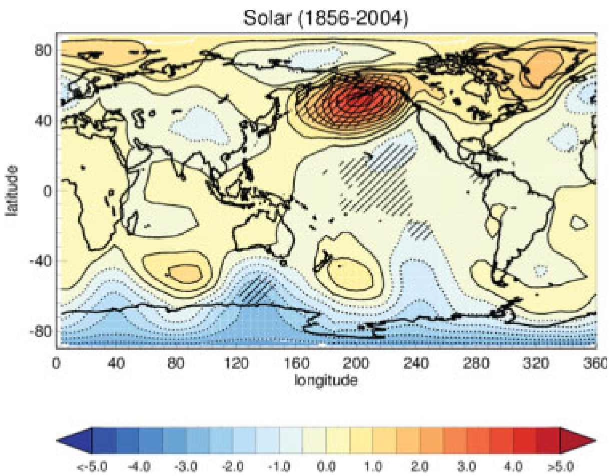

Figure 2. Amplitudes of the components of variability of SLP due to solar (using monthly SSN) during DJF (in hPa). Other independent parameters used are: trend, OD and ENSO. Dashed lines indicate negative values; hatching indicates areas assessed statistically significant at the 5% level.

© 2013 Royal Meteorological Society

influence is observed even during the two different time periods: period comprising 1850–1957 and 1958–1997 (Figure 3(a) and (b), also shown in Roy and Haigh (2012) as Figure 4(a) and (b)). Movements of the COA in the Pacific is also in agreement with the observational analysis of Haigh *et al.* (2005) and Brönnimann *et al.* (2006), in terms of poleward displacement of the Ferrel cell, Hadley cell and subtropical jet around the NH in Pacific. Although 'G_1' is found in observational results, whether weakening and shifting of the Ferrel cell is associated with subsequent changes in the AL and PH around Pacific, during DJF (and vice versa, shown with open arrow) needs investigation. Hence 'G_1' may be considered as a hypothesized mechanism.

During DJF, HS years are associated with intensification of Inter-tropical Convergence Zone (ITCZ) around the eastern Pacific – which is designated by 'H'. This study, using multiple regression analysis, suggests that during DJF, the solar signal (using monthly SSN), is significant around the ITCZ of the eastern Pacific (Figures 2 and 3(a)). During HS years, the ITCZ intensifies and thus enhances trade winds in the central and eastern Pacific region. Such 11-year solar cyclic variability around the ITCZ of the eastern Pacific has also been seen using the TSI reconstruction from Krivova and Solanki, and Foster (Figure 4). Moreover, Meehl *et al.*, in a succession of papers (2007, 2008, 2009), based on modelling and observational analyses, also showed that solar peak years are associated with the intensification of ITCZ around Pacific, during DJF. They proposed a mechanism ('bottom up') related to air–sea-radiative coupling at the surface in the tropics of Pacific, whereby the spatial asymmetries of solar forcing, induced by cloud distributions, result in greater evaporation in the subtropics and consequent moisture transport into the tropical convergence zones. It thus intensifies the trade wind around Pacific and shown here by pathways C^1 and D^1. The modelling study of Balachandran *et al.* (1999) also supports intensification of ITCZ during solar max years. Thus, 'H' is not only evidenced in observations but also explained by a mechanism. Whether it is associated with weakening and pole-ward positioning of the Hadley cell, as shown in the flow chart (Figure 1) using 'top-down' mechanism needs to be tested and hence may also be considered as a hypothesized mechanism. Thus, the evidence for each link may be summarized:

B: Kodera and Kuroda (2002), Haigh (2003), Frame and Gray (2010)
C: Haigh (1996)
D: Haigh and co-workers (Haigh (1996, 1999), Haigh *et al.* (2005, 2006), Simpson *et al.* (2009))

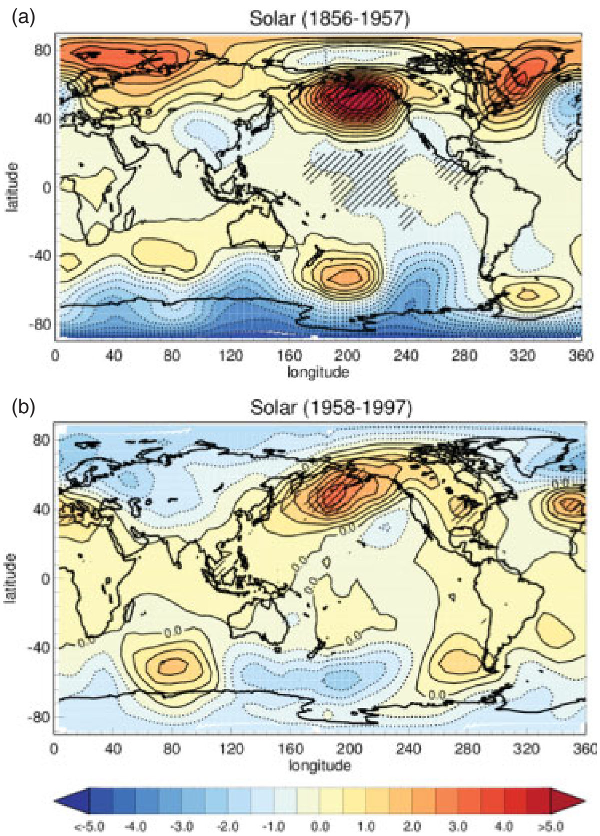

Figure 3. (a–b): Amplitudes of the component of variability of SLP in hPa due to solar (using monthly SSN) during DJF for period: (a) 1856–1957; (b) 1958–1997. Other independent parameters used are trend, OD and ENSO.

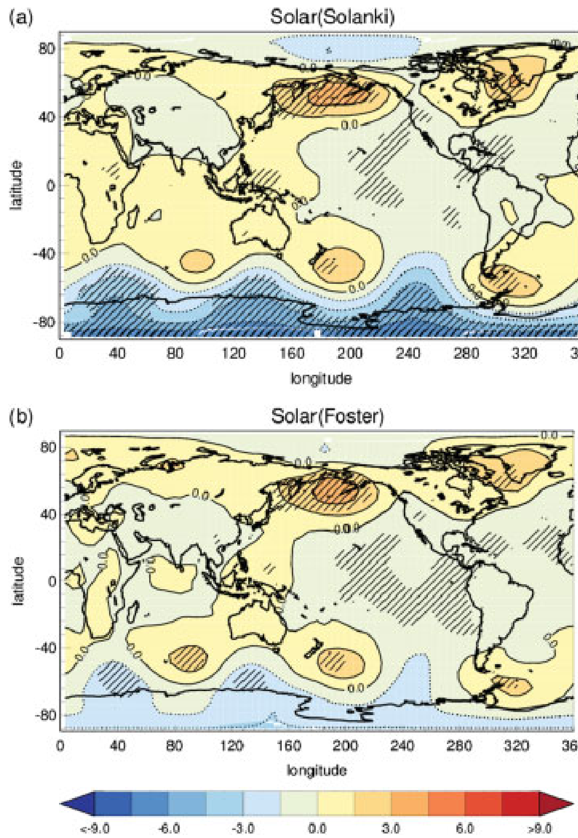

Figure 4. (a–b): Amplitudes of the component of variability of SLP during DJF, due to solar (using different solar indices: (a) Solanki and (b) Foster). Other independent parameters used are the linear trend, OD and ENSO.

C¹, D¹: Meehl *et al.* (2008, 2009)
E: Haigh and co-workers (Haigh (1996, 2003), Haigh *et al.* (2005, 2006), Simpson *et al.* (2009)), Brönnimann *et al.* (2006)
F: Haigh and co-workers (Haigh *et al.* (2005, 2006), Simpson *et al.* (2009)), Brönnimann *et al.* (2006)
G_1: Christoforou and Hameed (1997), vL07, Figure 2, Figure 4, 3(a) and (b) (also in Roy and Haigh (2012)).
H: Figure 2 (also in Roy and Haigh (2010)), Figures 3(a) and 4, Meehl *et al.* (2008, 2009), vL07, Balachandran *et al.*(1999).

Atmosphere only: sun via upper stratosphere (through Polar modes): (**A, I–K**)

'A' being described earlier, the discussion here is from label 'I' onward.

'I' indicates that strengthening of the polar vortex is related to an intensification of the upper tropospheric polar jet. Following the observational evidence of Baldwin and Dunkerton (2001) and Thompson and Wallace (2000), intensification of stratospheric polar vortex is very likely to be associated with the intensification of upper tropospheric polar jet. This has been described in Section 1 and hence it can be said that 'I' is evidenced in observations.

Intensification of the upper tropospheric polar jet is also allied with the positive phase of surface SAM [or Antarctic Oscillation (AAO)] and surface NAM [or Arctic Oscillation (AO)], shown by 'J' and 'K', respectively and discussed here briefly. There are strong similarities between the meridional structures of the annular mode in the NH and Southern Hemisphere (SH) and they follow similar mechanisms of formation (Thompson,

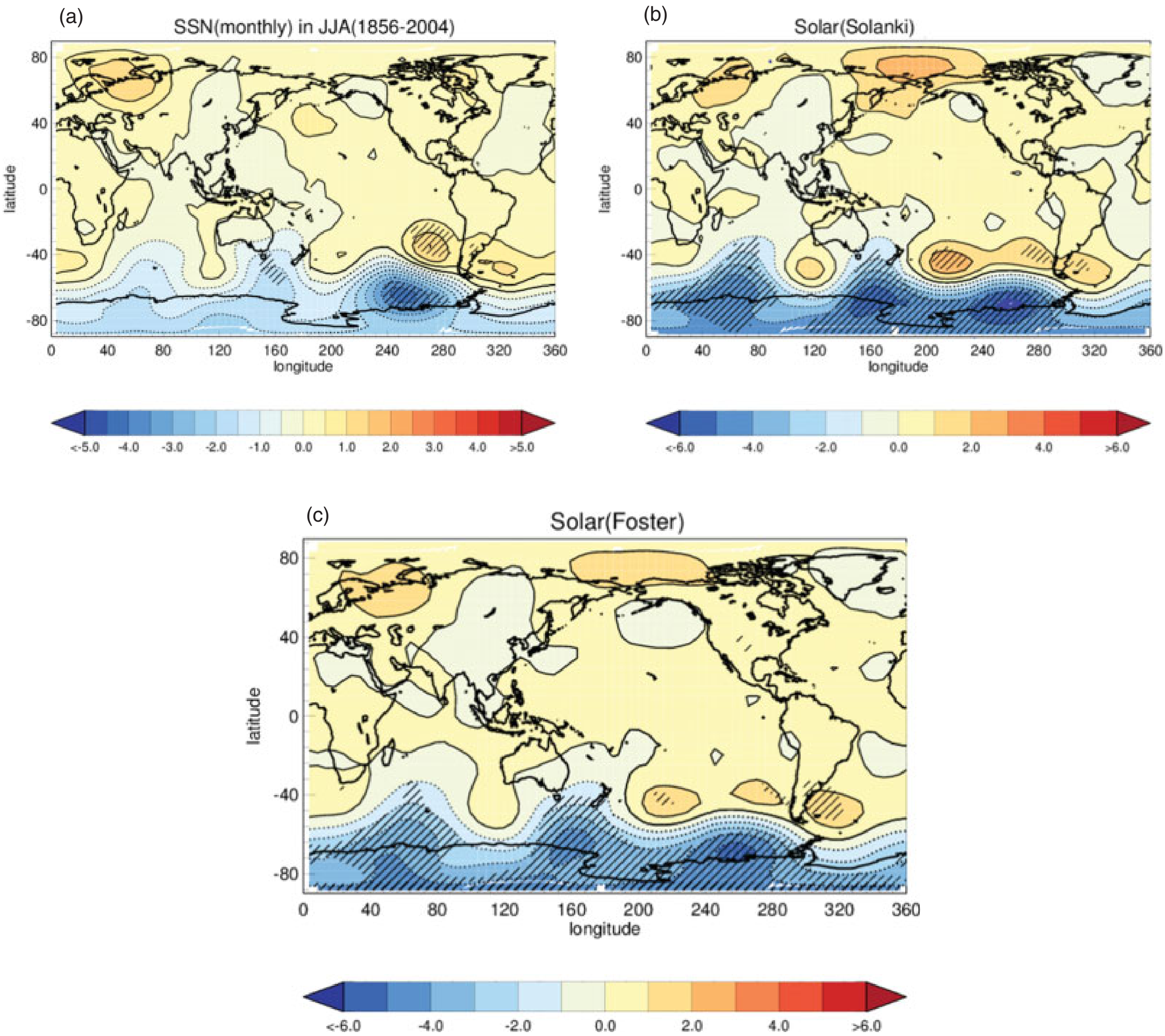

Figure 5. (a–c): Amplitudes of the components of variability of SLP during JJA, due to solar (using different solar indices: (a) SSN, (b) Solanki and (c) Foster). Other independent parameters used here are the linear trend and OD. (The inclusion of ENSO as an independent parameter in the regression does not affect these results).

© 2013 Royal Meteorological Society

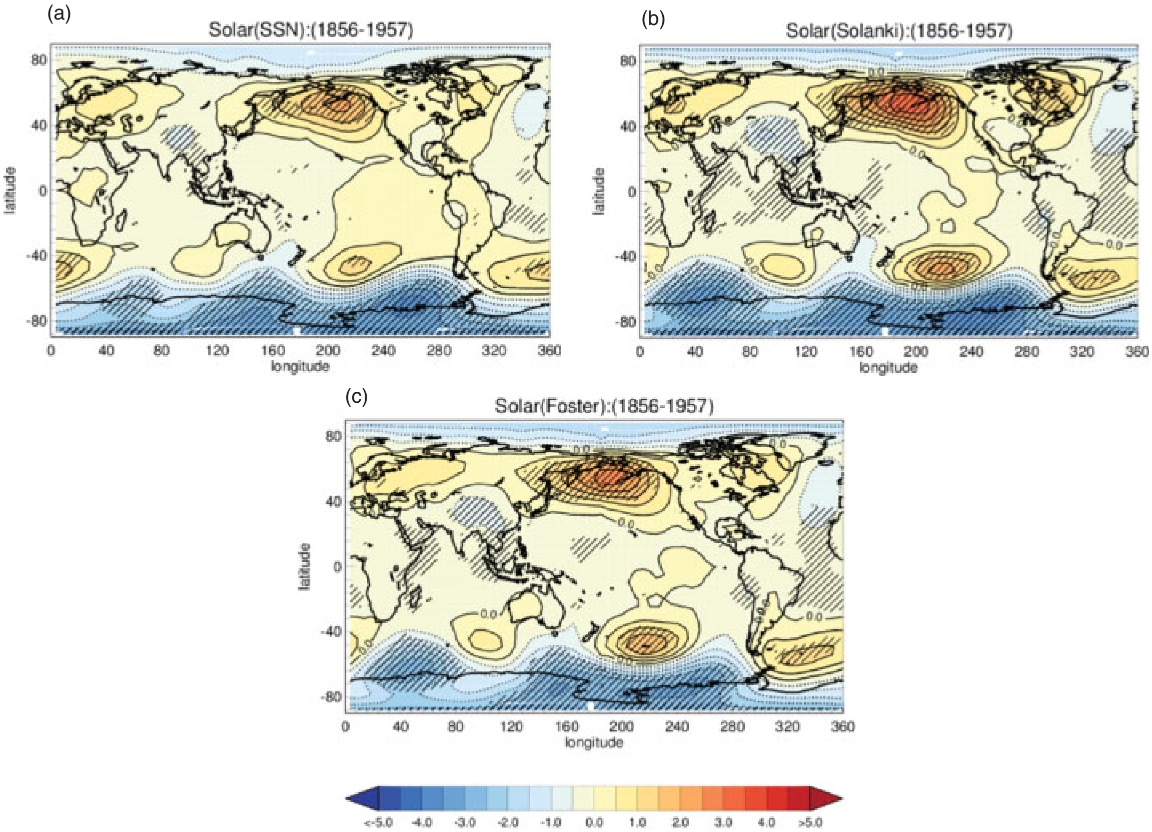

Figure 6. (a–c): Amplitudes of the component of variability of SLP due to solar (SSN (a), using TSI of Solanki (b) and that of Foster (c)) for period 1856–1957; using all months of year, represented by monthly average values, with annual cycle removed. Other independent parameters used are the linear trend and OD. (The inclusion of ENSO as an independent parameter in the regression does not affect these results).

Baldwin and Wallace, 2002; Thompson and Wallace, 2000). In addition, as mentioned earlier, Baldwin and Dunkerton (2001) discussed dynamical mechanisms for communicating stratospheric circulation anomalies downward to the troposphere and surface, via the polar modes of variability. Consistent with these studies, results shown in Figure 6(a)–(c) suggest the 11-year solar signal is a positive feature of both the polar modes, expressed in SLP during 1856–1957. The solar signal [during June-July-August (JJA)], considering a total of nearly 150 years data also reveals a positive signal in the surface SAM (AAO) (Figure 5). (Using ENSO as an additional independent parameter does not change the observed solar signal and hence not included here). Thus, there is evidence for ‘J’ and ‘K’ in observational data.

I: Baldwin and Dunkerton (2001), Thompson and Wallace (2000)
J: Figure 5.
J–K: Figure 6(a–c)

3.2. Atmosphere only: Sun combined with QBO (L–M; shown by dash-dotted line)

The role of sun combined with QBO is covered by L–M and shown by dash-dotted lines in Figure 7.

Following Baldwin and Dunkerton (2001), the QBO is introduced into the flow chart and the combined effect of the QBO and the Sun is shown by pathways ‘L’ and ‘M’, showing that the effect of the QBO combined with solar activity reveals a −ve signal in the de-seasonalized AO and AAO. This is based on studies of Labitzke and van Loon (1992), Labitzke (2004), Haigh and Roscoe (2006) and Baldwin and Dunkerton (2001) as described in Section 1. Results of multiple regression analysis [Figure 8 (for the QBO at the 50 hPa level), also shown by Roy and Haigh, 2011] show consistency with the studies mentioned above. It indicates that the effect of the QBO (irrespective of using the 30, 40 or 50 hPa levels), combined with solar activity, reveals a negative signal in the de-seasonalized AO and AAO. All these studies suggest that ‘L’ and ‘M’ are well-evidenced through observational analyses. The evidence for how variability from the upper stratosphere is carried to the troposphere (via the polar modes) may therefore be summarized as:

L–M: Labitzke and van Loon (1992), Labitzke (2004), Haigh and Roscoe (2006), Figure 8 (also Roy and Haigh, 2011).

© 2013 Royal Meteorological Society

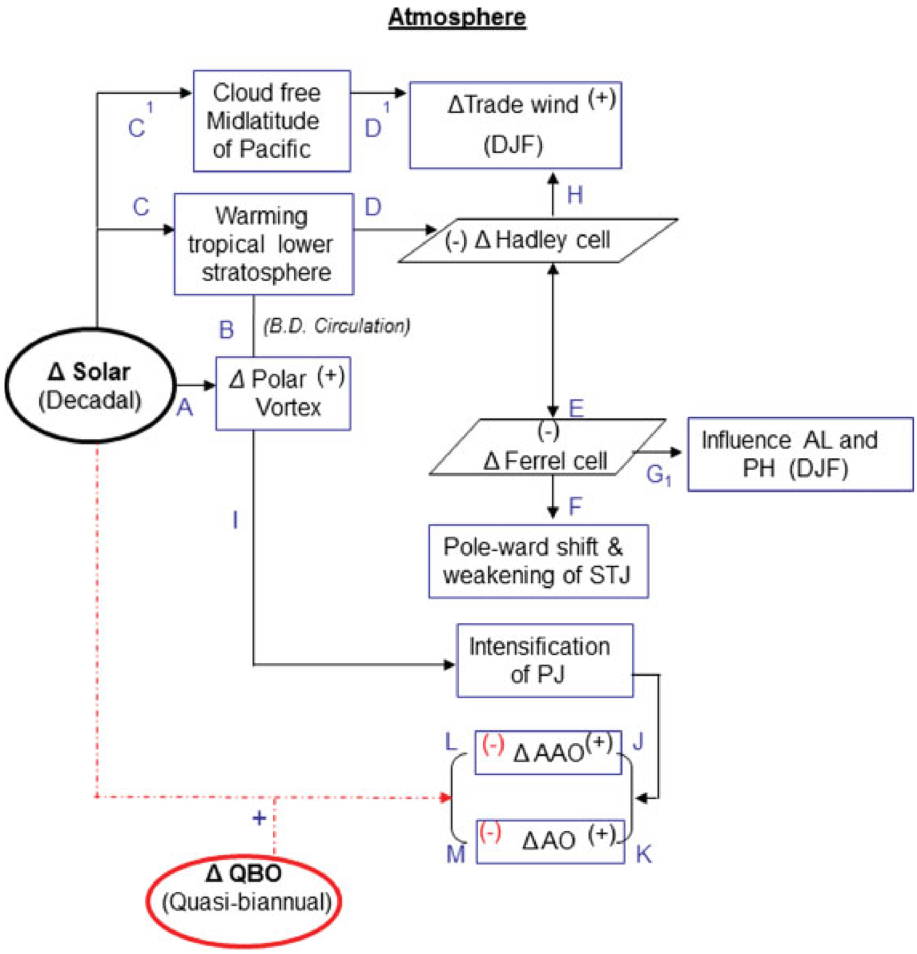

Figure 7. Flow chart showing solar signal combined with QBO in the atmosphere.

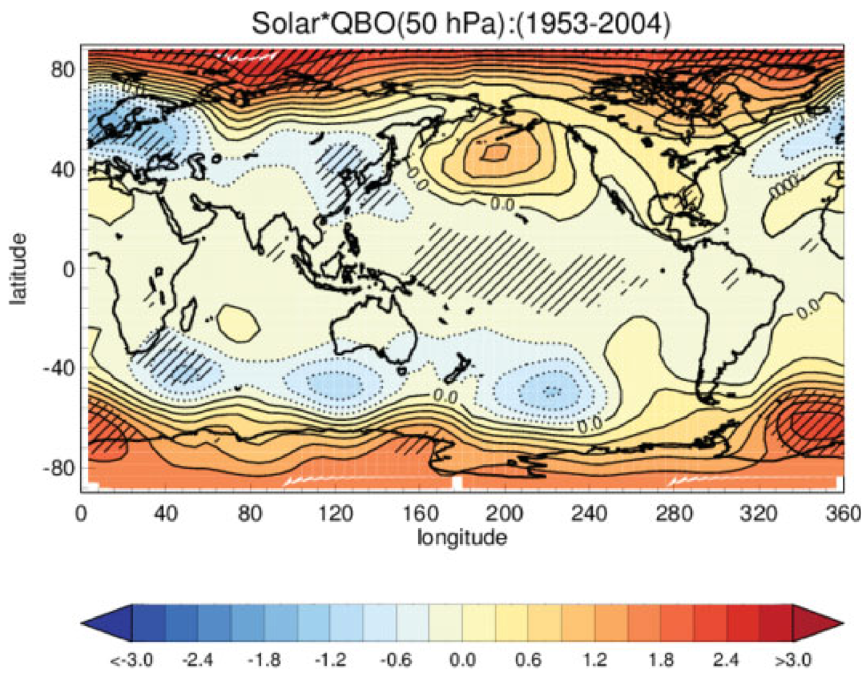

Figure 8. Results of multiple linear regression analysis of sea level pressure data during 1953–2004. Components (hPa) due to the compound Solar*QBO (at 50 hPa) signal with other independent parameters as trend, OD and ENSO.

© 2013 Royal Meteorological Society

3.3. **Sun, QBO and ENSO: atmosphere and ocean (only Pacific) coupling (N–S;** shown by dash-dotted line)

The role of '**atmosphere and ocean**' have been covered by 'N–S' and shown by dash-dotted lines in Figure 9.

In the process of ENSO, the role of Walker circulation, trade wind and thermocline shifting are inseparable. They are very well-documented, and their coherence is strongly established through various observational analyses and modelling studies. Thus, 'N' and 'O' are not only evidenced through observational results but also explained by a mechanism. A chain of cause and effect acts as follows: increase in the speed of trade wind (shown by 'H' with '+') – uplifting of the thermocline in the eastern Pacific basin (shown by 'N' with '+') – increase in the cold event of ENSO (shown by 'O_1' with '−') – increase in the strength of Walker circulation (shown by 'O_2' with '+') all linked together and shown by appropriate labels in the flow chart (Figure 9). Here cold (/warm) event of the ENSO is marked with '−'ve (/+ve) sign. Regression analysis suggests that the Sun (during DJF), via triggering a change in the trade wind (Figure 3(a), shown under Section 3.1.), can initiate ENSO cold event like situations during HS years (Figure 14(a) shown in Section 3.4.). This observation supports the proposed pathways 'N' and 'O' for a solar-ENSO link.

Another possible pathway, from atmosphere to ocean (around mid-latitudes), is shown by 'G_2', which associates a weakening of the AL with a warming of the north Pacific, during HS years. Due to a weakening of the Ferrel cell and the AL during HS years, the wind forcing of the north Pacific gyre circulation reduces in strength, causing less mixing in the north Pacific shallow ocean water which might act to increase warming around the north Pacific. Turbulent heat fluxes and Ekman transport are also sensitive to the changes in the surface wind field and act together to warm up SST around north Pacific.

Haigh (2003) suggests that there is a positive solar response in the tropical lower stratosphere which extends in vertical bands throughout the troposphere via mid-latitudes (with a maximum amplitude of 0.5°K around 40–50°N) in both the hemispheres. Frame and Gray (2010), using the multiple linear regression analysis of the ERA-40 dataset for the period 1979–2008, also noted a positive solar response in the annual temperature, at mid-latitudes in the troposphere, in both hemispheres. The results from the data analysis, Figures 10, 11(a) and (b) and 12 (a) and (b), all are in agreement with such mid-latitude warming during HS years. Thus, observational results provide support for 'G_2'. However, to verify the cause-effect relationship, i.e. whether solar influence during HS years, around the AL and PH, are related to the warming of north Pacific, needs to be tested in computer models and hence 'G_2' is also shown as a hypothesized mechanism.

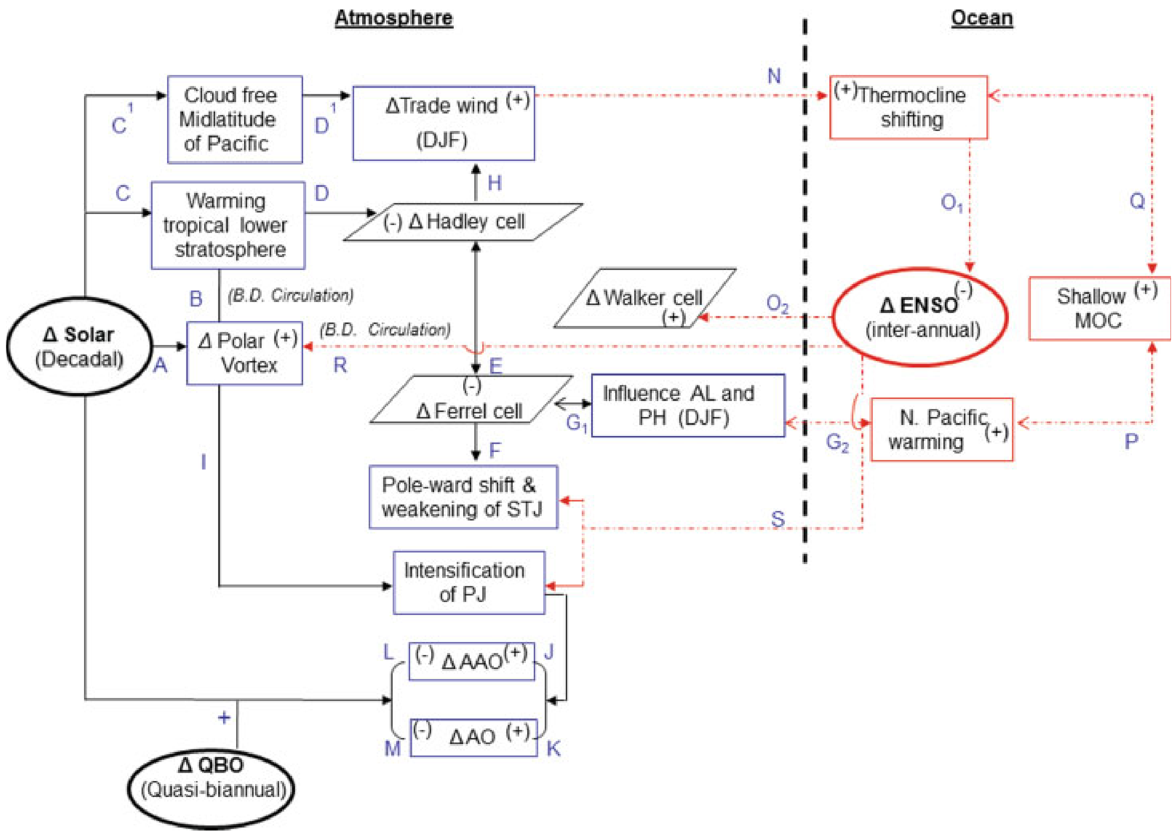

Figure 9. Flow chart showing atmosphere and ocean (only Pacific) coupling.

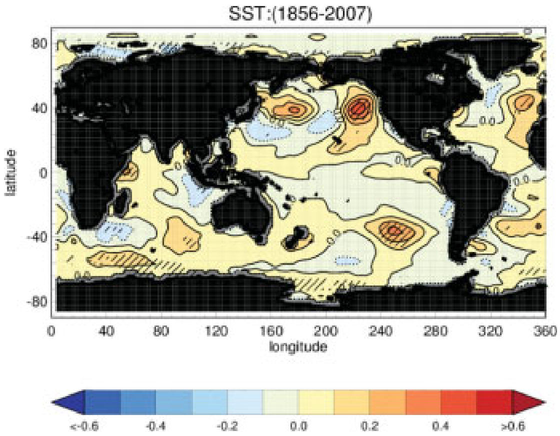

Figure 10. Amplitudes of the components of variability of SST (in °K) due to solar (using monthly SSN) with other independent parameters trend, OD and ENSO: using all months of year, represented by monthly average values, with annual cycle removed (dataset from NOAA). For SST, there is no data in land region and shown here in black.

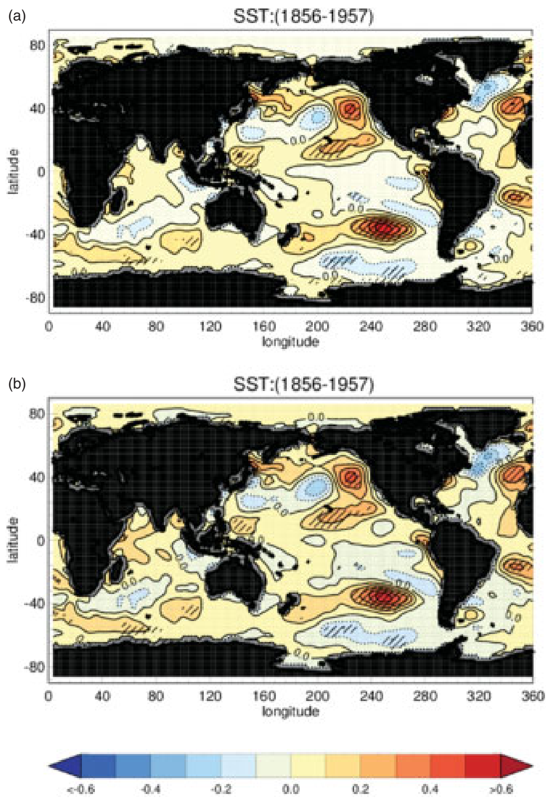

Figure 11. (a–b): Amplitudes of the solar (using monthly SSN) components of variability of SST during (1856–1957). Other independent parameters used are: (a) trend and OD; (b) trend, OD and ENSO. Regression was done annually removing annual cycle.

Links ‘O’, ‘Q’ and ‘P’ indicate a decadal signature in the Walker cell and ENSO (‘O’), the shallow Meridional Overturning Circulation (MOC) (‘Q’ via the thermocline and ‘P’ via north Pacific warming). On occasion, MOC is used for global thermocline circulation in ocean. The term MOC is used, as it is difficult to separate the part of the global ocean circulation which is actually

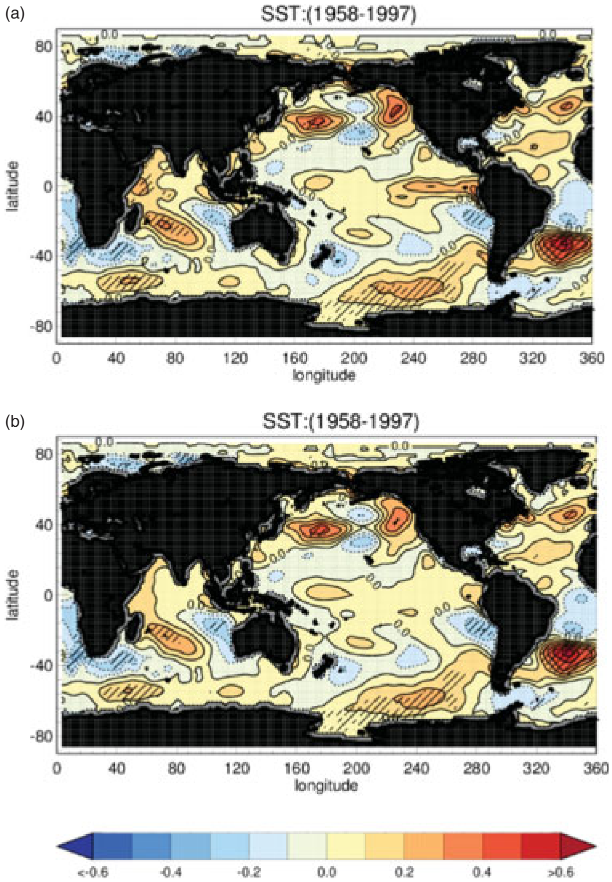

Figure 12. (a–b): Same as Fig 11(a–b) respectively; but for the period 1958–1997.

driven by temperature and salinity alone (hence that name thermocline), as opposed to other factors such as the wind. The shallow MOC is the shallow part of that circulation and characterized by equatorward geostropic volume transport convergence in the interior ocean pycnocline across 9°N and 9°S. It links the tropical pycnocline to the regions of subtropical subduction and is one component of the so-called subtropical cells or STCs (McCreary and Lu, 1994). This study focuses on the shallow MOC around east tropical Pacific. Observations during the period 1850–1957 suggest that the Sun, during HS years produces an impact in two regions of the Pacific: cooling in the tropics, but warming in the mid-latitude of north Pacific. Enhancement of the trade wind (Figure 3(a), shown in Section 3.1.) causes more uplifting of the thermocline around the eastern tropical Pacific, which might be accountable for more cold water in the tropical shallow oceanic basin. The warming in the northern Pacific occurs around the tip of shallow ocean conveyor belt in the north Pacific during HS years (Figure 11(a)). This produces an increase in the temperature gradient (between the tropics and North Pacific), which could be responsible for strengthening the shallow MOC (shown by ‘Q’ with ‘+’) around the tropical Pacific, during HS years. This is in line with the known fact that, during a warm ENSO, the shallow MOC is disrupted. Such analysis also agrees with Mantua

© 2013 Royal Meteorological Society

and Hare (2002) who indicate that the Pacific in the mid-latitude and tropics, is connected via ocean pathway. Apart from the shallow MOC in the Pacific, as mentioned here, there are some other possible mechanisms as well, for tropic mid-latitude and pole connection in the ocean, such as: subtropical ventilated thermocline propagating equator-ward (Huang and Liu, 1999a, 1999b, Liu and Zhang, 1999), sub-polar and subtropical gyre circulations spinning up and down (Latiff and Barnett, 1994, Gu and Philander, 1997, Schneider *et al.*, 2002), etc.

Thus, link ‘P’, which indicates more warming in the north Pacific, can strengthen the shallow MOC, but may be considered as a hypothesized mechanism. The Sun might be a potential driving factor to regulate such coupling mechanism, and may also characterize decadal fluctuations observed in some of the parameters mainly regulated by ocean in surface layer. For example, the study of Zhang and McPhaden (2006) using historical hydrographic data during last 50 years, observed decadal variability in the shallow MOC. The strength of equatorward convergence of the pycnocline volume transport across 9°N and 9°S around eastern tropical Pacific also characterize decadal variability and the circulation fluctuates significantly on decadal time scales, with maximum decade-to-decade variations of 7–11 Sv about the trend (Zhang and McPhaden, 2006). This analysis indicates that decadal signals in ENSO (White and Liu (2008); Zhao and Dirmeyer, 2003 and Chen *et al.*, 2004), in the thermocline around the tropical Pacific, in the strength of the shallow MOC (Zhang and McPhaden, 2006; Vecchi and Soden, 2007) and the Walker cell (Vecchi and Soden, 2007) can be originated via solar cyclic variability as indicated in the flow chart (Figure 9) by ‘O’, ‘Q’ and ‘P’.

I now discuss how signals from the ocean can be transmitted to the atmosphere and thus indicate the ‘bottom-up’ coupling processes with associated locations. First, I focus on signals from the ocean to the troposphere – shown with open arrows (‘P’ and ‘G’). The tropical MOC may influence the north Pacific and shown by ‘P’ with open arrow. More water circulation via the MOC in tropical Pacific during HS years imply more heat intake around the North of Pacific through the tip of shallow ocean conveyor belt (which is around the AL). Thus, more warming around the north Pacific during HS years, compared to the surroundings.

It can also be said that warming in the north Pacific can cause changes in the AL and PH (open ended ‘G_2’) and weakening and pole-ward positioning of the Ferrel cell (open ended ‘G_1’). During DJF, due to the positioning of AL and PH, warming around the North Pacific, can have an effect (by generating localized high pressure) on these COA (Figure 2, shown in Section 3.1.); consistent with the results of Christoforou and Hameed (1997) in terms of intensity as well as positioning (shown by ‘G_2’ with open arrow) (also vL07; Figures 2, 3(a) and (b) and 4, figures shown in Section 3.1.). Subsequently, this can influence the Ferrel cell as shown by ‘G_1’ (with open arrow) (Haigh *et al.*, 2005; Brönnimann *et al.* (2006)). However, whether warming in the north Pacific causes changes in the AL and PH and subsequently weakening and pole-ward positioning of the Ferrel cell remains to be established. Hence both open ended ‘G’ and ‘P’ are considered as hypothesized mechanisms.

Bottom-up processes can even be extended to the stratosphere. Link ‘R’ suggests that the warm events of ENSO are related to a warm polar vortex and vice versa. It has been claimed that the northern stratospheric polar vortex is more perturbed and warmer during El Niño winters than La Niña winters. Camp *et al.* (2007a), showed that during winter, warm-ENSO years are significantly warmer in the stratosphere at the NH polar and mid-latitudes than the cold-ENSO years. Using a GCM, Sassi *et al.* (2004) and Taguchi and Hartmann (2006), showed that the warming difference between El Niño and La Niña years is statistically significant and SSW are twice as likely to occur in the El Niño winters than La Niña, thus providing a possible connection between the polar stratosphere and ENSO. Moreover, Thompson, Baldwin and Wallace (2002) observed that pronounced strengthening (weakening) of the NH wintertime stratospheric polar vortex is allied with the cold (warm) phase of ENSO. Haigh and Roscoe (2006) pointed out that such association of ENSO with the polar vortex is very likely to be related to changes in the BDC. More recently, Ineson and Scaife (2009), using an atmospheric GCM, showed that there is a clear response of the ENSO in European climate via the stratosphere. This mechanism is restricted to years when an SSW occurs, leading to a transition to cold conditions in northern Europe and mild conditions in southern Europe in late winter during El Niño years (via pathway ‘R’, ‘I’ and ‘J’). All these studies provide observational evidences for ‘R’ and also offer mechanisms to explain this link.

How the influence of ENSO may be captured on the polar modes is shown by S’, ‘J’ and ‘K’. Carvalho *et al.* (2005), using data analysis for the period 1979 to 2000, observed that during the austral summer (DJF), cold events of the ENSO are linked with dominant positive AAO and vice versa. The alternation of AAO phases were also shown to be allied with the latitudinal migration of upper level (200 hPa) STJ (around 45°S) and the intensity of polar jet (around 60°S). Positive AAO phases are associated with the pole-ward shift and weakening of the subtropical feature accompanied by an intensification of the high-latitude feature. As discussed above, since the NAM and SAM follow similar mechanism (Thompson *et al.*, 2005); such behaviour is expected to be noticed in the surface NAM (AO) as well. It is in agreement with Haigh and Roscoe (2006), who, using multiple regression analysis, with data from the latter half of the 20th century, showed an anti-correlation between the polar modes and ENSO in the lower troposphere. In essence, labels ‘S’, ‘J’ and ‘K’ are validated by observations. The evidence for atmosphere–ocean coupling may be summarized:

O_1: Figure 3(a) of Section 3.1. and Figure 14(a) of Section 3.4.

O_2: Vecchi and Soden (2007)
Q and **P**: Zhang and McPhaden (2006), Vecchi and Soden (2007), Mantu and Hare (2002)
P(←) and **G_2**: Haigh (2003); Frame and Gray (2010); Figures 10, 11 and 12
G_2 (←): Christoforou and Hameed (1997), vL07, Figure 2, Figure 4, Figure 3(a) and (b) (also Roy and Haigh, 2012), all from Section 3.1.
G_1 (←): Haigh *et al.* (2005), Brönnimann (2005)
R: Camp and Tung (2007), Sassi *et al.* (2004), Taguchi and Hartmann (2006), Thompson, Baldwin and Wallace (2002), Ineson and Scaife (2009)
S: Carvalho *et al.* (2005)
J: Carvalho *et al.* (2005); Haigh and Roscoe (2006)
K: Haigh and Roscoe (2006)

3.4. **Atmosphere and ocean (only Pacific) coupling: climate change (T–Z;** shown by dash-dotted lines)

Finally, the **'climate change'** fingerprint is included in the flowchart and marked by 'T–Z' with pathways by dash-dotted lines (Figure 13).

In the flow chart 'T' and 'U' suggest climate change during the second half of the 20th century is responsible for a weakening of both the tropical circulations – the Hadley and Walker cells. Held and Soden (2006) were the first to document a weakening of the Walker Circulation in a warming climate. Observational results (Vecchi and Soden, 2007) also suggest such weakening though more pronounced in the Walker cell, during the last half of 20th century. Weakening of the Walker circulation in climate models, forced with increased greenhouse gases, has also been well-documented in various other studies (Meehl *et al.*, 2007; Tanaka *et al.*, 2004; Vecchi *et al.*, 2006). Thus 'T' and 'U' have an established mechanism as well as being evidenced in observational analyses. I now show that climate change, via the Walker circulation, probably plays a role in modifying the atmosphere–ocean coupling system as just presented.

In the section 'Atmosphere–Ocean coupling', it was suggested that an increase in the strength of the Walker cell (shown by 'O_2' with '+') is associated with the cold event side of ENSO ('O_1' with '–'). Likewise, weakening of the Walker cell ('U' with '–') is likely to favour a warm event side of ENSO ('V_1' with '+'). This, in turn, is allied with weaker uplift of the thermocline around the eastern tropical coast of Pacific ('V_2' with '–'), together with a deceleration of the trade wind system (marked as 'X' with '–'). Thus, the solar signal present around the ITCZ in the eastern Pacific during the earlier period (small in magnitude but statistically significant) is not observed during the latter period (Figure 3(b) compared to Figure 3(a), shown in Section 3.1.). Moreover, the solar signal which was shown could be a potential factor for triggering a cold event of the ENSO at HS years, during the earlier period (through pathway 'N', 'O' from tropics) may produce the opposite effect during the latter. Observational data shown in Figure 14(b) (compare Figure 14(a)) also

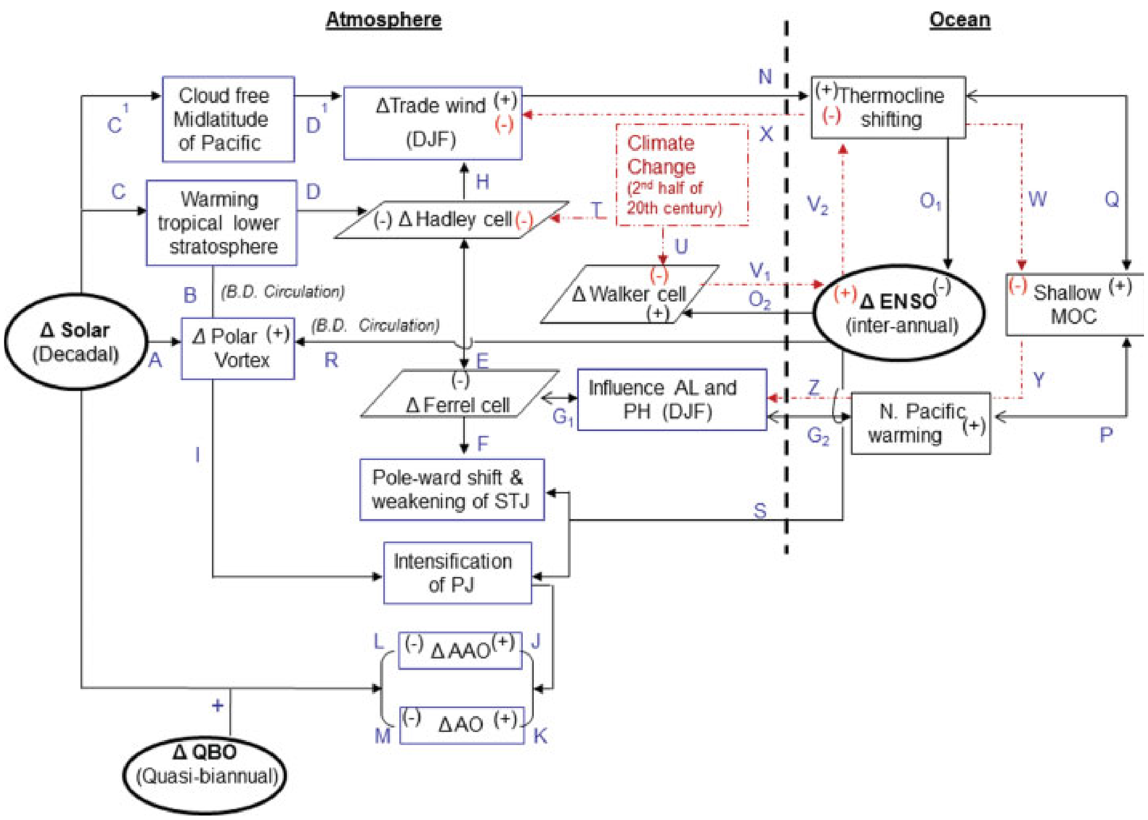

Figure 13. Flow chart of proposed atmosphere–ocean coupling with climate change.

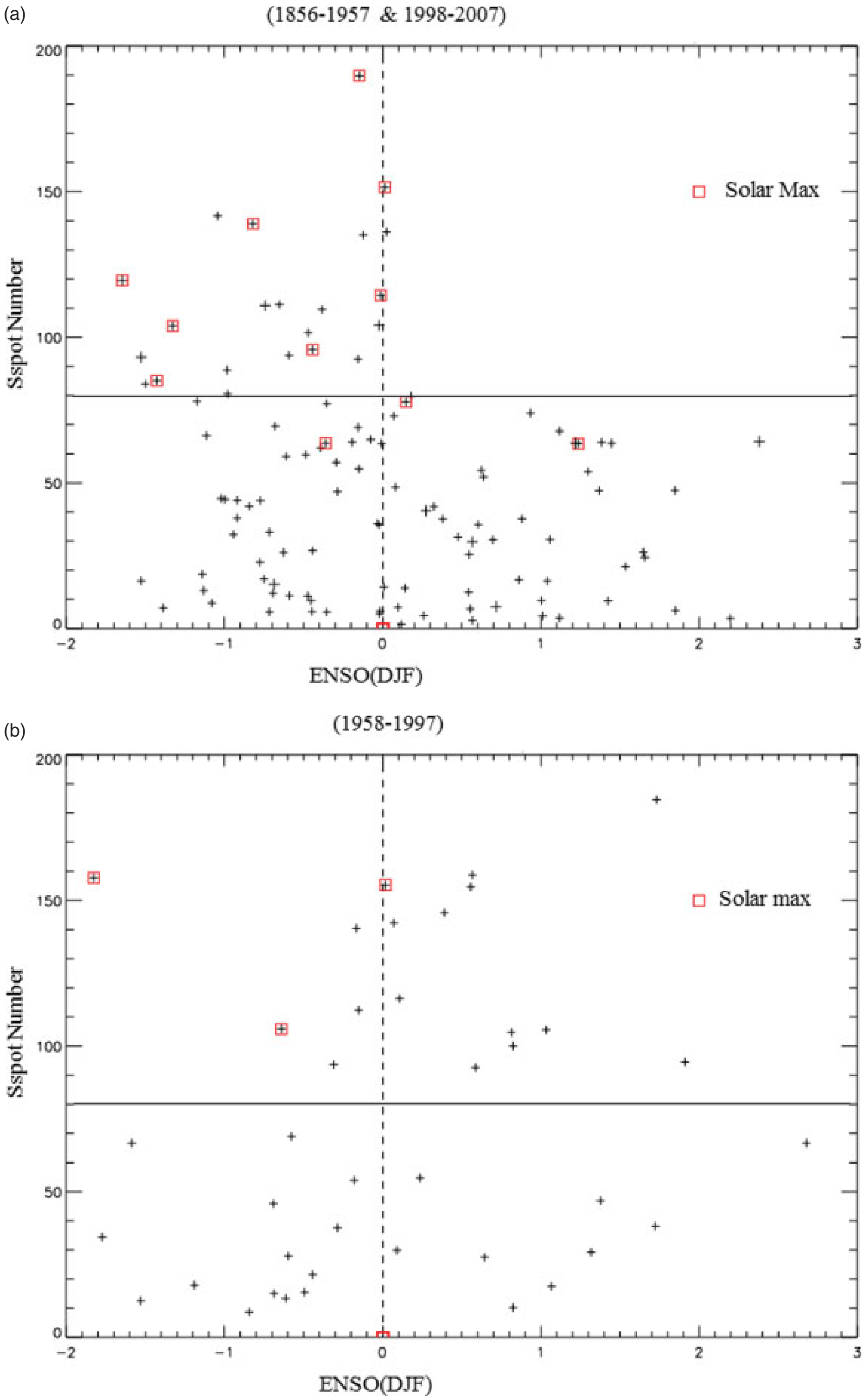

Figure 14. (a–b): Scatter diagram of DJF mean ENSO index *versus* annual mean SSN during: (a) (1856–1957) and (1998–2007); (b) (1958–1997).

indicate such a bias of HS years towards the warm event side of ENSO during the latter period. Thus, 'V' and 'X' are explained by the usual ENSO mechanism and are also evidenced in observations.

Pathways 'W' and 'Y' indicate that suppression of the uplift of the thermocline weakens the shallow MOC in the tropical Pacific ('W' with '−'), and subsequently reduces warming around the north Pacific (shown with 'Y'). This, in turn, can influence the AL (shown with 'Z'). Deepening the thermocline favours a warm shallow ocean current in the tropical Pacific basin, causing a reduction in the flow of equator-ward convergence of ocean current in Pacific. This was associated with the tropics and mid-latitude temperature contrast during the earlier period

© 2013 Royal Meteorological Society

(through pathways 'N', 'Q' in the tropics, alongside 'P' in mid-latitudes). Simultaneously, a climate change fingerprint, via the deepening of the thermocline in the tropical Pacific can be observed in the shallow MOC (via pathways 'V' and 'W'). Thus, climate change had a decelerating effect on the shallow MOC around the Pacific ('W' with '−') as reported during 1958–1997 by Vecchi and Soden (2007) and Zhang and McPhaden, 2006. Hence, 'W' is evidenced by observations. Moreover, weakening of the shallow MOC can influence the region around the north Pacific via a weaker intake of heat than in the earlier period. This is shown by 'Y' and is also detected in observational analysis (Figure 12(a) and (b), shown in Section 3.3.). With less warming around the AL, the solar signal observed there in SLP, during DJF in the earlier period is seen to be weakened during the latter (Figure 3(b) compared with Figure 3(a), shown in Section 3.1.). Thus, pathway 'Z' is evidenced by observations. It still needs to be verified whether reduced warming around the north Pacific is related to a strengthening of the AL compared to the earlier period. Hence, 'Z' may be considered to be the same hypothesized mechanism as proposed for 'G_2' earlier.

I now focus on the modified solar signal during the latter period. The shallow ocean pathway of the conveyor belt not only serves a role in mass exchange between the mid-latitudes and tropics of the Pacific but can also act as a medium to transport the solar signal. Another pathway can be ocean subduction, which links the subtropical gyre in the north Pacific to the shallow MOC in the tropic as previously mentioned. The solar signal (DJF), being missing in the tropics ('X') and weakened around the AL ('Y') during the latter period (Figure 3(b) compared to Figure 3(a)), indicates that the Sun can amend the strength of the shallow MOC around the tropical Pacific. For example, the Sun, during HS years for the latter period, can be responsible for weakening the shallow MOC circulation in the tropical Pacific by reducing the temperature contrast between the tropics and mid-latitudes (due to an absence of trade wind forcing in the tropics). This also suggests that a decadal footprint in the shallow MOC (though weaker and different in nature to the earlier period) is still there, during the latter. A decadal signature in the shallow MOC in the tropical Pacific has been reported by several authors (Vecchi and Soden, 2007; Zhang and McPhaden, 2006). A weakened, yet significant solar signal around the AL (Figure 3(b) compared to Figure 3(a), Figures shown in Section 3.1.) during that period (supported with the flow chart of Figure 13) still indicates more (less) heat intake from the north Pacific during HS (LS) years which is carried towards the tropical basin via the shallow MOC. Bearing in mind the role of the shallow ocean current in the Pacific, and acknowledging that the upper ocean heat content in the tropical basin is a pre cursor of ENSO, such behaviour during the latter period, suggests that – warm events of the ENSO during HS years and cold during LS years are favoured during the final half of the 20th century. A similar solar influence on the ENSO has been observed by White *et al.* (1997). The results of multiple regression analysis also suggest that during 1958–1997, omission of ENSO as an independent index in the regression assigns a false warming (cooling) signal to higher (lower) solar activity on SST in the tropics (Figure 12(a), shown in Section 3.3.), unlike the earlier period (Figure 11(a) shown in Section 3.3.). Thus, the Sun during the latter period is found to be influencing (or mixed up with) ENSO (Figure 12(a) and (b), shown in Section 3.3.), which is only via 'P', 'Q' (open arrow) and 'O_1', affected by climate change signal 'Y', 'W' and 'V_2' respectively. If ENSO is included in the regression, the solar signal in SST in the tropics is found to be weak, as ENSO is naturally very strong and dominates SST in the east tropical Pacific.

In summary, the evidence for an impact of climate change on the solar signal is evidenced by:

T: Held and Soden (2006), Vecchi and Soden (2007)
U: Held and Soden (2006), Vecchi and Soden (2007), Meehl *et al.* (2007), Tanaka *et al.* (2004), Vecchi *et al.* (2006)
V_1: Figure 14(b) (compared with Figure 14(a), shown in Section 3.1.)
W: Vecchi and Soden (2007), Zhang and McPhaden (2006)
Y: Figure 12(a) and (b), shown in Section 3.3.
X, Z: Figure 3(b) shown in Section 3.1. (compared with Figure 3(a))

3.5. **Other issues:**

Solar signal and ENSO: An underlying quasi-decadal variability in the inter-annual ENSO as detected in some recent studies (White and Liu, 2008; Zhang *et al.*, 1997; Zhao and Dirmeyer, 2003; Chen *et al.*, 2004) raises the question as to whether the Sun influence ENSO. Adding an 11-year period cosine signal of amplitude approximately 2.0 W m^{-2} to the solar constant in the fully coupled ocean–atmosphere general circulation model (e.g. the Fast Ocean–Atmosphere Model (FOAM) of Jacob *et al.* (2001)), White and Liu (2008) were able to simulate both ENSO and an estimated QDO. On the other hand, in the absence of the 11-year solar signal, the FOAM can simulate only ENSO. The observation presented here with regard to the solar-ENSO relationship in HS years (SSN > 80), adds evidence to this claim and hence to a plausible mechanism for solar-climate links.

Proposed mechanisms – earlier versus latter period

The multiple regression analysis for DJF, during the earlier period (Figure 3(a)), detected a weak yet significant solar signal in SLP around the tropical eastern Pacific, with a strong signal around the region of the AL. Such a signal around the tropics is missing during the latter period (Figure 3(b)). Moreover, the signal around the northern Pacific during this period is found to be weakened, though still significant.

© 2013 Royal Meteorological Society

Proposed mechanism – earlier period

A small but significant signal in the tropical eastern Pacific SLP, responsible for intensification of the ITCZ and associated enhancement of the trade wind, during HS years, can account for uplifting the thermocline at the eastern Pacific coast. It, consequently, can produce a situation similar to that of a cold event of the ENSO, during HS years, and to a warm event during LS years. Thus, by impacting the trade wind around the ITCZ in the eastern Pacific, a chain of processes similar to those of ENSO may be initiated by the sun on SLP during DJF.

Observations presented here captures this solar ENSO behaviour (during the earlier period), though only for HS years (say SSN > 80). The work of Dima *et al.* (2005) may shed some light on why the reverse fails to occur during LS years. This suggests that ENSO, a measure of the tropical Pacific SST and originated via atmosphere–ocean coupling around that region, possesses the potential strength to overpower the influence of solar mode, at the surface. However, the solar signal might make its presence felt differently during HS years and have the potential to overshadow the usual inter-annual ENSO characteristics. Thus during the earlier period the solar signal may influence tropical SSTs during HS years, but is overwhelmed by the innate strong ENSO variability at LS activity. Such an observation is consistent with that of Kodera *et al.* (2007), who found different ENSO behaviour during HS years. Nevertheless, the decadal signature in the ENSO, generated via the Sun cannot be ignored. It is possible that such analysis may also shed light on some of the unexplained behaviour of the ENSO cycle (viz. premature cessation or prolonged lifetime).

Why the regression fails to capture any detectable solar signal in SST around the tropical eastern Pacific during the earlier period, without or with the ENSO as an independent parameter, (Figure 11(a) and (b)) may be described as follows. As very few years show a bias towards the cold event side of the ENSO during HS years, compared to the whole set of observation (Figure 14(a)), the regression fails to find any strong result for the Sun and SST in the tropics (Figure 11(a)). Furthermore, including ENSO as an index in the regression, it still fails to capture any detectable solar signal in SST (Figure 11(b)), suggesting again that it is the ENSO which is dominating SST in the eastern tropical Pacific most of the time. Thus, the apparent influence of the Sun on ENSO during the earlier period, may be initiated through a triggering of the trade winds, but is not detectable by the regression analysis in tropical SSTs.

In mid-latitudes, a strong solar signal in SLP, around the AL ($\sim$6 hPa) is detected. Such a signal can be related to a weakening of the Ferrel cell around the north Pacific during HS years and vice versa during LS years. Two fundamentally different routes for a solar influence on the troposphere have been proposed: one is the ‘top-down’ mechanism and the other the ‘bottom up’ one. First, we address the ‘top-down’ solar influence, which is generated through the stratosphere. In an atmosphere-only GCM, Haigh (1996, 1999) also detected a weakening of the Ferrel cell, associated with enhancement of solar forcing in the lower stratosphere. Such a change should be reflected in the north Pacific sub-tropical gyre, which is wind driven. Weakening of the subtropical gyre will impede overturning (thus mixing with cold water) in the north-eastern part of Pacific, augmenting temperature around that place. As mentioned earlier, the Pacific is connected between the tropics and mid-latitude (north) via the shallow MOC, so the solar signal around the north Pacific can be transported to the tropical Pacific and vice versa. Through such a linkage, the Sun may influence not only the trade winds, but also the tropics via the mid-latitudes. In the ‘bottom-up’ pathway, the Sun directly influences SST without any stratospheric feedback. This pathway involves the shallow MOC and originates in the north Pacific. The shallow MOC, during HS years, absorbs more heat around the region of the north Pacific, and subsequently can cause weakening of the AL – which in turn, can reduce the strength of the Ferrel cell around the north Pacific. The heat absorbed can again be transported to the tropics of Pacific via the shallow conveyor belt.

Proposed mechanism – latter period

During the latter period, the solar signal on SLP in DJF is missing in the tropics, with a weakened yet significant signal around the AL. During the earlier period, the solar signal on HS years is responsible for warming in the north Pacific alongside cooling in the tropics. Such a strong temperature gradient can enhance the rate of flow of shallow ocean current from the mid-latitude (north) to tropics in Pacific and consequently, can hasten equatorward convergence. However, the said signal is different during the latter period – missing around the tropics and weakened in the mid-latitude. It indicates that the modified solar signal may have some role in decreasing the shallow overturning during 1950s to 1998, that has been reported by several authors (Zhang and McPhaden (2006), McPhaden and Zhang, 2002, Vecchi and Soden, 2007). The presence of a weakened solar signal in the mid-latitude, during the said period may be related to the decadal signature still present in the shallow MOC.

Results from the multiple regression analysis also suggest that warming in the tropics is observed around the eastern Pacific during the latter period (Figure 12(a)), unlike the earlier one (Figure 11(a)). It is also seen that the solar signal during the latter period is mixed up with ENSO in the tropics (Figure 12(a) and (b)). If the ENSO signal is not excluded, then the results of regression for the latter half of the 20th century suggest that the solar signal resembles that of a warm ENSO event; which is not the case during the earlier period (Figure 11(a) and (b)). Thus during 1958–1997, omission of ENSO from the regression gives a false warming (cooling) signal in SST related to higher (lower) solar activity (as observed

© 2013 Royal Meteorological Society

by White *et al.* (1997)). I now consider a plausible route for transporting such a solar signal.

During the latter period, the solar signal around the ITCZ is missing. However, the weakening of the Ferrel cell during HS years subsequently causes warming around the north Pacific (which also implies that the oceanic shallow MOC around that place absorbs more heat) and via shallow ocean pathways may cause warming around tropical Pacific. Such a route for the solar signal, via transporting heat from the mid-latitude to tropics, may activate a warm ENSO cycle in the tropics, during HS years. Figure 14(b) also indicates such a shift in the ENSO, towards a warm event side during the latter period for HS years, contrary to the observation of the earlier. Thus, during the latter, the solar signal in the regression is shown to be mixed up directly with the ENSO, producing a comparable effect on tropical SST (Figure 12(a)); however, the same is marginal, if the ENSO is separated from the regression (Figure 12(b)), as the ENSO is very strong in nature and dominates tropical SSTs (Dima *et al.*, 2005).

Thus, the Sun, which was shown, could be a potential factor for triggering a cold ENSO event at HS years, during the earlier period, may produce the opposite effect during the latter period. Such a bias of HS years on the warm ENSO side during the latter period, compared to the earlier one, has also been captured in the scatter plots (Figure 14(a) and (b)), though solar max years (used by vL07) are still found to be on the cold event side. During the earlier period, almost all peak solar years (and high solar years) were on the cold event side as discussed before, but one obvious question: why during latter period two peak years are still on the cold event side? Apart from addressing and proposing a plausible mechanism for solar ENSO behaviour, these analyses are also able to reconcile some of the contradictory previous results and discussed here.

Contradiction and Reconciliation

White *et al.* (1997), using an EOF analysis of SST, during the second half of the last century, detected a leading mode of variability, whose spatial pattern consists of a warming around the eastern Pacific in the tropics accompanied by cooling centred around the north Pacific (30°N and 160°W) with a approximately 11-year period lagging the solar cycle by approximately 1 year. Such a spatial pattern, with a reminiscence of the warm event of ENSO, contradicts that of vL07 who detect a solar signal analogous to the cold event of ENSO. Moreover, White and Liu (2008) shows a phase-locking of harmonics of the ENSO time series with the solar cycle resulting in a warm event-like signal for about 3 years around the peak of the DSO. The study of multiple regression of the 1958–1997 data is able to explain some of the inconsistencies relating to the solar signal around eastern tropical Pacific (for instance, the apparently contradictory results of vL07 and White *et al.* (1997), in addition to White and Liu (2008)). Regression analysis (during the time period, common to all the studies), accompanied by the observation that the year of peak annual SSN generally falls a year or more in advance of the maximum of the smoothed DSO (Roy and Haigh, 2010, Figure 4), provide coherence to these apparently conflicting findings as discussed below.

Earlier, it has been indicated that the methodology adopted to detect the solar signal by vL07 is not characterizing a true solar decadal variability. In fact, peak sunspot years (as considered by vL07) generally fall a year or more in advance of the broader maximum of the 11-year solar cycle, and thus reflects a different (rising) phase of the solar cycle to that of the peak year of smoothed DSO. It is observed that the peak years of the sunspot cycle are usually associated with the negative phase of ENSO cycles. As the ENSO usually takes 1–2 years to change from cold to warm phase, this explains why the results of vL07 differ to those of White *et al.* (1997). During 1958–1997, omission of ENSO from the regression gives a false warming (cooling) signal in response to higher (lower) solar activity in tropical SSTs. It clearly indicates why both White *et al.* (1997) and White and Liu (2008) not only detect warming in HS years, but also cooling in LS years, during the time period, common to all the studies. The trough and peak of ENSO shows a period of about 2 years due to its usual phase transition mechanism, throughout the solar cycle, as observed by White and Liu (2008); hence we find consistency between vL07, White *et al.* (1997) and White and Liu (2008) during the time period common to all the studies. Such an observation also explains why solar max years (as used by vL07), are still on the cold event side during 1958–1997; which is not any special feature of the rising phase of solar cycles – it is simply an artefact of ENSO.

Moreover, this study indicates that the composite of 9 solar cycles (during 1900–2000) as considered by White and Liu (2008) in their analysis, generally captures the behaviour of 1958–1997, the period having stronger solar cycles and strongly affected by the ENSO. It also suggests that the application of their approach to the period prior to 1958 may not be able to detect similar phase locking of the ENSO and solar. These analyses thus suggest that, mixing of ENSO with the solar signal during the latter period might modulate the true solar signal which needs to be accounted appropriately. This might shed light on some of the apparent discrepancies between other results of the solar influence on surface temperature.

ENSO and climate change: The regression results suggest that ENSO is not the same during the latter period, as was observed earlier. It is observed that the signal of ENSO during DJF (where the mean value during DJF represent the year), is associated with a strong NAO pattern which is not the case during the earlier period.

Regression of SLP: ENSO

Amplitudes of the component of variability of SLP due to the ENSO during DJF have been shown for

© 2013 Royal Meteorological Society

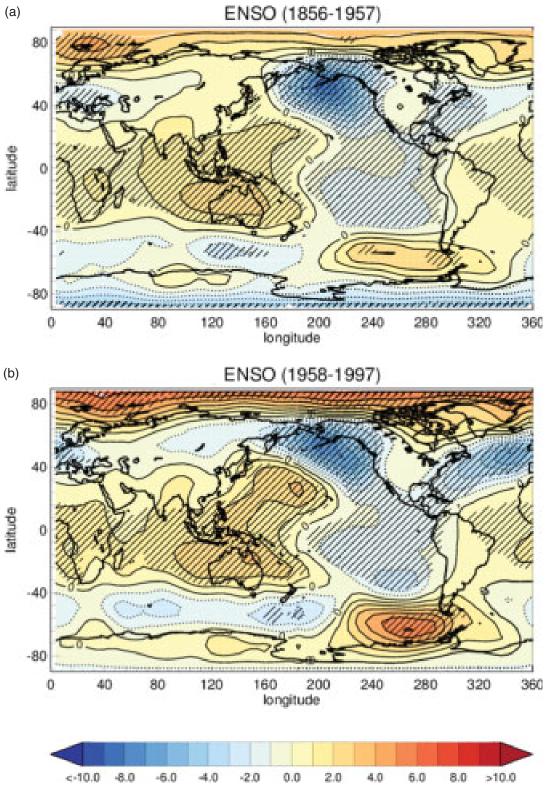

Figure 15. (a–b): Amplitudes of the component of variability of SLP due to ENSO during DJF for period: (a) 1856–1957; (b) 1958–1997. Other independent parameters used are the linear trend, OD and solar (using monthly SSN).

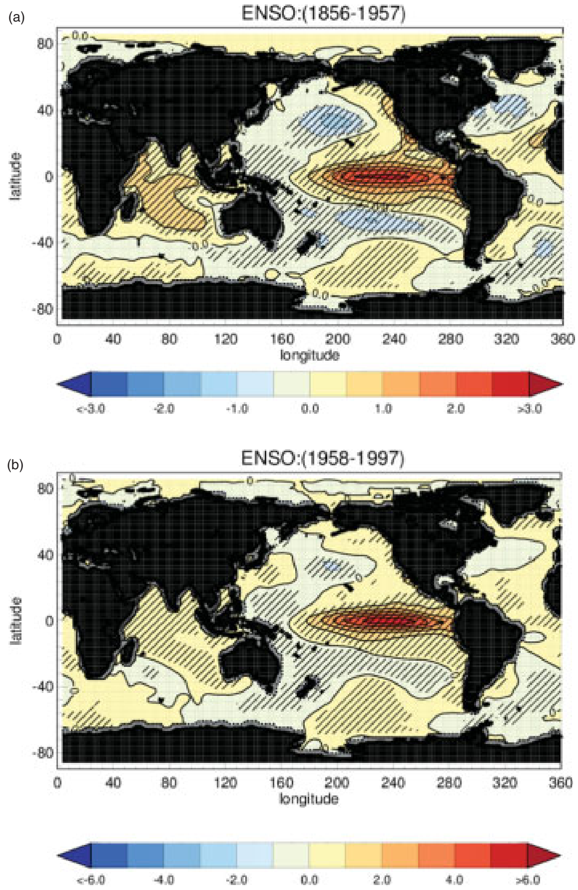

Figure 16. (a–b): Amplitudes of the component of variability of SST due to ENSO (annually removing annual cycle) for period: (a) 1856–1957; (b) 1958–1997. Other independent parameters used are the linear trend, OD and solar (using monthly SSN).

two periods, 1856–1957 (Figure 15(a)) and 1958–1997 (Figure 15(b)). Here, other independent parameters used are trend, OD and solar (using monthly SSN). The signal of ENSO, during the latter period, is associated with a strong NAO pattern (Figure 15(b)) which is not the case during the earlier period (Figure 15(a)). Such an observation is consistent with the study of Toniazzo and Scaife (2006), who also detected a signature of ENSO in the NAO. According to them, positive ENSO features are associated with the negative phase of NAO and vice versa. Moreover, during the latter period, the magnitude of the influence of ENSO on SLP, in two extremes of the SO has also increased.

Thompson and Solomon (2002) noticed that the surface temperatures, during last few decades of the 20th century, have decreased over most of the Antarctic continent, with the exception of warming over the Antarctic Peninsula. This current analysis suggests that there is a strong influence of the ENSO on SLP around the Antarctic Peninsula, (e.g. a raise from 3 to 6 hPa). It indicates a change in the strength of ENSO, as expressed in SLP, around that region may also have some role for recent warming in the Antarctic Peninsular.

Regression of SST: ENSO

It is also seen that amplitudes of SST variability associated with ENSO around the eastern Pacific have increased significantly (from 2.4 to 6.6°C) during the latter period, relative to the earlier one (Figure 16(a) and (b)). Such changes in intensity of ENSO indicate that climate change may be responsible for modifying SST, substantially, around the tropical Pacific via ENSO. These changes are likely related to anthropogenic influences, as discussed in detail by IPCC (2007).

Solar signal, polar modes and climate change: Solar signals on polar modes considering all months of the year were studied. To capture the robust features (and the difference, if any) of the 11-year cyclic variability of the Sun in SLP, during the two periods, three different solar indices (viz. SSN, Solanki and Foster's TSI) I used. It was found that the effect of solar activity (regardless of the choice of TSI reconstruction) before the 1950s, is to produce a clear positive signal in both the polar annular modes expressed in SLP. However, during the latter period, the solar signal does not conform with the signal observed during the earlier period, using any of the solar indices and fails to capture any clear signal in the polar annular modes expressed in SLP (Figure 17(a)–(c), compared to Figure 6(a)–(c) shown in Section 3.1., respectively).

As ENSO is affected by climate change during the latter half of the 20th century, 'S' of Figure 13 is also

© 2013 Royal Meteorological Society

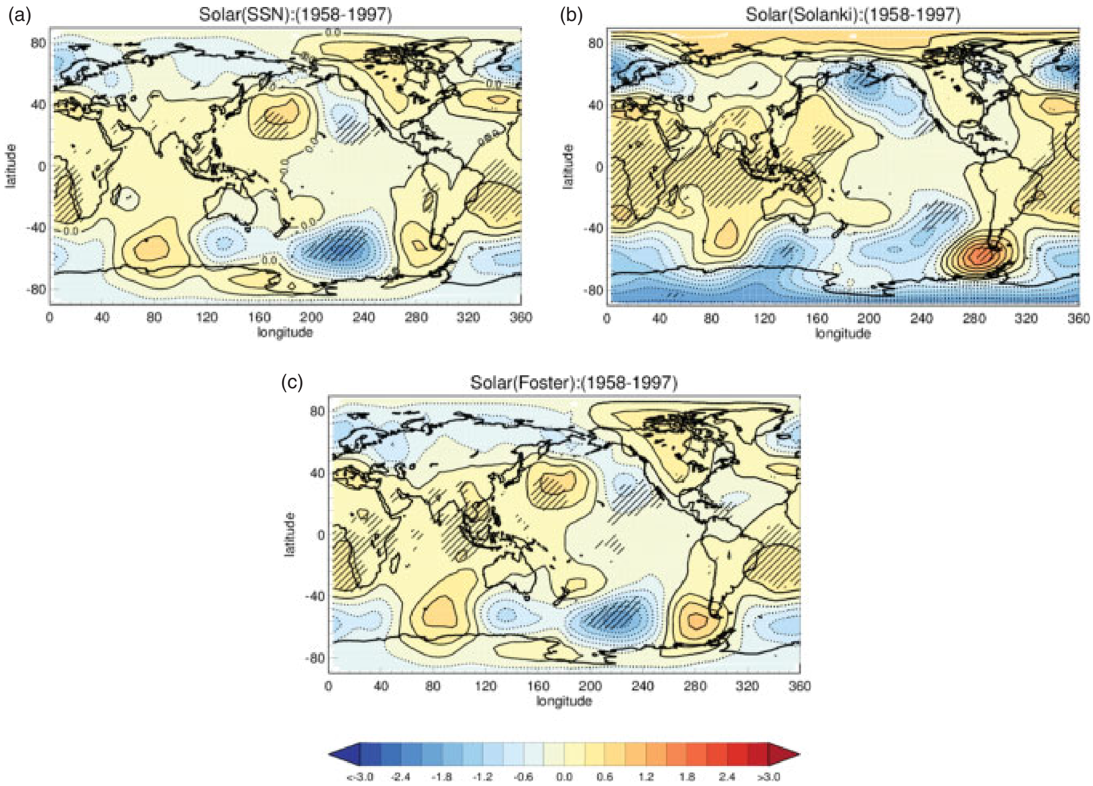

Figure 17. (a–c): Amplitudes of the component of variability of SLP due to solar (SSN(a), using TSI of Solanki (b) and that of Foster (c)) for period 1958–1997. Other independent parameters used are the linear trend and OD.

Table 1. Indicating whether the pathways are evidenced or hypothesized

			Mechanism	
		Observation	Explained	Hypothesized
Atmosphere (A–M)	Lower stratosphere and mid-latitude of Pacific (A–H)	A,B,D,E,F,G,H	A,B,C,D,E,F,H	G,H
	Upper stratosphere (A, I–M)	A,I,J,K,L,M	A	
Atmosphere–ocean coupling (N–S)		O,P,Q,R,S,G	R,N,O	P,G
Climate change (T–Z)		T,U,V,W,X,Y,Z	T,U,V,X	Z

likely to be influenced; hence are AAO and AO (via ‘J’ and ‘K’). Moreover, the climate change signal in the ENSO will also be captured in the polar stratosphere through modulating the strength of BDC via pathway ‘R’ and subsequently, can influence the polar modes via ‘I’. Thus, the solar signal during the earlier period, that captured a positive signal in both the polar modes expressed in SLP, are very likely to indicate differently during the latter period (Figure 17(a)–(c), compared to Figure 6(a)–(c)).

Table 1 indicates how each link is evidenced by observation, explained by a mechanism or only be viewed as a hypothesis at this stage.

4. Discussion

Using results of data analysis, supported by evidences from other research, the current work proposes a comprehensive overview including both the atmosphere and ocean, (mainly involving the Pacific Ocean) to account for the solar influences. On the basis of data analysis and empirical evidence, the current study mainly focuses on the technique of multiple regression, which can distinguish the solar signal from those due to other strong forcings such as ENSO, OD and a climate trend. Such analysis also indicates that the solar influence in the troposphere is governed by both mechanisms, i.e. stratosphere driven as well as via Pacific (Meehl *et al.* (2009)).

The purpose of the flow chart is mainly to capture solar behaviour during high and low phases of the 11-year solar cycle. Solar peak years during the 11-year solar cycle (as used in compositing methods by Meehl and co-authors) most of the time follow the behaviour of high solar phase. Hence, the results of the two methods (linear regression and solar max year compositing) though sometimes agree but differ on occasions. Compositing

© 2013 Royal Meteorological Society

study finds signals only during peak years of 11-year solar cycle. Compositing using solar minimum years could not detect any signal during min (trough) years of the solar cycle (vL07). Regression however detects a signal related to solar activity over the whole solar cycle (not only peak years). Compositing detects a signal on SLP at seasons other than DJF (van Loon and Meehl, 2008), while the regression does not.

There are also issues with the method of solar max compositing as used by Meehl and co-authors and discussed here. The detected signal, using this method may not only be sensitive to the choice of details of the compositing method (Tung and Zhou, 2010, Zhou and Tung, 2010 and Roy and Haigh, 2012), but also be strongly biased due to mixing up the signal with other strong variability, like ENSO (Roy and Haigh, 2010). Roy and Haigh (2010, Figure 3(b)) showed using a scatter plot that the peak years of solar sunspot cycle are usually associated with the negative phase of ENSO cycles. Thus, using the method of solar peak years compositing, the ENSO signal in the tropics might be misinterpreted as a solar.

This study also suggests the importance of atmosphere–ocean coupling which needs to be considered carefully. Some issues relating to Meehl *et al.* (2009) are discussed here. First of all, their model is recorded to produce frequent ENSO events (IPCC, 2007) and it is not clear that after few runs such a tendency does not dominate. Moreover, not all experiments are present in all models, making inter-comparison of model results difficult, especially in the absence of major statistical evidence. Furthermore, their observational results for the solar signal, which are compared with models, are again based on solar max years compositing. The limitations of that method are discussed in previous paragraph.

van Loon and Meehl (2008) showed that the peak solar conditions are different from La Niña events in the Southern Oscillation mainly in the equatorial stratosphere. If this is the case and the solar signal is not ENSO-like, then it would raise doubts with regard to any proposed mechanisms for a solar influence on climate which are based on ENSO-like atmosphere–ocean coupling and changes to the Walker cell, etc. The differences are confined, however, to pressures less than 25 hPa, i.e. right at the top of the NCEP/ NCAR Reanalysis Dataset domain.

This study shows a marked overall association of HS activity (not only peak solar years) with colder temperatures in the eastern tropical Pacific, although this weakened during the period spanning the mid-1950s–1997 (Figure 14(a) and (b)). Figure 14(a) indicates there is no consistent ENSO-like variation in tropical SSTs following peak years of the sunspot cycle as suggested by Meehl and Arblaster (2009) and Meehl *et al.*(2008) (also shown in Roy and Haigh, 2012, Table 1). Such behaviour occurs (Figure 14(b)) mainly during a period when ENSO activity was considerable higher (Figure 15(b) and 16(b)). This study also suggests that both the 'top-down' and 'bottom-up' pathways indicate differently during period affected by climate change. The flow chart tries to address other related issues as well and presents a holistic representation of all the mechanisms. It also attempts to pinpoint and reconcile some of the apparent contradictory findings by other authors. Thus, the proposed pathways, as shown by the flow chart (Figure 13) and discussed here, might lead towards better understanding of atmosphere ocean coupling system, accounting for solar cyclic variability. I hope it will be useful for improving understanding of the sun–climate relationship.

This analysis still indicates some unresolved areas. To mention a few:

a) Interaction between major modes of climate variability: solar, QBO and ENSO act together and the true nature of the linearity of their interaction is still unclear.
b) Mechanism for solar influence on SSTs: The Sun during HS years (say above SSN 80) has been shown to influence tropical SSTs before 1958 and after 1997, but to be overwhelmed by the innate strong ENSO variability at LS activity (Figure 14(a), shown in Section 3.4.). In a coupled atmosphere–ocean system, how the apparent influence is communicated/ reflected is still not fully understood.
c) Climate change during 1950s–1997: Climate change probably induced the atmosphere–ocean coupling system to behave differently during this period and this also affected the solar signal. Such observations identify the need for quantifying the true solar signal with and without the influence of climate change. Hence, it introduces more complications into the task of characterization of solar influence under global warming.

Overall, it can be stated that, in spite of the outstanding issues mentioned, we are now moving towards a better position in understanding the atmosphere–ocean coupling related to solar cycle variability. The identification of the solar influence, not only leads towards better prediction skill but also illuminates scientific communities to address/mitigate some of the crucial issues associated with climate change.

Acknowledgements

Author expresses her sincerest gratitude to Prof. Joanna D. Haigh, Imperial College London, for useful discussions and to Myles Allen for provision of the multiple regression code. This work was partially supported by a studentship from the UK Natural Environment Research Council and partially funded by the NERC SOLCLI consortium grant.

References

Allan RJ. 2000. ENSO and climate variability in the last 150 years, In *El Nino and the Southern Oscillation: multiscale variability, global and regional impacts*, H. F. Diaz and V. Markgraf (eds). Cambridge University Press: New York, 3–55.

© 2013 Royal Meteorological Society

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

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

Baldwin MP, Dunkerton TJ. 2001. Stratospheric harbingers of anomalous weather regimes. *Science* **294**(5542): 581–584. DOI: 10.1126/science.1063315

Barnett TP. 1989. A solar-ocean relation: fact or fiction. *Geophysical Research Letters* **16**(8): 803–806.

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

Brönnimann S, Compo GP, Sardeshmukh PD, Jenne R, Sterin A. 2005. New approaches for extending the 20th century climate record. Eos, Transactions. *American Geophysical Union* **86**: 2–7.

Brönnimann S, Ewen T, Griesser T, Jenne R. 2006. Multidecadal signal of solar variability in the upper troposphere during the 20th century. *Space Science Reviews* **125**(1-4): 305–317. DOI: 10.1007/s11214-006-9065-2

Brönnimann S, Annis JL, Vogler C, Jones PD. 2007. Reconstructing the Quasi-Biennial oscillation back to the early 1900s. *Geophysical Research Letters*, **34**, L22805, 10.1029/2007GL031354.

Camp CD, Tung KK. 2007. Stratospheric polar warming by ENSO in winter: a statistical study, *Geophysical Research Letters*, **34**, L04809, 10.1029/2006GL028521.

Carvalho LMV, Jones C, Ambrizzi T. 2005. Opposite phases of the Antarctic Oscillation and relationships with intraseasonal to interannual activity in the tropics during the austral summer. *Journal of Climate* **18**: 702–718. DOI: 10.1175/JCLI-3284.1

Chang CP, Li T. 2000. A theory for the tropical tropospheric biennial oscillation. *Journal of Atmospheric Sciences* **57**: 2209–2224.

Chen D, Cane MA, Kaplan A, Zebiak SE, Huang DJ. 2004. Predictability of El Nino over the past 148 years. *Nature* **428**: 733736.

Christoforou P, Hameed S. 1997. Solar cycle and the Pacific 'centers of action'. *Geophysical Research Letters* **24**(3): 293–296. DOI: 10.1029/97GL00017

Dima M, Lohmann G, Dima I. 2005. Solar-induced and internal climate variability at decadal time scales. *International Journal of Climatology* **25**: 713–733. DOI: 10.1002/joc.1156

Foster S. 2004. *Reconstruction of Solar Irradiance Variations, for Use in Studies of Global Climate Change: Application of Recent SoHO Observations with Historic Data from the Greenwich Observatory*, PhD thesis, University of Southampton, Southampton, UK.

Frame THA, Gray LJ. 2010. The 11-year solar cycle in ERA-40 data: an update to 2008. *Journal of Climate*Early online release. DOI: 10.1175/2009JCLI3150.1

Gleisner H, Thejll P. 2003. Patterns of tropospheric response to solar variability. *Geophysical Research Letters* **30**(13): 1711. DOI: 10.1029/2003GL017129

Gray LJ, Crooks SA, Palmer MA, Pascoe CL, Sparrow S. 2006. A possible transfer mechanism for the 11-year solar cycle to the lower stratosphere. *Space Science Reviews* **125**(1-4): 357–370. DOI: 10.1007/s11214-006-9069-y

Gray LJ, Beer J, Geller M, Haigh JD, Lockwood M, Matthes K, Cubasch U, Fleitmann D, Harrison G, Hood L, Luterbacher J, Meehl GA, Shindell D, van Geel B, White W. 2010. Solar influences on climate. *Reviews of Geophysics*, **48**, RG4001, 10.1029/2009RG000282.

Gu D, Philander SGH. 1997. Interdecadal climate fluctuations that depend on exchanges between the Tropics and extratropics. *Science* **275**: 805–807.

Haigh JD. 1996. The impact of solar variability on climate. *Science* **272**(5264): 981–984.

Haigh JD. 1999. A GCM study of climate change in response to the 11-year solar cycle. *Quaterly Journal of Royal Meteorological Society* **125**(555): 871–892.

Haigh JD. 2003. The effects of solar variability on the Earth's climate, *Philosophical Transaction of Royal Society of London A*, **361**(**1802**), 95–111.

Haigh JD, Blackburn M. 2006. Solar influences on dynamical coupling between the stratosphere and troposphere. *Space Sciences Reviews* **125**: 331–344.

Haigh JD, Roscoe HK. 2006. Solar influences on polar modes of variability. *Meteorologische Zeitschrift* **15**(3): 371–378. DOI: 10.1127/0941-2948/2006/0123

Haigh JD, Blackburn M, Day R. 2005. The response of tropospheric circulation to perturbations in lower-stratospheric temperature. *Journal of Climate* **18**(17): 3672–3685.

Held IM, Soden BJ. 2006. Robust responses of the hydrological cycle to global warming. *Journal of Climate* **19**: 5686–5699.

Huang B, Liu Z. 1999a. Pacific subtropical–tropical thermocline water exchange in the NCEP ocean model. *Journal of Geophysical Research* **104**(C5): 11 065–11 076.

Huang B, Liu Z. 1999b. Pacific subtropical–tropical thermocline water exchange in the NCEP ocean model. *Journal of Geophysical Research* **104**(C5): 11 065–11 076.

Ineson S, Scaife AA. 2009. The role of the stratosphere in the European climate response to El Niño. *Nature Geoscience* **2**: 32–36. DOI: 10.1038/ngeo381

IPCC. 2007. Climate Change (2007): The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK; New York, USA. http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

Jacob R, Schafer C, Foster I, Tobis M, Anderson J. 2001. Computational design and performance of the fast ocean atmosphere model, Version One. *Proceedings 2001 International Conference on Computational Science*, V. N. Alexandrov, J. J. Dongarra, C. J. K. Tan, Springer-Verlag: London, UK, 175–184.

Kodera K. 2002. Solar cycle modulation of the North Atlantic Oscillation: implication in the spatial structure of the NAO. *Geophysical Research Letters* **29**(8): 1218. DOI: 10.1029/2001GL014557

Kodera K. 2003. Solar influence on the spatial structure of the NAO during winter 1900-1999. *Geophysical Research Letters* **30**(4): 1175. DOI: 10.1029/2002GL016584

Kodera K. 2004. Solar influence on the Indian Ocean monsoon through dynamical processes. *Geophysical Research Letters*, **31**, L24209, 10.1029/2004GL020928.

Kodera K. 2005. Possible solar modulation of the ENSO cycle. *Meteorology and Geophysics* **55**(1/2): 21–32.

Kodera K, Kuroda Y. 2002. Dynamical response to the solar cycle. *Journal of Geophysical Research* **107**(D24): 4749. DOI: 10.1029/2002JD002224

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

Latif M, Barnett TP. 1994. Causes of decadal climate variability over the North Pacific and North America. *Science* **266**(5185): 634–637. DOI: 10.1126/science.266.5185.634

Labitzke K. 2004. On the signal of the 11-year sunspot cycle in the stratosphere and its modulation by the quasi-biennial oscillation. *Journal of Atmospheric and Solar-Terrestrial Physics* **66**: 1151–1157. DOI: 10.1016/j.jastp.2004.05.011

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

Lean J, Rind D. 2001. Earth's response to a variable Sun. *Science* **292**(5515): 234–236.

Lean JL, Rind DH. 2008. How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006, *Geophysical Research Letters*, **35**, L18701, 10.1029/2008GL034864.

Lean J, Rottman G, Harder J, Kopp G. 2005. SORCE contributions to new understanding of global change and solar variability. *Solar Physics* **230**: 27–53.

Liu Z, Zhang RH. 1999. Propagation and mechanism of decadal upper-ocean variability in the North Pacific. *Geophysical Research Letters* **26**: 739–742.

Lockwood M. 2012. Solar influence on global and regional climates. *Surveys in Geophysics* . DOI: 10.1007/s10712-012-9181-3

McCreary J, Lu P. 1994. On the interaction between the subtropical and the equatorial oceans: the subtropical cell. *Journal of Physical Oceanography* **24**: 466–497.

McPhaden MJ, Zhang D. 2002. Slowdown of the meridional overturning circulation in the upper Pacific Ocean. *Nature* **415**: 603–608.

Mantua NJ, Hare SR. 2002. The Pacific decadal oscillation. *Journal of Oceanography* **58**(1): 35–44.

Matthes K, Langematz U, Gray LJ, Kodera K, Labitzke K. 2004. Realistic solar signal in the FUB-CMAM, *Journal of Geophysical Research*, **109**, D06101, 10.1029/2003JD004012

Meehl GA. 1997. The south Asian monsoon and the tropospheric biennial oscillation. *Journal of Climate* **10**: 1921–1943.

Meehl GA. 2007. Global climate projections, In *Climate Change 2007: The Scientific Basis: Contribution of Working Group I to the*

© 2013 Royal Meteorological Society

Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon (ed). Cambridge University Press: Cambridge, UK, 747–845.

Meehl GA, Arblaster JM. 2009. A lagged warm event-like response to peaks in solar forcing in the Pacific region. *Journal of Climate* **22**(13): 3647–3660.

Meehl GA, Washington WM, Wigley TML, Arblaster JM, Dai A. 2003. Solar and greenhouse gas forcing and climate response in the 20th century. *Journal of Climate* **16**: 426–444.

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

Meehl GA, Arblaster JM, Matthes K, Sassi F, van Loon H. 2009. Amplifying the Pacific climate system response to a small 11-year solar cycle forcing. *Science* **325**: 1114–1118. DOI: 10.1126/science.117287

Rayner NA, Brohan P, Parker DE, Folland CK *et al.* 2006. Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: The HadSST2 dataset. *Journal of Climate* **19**(3): 446–469.

Rind D. 2002. The Sun's role in climate variations. *Science* **296**(5568): 673–677. DOI: 10.1126/science.1069562

Rind D, Lean J, Lerner J, Lonergan P, Leboissitier A. 2008. Exploring the stratospheric/tropospheric response to solar forcing. *Journal of Geophysical Research Atmosphere* **113**: D24103. DOI: 10.1029/2008JD010114

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

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

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

Sassi, F. *et al.*, (2004): Effect of El Nino-Southern Oscillation on the dynamical, thermal, and chemical structure of the middle atmosphere, *Journal of Geophysical Research*, **109**,D17108.

Sato M, Hansen JE, McCormick MP, Pollack JB. 1993. Stratospheric aerosol optical depths (1850–1990). *Journal of Geophysical Research* **98**(22): 987–994.

Schneider N, Miller AJ, Pierce DW. 2002. Anatomy of North Pacific decadal variability. *Journal of Climate* **15**: 586–605.

Simpson IR, Blackburn M, Haigh JD. 2009. The role of eddies in driving the tropospheric response to stratospheric heating perturbations. *Journal of Atmospheric Science* **66**(5): 1347–1365.

Shindell D *et al.* 1999. Solar cycle variability, ozone and climate. *Science* **284**(5412): 305–308.

Solanki SK, Krivova NA. 2003. Can solar variability explain global warming since 1970? *Journal of Geophysical Research* **108**(A5): 1200. DOI:10.1029/2002JA009753.

Tung KK, Zhou J. 2010. The Pacific's response to surface heating in 130 Yr of SST: La Niña–like or El Niño–like? *Journal of the Atmospheric Science* **67**(8): 2649–2657. DOI: 10.1175/2010JAS3510.1

Taguchi M, Hartmann DL. 2006. Increased occurrence of stratospheric sudden warmings during El Nino as simulated by WACCM. *Journal of Climate* **19**: 324–332.

Tanaka HL, Ishizaki N, Kitoh A. 2004. Trend and interannual variability of Walker, monsoon, and Hadley circulations defined by velocity potential in the upper troposphere. *Tellus* **56A**: 250–269.

Thompson DWJ, Wallace JM. 2000. Annular modes in the extratropical circulation. Part I: month-to-month variability. *Journal of Climate* **13**: 1000–1016.

Thompson DWJ, Baldwin MP, Wallace JM. 2002. Stratospheric connection to Northern Hemisphere wintertime weather: implications for prediction. *Journal of Climate* **15**(12): 1421–1428.

Thompson DWJ, Baldwin MP, Solomon S. 2005. Stratosphere-troposphere coupling in the Southern Hemisphere. *Journal of Atmospheric Science* **62**: 708–715.

Thompson DWJ, Solomon S. 2002. Interpretation of recent Southern Hemisphere climate change. *Science* **296**: 895–899.

Toniazzo T, Scaife AA. 2006. The influence of ENSO on winter North Atlantic climate, *Geophysical Research Letters*, **33**, L24704, 10.1029/2006GL027881.

van Loon H, Labitzke K. 1998. The global range of the stratospheric decadal wave. Part I: Its association with the sunspot cycle in summer and in the annual mean, and with the troposphere. *Journal of Climate* **11**: 1529–1537.

van Loon H, Shea DJ. 2000. The global 11-year solar signal in July-August. *Geophysical Research Letters* **27**(18): 2965–2968.

van Loon H, Meehl GA. 2008. The response in the Pacific to the sun's decadal peaks and contrasts to cold events in the Southern Oscillation. *Journal of Atmospheric and Solar-Terrestrial Physics* **70**(7): 1046–1055.

van Loon H, Meehl GA, Arblaster JM. 2004. A decadal solar effect in the tropics in July-August. *Journal of Atmospheric Solar-Terrestrial Physics* **66**(18): 1767–1778.

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

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

Vecchi GA, Soden BJ, Wittenberg AT *et al.* 2006. Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature* **441**. DOI: 10.1038/nature04744

Weng H. 2005. The influence of the 11-yr solar cycle on the interannual-centennial climate variability. *Journal of Atmospheric and Solar-Terrestrial Physics* **67**: 793–805.

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

White WB, Cayan DR, Lean J. 1998. Global upper ocean heat storage response to radiative forcing from changing solar irradiance and increasing greenhouse gas/aerosol concentrations. *Journal of Geophysical Research* **103**(21): 355–366.

White WB, Tourre YM. 2003a. Y. M.: Global SST/SLP waves during the 20th century. *Geophysical Research Letters* **30**: 1651, DOI:10.1029/2003GL017055.

White WB, Tourre YM, Barlow M, Dettinger M. 2003b. A delayed action oscillator shared by biennial, interannual, and decadal signals in the Pacific Basin. *Journal of Geophysical Research* **108**(C3): 3070. DOI: 10.1029/2002JC001490

White WB, Liu ZY. 2008. Non-linear alignment of El Nino to the 11-yr solar cycle, *Geophysical Research Letters*, **35**, L19607, 10.1029/2008GL034831.

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

Zhang Y, Wallace JM, Battisti DS. 1997. ENSO-like interdecadal variability: 1900–93. *Journal of Climate* **10**: 1004–1020.

Zhao M, Dirmeyer P. 2003. Pattern and trend analysis of temperature in a set of seasonal ensemble simulations. *Geophysical Research Letters* **30**. DOI: 10.1029/2003GL018579

Zhou J, Tung KK. 2010. Solar cycle in 150 years of global sea-surface temperature. *Journal of Climate* **23**: 3234–3248.

© 2013 Royal Meteorological Society