The effect of solar cycle modulation on the Northern hemisphere sea level pressure variability

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ABSTRACT

The Northern hemisphere sea level pressure(SLP) variability is affected by solar cycle modulation. In this study, we investigate the effect of solar modulation on simulated and reconstructed SLP with a focus on the spatial structure of the NAO/AO. The GISS ModelE simulations for maximum and minimum solar conditions and also reconstruction of the SLP for the past 1000 years allow us to look at NAO/AO spatial structure prior to industrial era, when solar and volcanic were the only external forcings. The results show clear differences in the spatial structure of SLP field in the Atlantic and the Pacific sector with solar cycle variation. The NAO pattern, in particular, seems to be sensitive to the phase of the solar cycle. However these results are not in good agreement with previous studies. This study also raises several questions about the use of EOFs and their NAO and AO interpretation.

1. Introduction

The focus of this analysis is to examine in some detail the regional patterns of climate response to solar forcing and their timescale dependence, and more importantly to gain insight into the possible underlying dynamical mechanisms associated with the response. Broadly, the motivation of this project is as follows. An increase in the global average temperature has been observed over recent decades. When the warming trend is broken down by season and by hemisphere, a seasonal contrast in the rate of warming is evident for the Northern hemisphere(NH) land average. We would like to determine if the observed regional warming and cooling patterns result from natural variability or are due to human activities. The comparison between historical and modern climate change is helpful in this regard because of the fact that prior to the industrial era, externally driven climate changes were forced by two primary factors: variations in solar output and volcanic aerosols whereas a modern climate change additionally has a very dominant anthropogenic driving component.

Furthermore, seasonality, the difference between summer(JJA) and winter(DJF) temperatures shows a clear decline in modern times implying more warming in winters relative to summers. This seasonal character of twentieth century warming is particularly important to the interpretation of recent millennial-scale paleoclimate data. It is known that summer trends are less representative of annual trends than winter trends, yet many of the most widely used proxies are more sensitive to summer conditions. Since the winter season in the Northern hemisphere dominates the annual averages, a comparison between summer versus winter changes could allow us a better understanding of the annual cycle. This seasonal character of the twentieth century also serves as a test see how well the model captures reality.

In this study, we have tried to study some of the above mentioned problems. However, this report focuses on detecting the effect of solar forcing on climate. The problem of detecting solar influence in twentieth century climate is hampered by the great similarity with greenhouse radiative forcing in both its (increasing) twentieth century temporal trend (Lean et al. 1995), and its apparent spatial influence. For this rea-

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son, solar influences can only be confidently established by examining a periods during which greenhouse radiative forcing played little role in governing climate variations. Since direct estimates of solar variability are not available prior to the 1970s, it is necessary to resort to indirect means of estimating solar variations.

The second section talks about solar forcing. The model and data used for this study are described in section 3, followed by results and discussion in section 4 and 5 respectively.

2. Solar forcing

Solar irradiance forcing appears to exhibit most of its variability at multidecadal and longer time scales. Detection of solar influence in the 20th century is hampered by the similarity of its temporal trend to that of increasing greenhouse gases. Therefore the period for the investigation must precede any apparent anthropogenic influence on the climate and should encompass a considerable range of estimated solar output (approximately 4 W/m^2) including the Maunder and Dalton Minima in solar irradiance. It is important to prevent the analysis period encroaching into the interval of potential anthropogenic interferences in the climate signal in order to empirically fully separate the climate responses.

Measurements show that 10 to 20% of solar cycle changes occur in ultraviolet(UV) radiation, which is largely absorbed by stratospheric ozone. Thus a spectrally discriminated representation of the irradiance is important to study the climate response to solar forcing. The variation in irradiance, as measured over the last two decades by satellite-borne instruments is quite modest(1-1.5 W/m^2 at the top of the atmosphere), fuelling some uncertainty as to weather or not solar irradiance changes farther back in time are likely to have been sizeable enough to force significant climate variations.

In two papers, Kodera (2002, 2003) confirmed the dependence of the spatial structure of the NAO on solar activity using historical surface data of one hundred years (1900-1999). They showed that the structure of NAO in winter is different if the data are stratified with respect to years of high or low solar activity. The regression maps for the Northern hemisphere winter mean sea level pressure show that the pattern is similar over the polar areas, but rather different over the mid and high latitudes. For low solar activity, the spatial feature of the NAO pattern in the Atlantic is manifested. In addition, there is a positive center of action present in the Pacific, so that the classical image of AO is displayed. During solar high activity, there is an eastward shift of the Atlantic positive center into Europe, while the feature over North Pacific vanishes. This difference in the spatial structure in the North Atlantic region between solar maximum and solar minimum years and the lack of the Pacific feature is also evident in the geopotential height analysis throughout the troposphere. Its been also showed that during the maximum phases of the solar cycle, the NAO has a hemispheric structure extending into the stratosphere, while during the minimum phases, the NAO is confined to the eastern Atlantic sector in the troposphere.

3. Model and Data

The climate simulation used here is the NASA Goddard Institute for Space Studies (GISS) ModelE atmospheric GCM (Schmidt et al.,2006) coupled to a fully dynamic ocean. The model includes fully interactive atmospheric chemistry extending from the surface to the lower mesosphere. The configuration used is horizontal resolution of 4 by 5 degrees with 23 vertical layers in the atmosphere, and including a gravity-wave drag (GWD) parametrization in the stratosphere. The HYCOM ocean model includes 16 vertical layers with horizontal resolution of 2 by 2 cos(latitude) degrees. Equilibrium simulations were performed for spectrally discriminated irradiances. Initial conditions were taken from pre-industrial simulations. The GCM was run for 100 years each at solar maximum and minimum irradiances specified by wavelength-dependant changes at longer wavelengths consistent with total solar cycle irradiance variations. A spin-up time of 30 years was required for equilibrium, results are therefore based on the last 70 years of 100-year simulation. The transient climate simulations are run from 1880 to 2003 using observed forcings (Hansen et al.,2005). These simulations explore the response to volcanic eruptions, solar variations, greenhouse gas increases and polar ozone depletion. The model is mainly driven by increasing anthropogenic, well-mixed greenhouse gases, other trace gases, and aerosols, among other forcings.

The model data is compared with observed and reconstructed data for verification. For sea level pressure verification, we have used SLP reconstruction from Michael Mann(not published) from 1 AD to 2004. The available data is only for cold (Oct-Mar) and warm (Apr-Sep) seasons. Surface air temperature(SAT) data is compared with NASA GISS Surface Temperature Analysis(GISTEMP). GISTEMP provides a measure of the changing global surface temperature with monthly resolution for the period since 1880, when a reasonably global distribution of meteorological stations was established. Input data for the analysis, collected by many national meteorological services around the world, is the unadjusted data of the Global Historical Climatology

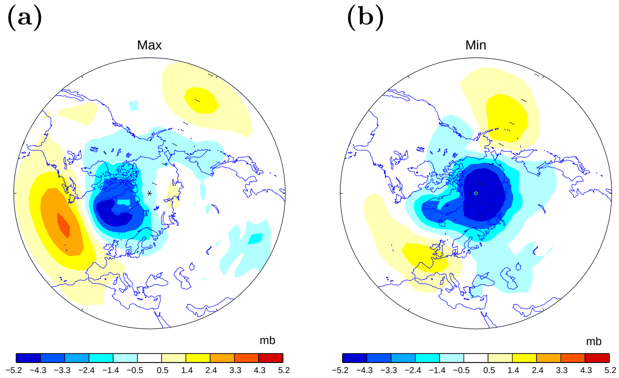

FIG. 1. Normalized SLP regressed onto first rotated, normalized principal component for (a)maximum and (b)minimum solar phases. (a) shows NAO-like pattern with a strong positive center of action in the Atlantic sector and a negative center of action over Greenland. (b) for solar minimum phase positive anomaly is shifted eastwards.

Network. These data were augmented by SCAR data from Antarctic stations. Documentation of GISTEMP analysis is provided by Hansen et al. (1999), with several modifications described Hansen et al. (2001). Solar forcing time series is taken from (Crowley 2000). This is Lean et al. (1995) time series (1610-1998) that has been extended to 1000 by splicing in different estimates of solar variability based on ice core measurements of ^{10}Be, residual ^{14}C from tree ring records, and an estimate of ^{14}C from ^{10}Be fluctuations.

4. Results

We focus on the region north of 20^o. The main variability in this region during cold season/winter is explained by NAO/AO. Thus our analysis mainly focuses on winter(DJF) and/or cold(Oct-Mar) season variability. We have also looked at summer(JJA) and warm(Apr-Sep) seasons to study seasonal range. The EOF analysis is performed on winter(DJF) SLP data from solar equilibrium simulations for maximum and minimum solar conditions. Regression maps of the normalized SLP field onto rotated leading principal components are shown in figure(1). During solar maximum phase, we see a strong positive anomaly in Atlantic whereas the positive anomaly is shifted eastwards during solar minimum phase. A positive center of action is present in the Pacific for both conditions. These results do not agree completely with (Kodera 2002, 2003) results.

When EOF analysis is done on SLP reconstruction of historical time from 1350-1800, the regression pattern figure(2) shows NAO-like structure. The first principal component time series shows strong correlation(figure 3)with the solar reconstruction. For his purpose, running mean of 59 years is calculated. This era is marked by a minima in solar irradiance and so we compare this result with solar equilibrium simulation for minimum solar forcing shown in figure(1a). Two regression patterns have similar spatial structure with positive anomalies in eastern Atlantic/western European sector and in the Pacific sector.

The results from the transient simulation with all forcings are compared with in situ, satellite, and reanalysis data, and are described in Schmidt and et al. (2006). We compared surface air temperature results with GISTEMP results (not presented here). The observed large scale spatial patterns are well produced in transient simulations. For EOF analysis, anomalies are calculated by subtracting 1951-1980 mean and the annual cycle is removed from the data set. The rotated(varimax) EOF analysis is performed on SLP data to determine climatic modes of variability. The SLP field is regressed onto principal component to study the contribution of a particular mode. The first regression pattern shows a classical NAO like pattern (not shown). The second regression pattern (figure 4)shows positive anomaly in the western Europe and negative anomaly over Siberia. The corresponding principal component(figure 5) correlates with solar irradiance time series when filtered to allow time scales greater than 20 years, thus taking into account multidecadal fluctuations in solar irradiance. Similar analysis

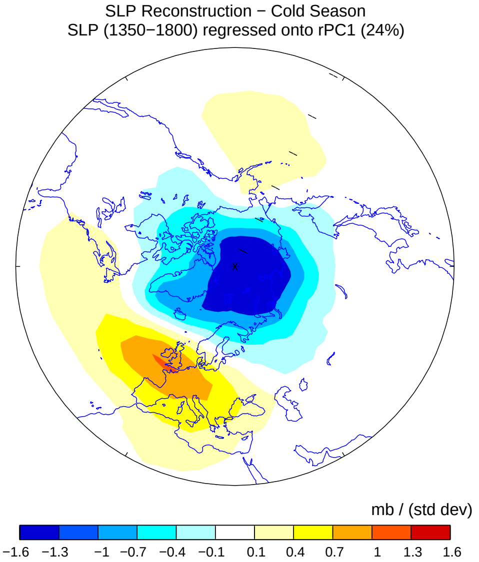

FIG. 2. Cold season reconstructed SLP regressed onto the first rotated normalized principal component of SLP field from 1350-1800.

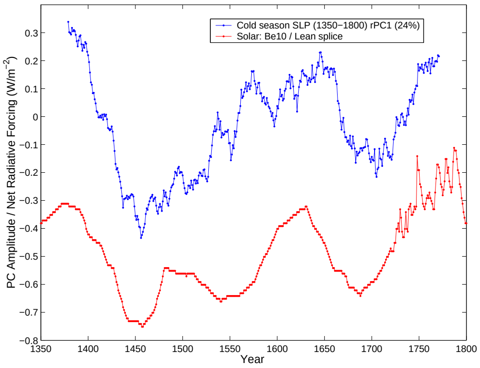

Fig. 3. A comparison between reconstructed SLP first principal component and solar forcing time series. The running mean of 59 years is calculated for SLP PC. The two series show similar variability at longer(multidecadal time scales.)

was carried out to see if 11-year solar cycle modulation signal is present in the model result. But no such correlation was observed.

These results show the dependence of winter SLP variability on the phase of the solar cycle. To understand the effect of solar variability, we calculate the difference between the climate response for maximum and minimum solar phases for cold season(Oct-Mar). The similar difference is also studied in the reconstructed SLP data. For reconstructed data, maximum and minimum solar phases are determined by plotting solar forcing time series and choosing years above and below a certain threshold, the choice of which is arbitrary, and then introducing a lag of 18 years. The difference between leading EOFs of SLP for maximum and minimum solar simulation and for SLP reconstruction are shown in figure(6). Although magnitudes of anomalies are different for simulated and reconstructed data, anomalies in the Atlantic sector have similar spatial structure, with the difference being negative in the Atlantic sector and positive over the pole and Greenland. Results do not match for Europe and Asian continents but this could very well be due the uncertainty in how the years of high and low solar phases are chosen. Besides, the results are also affected by the lag introduced and whether the solar forcing time series is de-trended or not.

5. Discussion

In general, it is difficult to detect solar signal in all forcings model run. This preliminary analysis shows, by comparing historical and modern climate data, we can detect a signature of solar forcing in the Northern hemisphere extra-tropical climate variability. When the SLP time series are regressed over the corresponding PC, we see a shift in positive anomaly over western Europe depending upon the phase of the solar cycle. This spatial feature is also observed in solar equilibrium runs for maximum and minimum solar phases. The European Maunder Minimum winter cooling with enhanced northeasterly advection of continental air is consistent with an anomalous negative NAO (Shindell et al. 2001). A lagged climate response to solar forcing is anticipated, but not studied in great detail here. EOF analysis to detect and attribute climatic modes of variability to various forcing poses several problems. The resultant EOFs and PCs depend on the methodological choices made such as, dispersion matrix, rotation and number

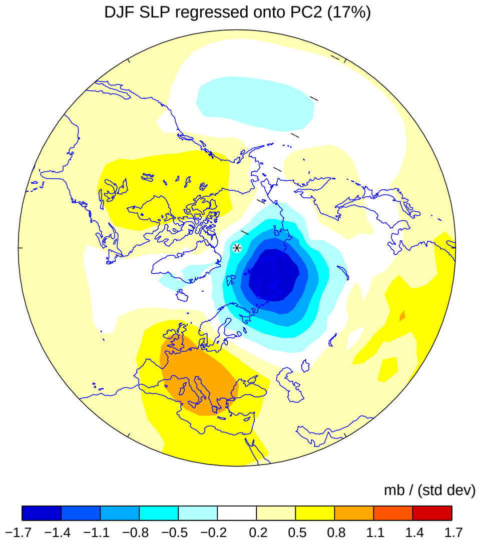

Fig. 4. Regression pattern of DJF SLP for GISS ModelE. The winter SLP field is regressed onto the second rotated principal component.

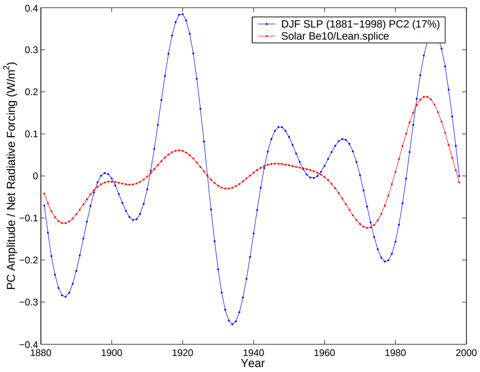

Fig. 5. A comparison between winter SLP second principal component and solar forcing time series. Both time series are filtered to include years greater than 20 years. There is no clear indication of lag between the two series.

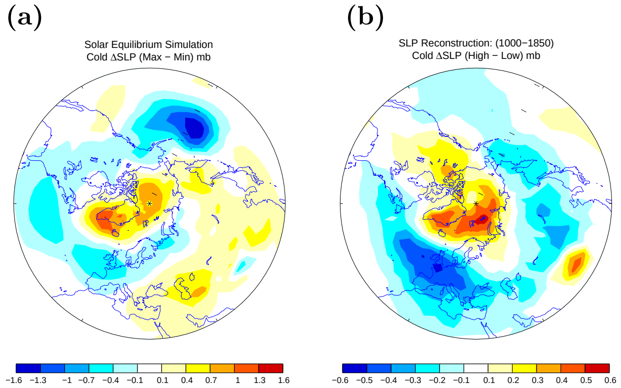

FIG. 6. The difference between maximum and minimum solar conditions for cold season. (a) the difference between regressed SLP field onto leading PC for solar maximum and minimum phases. (b) same as (a), but for reconstructed SLP with lag of 18 years.

of EOFs retained. The analysis for warm season is not presented here but it shows no definite spatial structure as seen in winter.

Shindell et al. (2003, 2000, 1999) describes a physical mechanism explaining the effect of solar forcing on climate. In contrast to the case of increasing greenhouse gases, the initial temperature changes induced by solar variability take place much higher in the stratosphere. The troposphere sees no direct change in thermal gradients, but instead sees altered planetary wave propagation as the driving force behind changes. It is the changes in wave propagation that lead to the altered temperatures and circulation patterns in the lower stratosphere, as well as in the troposphere. Stratospheric ozone feedback plays a crucial role in the amplification process whereby solar heating variations modify zonal wind, altering wave propagation, which then alters the equator-to-pole energy transport. So to understand a complete dynamics, a study of upper level fields is necessary.

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