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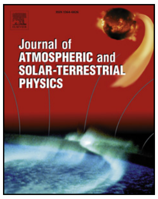

Decadal variability in the Northern Hemisphere winter circulation: Effects of different solar and terrestrial drivers

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ABSTRACT

Northern Hemisphere winter circulation is affected by both solar and terrestrial forcings. El-Niño events and volcanic eruptions have been shown to produce a negative and a positive North Atlantic Oscillation (NAO) signature, respectively. Recent studies show a positive NAO signature related to both geomagnetic activity (proxy for solar wind driven particle precipitation) and sunspot activity (proxy for solar irradiance). Here the relative role of these four different drivers on the Northern Hemisphere wintertime circulation is studied using a statistical analysis of observational and reanalysis data during 1868–2014. The phase of the Quasi-Biennial Oscillation (QBO) is used to study driver signals in different stratospheric conditions. Moreover, the effects are separated for early/mid- and late winter. Our findings suggest a stratospheric mediation of the ENSO signal to the Atlantic side, which is delayed and modulated by the QBO unlike the signal in the Pacific side. The positive NAO by volcanic activity is preferentially obtained in the westerly QBO. We also find a substantial QBO modulation for geomagnetic activity and late winter sunspot activity, which favours a stratospheric pathway and the top-down mechanisms. However, signal in the North Pacific produced by early/mid-winter sunspot activity remain rather similar in different QBO phases and supports a direct forcing from the troposphere by the bottom-up sunspot mechanism.

1. Introduction

Winter conditions at high-latitudes of the Northern Hemisphere are known to be affected by several climatic variables. ENSO (El-Niño Southern Oscillation) has been shown to affect European winter conditions at least since the early 1700s (Brönnimann et al., 2007b). Huang et al. (1998) have shown that there exists a significant coherence between ENSO and the North Atlantic Oscillation (NAO) during the 20th century. Positive ENSO (El-Niño) events have been shown to cause a negative NAO response (Pozo-Vázquez et al., 2001). On the other hand, this response has been found to be dependent on the strength of the ENSO event (Toniazzo and Scaife, 2006). Moderate El-Niño events have been shown to produce a negative NAO by intensifying the propagation of Pacific extra-tropical stationary planetary waves to the stratosphere and weakening the polar vortex (Bell et al., 2009). During the strongest El-Niño events the stratospheric pathway is saturated and forcing through the tropospheric tropical Atlantic produces a feature that resembles a positive NAO in Western Europe (Bell et al., 2009). Recently, Herceg-Buli et al. (2017) have shown that the ENSO signal in the North Atlantic can experience a lag so that in springtime it consists of a direct forcing from the stratosphere and a delayed forcing generated by the atmosphere-ocean interaction. Ineson and Scaife (2009) have also shown that the downward progression of an ENSO signal from the stratosphere reaches the surface level of the Atlantic in late winter (Feb/Mar) with a few months delay relative to the stratospheric signal.

Other significant contributors to the winter conditions in the Northern Hemisphere are volcanic eruptions (Fischer et al., 2007). Major volcanic eruptions are typically followed by global cooling because of the enhanced scattering of incoming solar radiation (Robock, 2000). On the other hand, warm conditions in European winter dominate after volcanic eruptions and a positive NAO response is observed over the Northern Hemisphere (Shindell et al., 2004). This is due to enhanced heating of the lower equatorial stratosphere in the volcanic aerosol layer, which leads to increased meridional temperature gradient and acceleration of the polar vortex (Otterå et al., 2010).

Two different types of solar activity-related drivers are connected to NAO surface signals, the solar irradiance related variations (Gray et al., 2010) and the solar wind-related variations (Seppälä et al., 2014). Solar irradiance (TSI and solar EUV/UV) variations roughly follow the sunspot cycle (Lockwood and Fröhlich, 2007), although recent observations have proposed that some other parts of the solar spectrum can vary differently (Ermolli et al., 2013). Enhanced solar UV irradiance

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during sunspot maximum years increases ozone production in the equatorial stratosphere (Haigh, 2007), leading to enhanced equatorial heating and larger meridional temperature gradient (Frame and Gray, 2010; Mitchell et al., 2015). This intensifies stratospheric westerly winds in the winter at mid to high latitudes (Mitchell et al., 2015) due to the thermal wind balance (Holton, 2004). Changes in the polar vortex strength are known to affect the surface circulation (Baldwin and Dunkerton, 2001; Kidston et al., 2015). In the context of solar forcing, this mechanism is often called the top-down mechanism (Kodera and Kuroda, 2002). Thiéblemont et al. (2015) suggested that this top-down mechanism synchronizes an intrisic decadal mode of the NAO, leading to a positive NAO signal in the years following solar maximum.

In addition, another forcing related to solar irradiance called the bottom-up mechanism is operating in the Pacific region (Cubasch et al., 1997; Meehl et al., 2008). It enhances the trade winds and produces a stronger ITCZ (intertropical convergence zone) due to increased total solar irradiance (TSI) energy input on the surface at cloud-free areas during sunspot maximum. This is seen in the surface temperature as a La-Niña type feature and as a positive sea-level pressure (SLP) anomaly in the Aleutian region (van Loon et al., 2007). Note however that this mechanism might be sensitive to the chosen time period (Roy and Haigh, 2012).

Another pathway whereby solar forcing can act terrestrial climate is by the high speed solar wind streams from coronal holes, which typically maximizes a few years after sunspot maximum (Mursula et al., 2015). The flux of magnetospheric energetic particles (Asikainen and Ruopsa, 2016) and the level of geomagnetic activity closely follow the solar wind speed. Enhanced energetic particle precipitation into the upper polar atmosphere during polar night produces reactive nitrogen (Funke et al., 2014) and hydrogen oxides (Andersson et al., 2014), which can destroy ozone in the mesosphere and the upper stratosphere in catalytic reactions (Rozanov et al., 2012; Andersson et al., 2014; Fytterer et al., 2015a; b; Arsenovic et al., 2016). This leads to thermal and dynamical changes in the stratosphere, accelerating the polar vortex (Baumgaertner et al., 2011; Seppälä et al., 2013) and enhancing the positive NAO (Maliniemi et al., 2016).

Long-term surface climate records have shown that the positive NAO conditions are systematically observed during the declining phase of the sunspot cycle when geomagnetic activity typically maximizes (Maliniemi et al., 2014). In addition, the long-term relation between geomagnetic activity and the NAO is better observed in late winter (Maliniemi et al., 2016). The descent of NO_x from the thermosphere/mesosphere can take months to reach the stratosphere (Funke et al., 2014). Seppälä et al. (2013) have noted that due to this delay, the late winter is affected by precipitation from the early winter, and geomagnetic forcing after January is less likely to result in a significant effect. Lu et al. (2008) have shown that zonal wind and temperature anomalies related to solar wind variability are stronger later in winter with a lag of a few months.

The quasi-biennial oscillation (QBO) operates in the equatorial stratosphere, affecting also the extra-tropical stratosphere and the strength of the polar vortex. The polar vortex is stronger (weaker) during the westerly (easterly) QBO phase (Holton and Tan, 1980, 1982; Anstey and Shepherd, 2014). This Holton-Tan effect is explained by the poleward movement of zero wind line during the easterly QBO, which guides planetary waves more to the high latitudes (Baldwin et al., 2001). Flury et al. (2013) have shown that the speed of the Brewer-Dobson circulation depends on the QBO phase so that the vertical speed in the tropical stratosphere is stronger during the easterly QBO measured at 30 hPa. Polar vortex strength and the Brewer-Dobson circulation are usually strongly anticorrelated, both depending strongly on the wave forcing in the stratosphere (Salby and Callaghan, 2003). The QBO has also been shown to control the sunspot (Labitzke and van Loon, 1988; Roy and Haigh, 2011) and the solar wind related (Maliniemi et al., 2016) signals in the troposphere, as well as the ENSO forcing of the Northern Hemisphere (Calvo et al., 2009; Hansen et al., 2016).

In this paper we study the statistical relationship of winter surface circulation (SLP and zonal wind) to ENSO, volcanic activity, geomagnetic activity and sunspot activity from the late 19th century to the modern times using a multilinear regression. Earlier studies have indicated that a notable variability in direct and lagged signal related to ENSO (Herceg-Buli et al., 2017), geomagnetic activity (Maliniemi et al., 2016) and sunspot activity (Gray et al., 2016) can exist within a winter. For this reason we study early/mid-winter (Dec–Jan) and late winter (Feb–Mar) separately allowing the possible lagged signals to emerge. In addition, we also study the effect of the above mentioned four forcings in the two QBO phases separately. This allows us to make tentative conclusions on how the different forcings are mediated and whether the stratosphere plays a major role. The paper is organized as follows. In Section 2 we present the data and the methods. In Section 3 we discuss the SLP results in early and late winter, and in Section 4 the effect of the QBO phase. Section 5 presents the results for the zonal wind. Conclusions are given in Section 6.

2. Data sets and statistical methods

We use the monthly SLP observations by the Hadley center (Allan and Ansell, 2006), available since 1850, and the 20th century reanalysis surface zonal wind (ZW) data (Compo et al., 2011), available since 1851, representing surface circulation during winter. Both of these data sets are gridded in latitude-longitude bins (5° × 5° for SLP and 2° × 2° for ZW) over the whole globe. The monthly Nino3.4 index of sea surface temperature (averaged over 5N-5S and 170W-120W) from NOAA, available since 1856, is used to represent ENSO. Volcanic activity is represented by the updated stratospheric optical depth data by NASA (Sato et al., 1993) averaged over the Northern Hemisphere. (This data is available since 1850 and we have extended this series from the end of 2012 to the end of 2014 with zero values). QBO at 30 hPa height is obtained from the long-term reconstruction by Brönnimann et al. (2007a), which extends to year 1900. This reconstruction is based on relatively sparse observations of ozone and balloon measurements before the 1950s and thus includes considerable uncertainty in the early 20th century. Yet, Brönnimann et al. (2007a) state that it captures reasonably well the maximum phases of the QBO already since 1910.

The sunspot number (SSN) is used as a proxy for total and UV solar irradiances. Sunspot data for monthly resolution extends to year 1749. Earlier studies have shown that solar TSI and UV closely follow sunspot activity (see e.g. Lockwood and Fröhlich, 2007) at monthly and longer timescales. Monthly averaged aa index of geomagnetic activity is used as a proxy for solar wind and particle precipitation related activity. This data is available since 1868 and is defined by the measurements from two stations, located in South England (Greenwich 1868–1925, Abinger 1926–1956 and Hartland 1957-) and Southeast Australia (Melbourne 1868–1919, Toolangi 1920–1979 and Canberra 1980-).

The solar dynamo defines the magnetic activity of the Sun and consists of two components, the toroidal and the poloidal phase (Ruzmaikin and Feynman, 2001). Sunspot activity follows the toroidal phase, whereas solar wind speed is related to the poloidal phase (Ruzmaikin and Feynman, 2001). Geomagnetic activity has contribution from both the toroidal and the poloidal phase, and we use the method introduced by Feynman (1982) to separate these contributions. Thus, the poloidal aa index (aa*) for Dec/Jan is obtained as $aa^* = aa - 0.0515 \times SSN - 6.3$, which removes the toroidal component from the aa index. Thereafter, the poloidal component aa* has only marginal correlation (0.09) with SSN, whose correlation with the Dec/Jan averages of the original aa index is 0.48 (p-value < 0.01) during 1868–2014. The correlation between the original aa index and the aa* index for the same time period is still very high (0.91, p-value < 0.01), which shows that the poloidal component dominates geomagnetic activity.

We use a multilinear regression with four explaining variables: the Nino3.4 index, the stratospheric optical depth, the aa* index and the