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Effects on winter circulation of short and long term solar wind changes

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Abstract

Indices of the North Atlantic Oscillation and the Arctic Oscillation show correlations on the day-to-day timescale with the solar wind speed (SWS). Minima in the indices were found on days of SWS minima during years of high stratospheric aerosol loading. The spatial distribution of surface pressure changes during 1963–2011 with day-to-day changes in SWS shows a pattern resembling the NAO. Such a pattern was noted for year-to-year variations by Boberg and Lundstedt (2002), who compared NAO variations with the geo-effective solar wind electric field (the monthly average SWS multiplied by the average southward component, i.e., negative Bz component, of the interplanetary magnetic field). The spatial distribution of the correlations of geopotential height changes in the troposphere and stratosphere with the SWS; the geo-effective electric field (SWS*Bz); and the solar 10.7 cm flux suggests that solar wind inputs connected to the troposphere via the global electric circuit, together with solar ultraviolet irradiance acting on the stratosphere, affect regional atmospheric dynamics.

Keywords: Arctic Oscillation; North Atlantic Oscillation; Solar wind speed; Relativistic electrons; Global electric circuit

1. Introduction

There is much uncertainty about the mechanism(s) of observed linkages between solar activity and weather and climate change, while there is a wealth of data to show that such linkages exist (a few examples are as in Roberts and Olson, 1973; Eddy, 1976; Fleitmann et al., 2003; Wang et al., 2005). Responses of the lower atmosphere to space weather for short timescales (a few hours to a few days) as well as long timescales (seasonal to decadal) have been observed. Changes in tropospheric dynamics are found to correlate on short time scales with solar wind parameters such as its speed and the components of its magnetic field. In addition, longer term tropospheric and stratospheric changes correlate with total solar irradiance and solar ultraviolet irradiance as well as space weather parameters (Gray et al., 2010). The influences of energetic space particles and space electric and magnetic fields can potentially account for some of the variability in the lower atmosphere, such as in cloud cover (Marsh and Svensmark, 2003; Kniveton and Tinsley, 2004) polar surface pressure (Burns et al., 2008) and winter cyclone vorticity (Roberts and Olson, 1973; Svalgaard, 1973; Tinsley and Deen, 1991; Veretenenko and Thejll, 2004; Tinsley et al., 2012).

A correlation between the interplanetary magnetic field (IMF) direction changes and changes in the vorticity of winter storms (represented by the Vorticity Area Index or VAI) was found by Wilcox et al. (1973) and confirmed by the later work by Kirkland et al. (1996) and Tinsley et al. (1994, 2012). The changes in the IMF direction occur as the heliospheric current sheets, that form the boundaries of solar wind magnetic sectors, pass over the Earth (HCS crossings), and the later work showed that these also coincide with changes in the solar wind speed (SWS) and the precipitation of relativistic electrons from the radiation belts. The VAI was defined by Roberts and Olson (1973), for extended winters, November through March, for latitudes poleward of 20°N, and for 300 hPa levels in the

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atmosphere, but can be evaluated for any latitude range; for any pressure level; with any threshold vorticity, and for any months. Systematic changes in the strength of cyclogenesis, measured by the VAI in a given hemisphere, affect the amplitude of Rossby waves, and these changes in atmospheric circulation, downstream of a cyclogenesis center, can affect regional climate. The short time scale of the day-to-day VAI responses avoids the confounding effects, such as cycles from ocean–atmosphere coupling, present in longer term atmospheric variability.

Starting from monthly averages, Boberg and Lundstedt (2002, 2003) constructed a proxy (E) for the solar wind geo-effective electric field, by taking the monthly average SWS and multiplying it by the monthly mean of the negative IMF Bz component. With negative Bz there is stronger coupling of solar wind energy into the magnetosphere for a given SWS than for positive Bz. They found that there was strong correlation between annual mean value of E and atmospheric pressure and temperature distributions that resembled the North Atlantic Oscillation (NAO). The NAO index (Visbeck et al., 2001) is the sea-level pressure difference between stations in the northern Atlantic (e.g. Iceland) and subtropical Atlantic (e.g., the Azores). Boberg and Lundstedt (2002, 2003) showed strong responses in both the high altitude region (above the 50 hPa level) as well as in the troposphere, and concluded that the high altitude change due to the solar wind geo-effective electric field subsequently propagated down into the troposphere. Downward propagation of zonal wind perturbations from the stratosphere can result in changes in the tropospheric circulation patterns. Baldwin and Dunkerton (2001) and Reichler et al. (2012) showed that changes in the stratospheric mean flow could influence the development of circulation patterns such as the NAO, with the downward propagation taking between 15 and 50 days. Because of this propagation time, such downward propagation cannot be the cause of the tropospheric responses to the solar wind input with a time delay no more than a day. Furthermore, stratospheric mean flow anomalies that propagate downward to induce tropospheric circulation patterns, such as the NAO, may not necessarily be due to external forcing of the stratosphere (e.g., by particle precipitation affecting ozone chemistry, or by solar UV changes). Baldwin and Dunkerton (2001) and Reichler et al. (2012) noted that the modification of the stratospheric mean flow that influences tropospheric circulation could be due to waves originating in the troposphere. Reichler et al. (2012) used a model with no external forcing to generate strong stratospheric zonal flow anomalies that then propagated down to the troposphere. They suggested that stochastic forcing from the troposphere, producing dynamic wave forcing of the stratospheric flow, was responsible for the stratospheric zonal flow anomalies. Thus a direct forcing of the troposphere from the solar wind, as suggested by Tinsley (2012) due to invigoration of cyclones due to changes in cloud microphysics, that respond to the current flow in the global electric circuit forced by the solar wind, could be a source of dynamic waves affecting stratospheric flow. On the other hand, there is evidence for changes in the mean flow and temperature of the stratosphere caused by UV and QBO and energetic particle forcing (Gray et al., 2010), so several mechanisms could be contributing to the observed stratospheric responses to solar activity.

The responses on the day to day time scale have been shown to involve both the relativistic electron flux (REF), precipitating from the radiation belts at subauroral latitudes, and stratospheric volcanic aerosols. A strong correlation between the REF and the SWS has been examined by Li et al (2001a,b). Tinsley et al. (1994, 2012) described a link between space weather and lower atmospheric dynamics through the global electric circuit. Minima in the SWS and deep minima in the REF are associated with the HCS crossings, as shown by Tinsley et al. (1994, Fig. 5). The REF can penetrate down to upper stratospheric levels, and the Bremsstrahlung radiation that they produce can impact the electric conductivity down to lower stratospheric levels and change the stratospheric electrical column resistance. The consequent changes in the ionosphere-earth current density (Jz) that flows as the downward return current in the global electric circuit was considered to be the physical link to the tropospheric cloud and dynamical changes, especially when there is high stratosphere aerosol loading due to volcanic eruptions, which will increase the proportion of the stratospheric column resistance to that of the whole atmosphere column. Observations of minima in tropospheric potential gradient and Jz at HCS crossings have been reported by Reiter (1977), and Fischer and Mühleisen (1980) also observed such potential gradient minima.

According to the hypothesis of Tinsley et al. (1994) this effect is considered to occur for several years following volcanic eruptions that inject large quantities of SO_2 gas into the stratosphere. This SO_2 forms H_2SO_4 on a timescale of months, followed by production of ultrafine aerosol particles from the gaseous H_2SO_4 (Goodman et al., 1994). When carried into the higher temperatures of the upper stratosphere by the Brewer–Dobson circulation, the aerosol particles formed in the lower stratosphere evaporate and/or are dissociated by radiation and become gaseous, but re-condense to form ultrafine aerosol particles as the air descends and diabatically cools in the downward branches of the circulation. Fig. 1 illustrates the variations in stratospheric aerosol content from 1850 to the present.

In this work the responses of Northern Hemispheric Annual Mode (AO index), NAO index, and surface pressure to SWS changes on the day-to-day timescale during the period 1963–2011 are evaluated. The AO index (Thompson and Wallace, 1998) is the leading empirical orthogonal pattern of sea level pressure anomalies. Both the AO and the NAO are indicators of baroclinicity, or the intensity of the general circulation in the North Atlantic, with the AO representing a larger area than the NAO. In winter the baroclinicity is one of the drivers for cyclogenesis in the north Atlantic. With positive NAO or AO

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