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Solar influences on atmospheric circulation

K. Georgieva [a], B. Kirov [a], P. Koucká Knížová [b], Z. Mošna [b], D. Kouba [b], Y. Asenovska [a]

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Abstract

Various atmospheric parameters are in some periods positively and in others negatively correlated with solar activity. Solar activity is a result of the action of solar dynamo transforming solar poloidal field into toroidal field and back. The poloidal and toroidal fields are the two faces of solar magnetism, so they are not independent, but we demonstrate that their long-term variations are not identical, and the periods in which solar activity agents affecting the Earth are predominantly related to solar toroidal or poloidal fields are the periods in which the North Atlantic Oscillation is negatively or positively correlated with solar activity, respectively. We find further that solar poloidal field-related activity increases the NAM index, while solar toroidal field-related activity decreases it. This is a possible explanation of the changing correlation between the North Atlantic Oscillation and solar activity.

Highlights

► Solar poloidal and toroidal fields have different long-term variations. ► The correlation NAO/solar activity changes with the ratio poloidal/toroidal field. ► Solar poloidal field-related activity increases the NAM index. ► Solar toroidal field-related activity decreases the NAM index.

Introduction

The influence of solar activity on the Earth's climate is a matter of high scientific as well as practical importance—not only because the chain of coupling processes from the Sun through the interplanetary medium to the Earth's magnetosphere, ionosphere and various atmospheric regions is a challenge to our present understanding of the underlying physical mechanisms, but also because the global warming observed in the XX century requires an objective estimation of natural versus anthropogenic factors for climate change in order to adopt the most appropriate strategies for environmental behavior with far reaching economical, political and societal consequences.

Solar variability is a result of the magnetic activity of the Sun, maintained by the action of the solar dynamo which transforms the solar poloidal field prevailing during sunspot minimum into toroidal field with a maximum at sunspot maximum, and back into poloidal field with the opposite magnetic polarity during the next sunspot minimum (Choudhuri, 2011). The different solar and heliospheric manifestations of solar variability are related to these two faces of solar magnetism: sunspots, solar flares, variations in total and spectral solar irradiance, coronal mass ejections and magnetic clouds – to the solar toroidal field, and coronal holes and high speed solar wind streams emanating from them – to the solar poloidal field (Feynman, 1982). These different manifestations of solar activity have different impacts on the terrestrial system (Boberg et al., 2005, Borovsky and Denton, 2006, Georgieva et al., 2006), resulting from different physical mechanisms. However, these impacts are not thoroughly studied, and the mechanisms are not yet clear enough.

The Earth's atmosphere is a highly complex system with a number of factors and processes determining its state which makes it difficult to detect the effect of solar activity on the background of the atmosphere's internal variability. An additional difficulty is that the effects are often nonlinear, and solar activity can at some times increase and at other times decrease the values of atmospheric parameters like surface air temperature, precipitation, circulation indices, etc. (Herman and Goldberg, 1978, and the references therein). This gives rise to doubts about the reality of the Sun–climate relations. An argument against the suspicion that the observed correlations between solar activity and atmospheric parameters are accidental is the finding that the way in which Sun affects the atmosphere changes rather systematically, depending on either the level of solar activity in its centennial cycle (Sazonov and Loginov (1969); Gimeno et al., 2003), or on the predominantly more active solar hemisphere (Georgieva and Kirov, 2007, Georgieva et al., 2007).

The present study is focused on the circulation in the northern hemisphere as characterized by the North Atlantic Oscillation (NAO) and quantified by the index of the Northern Annular Mode (NAM). The North Atlantic Oscillation is a large-scale seesaw oscillation of atmospheric mass between middle and high Atlantic latitudes determining the large-scale atmospheric circulation, temperature and precipitation over most of the northern hemisphere. This oscillation is detectable in all months but is most pronounced in winter. The NAO index is based on the difference of normalized sea level pressures between two atmospheric “centers of action” (large-scale semi-permanent high and low pressure systems): the Azores high and the Icelandic low. In winters in which the high pressure in the Azores is even higher than average, the low pressure in Iceland is even lower than average. In this case NAO is by definition in its positive phase associated with stronger than average midlatitude westerly (from the west) winds carrying warm and moist maritime air from the Atlantic over much of Europe and far downstream across Asia. This results in mild winters there. In the same time, the flow is anomalously southerly over the eastern United States and anomalously northerly across western Greenland, the Canadian Arctic, and the Mediterranean. The result is warming in North America and cooling in the North Atlantic, North Africa and the Middle East. The situation changes to the opposite in the NAO negative phase when both centers of action are weaker: the pressure is higher than average in the Icelandic low pressure region, and lower than average in the Azores high pressure region (Hurrell and Deser, 2009).

NAO is the surface manifestation of a more general hemispheric-scale pattern, the Northern Annular Mode (NAM) which is defined as the difference in atmospheric pressure between high (above 60°) and middle (around 45°) northern latitudes at pressure levels from 1000 hPa (surface) to 10 hPa (about 32 km). NAM in the lower stratosphere is also characterized by a seesaw in mass between the higher and middle latitudes, which is much more zonally symmetric than in the troposphere (Thompson and Wallace, 1998). In the NAM positive phase, the polar jet stream—stratospheric westerly winds that encircle the pole—is enhanced and the polar vortex is strong and anomalously cold. In the NAM negative phase, the polar vortex is weak, the polar jet stream slows and meanders so that the extensions of polar low pressure lobes reach much farther to the south and block the normal circulation of the atmosphere—the so called "blocking events" associated with cold waves in the Atlantic and in Europe (Rex, 1950).

Many authors have studied the effects of solar variability on NAO. Kodera (2002) showed that the spatial extent of NAO depends on the level of solar activity: during sunspot maximum, NAO has a hemispherical structure extending into the stratosphere, while during sunspot minimum, it is confined to the eastern Atlantic sector and to the troposphere. Huth et al. (2006) found that under solar maxima the NAO modes are more zonal, their teleconnections span longer distances, and their action centers occupy larger areas than during solar minima. Barriopedro et al. (2008) studied the solar activity effects on blocking events and demonstrated that the blocking episodes in the Atlantic last longer, are located further east and become more intense during low solar activity than during high solar activity.

On the other hand, it was pointed out that NAO depends more strongly on geomagnetic activity than on sunspot activity (Bucha and Bucha, 1998, Boberg and Lundstedt, 2002, Bochn变ček and Hejda, 2005) which could be an indication of the physical mechanisms involved. Woollings et al. (2010) argue that the open solar flux derivable from geomagnetic data is better correlated to atmospheric circulation variations than sunspot number or solar radioflux (proportional to the solar UV radiation), and that this means that the solar activity influences on the atmosphere could be realized via a modulation of the vertical propagation of planetary waves into the stratosphere in wintertime, or via anticyclonic Rossby wave-breaking. Model simulations of Baumgaertner et al. (2011) demonstrated that strong geomagnetic activity, through the associated NO_x (=NO+NO_2) enhancements, leads to a more stable polar stratospheric vortex associated with a positive NAM index.

However, the dependence of NAO on both solar (as measured by the number of sunspots) and geomagnetic activity varies in time. Thejll et al. (2003) found that the correlation between the geomagnetic Ap index and the NAO is high and significant since about 1970 but not before, which might indicate that a solar forcing, primarily acting in the stratosphere, is propagating its influence downward in the later period but not in the earlier. According to Palamara and Bryant (2004), the geomagnetic forcing of atmospheric circulation in the Northern Hemisphere is temporally and seasonally restricted and modulated by the Quasi-Biennial Oscillation (QBO), being significant for only January values after 1965, and for only years in which the January QBO is eastward. Lukianova and Alekseev (2004) placed the onset of "geomagnetic forcing" even earlier, in 1940s after which the rhythms of geomagnetic activity and NAO matched, while before that the correlation between them was weakly negative, possibly related to the reaching of a "threshold of sensitivity" of the atmospheric circulation to the high-latitude ionospheric electric field variations which are bigger for stronger interplanetary magnetic field. Georgieva et al. (2007) found that the correlation between the long-term variations of NAO and sunspot activity changes in consecutive secular solar cycles and seems related to the long-term variations in the north–south solar activity asymmetry: when the southern solar hemisphere is more active, increasing solar activity in the secular solar cycle results in increasing NAO, while when more active is the northern solar hemisphere, increasing solar activity decreases NAO, possibly due to the different effects on the atmospheric centers of action of magnetic clouds with different helicity originating from the two solar hemispheres. Li et al. (2011) suggested that the relationship between *aa*-geomagnetic index and the NAO is negative for small to medium *aa* and positive for medium to large *aa*. Besides, the *aa*–NAO relationship is dominated by the geomagnetic activity from the declining phase of even-numbered solar cycles, implying that an increase of long-duration recurrent solar wind streams from high latitude coronal holes during solar cycles 20 and 22 may partially account for the significant positive *aa*–NAO relationship during the last 30 years of the 20th century. Veretenenko and Ogurtsov (2012) studied the spatial and temporal structure of long-term effects of solar activity and galactic cosmic ray variations on the lower atmosphere circulation as well as possible reasons for the peculiarities of this structure. The study revealed that the temporal structure of solar activity/galactic cosmic rays effects on the troposphere circulation at high and middle latitudes is characterized by a roughly 60-year periodicity which is apparently due to the epochs of the large-scale atmospheric circulation. The authors suggest that a possible mechanism of long-term effects of solar activity and cosmic ray variations on the troposphere circulation involves changes in the evolution of the polar vortex in the stratosphere of high latitudes, as well as planetary frontal zones.

Geomagnetic activity results from different solar activity agents interacting with the Earth's magnetosphere, which are manifestations of the two types of solar magnetic field—toroidal and poloidal (Feynman, 1982, Georgieva et al., 2006, Verbanac et al., 2010). They are not independent as they are both produced by the action of the solar dynamo which transforms them into each other, similar to a simple harmonic oscillator transforming kinetic and potential energies into each other (Parker, 1955). However, their long-term evolutions may not be identical, and during a given period the one or the other may have the main impact to geomagnetic activity and terrestrial system in general (Georgieva et al., 2007). As the two types of solar agents have different effects on the Earth (Borovsky and Denton, 2006, Georgieva et al., 2006, Georgieva et al., 2007), the change in the correlation between geomagnetic activity and NAO may give a clue about the possible mechanisms through which the Sun affects atmospheric circulation and climate.

The goal of the present study is to investigate the long-term variations in the different manifestations of solar activity, and their influence on the atmospheric circulation in the Northern hemisphere. Section 2 presents the data sets we use. In Section 3 we derive the long-term variations in the solar poloidal field-related and toroidal field-related activity. In Section 4 we compare the influence of these two types of activity on the NAM index. In Section 5 we summarize and discuss our results.

Section snippets

Data

The International sunspot number R (http://solarscience.msfc.nasa.gov/SunspotCycle.shtml), the geomagnetic *aa*-index derived from two antipodal stations (Mayaud, 1972) available from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/RELATED_INDICES/AA_INDEX/, and its reconstruction back to 1844 based on data from Helsinki station only (Nevanlinna and Kataja, 1993), and F10.7—the solar radioflux at a wavelength 10.7 cm (http://www.ngdc.noaa.gov/stp/solar/flux.html) are used to quantify the different…

Solar activity and its geoeffective manifestations

By the term “solar activity”, all types of variations in the appearance and energy output from the Sun are denoted. The most prominent characteristic of the solar activity are the sunspots whose number increases and decreases cyclically with a period of ~11 years (Schwabe, 1843). Sunspots are associated with strong magnetic fields (Hale, 1912), and tend to occur in pairs, so that on one hemisphere the leading (with respect to the direction of the solar rotation) spots in all pairs have the same …

Effects of toroidal field-related and poloidal field-related sunspot activity on atmospheric circulation

To characterize the atmospheric circulation, we use the NAM-index calculated by Baldwin and Dunkerton, available online at http://www.nwra.com/resumes/baldwin/nam.php. The daily values of the NAM-index are calculated at 17 pressure levels: 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa based on the National Centers for Environmental Prediction (NCEP) reanalysis data for 1000–10 hPa during 1958–2006. For each pressure altitude, latitude, longitude, and day…

Summary and discussion

When evaluating the influence of solar activity on the terrestrial system, most often the number of sunspots is used because this is the solar activity index with the longest data record. However, sunspots themselves do not in any way affect the terrestrial system, they are just a manifestation of the solar activity caused by the solar toroidal magnetic field. The solar toroidal and poloidal fields are the two faces of solar magnetism, and in the course of the 22-year solar magnetic cycle, the…

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> …During Gleissberg minima, however, the two trends are opposite and are negatively correlated. The reasons for these phase reversals in correlation are still unclear and may be due to equator-to-pole temperature gradients (van Loon et al., 2012), variations in the solar dynamo fields (Georgieva et al., 2012), or just the confounding effects of internal variability. The variable relationship between solar forcing and NAO has also been discussed by Sjolte et al. (2018).…

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> …The solar-wind variables that control the viscous interaction are only known via theoretical analysis of physical processes that might be mediating the interaction (Eviatar and Wolf, 1968; Vasyliunas et al., 1982; Borovsky, 2013). Information about other impacts of the solar wind on the Earth system can be found in the literature (e.g. Tinsley, 2000; Georgieva et al., 2005, 2012; Rycroft et al., 2012; Rozanov et al., 2016; Lam and Tinsley, 2016; Georgieva and Shiokawa, 2018). This section discusses the solar wind coming from different types of regions on the solar surface.…

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Influence of solar activity changes on European rainfall

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> …During Gleissberg Minima, however, the two trends are opposite and are negatively correlated. The reasons for these phase reversals in correlation are still unclear and may be due to equator to pole temperature gradients (van Loon et al., 2012), or in the solar dynamo fields (Georgieva et al., 2012). The variable relationship between solar forcing and NAO has also been discussed by Sjolte et al. (2018).…

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2018, Journal of Atmospheric and Solar-Terrestrial Physics

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Solar signals detected within neutral atmospheric and ionospheric parameters

2018, Journal of Atmospheric and Solar-Terrestrial Physics

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>
> …A review of solar signals within meteorological data is provided by Haigh (2002) and references therein. However, the impacts of the various solar drivers on the atmosphere are not thoroughly studied, and the mechanisms are not yet clear enough (Georgieva et al., 2012). Around the year 1985, a change of the mechanism or a new forcing mechanism, different from solar activity, is detected in the climate evolution (Stauning, 2011).…

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