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Advances in Space Research 40 (2007) 1146–1151
Advances in Space Research (a COSPAR publication)
www.elsevier.com/locate/asr

Effect of solar variability on the Earth's climate patterns

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Received 30 October 2006; received in revised form 8 January 2007; accepted 8 January 2007

Abstract

We discuss effects of solar variability on the Earth's large-scale climate patterns. These patterns are naturally excited as deviations (anomalies) from the mean state of the Earth's atmosphere-ocean system. We consider in detail an example of such a pattern, the North Annular Mode (NAM), a climate anomaly with two states corresponding to higher pressure at high latitudes with a band of lower pressure at lower latitudes and the other way round. We discuss a mechanism by which solar variability can influence this pattern and formulate an updated general conjecture of how external influences on Earth's dynamics can affect climate patterns.
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Keywords: Solar irradiance; Climate and inter-annual variability; Solar variability impact; Climate dynamics

1. Introduction

The center of attention of this paper is the response of the Earth to solar variability on Space Climate time scales. In the context of Space Climate, the Earth can respond to solar variability on the 27-day solar rotation time scale, the 11-year solar cycle, the century scale Grand Minima, and even longer time scales. The shorter time scale effects are referred as Space Weather. Similar time scales discriminate the Earth's weather from the Earth's climate. Month-to-month and lower frequency variability on the Earth is considered to be climatic.

Observations, such as sunspot number records, indicate that the magnitude of solar variability increases from the solar rotation time scale to longer time scales. We can expect that in turn the Earth's responses become more pronounced with the increase of time scale. A transition from shorter to longer time scales implies averaging over small-scale atmospheric disturbances and the involvement of systems with more inertia than the atmosphere, in particularly the oceans.

Physical effects of solar variability involve either particles or irradiance. Here, we discuss the responses to variations in solar irradiance. The solar cycle variations in total solar irradiance are small, 0.1%. However the magnitude of irradiance variations strongly depends on the wavelength and increases for the shorter wavelengths. Thus solar UV, which amounts to only a few percentage of the total irradiance, contributes 15% to the change in total irradiance (Lean et al., 2005). Solar UV mainly affects the stratosphere by creating and destructing ozone (in different parts of the atmosphere and at different wavelengths of radiation) and causing temperature changes. Effects of these changes on the underlying troposphere, where we live, depend on stratosphere–troposphere interactions. These interactions, as we show below, involve large-scale dynamical climate patterns.

2. Climate patterns

Sir Gilbert Walker (Walker, 1928), who summarized anecdotal evidence on the connections between weather in distant parts of the Earth, introduced three large-scale coherent "swaying": North Atlantic Oscillation, North Pacific Oscillation, and Southern (South Pacific-Indian Ocean) Oscillation. Subsequently, numerous studies have demonstrated that the atmospheric and ocean variability on monthly and longer time scales is associated with

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doi:10.1016/j.asr.2007.01.076

large-scale spatial patterns. The North Atlantic Oscillation (NAO) was originally defined as a December to March mean of the sea level pressure difference between Iceland and Portugal (Hurrell, 1995). It is closely related to the North Annular Mode (NAM) (Thompson and Wallace, 1998), see Fig. 1. The counterpart of the NAM in the Southern hemisphere is called the SAM. Other examples of climate patterns are the Pacific-North America (PNA) pattern (Fig. 2), the Cold Ocean-Warm Land (COWL) pattern (Wallace et al., 1995), the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997), the well-known El Nińo – Southern Oscillation (ENSO), and the Quasi-Biennial Oscillation (QBO) in the stratosphere.

Recent studies of wintertime variability in the Northern hemisphere showed that all extratropical patterns can be effectively represented by linear combinations of the first two Empirical Orthogonal Functions (EOFs) calculated from the monthly grids of the sea level pressure or geopotential heights (Quadrelli and Wallace, 2004). The time series of principal components (PC) of these EOFs replace empirical indices of patterns. Hence the first two orthogonal EOFs and their PCs are sufficient, at least in the first approximation, to characterize the patterns and their persistence. More detailed climate properties, such as local precipitation, require higher-order EOFs. The NAM pattern (Fig. 1), which involves displacements of atmospheric mass between the Arctic basin and mid-latitudes, occupies a planetary-scale area north of 20° latitude (Thompson and Wallace, 1998). It is characterized by the change of the sign of geopotential height anomalies and the direction of the zonal wind anomalies at about 45°N. The NAM extends from sea level (1000 hPa) to at least the 10-hPa height in the stratosphere (Baldwin and Dunkerton, 1999). The pattern was identified as the first EOF of geopotential heights based on the data from the National Centers for Environmental Prediction (NCEP). This pattern and the PNA pattern (Fig. 2), which is close to the second EOF of geopotential heights (Quadrelli and Wallace, 2004), can approximately represent all major extratropical patterns in the Northern hemisphere. The positive phase of the PNA pattern features above-average heights in the vicinity of Hawaii and over the intermountain region of North America, and below-average heights located south of the Aleutian Islands and over the southeastern United States. This phase of the PNA pattern is also associated with above-average temperatures over western Canada and the extreme western United States, and below-average temperatures across the south-central and southeastern US (http://www.cpc.noaa.gov).

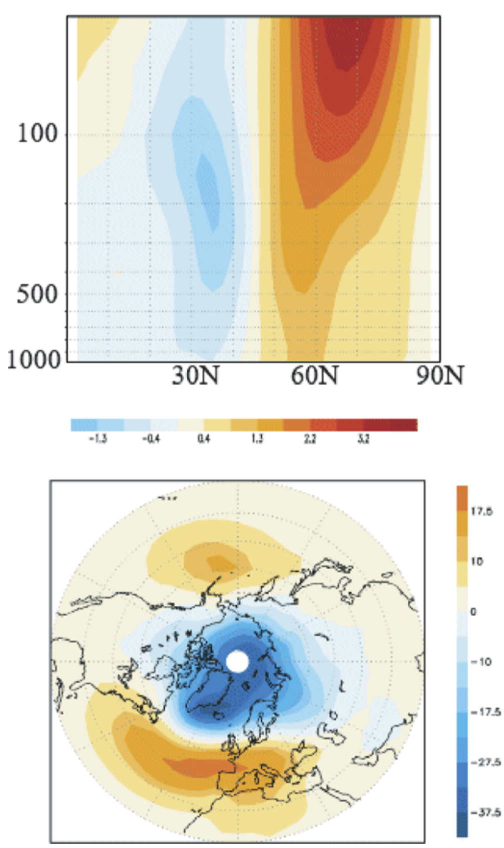

Fig. 1. The NAM pattern for zonal-mean wind in the height-latitude plane (top) and for the SLP (bottom), http://www.atmos.colostate.edu/ao.

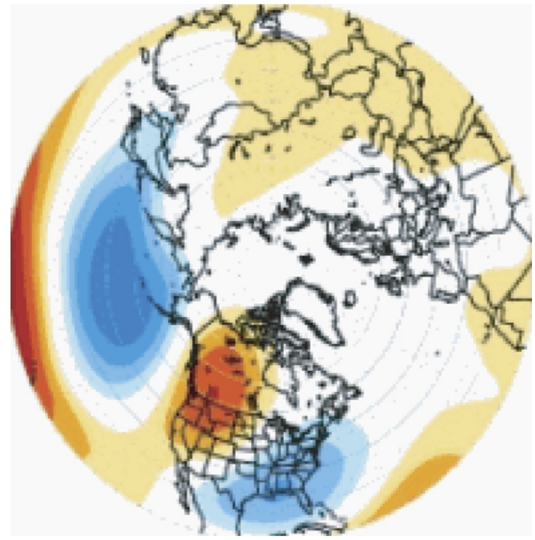

Fig. 2. The PNA pattern for geopotential height anomalies at 500 hPa. The pattern varies on monthly basis and shown for January (http://www.cpc.noaa.gov).

3. The influence of solar variability on the NAM

Since the North Annular Mode is one of the fundamental and better-known components of the atmospheric variability we focus our attention here on the influence of solar variability on the NAM.

Variability in the NAM is represented by its principal component, called "the NAM index", which is pronounced mainly during the winter season (December to March or often October to March). The PC can be positive or negative thus indicating two states of the NAM. Thompson and

Wallace (2001) found a significant difference in cold weather events in diverse regions (such as minimum winter temperatures in Chicago, Paris, and Tokyo) dependent on the sign of the NAM index. Hence, a connection between solar variability and the NAM would indicate that the Sun affects climate.

It has been shown that the NAM index at different heights of the atmosphere is statistically significantly affected by the solar variability (proxied by solar 10.7 cm flux) (Ruzmaikin and Feynman, 2002). The effect varies depending on the time in the winter and the direction of the tropical stratospheric winds (the QBO), see Fig. 3. A response of the stratosphere to solar variability, in particular at 30 hPa, and dependence of this response on the QBO phase was first discovered by Karen Labitzke (Labitzke, 1987) and further investigated by Labitzke and van Loon. For updated summary of their results see Labitzke, 2004. The most interesting new finding by Ruzmaikin and Feynman was that in the beginning of winter at West phase of the QBO and in the end of winter at East phase of the QBO the atmosphere responds to solar activity in a coherent manner stretching from sea level to the top of the stratosphere, thus outlining a vertical extension of the NAM pattern. For comparison we show the effect of solar variability on the PNA index (Fig. 4) calculated for the same time period 1958–1997 as used for Fig. 3. Note that although the PNA is close to the second EOF it is still a linear combination of the two EOFs (a reduced first and a strong second EOF).

Time evolution of the NAM spatial pattern can also be traced. Data analyses (Kodera, 1995; Baldwin and Dunkerton, 1999) and modeling (Shindell et al., 1999; Gray et al., 2003) show that wind anomalies in the upper middle stratosphere move poleward and downward during the winter. Hameed and Lee (2005) found that a greater fraction of stratospheric perturbations penetrate to the Earth's surface during solar maximum conditions than during solar minimum conditions. These anomalies are affected by the variable solar UV flux that impinge on ozone and temperature at the top of the stratosphere (Haigh, 1994). Through the thermal wind relationship temperature changes induce a gradient in the zonal wind that influences propagation of planetary waves. Since the interaction of the zonal-mean wind and planetary waves is considered as a probable mechanism of the NAM generation (see the next Section) the solar influence on this interaction may explain why the poleward–downward propagation of anomalies depends on the level of solar activity.

The effect of solar variability on the NAM is more pronounced on time scales longer than the solar cycle due to the thermal inertia of the oceans (Ruzmaikin et al., 2004). Empirical studies show that solar variability influences North African climate on multi-decadal time scales (Stager et al., 2005; Ruzmaikin et al., 2006). For example, using annual records of the water level of the Nile collected in 622–1470 A.D. two characteristic time scales that may be linked to solar variability were identified: a period of about 88 year and a period just exceeding 200 years (Ruzmaikin et al., 2006). These time scales are characteristic of the rate of auroras (caused by solar activity) that were recorded in the Northern hemisphere at the same time interval (Feynman and Fougere, 1984; Ruzmaikin et al., 2006). Ruzmaikin et al. (2006) suggested that a possible physical link between solar variability and the low-frequency variations of the Nile water level involves the influence of solar variability on the NAM and on its North Atlantic Ocean and

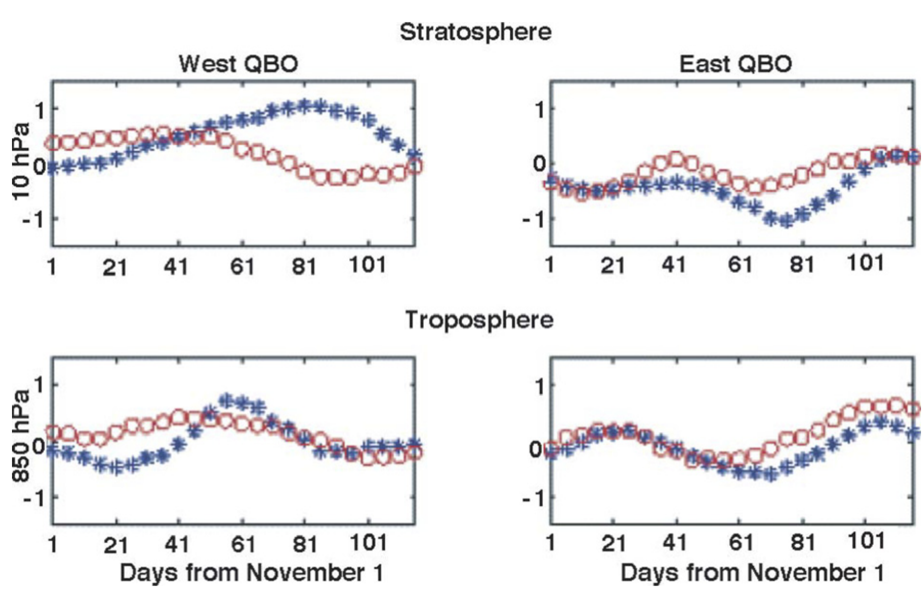

Fig. 3. The NAM index for the low-flux (asterisks) and high-flux (circles) conditions in the stratosphere (at 10 hPa) and in the troposphere (at 850 hPa) in winters 1958–1997. The values for the West QBO phase are on left panels, and the values for the East QBO phase are on right panels (Ruzmaikin and Feynman, 2002).

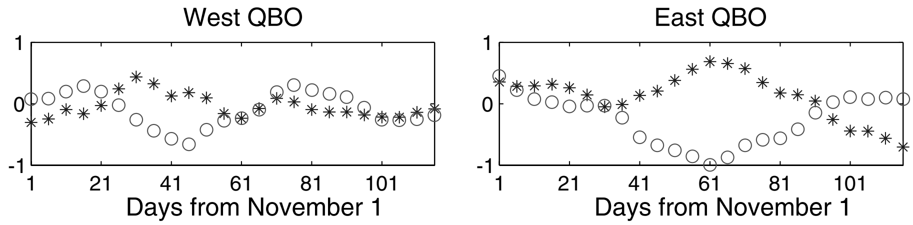

Fig. 4. The same as Fig. 3 for the PNA index extracted from 500 hPa winter anomalies in 1958–1997.

Indian Ocean patterns that affect the rainfall over the sources of the Nile in Eastern Equatorial Africa.

It has also been shown that the reconstructed sensitivity of the sea level temperature to a longer-term (multi-century) solar forcing in the Northern hemisphere (Waple et al., 2002) is in very good agreement with the empirical temperature pattern corresponding to changes of the NAM (Ruzmaikin et al., 2004). The temperature pattern (cold in Europe-warm in Greenland) associated with this mode was dominant during the Maunder Minimum.

Due to the fundamental nature of climate patterns it is important and challenging task to find out whether patterns like the NAM were present on millennium time scale. Solar variability on these time scales is well characterized by the ^{14}C and ^{10}Be records (Beer et al., 1994). Climate patterns on these time scales can in principle be inferred from paleo data collected over the globe.

4. Understanding the dynamics of climate patterns and the influence of solar variability

It is imperative to first understand the origin of the climate patterns before considering how solar variability could affect them. Although it is generally agreed that climate patterns are naturally excited by the atmosphere-ocean dynamical system the physical mechanisms of the excitation are still in an early state of investigation.

Carl-Gustaf Rossby (e.g. Rossby, 1941) was the first to emphasize the importance of two main ingredients of atmospheric dynamics: the zonal-mean zonal wind and non-zonally symmetric deviations of pressure (or geopotential heights). He described the non-zonally symmetric deviations as waves, which are now known as Rossby or planetary waves. These large-scale waves (the lowest mode changes its sign once over the 360°-long longitudinal circle) are generated by winter flow over mountains and by sea-land temperature contrasts and propagate in horizontal and vertical directions (Charney and Darzin, 1961). The vertical propagation of the waves into the stratosphere along the decreasing air density dramatically increases their amplitude. This increase often leads to non-linear wave breaking accompanied by energy release that produces temperature anomalies and sometimes reverses the direction of the zonal wind. The zonal wind in turn affects the wave propagation by modifying the refraction index. It was suggested and demonstrated in numerical simulations that the excitation of the first EOF (i.e., the NAM), which characterizes the zonally symmetric anomaly of atmospheric circulation, involves interaction between the planetary waves and the zonal-mean flow in the atmosphere (Limpasuvan and Hartmann, 2000). The second EOF (PNA-type pastern) reflects the non-zonally symmetric structure of the planetary waves (Quadrelli and Wallace, 2004).

The non-linear wave-zonal flow interaction (Holton and Mass, 1976) can be envisioned as a dynamical system with two basic states in its phase space corresponding to positive (negative) anomalies (Chao, 1985; Yoden, 1987; Ruzmaikin et al., 2003, 2006), i.e., positive (negative) NAM. The system, wandering between the two states, spends some time in residence at one or another state. Introducing an external forcing may change either the states or the residence times (occupation frequencies) of the states. Rossby (1941) hypothesized that forcing does not change the states (i.e., the spatial structure of the climate patterns usually characterized by the EOFs) and only affects the mean residence times of the states. The Rossby conjecture was further developed by Palmer (1999) and Corti et al. (1999). For visual illustration Palmer presented a picture with two cups representing the states, a ball randomly thrown from above for simulating occupation of the states, and a fan imitating the external force (Fig. 5a). He also supported the hypothesis by using as an example the well-known Lorenz dynamical system, which (for a certain range of parameters) has two basic states. However a further analysis of the forced Lorenz system (Khatiwala et al., 2001) showed that the change in the mean residence times is a small effect compared with a more dramatic change in the tail of the probability distribution of the residence times, meaning the increase in the frequency of occurrence of extremely persistent events. The main cause of this response can be understood when we consider the energetic barrier ΔU that impedes the system (the ball) from transition to the other state (Fig. 5b). (This feature is missing in the Rossby–Palmer conjecture, which deals only with EOFs and PCs.) As known from the 20th century studies, the probability of having a residence time T is $p = \exp(-T/T_K)$, where $T_K \propto \exp(\Delta U/\sigma)$ with σ describing a level of stochastic forcing that provides transitions from one state to the other (the Kramer's formula). An external forcing affects the depth of a state thus effectively increasing (or decreasing) the barrier. Due to the exponential sensitivity of the mean

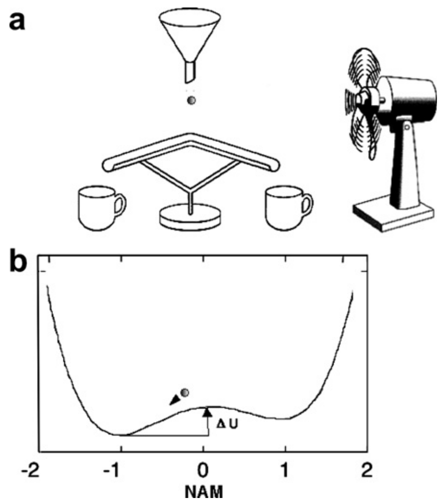

Fig. 5. A pictorial illustration of possible mechanisms by which solar variability could influence a climate pattern. (a) As envisioned by Palmer (1999). Solid caps correspond to two states of the pattern. Random dropping the ball controls population of the cups. Forcing is depicted as a fan, which tends to blow the ball toward the left hand cup. (b) As suggested here (see also Khatiwala et al., 2001). There is a barrier between the states. Random transitions from one state to another are controlled by internal Earth's dynamics. Solar variability (forcing) slightly changes the depth of one of the potential wells for some time leading to an exponentially amplified increase of the residence time in that well and, as a consequence, a longer persistence of this state.

residence time T_K, even a small change of the barrier may induce noticeable effect on the mean residence time. But the change in the probability of having residence sittings longer than $T_c \gg T_K$ is larger by a factor T_c/T_K ($\delta p/p = (T_c/T_K)\delta T_K/T_K$). Numerical simulations of a model double-well potential system with stochastic transitions between the wells support this rough estimate. When one of the wells is made deeper (by changing a parameter in the potential) the probability distribution of residence times in this well displays a longer tail (Khatiwala et al., 2001).

Does external forcing change the spatial structure of patterns? The model studies of simple Lorenz and double-well systems show that the positions of the wells are changed only slightly. Observational evidence of change in real patterns is limited so far, but Kodera (2003) found that during low solar activity the NAO pattern is confined to the Atlantic sector, while during the high solar activity the NAO-related anomalies extend over the whole Northern hemisphere.

5. Discussion

Linear and non-linear systems respond differently to external forcing. A classical example of a linear system response is the Hooke's law of elasticity that states that the amount by which a material body is deformed is linearly proportional to the force causing the deformation. Earlier climate change studies used this linear approximation to evaluate the sensitivity of the global temperature change caused by external forcing. However the response of non-linear systems to external forcing is conceptually different; the issue is not a magnitude (sensitivity) of the response. Non-linear systems have internally defined preferred states (called attractors in mathematics) and variabilities driven by residence in the states and transitions between them. The question is what is the effect of an external forcing: change of the states, residence times or something else? Answer to this question is critical to our understanding of climate change.

Based on the model studies mentioned above we can formulate the following, updated conjecture of the climate system response to external forcing: external effects, such as solar, the QBO and anthropogenic influences, weakly affect the climate patterns and their mean residence times but increase a probability of occurrence of long residences. In other words, under solar or anthropogenic influence the changes in mean climate values, such as the global temperature, are less important than increased duration of certain climate patterns associated say with cold conditions in some regions and warm conditions in the other regions.

Fig. 5b illustrates the updated conjecture in comparison with the Palmer illustration (Fig. 5a). Solar variability affects the state by making one potential well ('cup') deeper than another. When a change in the depth is significant the system ('ball') more often stays longer in the deeper well thus explaining a prolong persistence of this state (pattern). An example of a two-state system is the NAM. This example may be relevant to the predominance of the negative NAM pattern during the prolong period of reduced solar activity at the Maunder Minimum (Ruzmaikin et al., 2004).

Acknowledgements

I thank the reviewer for helpful comments. This work was supported in part by the Jet Propulsion Laboratory of the California Institute of Technology, under a contract with the National Aeronautics and Space Administration funded through the internal Research and Technology Development program.

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