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Solar forcing of the terrestrial atmosphere

Le forçage solaire sur l'atmosphère terrestre

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ABSTRACT

The Sun provides the main energy input to the terrestrial atmosphere, and yet the impact of solar variability on long-term changes remains a controversial issue. Direct radiative forcing is the most studied mechanism. Other much weaker mechanisms, however, can have a significant leverage, but the underlying physics is often poorly known. We review the main mechanisms by which solar variability may impact the terrestrial atmosphere on time scales ranging from days to millennia. This includes radiative forcing, but also the effect of interplanetary perturbations and energetic particle fluxes, all of which are eventually driven by the solar magnetic field.

RÉSUMÉ

Le Soleil est la principale source d'énergie de l'atmosphère terrestre, mais l'impact de sa variabilité reste un sujet à controverse. Le mécanisme le plus étudié est le forçage radiatif direct. Or d'autres mécanismes bien moins intenses peuvent avoir un effet de levier non négligeable. La plupart est mal comprise. Nous passons en revue les divers mécanismes par lesquels le Soleil peut affecter l'atmosphère terrestre sur des échelles de temps allant du jour aux millénaires. La liste inclut le forçage radiatif, mais aussi l'effet des perturbations interplanétaires et des particules de haute énergie. Tous ces mécanismes sont *in fine* entraînés par le magnétisme solaire.

1. Introduction

In two decades, the connection between solar activity and the Earth's atmosphere has moved from a mere curiosity to a hotly debated topic. Many reviews have been written, emphasising either the radiative forcing from a solar viewpoint (Foukal et al., 2006; Fröhlich and Lean, 2004; Lean, 1997; Lean, 2005; Lean and Rind, 1998) or from a terrestrial viewpoint (Haigh, 2005; Haigh, 2007), solar variability in general (Alley et al., 2007; Benestad, 2006; Calisesi et al., 2007; Friis-Christensen et al., 2000; Lockwood, 2005; Pap et al., 2004; Rind, 2002), historical aspects and long-term effects (Bard and Frank, 2006; Beer et al., 2006; de Jager, 2005; Hoyt and Schatten, 1997; Usoskin, 2008; Versteegh, 2005), and other, indirect mechanisms (Marsh and Svensmark, 2003; Tinsley, 2008). Here, we review the solar inputs to the terrestrial atmosphere and focus on their origin, the underlying physics and their observation.

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The Sun–Earth connection is a world of paradoxes. Until recently, this seamless system was widely considered as a stack of independent layers, and only in recent times did the interactions between these layers really attract attention. The role of the Sun in our solar system goes undisputed, and yet the effect of solar variability on the atmosphere remains quite controversial. As we shall see later, the main mechanisms by which the Sun affects the Earth are not the most immediate ones in terms of energetic criteria.

The Sun – like any living star – continuously radiates energy outward into the heliosphere. The radiated energy is carried by:

- electromagnetic waves over a frequency band ranging from radio waves to hard X-rays;
- a stream of hot plasma (the solar wind) consisting primarily of electrons and protons with a small fraction of heavier ions;
- an interplanetary magnetic field (IMF) which is carried along with the solar wind (often referred to as a frozen-in magnetic field);
- violent solar outbreaks such as solar flares and coronal mass ejections (CME) (Kamide and Chian, 2007).

The solar radiative output is nearly constant in time and accounts for about 1365 W/m^2 at a solar distance of 1 Astronomical Unit (AU), with a solar cycle dependent variation of the order of 0.1%. Under quiet solar conditions, the flow rates of the kinetic energy of the solar wind bulk motion and the solar wind thermal energy amount to about 5×10^{-4} W/m^2 each at 1 AU, i.e., a million times less than the radiative input. The energy flow rate of the IMF is another two orders of magnitude smaller, about 5×10^{-6} W/m^2. Yet, these different mechanisms all have a distinct impact on the terrestrial atmosphere and none of them can be ruled out, a priori.

Nearly 70% of the solar radiation that arrives at the top of the Earth's atmosphere is absorbed in the atmosphere or at the Earth's surface; the rest is immediately reflected. In contrast, the efficiency of energy transfer from the solar wind into the magnetosphere is only 1–10%, depending on the orientation of the IMF.

Wave and particle emissions are not the only means by which the Sun can influence the Earth's atmosphere. The solar wind plasma, more precisely, the IMF associated with it, modifies the rate of penetration of interstellar energetic particles into the heliosphere and eventually into the atmosphere. This has led to one of the more controversial aspects of Sun–climate studies.

In this review, we first start with an illustration of solar variability on time scales from days to decades (Section 2). Section 3 then addresses the solar radiative output and its effects, and Section 4 the role of orbital changes. Thereafter, we focus on indirect effects, the electric circuit (Section 5, including galactic cosmic rays [GCR]), atmospheric convection under quiet (Section 6) and active (Section 7) solar conditions, and the role of the coupling with upper atmospheric layers (Section 8). Conclusions follow in Section 9. External forcings that are not related to the Sun (such as volcanic activity) and internal forcings are not addressed.

2. Solar variability

Solar activity affects the Earth's environment on time scales of minutes to millions of years. The shorter time scales are of particular interest in the frame of *space weather*[1] (Schwenn, 2006), but will not as much be considered here. Long-term changes of solar and heliospheric conditions and their manifestation in the Earth's space and atmospheric environment are typically considered to be in the realm of space climate (Mursula et al., 2007). It is often believed that only slow variations (i.e. time scales of years and above) can affect climate. This is not fully correct in the sense that the rate of occurrence of fast transients such as solar flares is modulated in time, so that all time scales eventually matter.

To give a glimpse on the complexity of solar variability, we illustrate in Fig. 1 the variation of some key solar-terrestrial parameters; several of them will be discussed in later sections. The long time interval (left panel) covers 3 decades only because very few accurate solar observations were available before the advent of the space age. One of the main tasks in solar-terrestrial physics today is to extrapolate these tracers backward in time.

The tracers (or *proxies*, as they are usually called) of solar activity that are shown in Fig. 1 are respectively:

- *X-ray*: the soft X-ray flux between 0.1 and 0.8 nm, which is indicative of the energy released during solar eruptive phenomena such as flares. Most of this radiation is absorbed in the upper atmosphere (above 60 km) and above;
- *Lyα*: the intensity of the bright H Lyman-α line at 121.57 nm, which is mainly emitted in the solar transition region and is absorbed in the ionosphere (above 90 km);
- *MgII*: the core-to-wing ratio of the Mg II line at 279.9 nm, which is a good proxy for the solar irradiance in the ultraviolet (UV). This radiation is primarily absorbed in the stratosphere, where it affects ozone concentration;
- *TSI*: the Total Solar Irradiance (TSI), which represents the total radiated power measured at 1 AU, above the atmosphere. This quantity summarises the total radiative energy input to the Earth;
- *10.7 cm*: the radio flux emitted at 10.7 cm, or decimetric index. This radiation has no direct impact on climate, but it is widely used in Global Circulation Models (GCM) as a proxy for solar activity. It is measured daily since 1947;
- *ISN*: the International Sunspot Number (ISN), one of the most ancient gauges of solar activity, with almost daily measurements since 1749;
- $|B|$: the intensity of the IMF at the L1 Lagrange point, just upstream of the Earth;

[1] Space weather mostly deals with short-term impacts and forecasting of solar activity, with a particular focus on its societal effects: impacts on space systems, navigation, communications, ground technology, etc.