The Relationship between 11-Year Solar Cycle and Midlatitude Precipitation

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Abstract

The monthly sunspot number and global precipitation over the midlatitude region (30º-60º in both hemispheres) have been analyzed to provide a re-evaluation of the hypothesis on the possible links between the 11-year solar cycle and precipitation. The sunspot variability significantly leads the midlatitude precipitation variability by 2.75 years. Both the cross-wavelet power and wavelet coherence also confirm that this lead-lag relationship is less likely to exist by coincidence. The results indicate that the cosmic ray flux-cloud hypothesis, which might lead to an almost simultaneous response of precipitation to the solar cycle, is physically less plausible. Another possible mechanism including the changes in upward waves is discussed as an amplifier of the solar forcing.

Key words: Sunspot, Precipitation, Cosmic ray flux

1. Introduction

Over the past decades, an emphasis on the connection between the sun and earth climates has emerged. Although many meteorological variables are correlated with the solar cycle (Labitzke and van Loon, 1989, 1992; van Loon and Labitzke, 1998; Lim and Suh, 2006), how small changes in solar radiation (~0.1%) (Fröhlich, 2000) could have an impact on climate remains unknown. Svensmark and Friis-Christensen (1997) emphasized the role of cosmic ray flux from the galaxy in modulating clouds. Another factor impacting climate, as suggested by Haigh (1996), was an amplification process of solar variability via stratospheric heating.

The cosmic ray flux varies out of phase with the 11-year solar sunspot cycle due to changes in the interplanetary magnetic field related to the solar activity; the low cosmic ray flux corresponds to the periods of high irradiance and vice versa. Thus, as the solar activity increases, fewer cosmic rays are able to penetrate the inner solar system including the earth. The cosmic rays may produce molecular cluster ions in the atmosphere: these clusters could serve as cloud condensation nuclei (Harrison and Carslaw, 2003). Therefore, the enhanced (weakened) cosmic rays associated with the relatively inactive (active) sun leads to an increase (decrease) in ice nucleation, and consequently, precipitation (Marsh and Svensmark, 2000). On the other hand, the changes in the absorption of the ultraviolet (UV) radiation affect the upper stratospheric winds, which in turn alter the upward propagation of planetary waves and hence the troposphere (Shindell et al., 1999). A criticism on the cosmic ray-precipitation hypothesis also has been raised; for example, Kristjánsson et al. (2002) showed that there seems to be a negative correlation between the cosmic ray flux and the cloud cover, which contradicts the Svensmark and Friis-Christensen (1997) hypothesis.

To evaluate which mechanism is crucial to the sun-earth connection, there is a statistical aspect (lead-lag relationship) that has not been considered...
sufficiently by previous studies. According to the cosmic ray mechanism, there should be no lags between the solar cycle and the meteorological quantities at surface (e.g., precipitation), but rather an almost immediate relationship (see Fig. 1 in Kniveton and Todd, 2001). In the case of UV radiation hypothesis, however, a lagged correlation between the solar activity and surface weather condition should be expected due to the propagation of signature from the upper atmosphere to the surface (Haigh, 1996).

In this study, we will concentrate our analysis on the statistical relationship between 11-year solar oscillation and midlatitude precipitation to provide evidence of the possible causal mechanism. Although this study failed to explain the complex processes, we attempted to further investigate the theory that solar forcing may induce the climate variability through the stratosphere-troposphere exchange. The investigation used the recently-released global precipitation data and sunspot number. Of course, additional details on the exact processes involved are required.

2. Data and method

In our study, the global gridded monthly precipitation data (1900-2004) from the Global Historical Climatology Network (GHCN) version 2 data set (Peterson and Vose, 1997) have been used. This data set, which is designed for monitoring and detecting the climate change, is based on the surface station observations over 20,000 stations and more than 30 different sources. The precipitation data in the global midlatitude (30º-60º in both the hemispheres) are analyzed.

For the solar cycles, the monthly sunspot numbers from the Solar Influences Data analysis Center (SIDC) are used. The reader is invited to visit http://www.ncdc.noaa.gov and http://sidc.oma.be for a detailed description of the method and for downloading the data of the precipitation and sunspot number, respectively.

In addition to the simple lead-lag correlation, both the cross-wavelet and cross-wavelet coherence analyses are used to determine the causality between the global midlatitude precipitation and 11-year solar cycle. The wavelet transform is a useful method for analyzing localized variations of power within a time series (Holschneider, 1995).

For the analysis of the nonstationary covariance of two time series, as per Torrence and Compo (1998), we define the cross wavelet transform (hereafter, XWT) of two time series \( X \) and \( Y \) with wavelet transforms \( W_X \) and \( W_Y \) as

\[
W_{XY} = W_X W_Y^* ,
\]

where the asterisk mark denotes a complex conjugate. We applied the Morlet wavelet transforms with the dimensionless frequency \( \omega_0 = 6 \) for a good balance between time and frequency localizations. Furthermore, we define the cross-wavelet power \( |W_{XY}| \) and the complex argument of \( W_{XY} \), which will express their common power and local relative phase in the time-frequency space, respectively. A statistical significance test against red noise has been performed based on Monte Carlo methods with 300 surrogate data sets.

Another useful measure is the manner in which the cross wavelet transforms are coherent in time-frequency space. We define the wavelet coherence (WTC) as the square of the cross-wavelet power normalized by the individual wavelet power as per Grinsted et al. (2004). This gives a quantity between 0 and 1 and measures the cross-correlation between the two time series. Here, we again use Monte Carlo
methods with the red noise to determine the confidence level of coherence. Additional details of wavelet analysis can be found in Torrence and Compo (1998) and Grinsted et al. (2004).

3. Results

Figure 1 shows the time series of precipitation anomalies averaged over two latitudinal bands (30º-60º in both the hemispheres) and the sunspot number anomalies for the period of 1900-2004. The anomaly is defined as a deviation from the mean annual cycle over the analyzed period. The time series have been smoothed by applying a 12-month running mean for filtering out the high-frequency component. The sunspot number shows the regular variation on a decadal timescales, i.e., a dominant 11-year solar cycle. The period of time series is somewhat short to identify the variability longer than centennial timescale; however, the interdecadal variations are apparent in the sunspot number. For instance, the peaks of the envelope of the sunspot number have occurred at approximately 1920, 1960, and 1980.

The midlatitude precipitation is relatively irregular on both the interannual and decadal timescales. In addition, there is an increasing trend in the precipitation from 1920 to 2000. This recent increase in the precipitation is also reported for the East Asian monsoon precipitation, which indicates that the GHCN precipitation data reasonably agree with the station observation (Wang et al., 2006). Our power spectrum analysis indicates that the precipitation has both interannual (2-6 years) and decadal (8-15 years) periodicities, which reflect the influence of El Nino and the possible solar forcing, respectively (figure is not shown). The simultaneous correlation between these two time series is 0.007, indicating that there is no immediate linkage between the 11-year solar cycle and precipitation. This low simultaneous correlation implies that it is very unlikely that the solar variability affects the lower troposphere via the cosmic ray mechanism.

On comparing the time series of precipitation with the sunspot number, it is revealed that large positive peaks of the sunspot number occur prior to the maximum precipitation events. For example, the positive sunspot number is dominant in the years 1918, 1928, 1938, 1948, 1969, 1980, 1990, and 2001 and maximum precipitation events subsequently occur in the years 1920, 1931, 1941, 1952, 1972, 1983, 1992, and 2002. This result indicates that the maximum sunspot number is a precursor of the maximum precipitation in the global midlatitude. Similarly, ancient precipitation data showed that large precipitation events over Korea occurred during periods of decreasing sunspot number (Kim, 1976). Note that the precipitation in extratropics was used because the inclusion of precipitation in the tropics did not result in a clear relationship between the precipitation and the sunspot number (not shown).

In order to examine the midlatitude-precipitation variability associated with the solar cycle, the lead-lag correlation coefficients between the two time series are shown in Fig. 2. We have performed the statistical significant test, based on the non-parametric method, so-called random-phase test, described by Ebisuzaki (1997). This is because the sunspot number is so strongly serially correlated that the
simple t-test is not adequate. Surprisingly, the sunspot variability significantly leads the global precipitation variability by 2.75 years, i.e., a quarter of the solar cycle. This result suggests a possible influence of the decadal solar forcing on the earth’s surface. Moreover, the cosmic ray mechanism (Marsh and Svensmark, 2000) does not seem to be applicable to the connection between the 11-year solar cycle and precipitation because it takes a few years for the solar signal to reach the surface of the earth.

Haigh (1996) suggested that any changes in the temperature of the stratosphere due to the solar forcing may result in a feedback on the weather patterns in the troposphere by modulating upward planetary waves. These large scale waves, generated in the lower atmosphere by topography, propagate from the troposphere to the stratosphere. These waves may be absorbed and their momentum and heat are deposited at a level that depends on the temperature and wind profiles. Consequently, the atmospheric circulation and the lower-level pressure field could be changed by anomalous heating in the upper level.

Although the lead-lag correlation is significant, it is marginal and therefore, it is difficult to comment whether it is a mere coincidence. The XWT is helpful in this regard. The XWT of global precipitation and solar cycle is shown in Fig. 3. Note that there is a significant common power in about the 8-13 year band for the entire period. Here we also notice that a significant common power from the individual wavelet transforms can be found (not shown).

In order that a simple cause and effect relationship exists between the 11-year periodic solar forcing and precipitation, we expect that the two time series are phase locked. In accordance with the lead-lag correlation, Fig. 3 confirms a 90° out of phase relationship on the decadal scale (8-13 years), on which the solar cycle leads the global precipitation. In particular, this lead-lag relationship appeared after the late 1920s. Before that period, the two time series varied with an anti-phase relationship or the precipitation leads the sunspot number; however, this relation holds only over a small period or cone of influence region (Torrence and Compo, 1998 for cone of influence). Thus, we could safely say that the global precipitation over the midlatitudes follows the 11-year solar cycle. Therefore, we could again conclude that the solar forcing can affect the earth surface dynamically (e.g., UV radiation mechanism) rather than instantaneously (via cosmic ray flux). The common power became stronger after the 1980s, which could be associated with the solar impact on the recent global warming (Scafetta and West, 2006).

To evaluate the common variability between the two time series, a WTC analysis has been performed (Fig. 4). The WTC closely resembles a traditional correlation coefficient (Torrence and Compo, 1998). In comparison with the XWT, in WTC, a larger section (particularly, greater than the 16-year period) significantly stands out and shows the 90° out of phase relationship between the two time series. This consistent phase relationship also indicates that the solar cycle leads the global midlatitude precipitation, especially after the 1930s. Since the significant correlation of Fig. 4 is clear, it is very unlikely that its occurrence was a coincidence.

4. Summary and discussions

We have analyzed the monthly sunspot number (SIDC) and the midlatitude (30°-60° in both the hemispheres) precipitation (GHCN) data for the period 1900-2004 to present a re-evaluation of the hypothesis of the possible links between the 11-year solar cycle and global precipitation. The sunspot variability leads the midlatitude precipitation variability by 2.75 years. Both the cross-wavelet power (XWT) and wavelet coherence (WTC) also confirmed that this lead-lag relationship is dominant on a decadal timescale (8-13 years).

The results indicate that the cosmic ray-cloud mechanism proposed by Svensmark and Friis-Christensen (1997), which might lead to an almost immediate response of precipitation to the solar cycle, is physically less plausible. Its cause is as follows. The cosmic ray flux to the atmosphere strongly corresponds to the minimum solar cycle. In addition, the increased cosmic ray leads to a simultaneously enhanced condensation nuclei. As a result, the 11-year solar cycle and the precipitation amount should be nearly antiphase.
However, the mechanisms by which the solar influence acts, as shown in this study, remain unexplained. Since the irradiance variances are small, an amplifier for solar forcing should be considered. For centennial to millennial time scales (e.g., Maunder Minimum), the oceanic thermohaline circulation may amplify the effects of solar irradiance (Bond et al., 2001). In the short-term (11-year cycle) solar variability, the NAO/AO (Kodera and Kuroda, 2005; Tourpali et al., 2005) and QBO (Mayr et al., 2006; Cordero and

**Fig. 3.** Cross-wavelet transform $|W_{xy}|$ of the standardized extratropical precipitation (30°-60° in both hemispheres) and the sunspot number. The 95% confidence level against the red noise is shown as a thick contour; the dashed line indicates the region where the edge effects become significant. The arrows indicate the phase relationship, argument of $W_{xy}$; the arrows pointing to the right and left signify in-phase and antiphase, respectively and the sunspot number leading the precipitation by 90° points straight upward (for additional details, see Torrence and Compo, 1998).

**Fig. 4.** Same as Figure 3 except the wavelet coherence. The statistical significant level is estimated using the Monte Carlo methods based on 1000 surrogate data set pairs as shown in Grinsted et al. (2004).
Nathan, 2005) are considered as potential amplifiers accompanied by a stratosphere-troposphere coupling.

Although we did not report the particular mechanism involved in the connection between the 11-year solar cycle and extratropical precipitation, it is clear that the dynamical links between the upper atmosphere and the troposphere are more crucial rather than the cosmic ray influence. In response to the related mechanism, our results need to be confirmed with a complete chemistry-climate model that includes the upper atmosphere.

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