# A time-frequency analysis of the effects of solar activities on tropospheric thermodynamics

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## ABSTRACT

Whether the Sun has significantly influenced the climate during the last century has been under extensive debates for almost two decades. Since the solar irradiance varies very little in a solar cycle, it is puzzling that some geophysical parameters show proportionally large variations which appear to be responding to the solar cycles. For example, variation in low-altitude clouds is shown correlated with solar cycle, and the onset of Forbush decrease is shown correlated with the reduction of the vorticity area index. A possible sun-climate connection is that galactic cosmic rays modulated by solar activities influence cloud formation. In this paper, we apply wavelet transform to satellite and surface data to examine this hypothesis. Data analyzed include the time series for solar irradiance, sunspots, UV index, temperature, cloud coverage, and neutron counter measurements. The interactions among the elements in the Earth system under the external and internal forcings give out very complex signals. The periodicity of the forcings or signals could range widely. Since wavelet transforms can analyze multi-scale phenomena that are both localized in frequency and time, it is very useful techniques for detecting, understanding and monitoring climate changes.

## 1. INTRODUCTION

The Earth's temperature has increased by 0.6 degree since the beginning of the Industrial Revolution. Growing evidence indicates that we are in the midst of a global warming trend. Since $CO_2$ has increased by approximately 30% in this period, a common conjecture is that anthropogenic greenhouse gases have contributed to global warming. Another probable factor for the warming is the natural variation of solar irradiance, since energy output from the Sun has been on an increasing trend during the past two centuries. There are indications that points to the possible link between the Sun and the climate. For example, surface temperature of the Northern Hemisphere is shown to correlate with solar cycle length[1,2] with a time lag of approximately 5 years. At a much shorter, daily timescale, it has been discovered that cloud and rainfall appear to be related to solar activities. A plausible conjecture is that cosmic rays, when modulated by the Sun, provide the additional influence on climate through changes in cloud formation.

Recent studies strongly indicate that both mechanisms have been at work in the twentieth century[3,4]. During the first half of the century, warming is mainly due to the natural causes. But during the second half of the Century, it was dominated by the rapid increase in anthropogenic greenhouse gases. It is also estimated the warming trend will continue in the 21st Century and its effects will be more clearly manifested in weather patterns.

In this paper, we use wavelet transform to attempt to detect signals in time series that appear to be related to the Sun. In Section 2, the wavelet transform with Morlet wavelet used in the study is briefly explained; Section 3 discusses time series for the solar irradiance, sunspot number, ultraviolet, and Northern Hemisphere surface temperature, and their wavelet transforms. Section 4 discusses time series for cosmic rays and cloud coverage, their wavelet transforms, and the possible theoretical bases linking cosmic rays to cloud formation. Section 5 summarizes the study and provides direction for future studies.

## 2. WAVELET TRANSFORM

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Wavelet transform (WT) is a useful technique for the analysis of non-stationary signals. For climate research, it provides a powerful method to isolate events in time and frequency domains. The technique has been well documented elsewhere[5,6]. The continuous WT is given by

$$W(a, b) = \frac{1}{a} \int_{-\infty}^{\infty} h\left(\frac{t-b}{a}\right) s(t)\, dt, \tag{1}$$

where h(t) is the wavelet function, and a and b are the dilation and shift parameters. We use the Morlet wavelet

$$h(t) = e^{ict - \frac{t^2}{2}} \tag{2}$$

with $c = 5$ so that the wavelet is approximately admissible.

Wavelet transform provides an alternative to short-time Fourier Transform or Gabor transform. The Gabor transform is identical to the Morlet WT, except that the wavelet window width decreases with the increase of frequency. This property gives the Morlet WT better time resolution at high frequencies and better frequency resolution at low frequencies, such that a constant fidelity $Q = \Delta f/f$ (the number of oscillations within the window) is maintained.

## 3. SOLAR IRRADIANCE, SUNSPOTS, AND TEMPERATURE

### 3.1 Solar Irradiance

The 117 years of proxy derived monthly solar irradiance data was created by Judy Lean of the Naval Research Laboratory and was obtained from Goddard Institute for Space Studies (GISS). As satellite measurement of solar irradiance did not begin till approximately 20 years ago, the major portion of the long-term dataset is inferred from surface measurements of solar parameters. Empirically the solar irradiance has been observed to change as bright faculae increase the irradiance and dark sunspots decrease it. An empirical model can be set up by fitting the proxy model to the accurate satellite measurements of the solar irradiance[7]. This dataset has been used in the GISS Global Circulation Model.

Fig. 1(a) shows the monthly solar irradiance data. The downward spikes in the irradiance occur when large sunspot groups face the Earth. Smaller upward spikes occur when bright faculae face the Earth. At low solar latitudes, the synodic rotation period is about 27.3 days; this period increases somewhat at higher latitudes. Short term periodicities are determined by the lifetimes and relative positions of the excited regions combined with the synodic rotation period. At sunspot maximum, excited regions are common and may persist for several solar rotations. At sunspot minimum, excited regions are rare and may last only a few days. The brightening cycle due to the faculae is approximately in phase with the sunspot cycle. Although large sunspot groups cause the most dramatic short-term changes in the solar irradiance, the more wide spread and longer lasting faculae dominate the year to year changes in the irradiance. Fig. 1(b) shows the wavelet transform of the monthly time series. Highest magnitudes are darkest. The approximately 11-year solar cycle is clearly indicated in the wavelet transform. The 11-year solar cycle is due to cyclic variations in the Sun's magnetic activity. The Sun's magnetic polarity switches about every 11 years. Conceptually this is driven by a dynamo process that is only partially understood[8]. The variation is approximately 0.1% higher at maximum than at minimum.

### 3.2 Sunspots

Sunspots are dark, relatively cool areas of irregular shape on the Sun's surface. They are located at areas where twisted solar magnetic field lines poke through the photosphere. It has been discovered that solar flares are closely associated with the sheared magnetic fields and sunspots. The method of counting sunspots was developed by Rudolph Wolf in 1848. He defined sunspot number as the total number of individual spots plus 10 times the number of sunspot groups, since solar activities appeared to be related to both individual spots and groups. This definition is still in use today in order to compare observations with historical sunspot records. As subjectivity has a role in counting sunspots, and the atmosphere and cloud cover would certainly influence observation, sunspots measurements nowadays obtained from averaging the measurements at stations around the globe. The 251 years of sunspot numbers are obtained from the NOAA NGDC solar data archive.

Fig. 2(a) shows the monthly sunspot time series, and Fig. 2(b) shows its wavelet transform. The dark band in Fig. 2(b) indicates the 10-12 years solar cycle. Since it is easier to observe sunspots than measuring solar irradiance, it was known in the history that the number of sunspots varied. Wolf himself observed a 11.1 years of cyclical variation of sunspot numbers. The sunspot cycle is in phase with the solar irradiance cycle.

### 3.3 Ultraviolet

The Mg II core-to-wing index was first developed for the Nimbus 7 Solar Backscatter Ultraviolet Spectrometer (SBUV) as an indicator of solar UV flux temporal variation[9]. It is considered a robust UV measure since it is insensitive to instrument artifacts. The 16-year Mg II composite dataset is composed of SBUV data from Nimbus-7, NOAA-9, and NOAA-11. The dataset was produced by Goddard Space Flight Center and is archived at NOAA/NGDC.

Fig. 3 shows the 16-year time series in daily resolution. The Mg II index varies in phase with the solar irradiance and has a much larger variation – approximately 10% with respect to 0.1% for solar irradiance. The UV indeed warms up the stratosphere once it is absorbed by the atmospheric ozone. Vertical mixing between the stratosphere and the troposphere is weak. Since there is no efficient mechanism to transport this thermal energy to troposphere, it may take a few weeks before its effect reaching the troposphere and the Earth's surface. On the other hand, Forbush decrease, which is the decrease of cosmic rays reaching the Earth during solar flares and intensified magnetic activities, takes place almost immediately.

### 3.4 Temperature

The 144 years of temperature anomalies record for the North and the South Hemisphere are acquired from the Climate Research Unit (CRU), University of East Anglia, UK. The CRU dataset is a combination of land air temperature anomalies and sea surface temperature anomalies. The period 1961-1990 is considered the normal period for comparison. The data have been used in various Intergovernmental Panel on Climate Change (IPCC) reports[10]. The temperature time series for North Hemisphere is plotted in Fig. 4(a), in which the upward trend especially since 1970 can be seen clearly.

Using the WT of the 117 years of monthly solar irradiance record shown in Fig. 1(b), the length of the solar cycle is extracted and plotted with an inverted scale in Fig. 4(b). The distribution show reasonable correlation with the 114 years of monthly North Hemisphere temperature anomalies from CRU between 1890-1990 as shown in Fig. 4(a). The time lag, although not fitted here, appears to be shorter than what was indicated in proposed previously[1]. The behavior of the solar cycle length at the two ends of the time series could be an artifact of the WT; it will be explored further in future studies. For the South Hemisphere which is mostly covered by oceans, there does not appear to be a correlation between the solar cycle length and the temperature time series[2].

## 4. CLOUDS, COSMIC RAYS, AND THE POSSIBLE LINKAGE

### 4.1 Clouds

Depending on the variety, clouds can either cool or warm the Earth. They cool the Earth by reflecting back to space incoming shortwave solar energy. They warm the Earth by partially blocking escaping longwave energy emitted by the Earth. Thin, high cirrus clouds let most of the incident shortwave radiation in, while blocking much of the surface emitted longwave radiation. These clouds thus have a warming effect. Thick, low cumulus clouds block the short-wave radiation and reflect most of it back to space. Because their cloud tops are relatively warm they radiate longwave radiation efficiently to the upper atmosphere and space. They have thus a strong net cooling effect. These are two extreme cloud types. Satellite measurements of clouds and the Earth's radiation budget show that at present the shortwave cooling due to clouds is greater than the longwave warming[9]. If the Earth does not experience additional external or internal forcings, the net effect of clouds is to make the Earth cooler.

Cloud data are obtained from the International Satellite Cloud Climatology Project (ISCCP) database. ISCCP was established in 1982 as a component of the World Climate Research Program. The project processes raw data from various weather satellites to extract information on cloud distributions, properties, as well as the diurnal, seasonal, and interannual variations. ISCCP's Global Processing Center is located at the Goddard Institute Space Studies (GISS).

Fig. 5(a) shows the 10 years of cloud cover data over oceans. Land data were excluded because cloud data from the Defense Satellite Meteorological Program (DMSP) will be included and intercompared with other data in the study, and the DMSP only produces cloud data over oceans. Equatorial area is not excluded although it is mostly shielded from galactic cosmic rays by the Earth's magnetic field. Extraction of cloud coverage over oceans is less difficult than over land. Since most oceans are in the Southern Hemisphere, and also it has been reported that cloud coverage over land may be under estimated[12], previous studies exploring the relationship between clouds and cosmic rays was performed for the Southern Hemisphere[13]. The wavelet transforms of the three time series are shown in Fig. 5(b). The yearly cycles can clearly be seen. The Southern Hemisphere cloud coverage shows the strongest and clearest annual and seasonal variation.

### 4.2 Cosmic Rays

Cosmic rays consist of mainly protons, alpha particles and small amount of heavier elements. They are produced by sources ranging from the Sun, stars, supernova, to other galaxies. The cosmic rays analyzed in this study are the galactic cosmic rays, whose intensity in the solar system is modulated by the solar activity. Intensified solar wind will shield the solar system from the galactic cosmic rays. Solar wind is composed of protons, electrons, and a small amount of alpha particles ejected from the Sun's corona. Reaching almost 100 astronomical units away from the Sun, the solar wind forms the heliosphere and affects most planets in the solar system. As can be expected, the intensity of solar wind varies in phase with the sunspots and solar irradiance. When cosmic ray particles collide with particles in the atmosphere, cosmic ray showers will be generated. The showers are composed of cascades of protons, neutrons, pions, muons, etc. The intensity can thus be measured by neutron monitors on the ground. Galactic cosmic rays provide the major mechanism for ionization in the Earth's atmosphere at altitude below 35 km, the region in which clouds are formed.

Neutron monitor data at Climax, Colorado are used for this study. The 48-year monthly data are shown in Fig. 6(a), and the wavelet transform of the time series is shown in Fig. 6(b). The dark band at the bottom of Fig. 6(b) indicates the 10-12 years solar cycle. The upward bending of the dark band indicates solar cycle length apparently has been decreasing since about 1970. This decrease can also be seen in the wavelet transform for the solar irradiance time series (Fig. 1(b)), and also the solar cycle length extracted (Fig. 3(b)). These three figures show that the solar activities have been increasing since about 1970. The neutron monitor time series at Calgary, Canada has been examined also but is not presented here. It is very similar to the time series at Climax. Averaged over the globe, the variation in cosmic ray intensity is approximately 15% between solar maximum and minimum.

### 4.3 The Possible Linkage

In this section, we will discuss the possible relationship among solar activities, galactic cosmic rays, and cloud formation. Generally speaking, the Sun may affect the Earth's climate in the following ways[14]:

(1) Variation of solar irradiation. The solar irradiance has a cycle of 9 to 11 years. The variation of the irradiance in a solar cycle is merely one part in a thousand. However, it has been observed that the Earth does respond to this small variation. For example, Fig. 4 shows that North Hemisphere temperature correlates with the length of the solar cycle, with a time-lag of approximately 5 year (see also[1]).

(2) Variation of the ultraviolet in the solar irradiance. Although the total solar irradiance has very small variation (0.1%) in a solar cycle, the UV portion shows much more pronounced variation, from 5% in 200-300 nm to 50% in 100-150 nm. The UV is absorbed by the stratospheric ozone and warm the stratosphere. Troposphere may be warmed slowly afterwards.

(3) It is known that the cosmic rays have a much larger variation (15%) and the variation could affect the Earth almost immediately. For example, Forbush decrease in galactic cosmic ray intensity can be observed after solar magnetic activities take place.

A hypothesis explaining how the cosmic rays, modulated by the sun, may affect troposphere thermodynamics was proposed by Tinsley[14]. The suggested electrofreezing process is a chain reaction that affects general circulation in the troposphere:

(1) Cosmic rays generate showers in the atmosphere. The electric fields associated with the showers charge the supercooled water droplets and aerosols. Ice crystals will form.

(2) Micron-size ice crystals combine with supercooled water droplets and become millimeter-size ice crystals.

(3) These larger ice crystals descend to mid-level clouds. Supercooled water droplets in the clouds become glaciated. Latent heat is released.

(4) The latent heat may establish convection cells and strength cyclones.

Recently, more detailed processes are suggested with which cosmic rays may affect the formation of large ions, aerosol particles, cloud droplets and ice crystals[15]. These processes are summarized as follows:

(1) Ions generated by the cosmic rays may affect aerosol microphysical processes. Cloud condensation nuclei may become more abundant. The cloud droplets are therefore smaller with the same available amount of liquid water. This would make raining less likely and prolong cloudiness. It has also been observed that more and smaller cloud condensation nuclei increase shortwave reflectance of the cloud and make the clouds look brighter. As the intensity of cosmic rays increases, it would thus decrease the possibility of raining and at the same time let the cloud reflect more solar radiation back into the space (see, for example[16]).

(2) Aerosols may become charged due to cosmic ray ionization. It is hypothesized that such charging may reduce the amount of water needed from supersaturated vapor to grow the aerosol into a large water droplet. If charging alters the cloud drop activation process, increase of cosmic rays intensity would have the same consequence as described above.

(3) Aerosols may grow when ions and radicals enhance vapor condensation in the presence of trace atmospheric gases. This would lead to a higher concentration of cloud condensation nuclei and droplets at lower supersaturation.

(4) Ionization produced by cosmic rays may promote ice nucleation and the formation of ice particles by direct sublimation and freezing of liquid droplets.

Fastrup et al.[15] proposed to use cloud chamber to study these possible links between cosmic rays and clouds under realistically simulated atmospheric conditions.

## 5. SUMMARY AND DISCUSSION

The six time series analyzed in this study are displayed together in Figure 7 for comparison. All time series have been shown earlier, except the cloud coverage time series is now for higher latitude in Southern Hemisphere only. Since the equatorial area is largely shielded from galactic cosmic rays, and also cloud processes are different in the tropics from those at higher latitude[13], tropical clouds should be excluded in examining the possible link between cosmic rays and cloud formation. The replotted cloud time series only includes cloud statistics below 35 degrees South. In addition, a 12-month moving average is used to remove the annual fluctuation. The time series is thus 8.5 years long. Variation of cloudiness within this period appears to be slightly smaller than what was discovered before[13].

The solar irradiance, sunspots, Mg II indices are all in phase. Variation in the UV is much larger than the variation in solar irradiance. But it is the sunspot number that shows the largest variation over time. The solar cycles are clearly manifested in the wavelet transforms for the solar irradiance and the sunspot numbers. As originally discovered by Friis-Christensen et al.[1], we also see that the Northern Hemisphere surface temperature correlates with the length of the solar cycles extracted from the wavelet transform with a time lag. The time lag, although not fitted here, appears to be shorter than the nearly 20 years proposed previously. This is an indication that the Earth's surface temperature is indeed affected by solar activities, through a still unknown mechanism.

The cosmic ray intensity is seen anti-correlated with those for solar irradiance and sunspots, as it is modulated by solar magnetic activities. The replotted cloud coverage is very well correlated with the cosmic rays. Hence it strongly suggests that cosmic rays contribute to cloud formation.

Therefore, in addition to anthropogenic forcings from greenhouse gases, solar activities may have provided certain amount of forcing to the climate as well. The forcing is provided through the modulation of galactic cosmic rays, which in turn affect cloud formation and the temperature of the Earth. However, even if this hypothesis can be verified, another mystery - how a changed climate may affect cloud formation – must still be resolved. Whether it is a positive or negative feedback could only be determined through long-term observation and detailed modeling.

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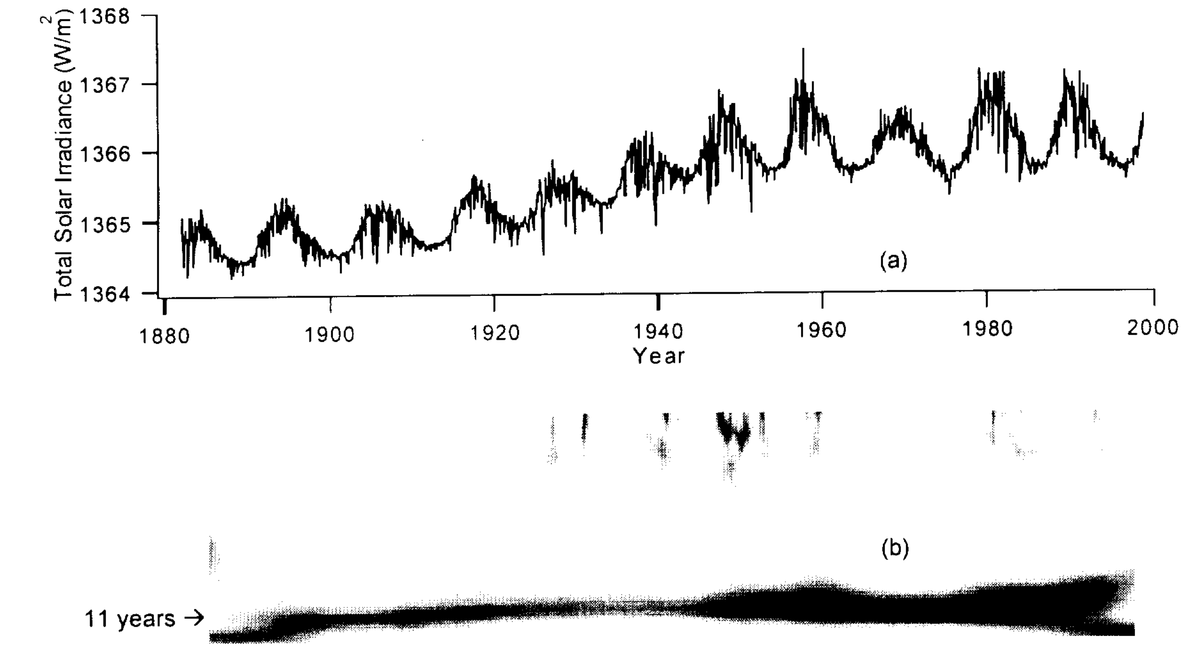


Figure 1. (a) 117 years of monthly solar irradiance record compiled by J. Lean. (b) The wavelet transform of the data. The dark band indicates the 10-12 years solar cycle.

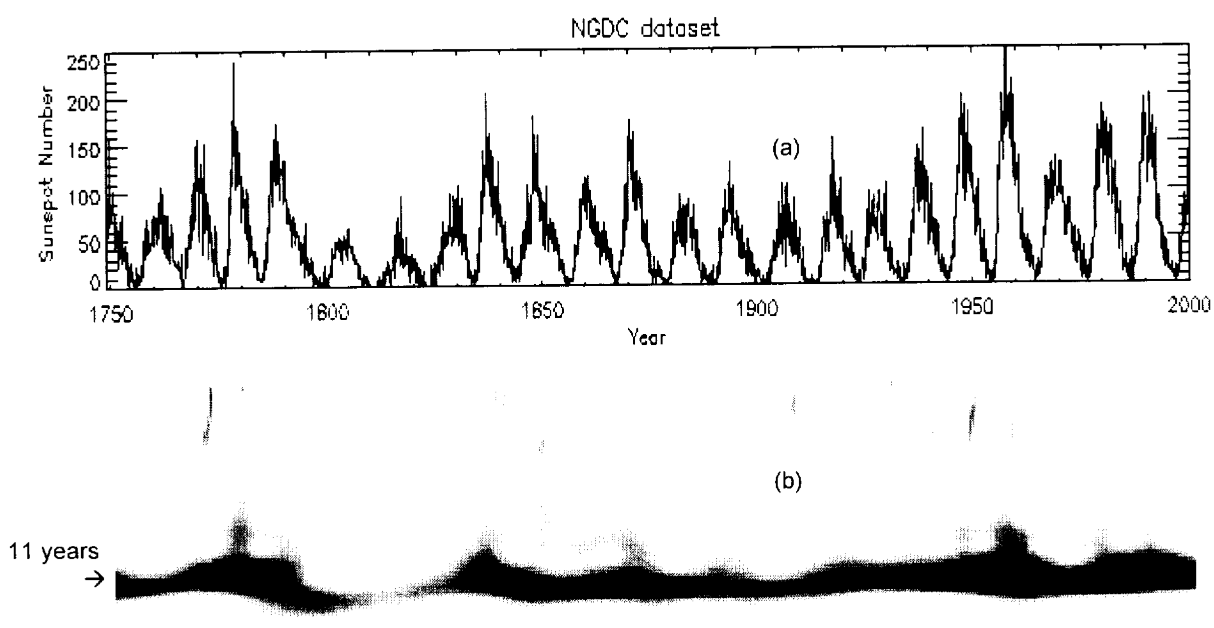


Figure 2. (a) 251 years of monthly sunspot numbers. (b) The wavelet transform of the data. The dark band indicates the 10-12 years solar cycle.

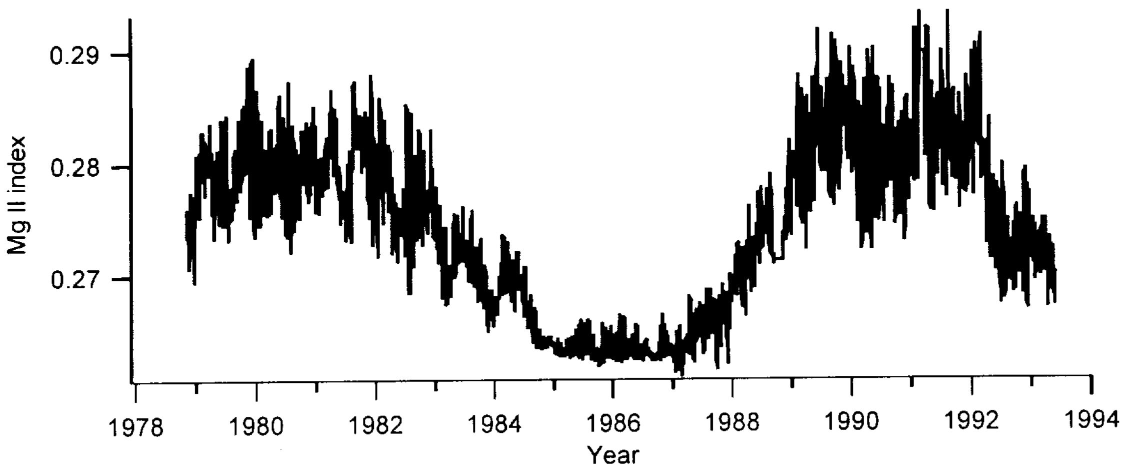


Figure 3. 16 years of daily Mg II indices from NOAA/NGDC archive.

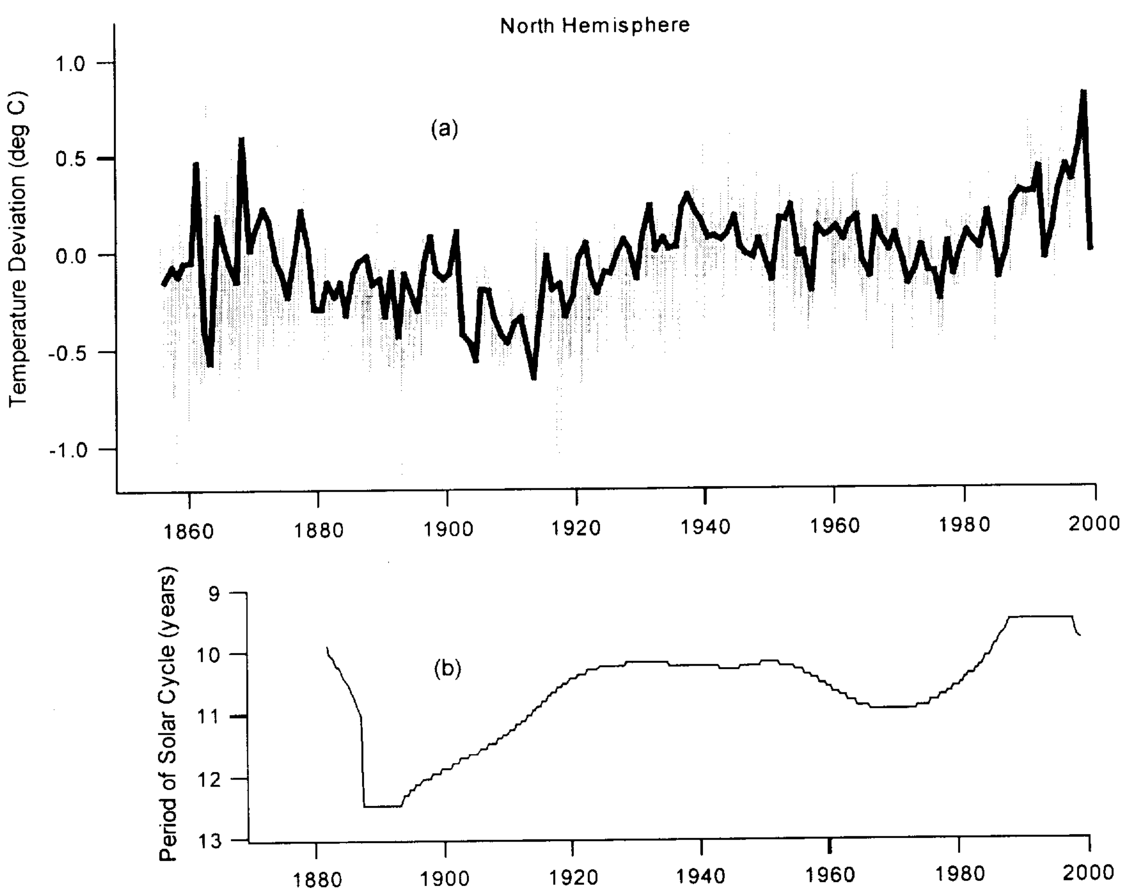


Figure 4. The north hemisphere monthly temperature deviation, as in Fig.5, is replotted in (a). The length of the solar cycle (b) extracted from Fig. 2(b) shows a similar distribution with some phase difference.

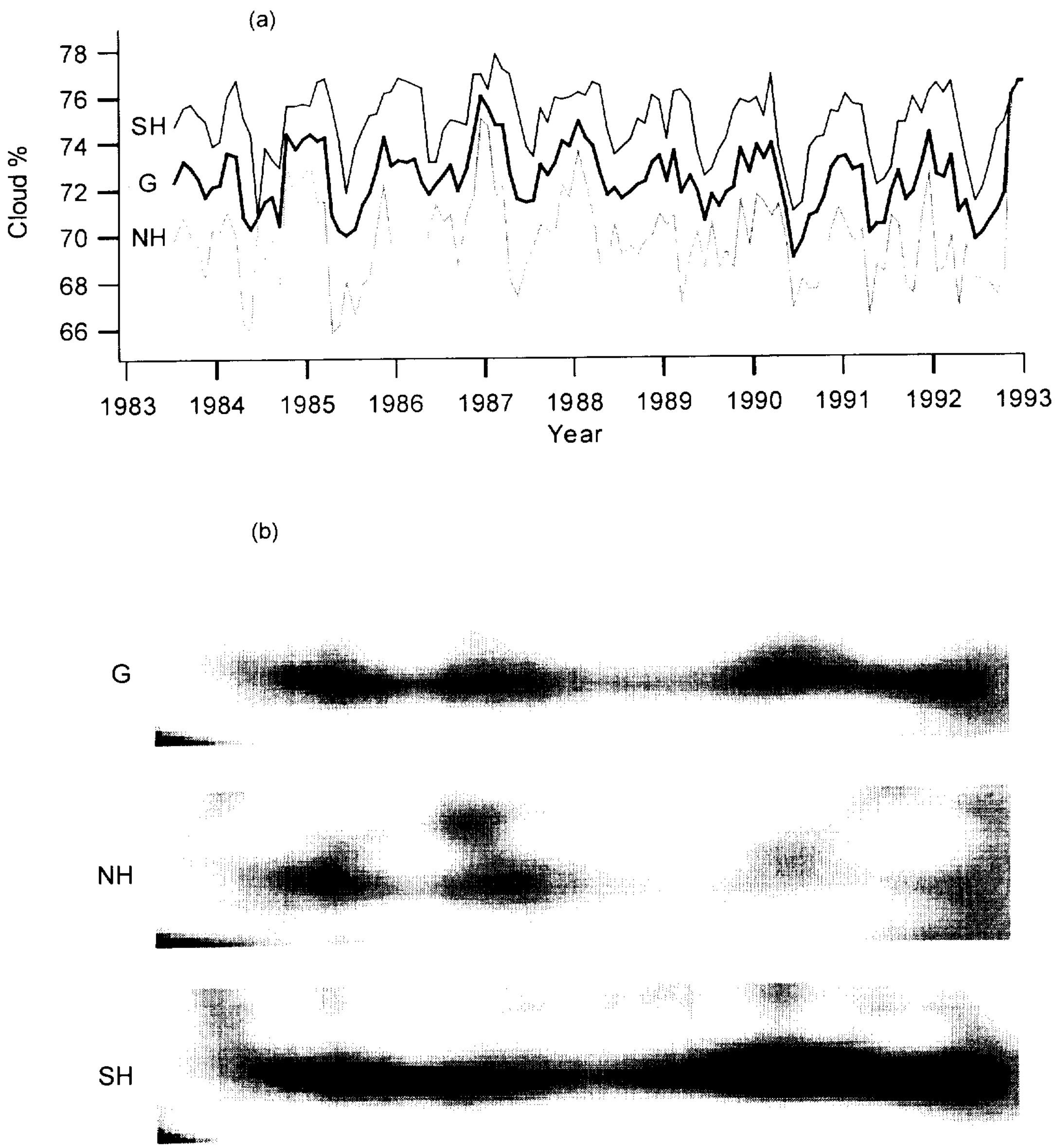


Figure 5. (a) Cloud cover percentage over oceans for the entire globe (G), North Hemisphere (NH) and South Hemisphere (SH). The 10 and half years of data are from the ISCCP database.
(b) Wavelet transforms for cloud cover percentage over oceans: for the entire globe (G), North Hemisphere (NH) and South Hemisphere (SH). The dark bands correspond to annual cycle. Cloud coverage for the South Hemisphere show more regular variation and the most distinc annual cycle.

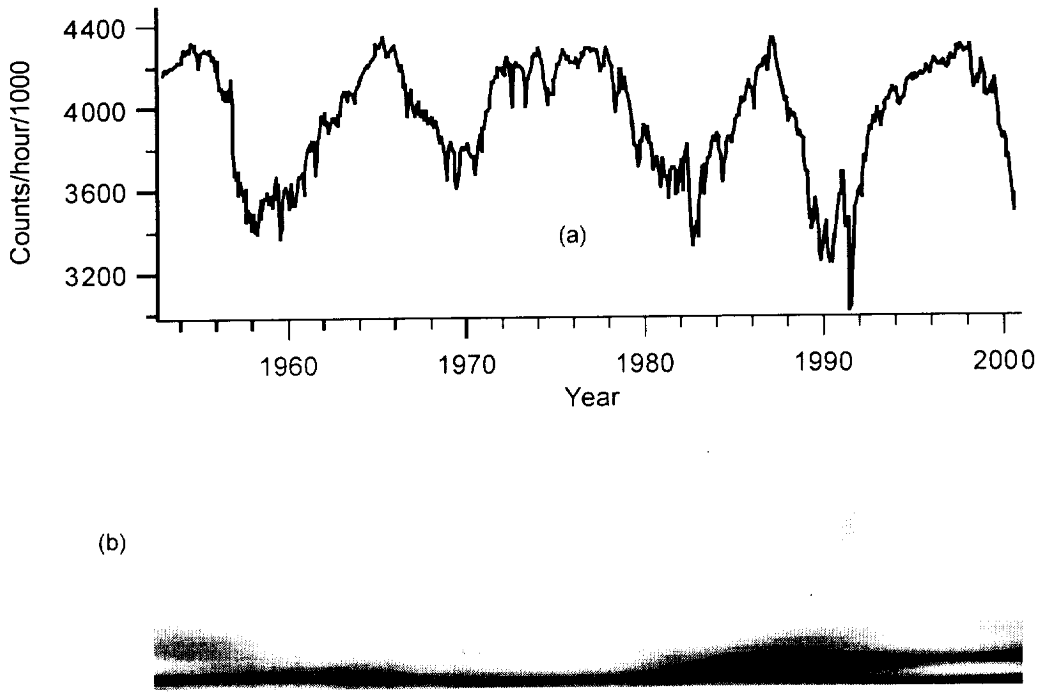


Figure 6. (a) 48 years of monthly averaged neutron monitor data at Climax, Colorado. (b) The wavelet transform of the data. The dark band at the bottom of the figure indicates the 10-12 years solar cycle. The upward bending of the dark band indicates solar cycle length apparently has been decreasing since about 1970.

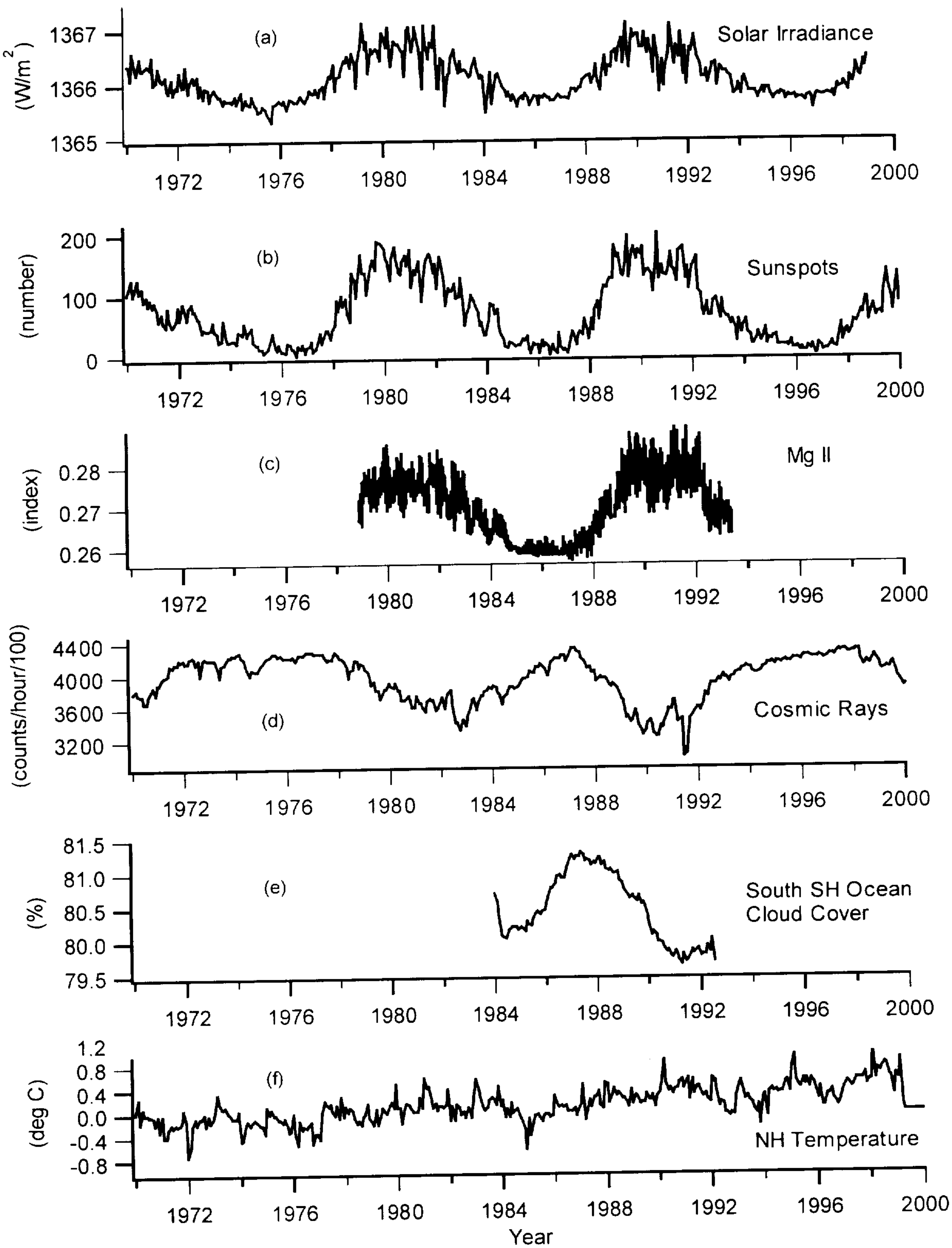


Figure 7. Comparison of six time series.