Quaternary International 397 (2016) 289–299

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Relationships between solar activity and variations in SST and atmospheric circulation in the stratosphere and troposphere

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ARTICLE INFO

Article history:
Available online 5 March 2016

Keywords:
Solar activity
Sunspot number (SSN)
Sea surface temperature (SST)
Teleconnection
Pacific Decadal Oscillation (PDO)
CP El Niño

ABSTRACT

Relationships between solar activity and variations in both sea surface temperature (SST) and atmospheric circulation at the time of the solar maximum are presented. The global distribution of correlation coefficients between annual relative sunspot numbers (SSN) and SST from July to December was examined over a 111-year period from 1901 to 2011. Areas with a significant positive correlation accounted for 11.7% of the global sea surface in December, mainly over three regions in the Pacific. The influence of solar activity on global atmospheric pressure variations and circulation in the maximum years was also analyzed from 1979 to 2011. The results indicated that higher geopotential height anomalies tended to appear in the stratosphere and troposphere in the northern hemisphere, centering on around the Hawaiian Islands from November to December, in the second year of the solar maximum. The SST distribution in the Pacific with strong north and south Pacific Highs produced a pattern that resembled teleconnection patterns such as the Pacific Decadal Oscillation (PDO) and the Central-Pacific (CP) El Niño, or El Niño Modoki (ENM). It is suggested that the solar activity had an influence on the troposphere via not only the stratosphere but also the sea surface.

1. Introduction

The global climate has experienced pronounced changes in the past (Lamb, 1972). A number of climatic cyclic and quasi-cyclic phenomena such as El Niño events and the quasi-biennial oscillation (QBO) affect the climate on an interannual time scale. Mean zonal wind, which has a strong QBO signal in the tropical stratosphere, switches between westerly and easterly phases on an approximately 27-month timescale (Pascoe et al., 2005; Inoue and Takahashi, 2009; Inoue and Yamakawa, 2010). Tree rings, ice cores, ocean sediments, corals, and stalagmites have displayed a cyclic behavior in the past (Lamb, 1972; Burroughs, 2003, 2007; Yamaguchi et al., 2010; Kataoka et al., 2012). Earth's climate is influenced by natural fluctuations. Meteorological disasters, which cause extensive damage to human society, economic systems, and ecosystems are considered to be associated with many overlapping factors as part of the natural variations in the climate system (Yamakawa, 2005; Yamakawa and Suppiah, 2009).

The 11-year cycle (Schwabe cycle; Miyahara et al., 2010) detected in sunspot numbers is strongly related to changes in solar radiation. Variation in sunspot numbers is used as an indicator of variation in solar activity. Individual sunspots and/or groups of sunspots first appear in middle latitudes. As the solar cycle progresses, sunspots tend to appear in lower latitudes. When sunspots wane in low latitudes, they reappear in middle latitudes, and the cycle is repeated. The solar magnetic field, which is characterized by opposite polarity in the two hemispheres, reverses around the peak of solar activity. The 22-year period in which the magnetic field reverses and returns to its original state of polarity, called the "Hale cycle", has been identified in tree rings (Douglass, 1919; Biondi et al., 2001; Miyahara et al., 2010). The 11-year and two-fold sunspot number cycles are regarded as important indicators of solar activity, and are the most marked periodic events of the sun's circulation patterns.

The link between solar or cosmic ray variation and climate variability has been extensively reported in the literature. However, conflicting results have been reported regarding the relationship

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http://dx.doi.org/10.1016/j.quaint.2015.11.018
1040-6182/

between solar activity and Earth's climate. The sun is the primary energy source for Earth, and any changes to the energy balance can have a significant effect on Earth's climate. Many studies have claimed correlations between 11- and 22-year sunspot cycles and tropospheric or surface weather patterns (Pittock, 1978, 1983). For example, Xanthakis (1973) showed correlations between rainfall and solar activity at many locations, with the correlations also showing conflicting signs. However, Duffy et al. (2009) argued that there is no relationship between solar activity and late twentieth-century warming. Despite the vast amount of literature on this subject, Pittock (2009) identified a number of problems associated with the results derived from these studies, including poor data quality (especially the poor dating of non-instrumental data), data selection, data smoothing and autocorrelation, and post hoc elaboration of hypotheses to explain discrepancies.

Lately, analyses of the relationships between solar activity and surface temperature, rainfall, sea level pressure (SLP), sea surface temperature (SST), upper ocean temperature, and other factors have been conducted by several researchers (*e.g.*, White, et al., 1997; van Loon et al., 2007; Meehl and Arblaster, 2009; Zhou and Tung, 2010; Gray et al., 2010; Semeniuk et al., 2011; Gray et al., 2013; Hood et al., 2013; Kuchar et al., 2014; Yamakawa and Ohishi, 2015). In light of the many controversial results regarding solar variability and climate that have been reported in the past, we investigated the regional and global relationships between solar activity and variations in SST and atmospheric circulation during the instrumental record period.

2. Data and methods

Relative sunspot numbers (SSN) were obtained from the Scientific Chronological Tables published by the National Astronomical Observatory of Japan. Global SST data were obtained from the Hadley Centre for Climate Prediction and Research, British Meteorological Office. This data set has a horizontal resolution of 1° latitude × 1° longitude.

Monthly data for geopotential height, air temperature, and horizontal (*u*-wind, *v*-wind) and vertical wind (omega below 100 hPa) were obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) global atmospheric reanalysis data (Kalnay et al., 1996). These data sets have a 2.5° × 2.5° grid resolution. Outgoing longwave radiation (OLR) data were also obtained from the NCAR archive. Monthly precipitation data for the same grids were obtained from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) dataset (Xie and Arkin, 1997). Correlation coefficients between annual sunspot numbers and monthly SST from 1901 to 2011 were calculated, and the areas where the r-values were equal or greater than the 95% significance level (<0.05) were plotted (Fig. 1). To determine the influence of solar variability on weather conditions during the solar maximum phase, we selected three periods (9 years in total) when solar activity was at a maximum during the period from 1979 to 2011: 1979–1981, 1989–1991 and 2000–2002.

For climatic elements such as geopotential height, wind, SLP, OLR and precipitation, the differences from the 30-year mean were determined by a two-sided t-test. Differences with $P < 0.05$ were considered significant. Geopotential heights at nine levels (10, 50, 70, 100, 200, 300, 500, 850 and 1000 hPa) were examined, but only results for six levels (50, 70, 100, 200, 500 and 850 hPa) were presented here. We investigated the climatic response with a 1- to 36-month lag. Significant areas were plotted in Figs. 4 to 11. The percentage of significant grids was calculated. The areas of significance were generally more obvious in the second year than in the first year. In the third year, significant areas were identified in the stratosphere, but less significant and fluctuating areas were recognized in the troposphere. Therefore, we focused on the climatic response in the second year.

Furthermore, the analysis period included the strong El Niño event in 1982 and the eruption of Mt. Pinatubo in 1991. The results obtained did not show any significant differences when these events were excluded from the analysis.

Data concerning monthly SSN, Pacific Decadal Oscillation (PDO), Central-Pacific (CP) and Eastern-Pacific (EP) El Niño, El Niño Modoki (ENM) and Southern Oscillation Index (SOI) were obtained from the sources cited below. SSN data were acquired from WDC-SILSO, Royal Observatory of Belgium, Brussels. PDO index data were obtained from the Meteorological Agency, Japan (http://www.data.jma.go.jp/kaiyou/data/shindan/b_1/pdo/pdo.html). CP and EP El Niño index data were obtained from ERSST data set (http://www.ess.uci.edu/~yu/2OSC/), calculated using the regression-EOF method (Kao and Yu, 2009; Yu and Kim, 2010). ENM index data were provided by JAMSTEC (Japan Agency for Marine-Earth Science and Technology; http://www.jamstec.go.jp/frcgc/research/d1/iod/modoki_home.html.en). SOI index were obtained from Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices/soi).

3. Relationships between SSN and SST in 1901–2011

Positive correlation coefficients (r) between solar activity and global mean SST were reported by Reid (1987, 1991). However, a detailed investigation of the relationships between solar activity and the regional characteristics of SST has not been attempted. Therefore, we calculated correlation coefficients between annual mean relative SSN and monthly SST to investigate regional variations over the globe. Significant positive correlations were found in several areas during the period from 1901 to 2011, which included eight cycles of solar variations. In this study, areas with equal or greater than the 95% significance level, *i.e.*, $r = 0.187$, $n = 111$, were considered.

The global distributions of the correlation coefficients (r) between annual SSN and SST from July to December for the period from 1901 to 2011 are shown in Fig. 1. In this study, we focused on areas with a greater than 95% significance level, which accounted for 11.7% of the global sea surface in December; correlation based on latitudes were not attempted.

We focused on the results from autumn to early winter because some interesting results were apparent from November to December (Figs. 4 to 11) in the second year of the solar maximum. Both significant positive correlation areas (SPCAs) and the significant negative correlation areas (SNCAs) were considered in this study. The regional features of each sea area from July to December were as follows.

The SPCAs tended to occur in the Circum-North Pacific. In July, SPCAs in the Circum-North Pacific were distributed from around Japan via the Aleutian Islands to the west of North America.

This relationship was less obvious in August and September, but SPCAs were concentrated in the eastern parts of the Circum-North Pacific in October, centered off northern California, and this was maintained throughout December.

In December, the SPCAs in the Circum-North Pacific shifted farther toward the southern part, and they were linked to SPCAs around the Hawaiian Islands (Fig. 1f). SPCAs were apparent near Japan, especially off eastern Japan, in July and from November to December, although they were less common from August to October.

In the Southern Hemisphere, SPCAs were found over the southern Pacific Ocean, including off eastern Australia and around New Zealand. These extended into the Antarctic Ocean in August