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Research Paper

Decadal variability of upper ocean heat content in the Pacific: Responding to the 11-year solar cycle

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ABSTRACT

Ocean heat content anomaly (OHCa) time series in some areas of the Pacific are significantly correlated with the total solar irradiance (TSI). Using the composite mean-difference method, we determined the mean response of OHCa in the upper-700 m of the ocean to the TSI. Among the high solar response areas, we figure out two regions, one in the tropical mid-Pacific and the other in the western Pacific, where the OHCa present decadal variations, but different phases. The variation in phase of the solar response indicates that there exists an agency for the OHCa's response to TSI.

1. Introduction

Solar irradiance is the most important driving force for the Earth's climate system. The total solar irradiance (TSI), also known as 'solar constant', measures the radiant energy flux incident on the outer surface of the Earth's atmosphere at a standard Earth–Sun distance. Before the satellite era, TSI was considered a constant, about 1367 W m^{-2}. It was not until recently, that the value was revised to a lower value of about 1361 W m^{-2}, based on observations by satellites since 1978 (Kopp and Lean, 2011). The satellite-based measurements also revealed slight changes of TSI due to sunspot blocking, facular emission, network emission, etc. (Beer et al., 2000). TSI varies by approximately 1 W m^{-2} from solar minimum to solar maximum (Kuhn et al., 1988; Willson and Hudson, 1991), in phase with solar activity. For instance, it shows a close correlation with the 11-year sunspot cycle. TSI also varies on a number of timescales ranging from minutes to millennia, including the 22-year Hale solar magnetic cycle, and the 80–90-year solar Gleissberg cycle (Tsiropoula, 2003). Therefore, TSI is a reasonable proxy for the entire solar activity. By using the length of the sunspot cycle (9–13.6 years), the normalized decay rate of the sunspot cycle and the mean level of solar activity and other proxies, TSI has been reconstructed back a few hundred years prior to 1978 (Hoyt and Schatten, 1993; Lean, 2000).

The variability of the TSI at several timescales is expected to affect the Earth's climate system (Camp and Tung, 2007; Tung and Camp, 2008; Zhou and Tung, 2010). It was estimated that the TSI had contributed to about 40% of the global warming during 1850 and 1990 (Beer et al., 2000), or 45–50% of the 1900–2000 global warming, and 25–35% of the 1980–2000 global warming (Scafetta and West, 2006). Friis-Christensen and Lassen (1991) suggested that the length of the TSI cycle is a possible indicator of solar activity associated with climate. Using the measurements of solar activity and global-averaged sea surface temperature (SST), Reid (1987, 1991) deduced that the SST may have varied in-phase with the envelope of the 11-year solar cycle. By focusing on time series of basin-averaged and global-averaged upper ocean temperatures, White et al. (1997) found ocean temperatures responding to changing solar irradiance in a frequency band with periods of 9–13 year. White et al. (1998) constructed gridded fields of diabatic heat storage changes in the upper oceans and revealed decadal (8–15 years) and interdecadal variability significantly correlated with changing surface solar irradiative forcing. Qu et al. (2004) found that a variation, which has a period twice the 11-year TSI cycle, prevails in the global marine temperature changes. The 11-year TSI cycle might also serve as an external forcing of the Pacific Decadal Variability (Minobe et al., 2004).

So far, little is known of how TSI acts at different time scales on climate and how the climate system reacts to changes in this forcing. Njau (2000a, 2000b) established a Sun–climate/weather

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model to explain the relationship between Sun activity and climate variability. Kristjansson et al. (2002) proposed a mechanism which says that TSI variations are amplified by interacting with SST, and subsequently low cloud cover. However, there are still some climate observations that are difficult to explain in regimes of solar response. For example, in the equatorial Pacific, SST may present negative anomalies during high solar activity years (Meehl et al., 2008). White et al. (2003) believed that even though the global quasi-decadal signal is phase-locked to the 11-year signal in the Sun's surface irradiative forcing, the anomalous global tropical diabatic heat storage tendency cannot be driven by it directly. Small changes in the TSI give rise to small variability in the global energy budget; therefore, variations of solar activity must be amplified through some mechanisms to give large climatic effects (Shaviv, 2008). The mechanism for solar activity to drive climate variability is still under debate.

It was confirmed that ocean heat content (OHC) plays a critical role in the Earth's heat balance for the climatological annual cycle (Ellis et al., 1978) and for interannual-to-decadal scales (Levitus et al., 2000; Willis et al., 2004). White et al. (1997) suggested that the solar-related signals in the upper ocean temperature can penetrate to 80–160 m depth. Therefore, the upper OHC might also be a robust parameter for characterizing the response of ocean to the TSI.

Most of the previous researches gave the correlation of solar activity and climate variability in a globally averaged or basin averaged sense. This work aims to confirm the existence of oceanic areas where the OHC anomaly (OHCa) clearly bears an 11-year solar cycle.

2. Methods

2.1. Data

The TSI data between 1950 and 2003 are from Wang et al. (2005), with an offset to match the SORCE/TIM extended value from Kopp and Lean (2011). Fig. 1 gives the annual mean TSI from 1950 to 2011.

The OHC is a major component of the Earth's energy budget. It is the spatial integration of the heat T contained in ocean waters. That is

$$Q = \iiint C_p \cdot \rho \cdot T \, dx \, dy \, dz, \tag{1}$$

where the seawater density ρ and the specific heat at constant pressure of seawater C_p are commonly taken as constants, for instance, $\rho = 1025$ kg m^{-3} and $C_p = 4000$ J kg^{-1} K^{-1}. This study uses

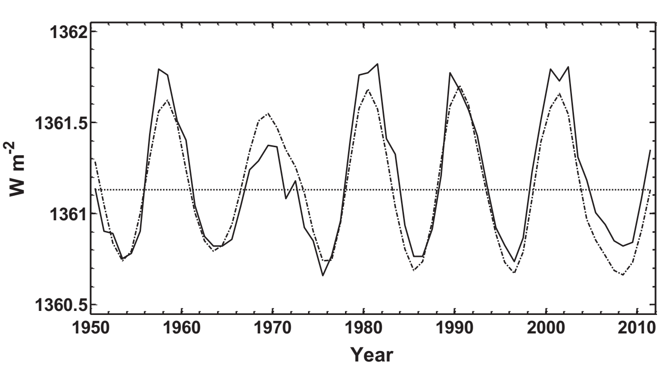

Fig. 1. The annual-mean TSI for the period 1950–2011 (solid line) and its decadal-scale component (dot-dashed line) derived from the EMD method, offset the mean TSI during 1950–2011 (dotted line). Annual mean TSI includes some values that are difficult to ascribe to high solar activity periods or low solar activity periods. Its decadal component however avoids this problem.

two sets of OHCa products provided by National Oceanic and Atmospheric Administration (NOAA) National Oceanographic Data Center (NODC) and Japan Meteorological Agency (JMA), respectively. NOAA's dataset is produced by Levitus et al. (2012). They provided estimates of the change of ocean heat content and the thermosteric component of sea level changes based on data from the World Ocean Database 2009 (WOD09), plus additional data processed through recent years. The dataset used here is the annual mean anomaly from 1955 to 2011, which includes the OHCa data from the surface to the depth of 700 m at $1° \times 1°$ grids. JMA's global OHCa are calculated from the monthly temperature and monthly climatological salinity data prepared by Ishii and Kimoto (2009). The global historical ocean temperature and salinity dataset are reconstructed based on the observed data from World Ocean Database 2005 (WOD05) and climatology data from World Ocean Atlas 2005 (WOA05). A near-real-time data archived through the Global Temperature–Salinity Profile Program (GTSPP), and a set of XBT observations compiled by the Japan Oceanographic Data Center are also used to compensate for the data sparseness of WOD05. The $1° \times 1°$ gridded data used in this work are annual mean OHCa from 1950 to 2011.

2.2. Methods

This work uses the composite mean-difference (CMD) method (Camp and Tung, 2007) to study the response of the upper ocean heat content to the 11-year TSI variation. Both NOAA's and JMA's OHCa data are 5-points smoothed using a zero-phase filter. We then classify the smoothed OHCa time series according to the high solar activity periods (HS, the years around solar maximum when solar activity is energetic) and low solar activity periods (LS, the years around solar minimum when solar activity is plain). The mean difference of OHCa data during the two periods is then calculated via

$$P(x, y) = \sum_{i=1}^{n} w_i H_i(x, y) \tag{2}$$

where $w_i = 1/n_1$ if the ith year is in HS, and $w_i = 1/n_2$ if it is in LS, n_1 and n_2 are the number of years in HS and LS, respectively; $H_i(x,y)$ is the OHCa at grid (x,y) in the ith year; $P(x,y)$ is the resultant spatial pattern which is supposed to be the response of OHCa to the forcing of TSI with an 11-year variation. We need to determine the HS and LS first. As the 11-year solar cycle is modulated by fast varying components of solar activities, we use the Empirical Mode Decomposition (EMD) method to pick out the component with 11-year cycle from the TSI time series. EMD is an adaptive method which decomposes the data into signals from high frequency to low frequency, each of variable frequency or amplitude (Huang et al., 1998; Wu and Huang, 2009). It is an effective approach for processing nonlinear and non-stationary data. The HS and LS are then separated naturally according to the decadal-scale component of TSI. Fig. 1 shows the annual mean TSI, its mean during the period 1950–2011, and its decadal-scale component derived from EMD. The years that are difficult to ascribe to HS or LS in the annual-mean are clearly defined in its decadal-scale component.

3. Results

The correlations between OHCa time series at each grid and TSI are presented in Fig. 2. The pattern based on either NOAA's data (Fig. 2a) or JMA's data (b) illustrates a feature: positive/negative correlated areas are not randomly organized; they tend to cluster in large blocks. It indicates there might be causality between TSI and OHCa.

Spatial pattern of OHCa in the Pacific response to the 11-year