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ENSO response to external forcing in CMIP5 simulations of the last millennium

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ABSTRACT

The El Niño–Southern Oscillation (ENSO) is dominant mode of interannual climate variability, but its response to external climate forcings remains uncertain. Past studies have limitations including the use of short datasets and the uncertainty contained in reconstructions or simulations of past ENSO variations. To improve our understanding on ENSO variations, it is important to examine its response to these forcings by using multi model simulations since they provide longer datasets and help improving the statistical significance of the results. In this study, Granger causality test is applied to investigate the influence of external forcings on ENSO by using past millennium simulations (period 850–1850 CE) of Coupled Model Intercomparison Project Phase 5 (CMIP5) models. The results show robust influence of volcanic forcing to ENSO during preindustrial times of last millennium. The response of ENSO to solar forcing is more likely to be weak. Detection of GHGs variations signal in ENSO response is not significant. However, this study also indicates that there are uncertainties in the responses of ENSO to solar forcing and GHGs radiative forcing. The possibility of the true causal connection between Total Solar Irradiance (TSI) or GHGs radiative forcing and ENSO cannot be rejected at 95% significance level.

1. Introduction

The El Niño–Southern Oscillation (ENSO) is dominant mode of interannual climate variability and understanding its response to external forcings (i.e. solar forcing, volcanic radiative forcing and greenhouse gases radiative forcing) is of great interest.

The link between ENSO and solar forcing has remained unclear and it is difficult to detect (Cobb et al., 2003, 2013). While D'Arrigo et al. (2005) conclude that period of high variance ENSO index coincides with low radiative forcing period, Emile-Geay et al. (2007) suggest that large or moderate scenario of solar forcing have influence on ENSO variability at century-to-millennial-scale. Several studies emphasize the importance of ocean-atmosphere coupling mechanisms in the influence of solar forcing on tropical Pacific (Misios and Schmidt, 2012) and the importance of Bjerknes feedback in the connection between solar forcing or volcanic forcing and ENSO strength in the past 1000 years (Cane, 2005).

Recent studies showed a doubling in the occurrences of extreme El Niño events (Cai et al., 2014) and a near doubling in the frequency of future extreme La Niña events (Cai et al., 2015) in response to simulated future greenhouse warming. Besides, the influence of future increased greenhouse gases (GHGs) concentrations on the frequency of central Pacific El Niño and eastern Pacific El Niño is suggested for several models best able to simulate observations (Yeh et al., 2009; Power et al., 2013). However, such changes in ENSO characteristics are normally not consistent between all model simulations (Power et al., 2013).

The connection between explosive volcanic eruptions and ENSO has remained controversial. Several studies of both proxy data and model simulations suggested an association between volcanic eruptions and ENSO events (Handler, 1984; Adams et al., 2003; Mann et al., 2005; McGregor et al., 2010; McGregor and Timmermann, 2011; Wahl et al., 2014; Maher et al., 2015). In contrast, other studies found that the influences of volcanic radiative forcing (VRF) on ENSO are weak (Robock et al., 1995; Self et al., 1997; Ding et al., 2014). Previous studies might only use a small number of volcanic eruptions and there is uncertainty contained in reconstructions or simulations of past ENSO variations. These limitations might affect the statistical significance for establishing the true linkage between volcanic eruptions and ENSO. Moreover, past studies only investigate the VRF-ENSO relationship without accounting for the effects of other confounding factors (i.e. solar forcing, GHGs radiative forcing). These factors might have impacts on the ENSO and thus omitting these factors can lead to false conclusion about true VRF-ENSO relationship.

The current observational records are not long enough to investigate the response of ENSO to external forcings. Detecting the signal of external forcing in the variations of ENSO is difficult because of the large intrinsic changes in ENSO behavior (Collins et al., 2010). However, this problem can be solved by using large multi-model results, which consider that internal variability is taken into account.

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Here, the author evaluates the causal relationship between external forcings and ENSO of past 1000-yr model simulations using multivariate vector autoregressive time series models and Granger causality tests (See Methods Section 2). This method accounts for the simultaneous effects of different factors (i.e. solar forcing, VRF and GHGs radiative forcing), thus, it might show a more clearly picture of ENSO response to external forcings. The current study is independent from previous studies in both aspects of datasets and statistical methods used. The results of this study might also serve as a test for the consistency of climate models in simulating the response of ENSO to external forcings.

2. Data

Monthly mean near-surface air temperature (TAS) data is used from the Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulations of past 1000-yr (Taylor et al., 2012). The data is available for the period from 850 to 1850 CE. Thus, in this study, the last millennium refers to this period. The models were forced with Total Solar Irradiance reconstructions from either Delaygue and Bard (2010) or Vieira et al. (2011) or Steinhilber et al. (2009) or Wang et al. (2005), as shown in Table 1. Table 1 also shows the volcanic forcing (from either Crowley et al. (2008) or Gao et al. (2008)) used in each simulation (See Fig. 1 for the time series of these climate forcings). Other forcings include well-mixed greenhouse gases (GHGs) variations, orbital variations, land cover change and solar-related ozone change. The full details of climate forcing reconstruction options used in CMIP5 past 1000-yr simulations are described in Schmidt et al. (2011) and Schmidt et al. (2012).

The simulation of ENSO in CMIP5 models is an important aspect and it is discussed in previous studies. The large diversity in ENSO amplitude between models is improved in CMIP5 models compared to CMIP3 models (Bellenger et al., 2014). Though 50% of CMIP5 models cannot simulate the strength of EP and CP ENSOs, the spatial pattern and inter-model difference are improved (Kim and Yu, 2012). The observed intensity and the location of maximum SST anomalies are well captured in CMIP5 models of historical simulation. However, there are biases associated with the westward extent of SST anomalies (Taschetto et al., 2014). Besides, CMIP5 models still have systematical narrow bias in the simulated ENSO meridional width of SST anomaly (Zhang and Jin, 2012). Although CMIP5 models still have biases in simulating ENSO variability, these models provide valuable datasets to understand the response of ENSO to external forcings.

3. Methods

The ENSO index is defined as the leading empirical orthogonal function (EOF) of the winter (December–January–February) sea surface temperature (SST) anomalies in the Niño3.4 region (120°W-170°W; 5°N-5°S). The leading EOF reflects El Niño or La Niña pattern, featuring warm or cool anomalies of central Pacific SST in Niño3.4 region. This EOF mode explains 65–90% of total variance, depending on specific model. The changes of ENSO of past 1000-year is highly model dependent (See Fig. 2 for filtered ENSO time series of individual models). However, the range of simulated ENSO's amplitude is consistent between models, except the wide spread of ENSO's amplitude in the model MIROC-ESM (solid green line).

Note that the results of the relationship between ENSO and external forcings show no significant change if Niño3 (region of 90°W-150°W; 5°N-5°S) and Niño4 (region of 150°W-160°E; 5°N-5°S) indices are used. The analysis based on tropical Pacific region (100°E-70°W; 30°N-30°S) also has similar results (See Section 4.3 for brief discussion).

Multivariate vector autoregressive (VAR) time series models (e.g. Mosedale and Stephenson, 2006; Stern and Kaufmann, 2013) is used to estimate the influence of external forcings (i.e. solar forcing, volcanic forcing and GHGs radiative forcing) to ENSO. This method uses the definition of Granger causality (Granger, 1969) as follows: A variable Y has causal impact on another variable X if the knowledge of the past values of Y is useful in improving the prediction of X. The p^{th} order vector autoregressive VAR(p) is defined by:

$$X_t = \sum_{i=1}^{p} \alpha_i X_{t-i} + \sum_{i=1}^{p} \beta_i Y_{t-i} + \sum_{j=1}^{m} \sum_{i=1}^{p} \delta_{j,i} Z_{j,t-i} + \varepsilon_t \tag{1}$$

where X_t is the ENSO index at year t, Y_t is the considered forcing at year t, $Z_{j,t}$ is the control forcing j at year t, m is total number of control forcings, and $p \geq 1$ is the order of the causal model. The considered forcing is either Total Solar Irradiance (TSI) or volcanic radiative forcing (VRF) or GHGs radiative forcing. The forcing other than considered forcing is control forcing (or control variable (Stern and Kaufmann, 2013) or confounding factor (Hegerl et al., 2010)). Control forcings might have effects on the relationship between considered forcing and ENSO. In Eq. (1), m equals to 2, indicating that there are two control forcings. The terms α_i, β_i and $\delta_{j,i}$ are regression coefficients, ε_t is noise residual in the regression. The data of X, Y and $Z_{1\rightarrow m}$ are detrended and normalized to produce stationary time series before computation.

Granger causality test (e.g. Mosedale and Stephenson, 2006; Le, 2014) is applied for the causal model shown in Eq. (1). This test accounts for the optimal order p for the VAR time series models by using Schwarz criterion or Bayesian information criterion (Schwarz, 1978). This criterion is required to avoid the model to become overly complex (i.e. too many parameters are added to the model). The optimal order is normally <8 for our current datasets. Thus, in our analysis, the maximum order is set at 8, indicating that the influence of external forcing to ENSO is only investigated at lagged timescale shorter than 10-year. The model given in Eq. (1) is complete model. The null model of no causality from Y to X is obtained by setting the $\{\beta_i; i = 1, 2, \ldots, p\}$ coefficients to zero. These two models are compared using the log likelihood ratio statistic:

$$L_{Y\rightarrow X} = n\left(\log|\Omega_{p,\beta_i=0}| - \log|\Omega_p|\right) \tag{2}$$

where $|\Omega_p|$ is the determinant of the covariance matrix of the residual, n is the sample size.

If the statistic $L_{Y\rightarrow X}$ in Eq. (2) is close to zero, then the null model is as equally good as the complete model in predicting the data of X, thus, Y has no causal impact on X. If this statistic is large, then the additional terms of Y help to predict the variability of X and we say that there is Granger causality. Statistical significance of the test is evaluated by comparing the $L_{Y\rightarrow X}$ statistic against the χ^2_p null distribution. If the p-value is smaller than 0.05, then the null hypothesis of no Granger causality is rejected at 5% level of significance.

Table 1
Last Millennium modelling institutes and model IDs and volcanic and solar forcing[a].

Institute	Model ID	Abbreviation	Volcanic forcing	Solar forcing
BCC	BCC-CSM1-1	BCC	GRA	VSK and WLS
NASA-GISS	GISS-E2-R	NASA	CEA	SBF
IPSL	IPSL-CM5A-LR	IPSL	GRA	VSK and WLS
LASG - IAP	FGOALS-s2	LASG-IAP	GRA	VSK and WLS
MIROC	MIROC-ESM	MIROC	CEA	DB and WLS
MPI-M	MPI-ESM-P	MPI-M	CEA	VSK and WLS
MRI	MRI-CGCM3	MRI	GRA	DB and WLS
NCAR	CCSM4	NCAR	GRA	VSK
UOED	HadCM3	UOED	CEA	SBF and WLS
UNSW	CSIRO-Mk3L-1-2	UNSW	CEA	SBF

[a] CEA = Crowley et al. (2008), DB = Delaygue and Bard (2010), GRA = Gao et al. (2008), SBF = Steinhilber et al. (2009), VSK = Vieira et al. (2011), WLS = Wang et al. (2005). The forcings of model GISS-E2-R are shown for selected ensemble of r1i1p121.