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Tropical Pacific interactions in the WCRP-CMIP3 multi-model dataset

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ABSTRACT: The ability of numerical models in reproducing the observed statistical links between the sea surface temperature of central and eastern tropical Pacific Ocean is analysed in this paper. Significant links in the whole spectrum of frequency were studied for models of the World Climate Research Program (WCRP-CMIP3/IPCC-AR4) using the methodology of wavelet coherence.

During the second half of the twentieth century, in-phase or quasi-in-phase links in oscillations of 2–6 years, a lack of relation in oscillations of 8–12 years and time lagged links in the longest periodicities are detected in the observed dataset. Some of the analysed models are able to reproduce the observed relationships in oscillations shorter than 6 years and few of them also reproduce the lacks of significant relation in the band of 8–12 years. On the other hand, all models have serious problems representing the observed time lagged links in the longest waves.

The analysis shows that climate models are still unable to reproduce specific features of tropical Pacific interactions with potential effect on the Southern Hemisphere atmospheric circulation and, in particular, the South American climatic variability. Copyright © 2011 Royal Meteorological Society

KEY WORDS sea surface temperature; tropical Pacific; global climate models; oceanic interactions; Wavelet Coherence analysis

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1. Introduction

The variability of sea surface temperature (SST) anomalies in the tropical Pacific displays a wide range of temporal scales. In fact, previous investigations describe important variability on near-annual (e.g., Jin *et al*., 2003), interannual (e.g., Kawamura, 1994; Wallace *et al*., 1998), biennial (e.g., Meehl, 1987; Ropelewski *et al*., 1992), decadal (e.g., Trenberth and Hurrell, 1994; Tourre *et al*., 1999) and bidecadal (e.g., Cerveny and Shaffer, 2001) time scales. In particular, the El Niño-Southern Oscillation (ENSO) dominates the interannual variability in the tropical Pacific and it is the most important forcing of interannual world climate variability (e.g., Pan and Oort, 1983; Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989; Philander, 1990).

Different theories have been proposed to explain the physical processes associated with the occurrence of ENSO (e.g., Bjerknes, 1966, 1969; Suarez and Schopf, 1988; Battisti and Hirst, 1989) and recent studies have been focused in separate the interactions of the SST in the central tropical Pacific from that the SST in the eastern tropical Pacific during these events (e.g., Larkin and Harrison, 2005; Yu and Kao, 2007; Kao and Yu, 2009). The contrast central-east tropical Pacific was also taken into account by Trenberth and Stepaniak (2001) in the definition of the Trans-Niño Index (difference EN1 + 2 − EN4). They postulate that this gradient of SST across the tropical Pacific can help to better describe the specific character and evolution of each ENSO event.

Different conditions in the central and eastern tropical Pacific have important effects on the climatic variability of South America. Recently, the numerical experiments performed by Hill *et al*. (2011) describe the response of the Southern Hemisphere atmospheric circulation to the location of SST anomalies over the tropical Pacific Ocean. In particular, they show an approximately opposite pattern of South American precipitation during austral summer when the SST forcing is applied over the western and eastern tropical Pacific.

Our interest is to evaluate how well different climatic model simulations reproduce specific characteristics of the tropical Pacific variability that can have an important impact on the South American climatic variability. In this sense, the analysis of the relationships between central and eastern tropical Pacific in models of the Phase 3 of the World Climate Research Programme – Coupled Model Intercomparison Project (WCRP-CMIP3) will be useful

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in improving knowledge about the limits of the coupled global climate models (CGCMs) in the prediction of future climate and climate change. Therefore, the purpose of this paper is to investigate the ability of the WCRP-CMIP3 numerical models in reproducing the interactions among the central and eastern tropical Pacific in the space of frequency and the evolution of such relationships across the time. Although several papers have analysed different aspects of the tropical Pacific variability in the WCRP-CMIP3 models (e.g., Capotondi *et al.*, 2006; Joseph and Nigam, 2006; Lin, 2007; Wang *et al.*, 2009), an analysis from a different point of view is presented here.

The paper is organized as follows. Data and methodology are described in Section 2, results are presented in Section 3 and the conclusions are summarized in Section 4.

2. Data and methodology

2.1. Data

Observed monthly anomalies with respect to the 1961–1990 means of SST for El Niño 3.4 (EN3.4) and El Niño 1 + 2 (EN1 + 2) regions were extracted from the Hadley Centre SST data set (HadSST2, Rayner *et al.*, 2006). These monthly anomalies were annually averaged and the same process was made in the modelled data.

The twentieth century climate simulations analysed in this study were generated by the scientific groups participating in the World Climate Research Program for the IPCC-AR4. Runs of the 'climate of the twentieth century experiment' (20C3M) are available at the Program for Climate Model Diagnosis and Intercomparison (PCMDI). The models individualized as the CMIP3 codes and the number of runs considered for each one are: BCCR-BCM2.0 (1 run), CCSM3 (4 runs), CGCM3.1(T47) (1 run), CNRM-CM3 (1 run), CSIRO-Mk3.0 (3 runs), ECHAM5/MPI-OM (3 runs), ECHO-G (5 runs), FGOALS-g1.0 (3 runs), GFDL-CM2.0 (3 runs), GFDL-CM2.1 (3 runs), GISS-EH (5 runs), GISS-ER (9 runs), INM-CM3.0 (1 run), IPSL-CM4 (1 run), MIROC3.2 (3 runs), MRI-CGCM2.3.2 (5 runs), PCM (4 runs) and UKMO-HadGEM1 (2 runs). Detailed information about each model and simulation forcing can be found at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php

Although the observed SST data are available since 1850, only the more reliable information starting in 1950 (Thompson *et al.*, 2008) was used in this study. Therefore, the analysis was performed for the period 1950–1999.

2.2. Methodology

The analysis was made considering the methodology of wavelet coherence (WTC) (e.g., Torrence and Compo, 1998; Torrence and Webster, 1999; Grinsted *et al.*, 2004) which allows the relationships among two temporal series in all bands of periodicities, as well as the evolution of such relationships across the time, to be described. This methodology finds regions in time frequency space where the two time series co-vary but does not necessarily have high power.

A detailed guide about calculation and interpretation of results from the WTC analysis can be found in different papers (e.g., Grinsted *et al.*, 2004). As a synthesis, the methodology individualizes areas where two time series are statistically linked. The magnitude of the WTC between synchronized time series is near 1 whereas it is near 0 between time series without connection. The phase relations between the series are graphically described by the phase vectors. In-phase (anti-phase) relationships are indicated by arrows pointing right (left) while lagged time links are described by non-horizontal arrows. In all figures presented in this work, arrows pointing upward (downward) means that the SST in EN1 + 2 leads (follows) EN3.4.

It is important to mention that the definition of wavelet coherence closely resembles the typical correlation coefficient being useful to think of it as a localized correlation coefficient in the space of time frequency (Moore *et al.*, 2006). It is also very important to take into account that significant areas in the space of time frequency is not an indication of physical connection among the analysed time series because, as in a simple correlation analysis, the significant relations could be showing spurious results simply by chance.

Several antecedents exist about the use of this mathematical tool in different scientific disciplines including research about oceanic and atmospheric variability (e.g., Jevrejeva *et al.*, 2004; Müller *et al.*, 2008).

3. Results

Outputs of the WTC analysis describing the observed and modelled relations between the central and eastern tropical Pacific during the second half of the twentieth century are shown in Figure 1.

The main characteristics of the observed pattern are the in-phase relations in the shortest periodicities with interruptions during the 1950s and 1980s, stationary in-phase or quasi-in-phase links in oscillations of 2–6 years, a lack of significant relationships in periodicities around 8–12 years and lagged time links in the longest periodicities (Figure 1(a)). As commented on in the previous section, in the lagged relations arrows pointing upward (downward) means that the SST in EN1 + 2 leads (follows) EN3.4. To analyse the causes or physical mechanisms involved in all mentioned characteristics is beyond the objectives of this paper.

The analysed models exhibit a wide variety of central-eastern tropical Pacific relationships. The main features are described in the following paragraphs.

The BCCR-BCM2.0 model is not able to represent the observed pattern because the modelled relations are significant only in oscillations shorter than 8 years having a clear sporadic and lagged time character (Figure 1(b)).

Outputs of the CCSM3 model reproduce significant in-phase or quasi-in-phase links in the shortest oscillations but they have important deficiencies in the representation of the links in waves longer than 4 years (Figure 1(c)). In particular, run 1 has a disconnection in oscillations of 4–12 years before the 1990s which is not coincident with the characteristics of the observed pattern. Run 2 is not able to reproduce the observed lack of relation in waves longer than 6 years while such disconnection takes place in different regions of the spectrum in runs 3 and 4.

The CGCM3.1 model has problems to reproduce the observed interactions because important disconnections are detected in the shortest periodicities and significant links take place in oscillations around 8 years (Figure 1(d)).

The simulation of the CNRM-CM3 model captures two important aspects of the observed pattern: the in-phase relations in oscillations shorter than 6 years and the lack of connection in oscillations of 8–12 years (Figure 1(e)). On the contrary, this model is not able to represent the lagged time relations in waves longer than 12 years.

The 3 runs of the CSIRO-Mk3.0 model reproduce the in-phase or quasi-in-phase relations in oscillations shorter than 6 years but they have problems to represent

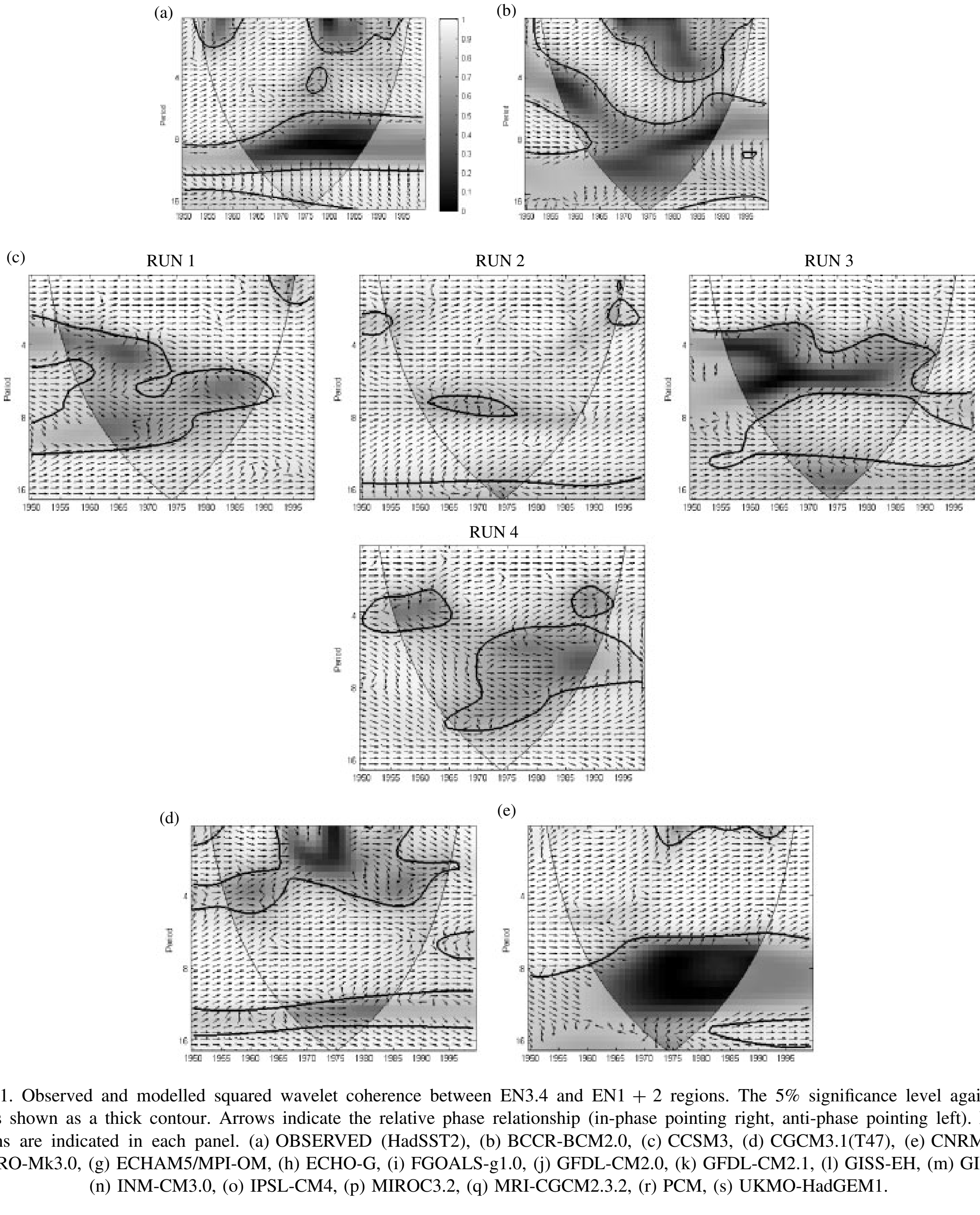
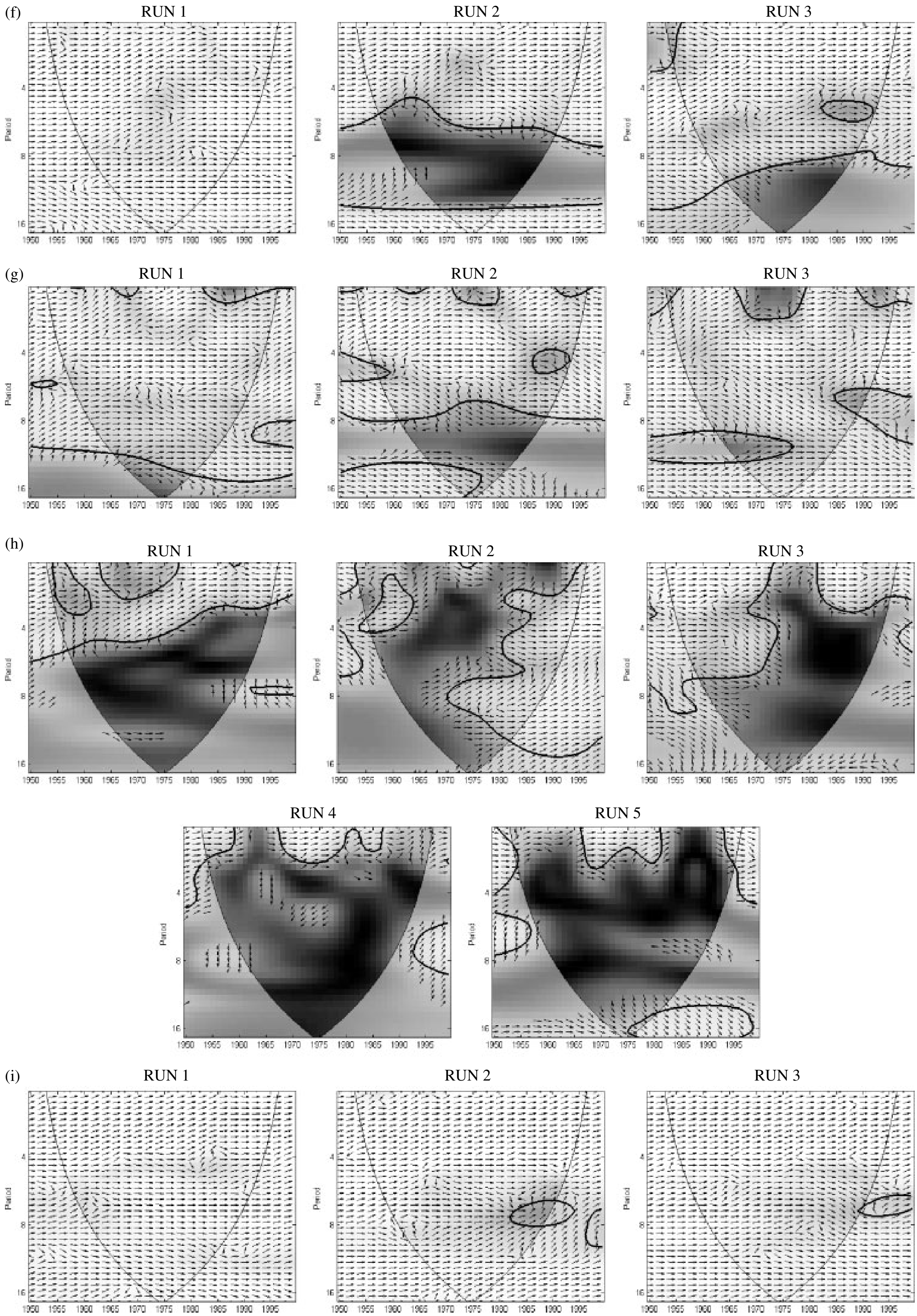


Figure 1. Observed and modelled squared wavelet coherence between EN3.4 and EN1 + 2 regions. The 5% significance level against red noise is shown as a thick contour. Arrows indicate the relative phase relationship (in-phase pointing right, anti-phase pointing left). Models and runs are indicated in each panel. (a) OBSERVED (HadSST2), (b) BCCR-BCM2.0, (c) CCSM3, (d) CGCM3.1(T47), (e) CNRM-CM3, (f) CSIRO-Mk3.0, (g) ECHAM5/MPI-OM, (h) ECHO-G, (i) FGOALS-g1.0, (j) GFDL-CM2.0, (k) GFDL-CM2.1, (l) GISS-EH, (m) GISS-ER, (n) INM-CM3.0, (o) IPSL-CM4, (p) MIROC3.2, (q) MRI-CGCM2.3.2, (r) PCM, (s) UKMO-HadGEM1.



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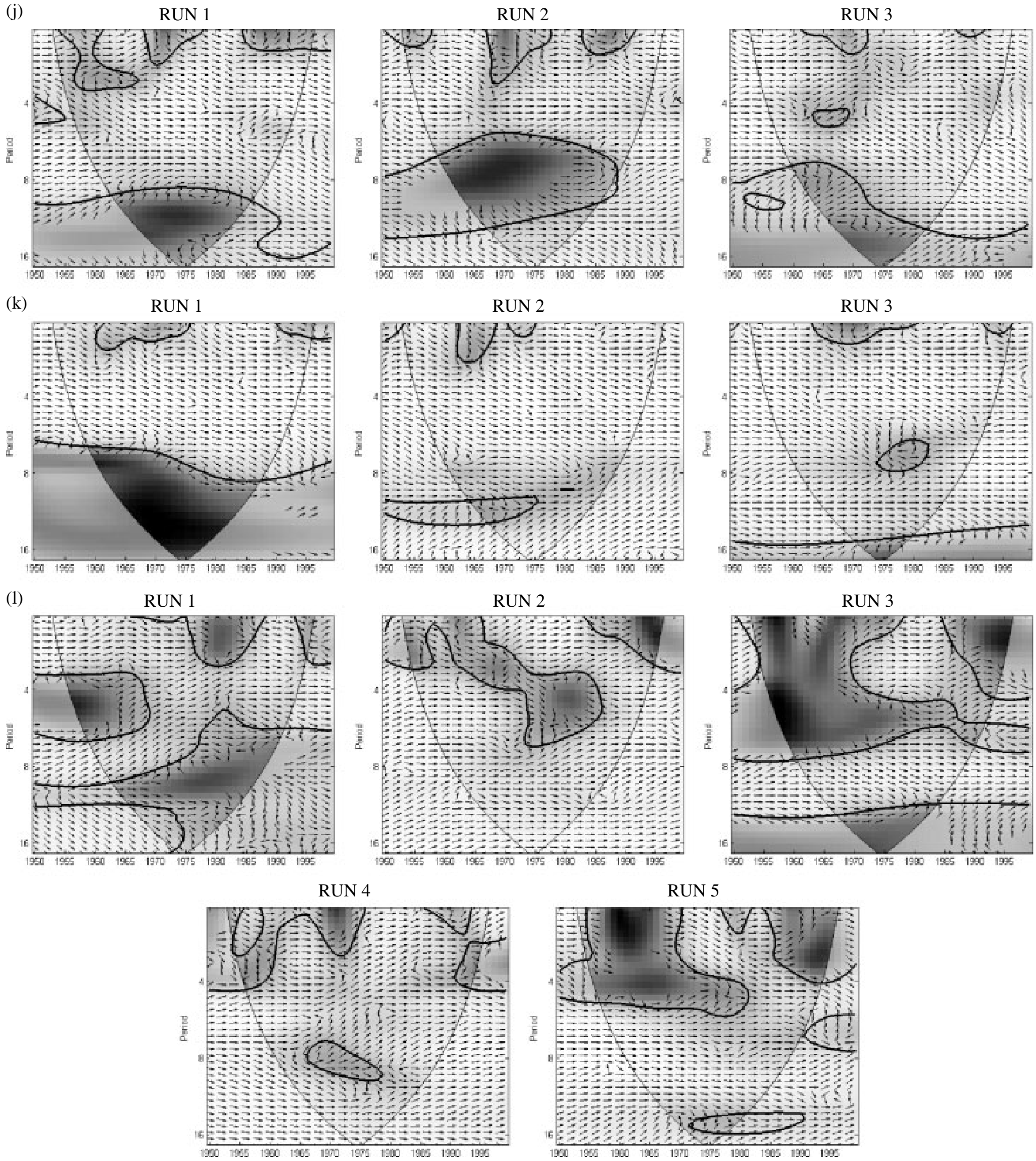


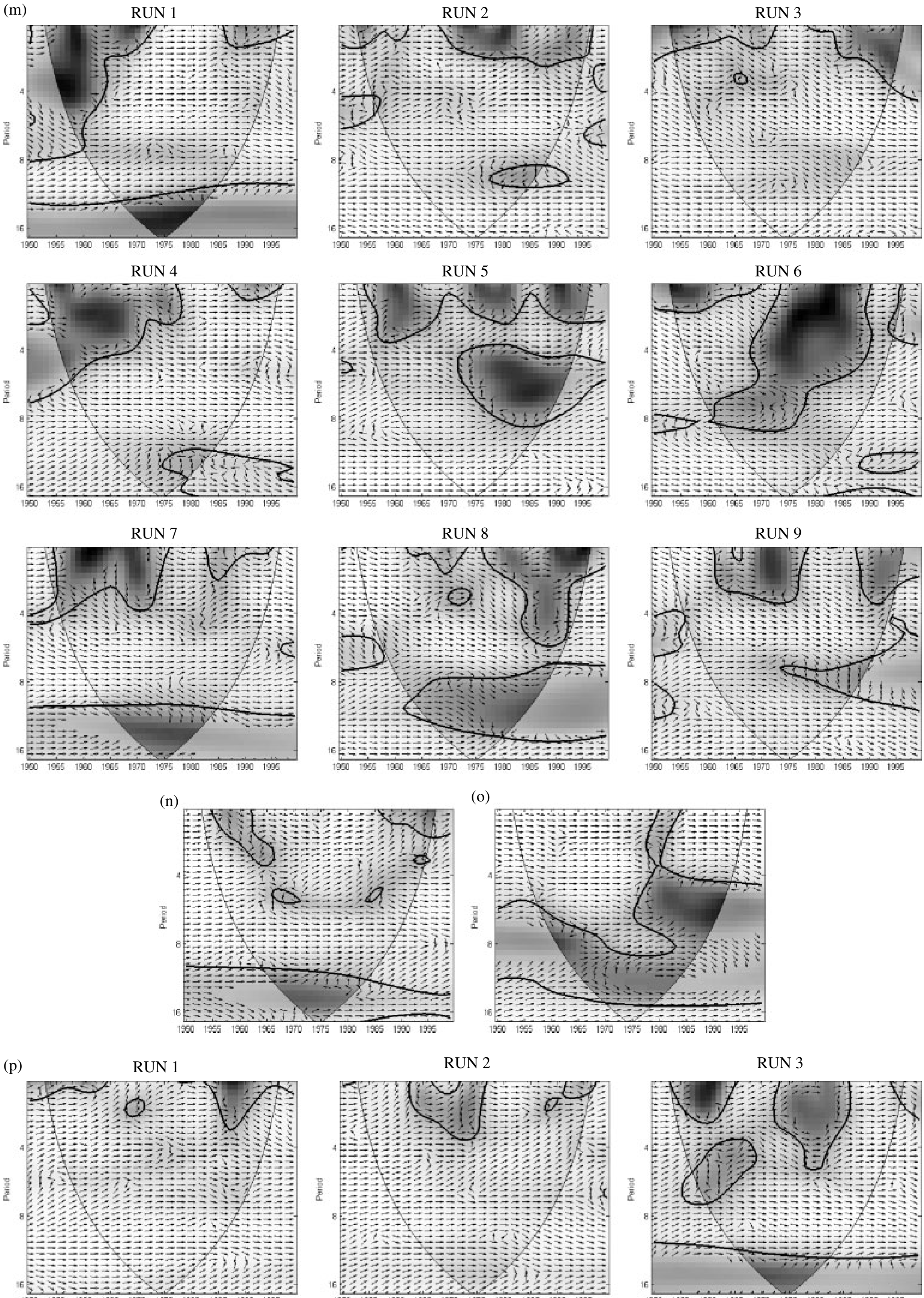
Figure 1. (*Continued*).

the disconnections in the shortest periodicities during the 1950s and 1980s (Figure 1(f)). These runs also have problems reproducing the interactions in oscillations longer than 6 years. In fact, run 1 shows stationary in-phase relations over all the space of variability, run 2 contains a disconnection in the band of 6–14 years with in-phase relations in the longest periodicities and there is a lack of relations in oscillations longer than 8 years in run 3, especially after the 1970s.

Outputs of the ECHAM5/MPI-OM model reproduce the observed in-phase or quasi-in-phase relations in oscillations of 2–6 years (Figure 1(g)). For periodicities longer than 8 years, runs 1 and 3 are not able to reproduce the observed features but run 2 captures the lack of significant relationships in periodicities around 8–12 years.

The disconnection between the central and eastern tropical Pacific in almost all the space of variability represented by the 5 runs of the ECHO-G model (Figure 1(h)) and the strong co-variability in all periodicities reproduced by the 3 runs of the FGOALS-g1.0 model (Figure 1(i)) are clearly different to the observed features.

Runs of the GFDL-CM2.0 model reproduce significant co-variability in oscillations shorter than 6 years (Figure 1(j)). Although there is a lack of statistical connection in long periodicities in the 3 runs, the characteristics are clearly different to the observed pattern.



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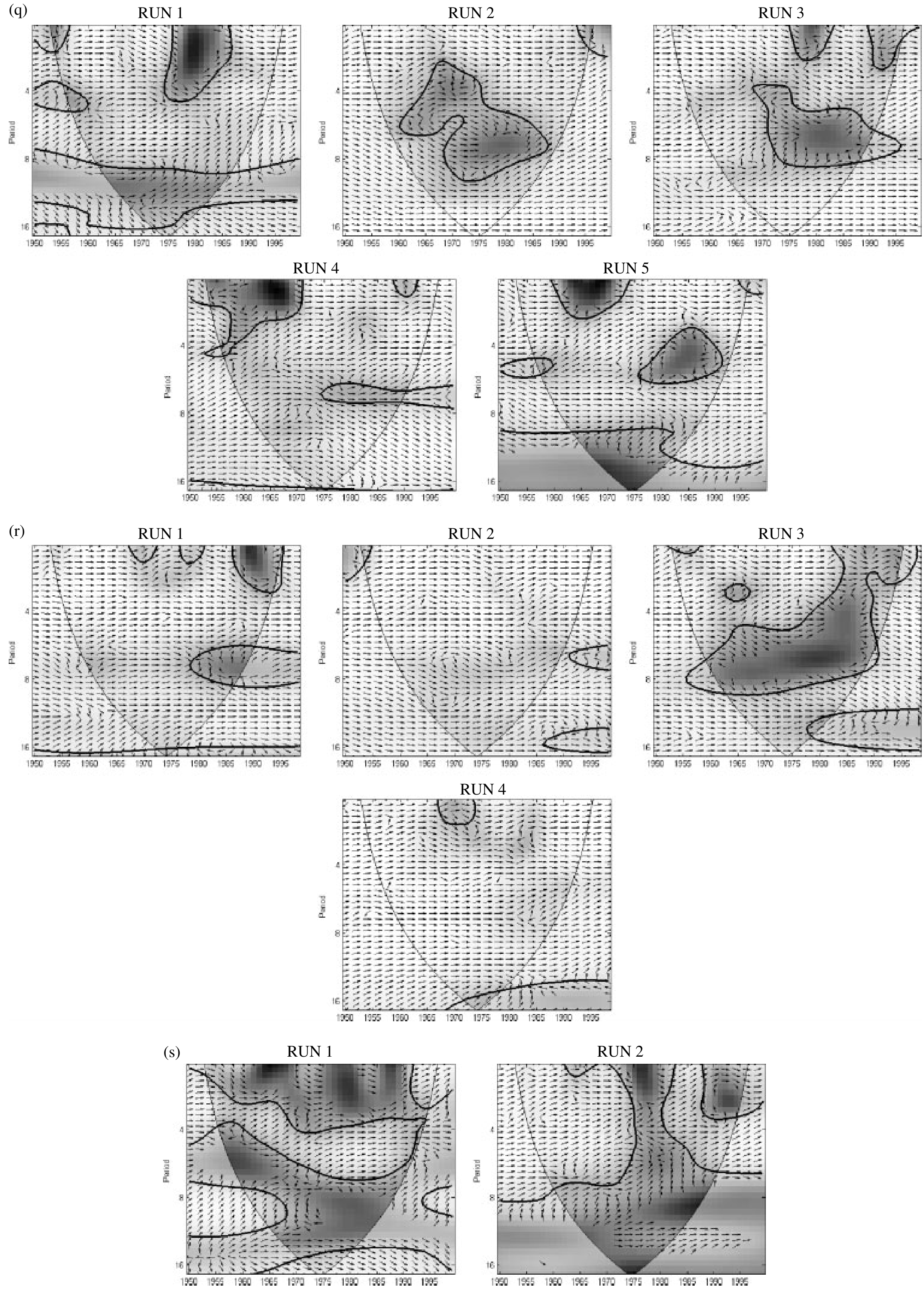

Figure 1. (*Continued*).

In the GFDL-CM2.1 model, run 1 reproduces the in-phase links in short oscillations and the disconnection in waves of 8–12 years but it is not able to represent the time lagged relations in waves longer than 12 years (Figure 1(k)). The other 2 runs of this model simulate significant in-phase or quasi-in-phase links over almost all periodicities, not being able to represent the observed disconnections in long waves.

Each run of the GISS-EH model exhibits a particular pattern of relationships but none of them reproduce the observed characteristics having problems representing even the links in short waves (Figure 1(l)). Notorious deficiencies are also detected in the nine simulations of the GISS-ER model (Figure 1(m)). Only runs 2 and 3 of this model simulate the in-phase or quasi-in-phase links in oscillations of 2–6 years and all runs have serious problems representing the interactions in long periodicities.

The observed significant in-phase or quasi-in-phase links in waves shorter than 6 years are reasonably well represented by the INM-CM3.0 model but it has problems to reproduce the lack of connection in oscillations of 8–12 years and it is not able to represent the time lagged links in the longest oscillations (Figure 1(n)).

The IPSL-CM4 model has the ability to reproduce significant in-phase links in oscillations shorter than 6 years as well as a disconnection in the band of 8–12 years but it is not able to represent the lagged links in the longest oscillations (Figure 1(o)).

Runs 1 and 2 of the MIROC3.2 model exhibit significant in-phase or quasi-in-phase links over almost all periodicities not being able to reproduce the observed features in oscillations longer than 8 years (Figure 1(p)). Although in run 3 there are lacks of the significant links in different regions of the space of frequency, the specific characteristics are clearly different than the observed ones. The observed interruptions during the 1950s and 1980s of the in-phase relations in the shortest periodicities are captured by run 3.

The MRI-CGCM2.3.2 outputs reproduce significant in-phase or quasi-in-phase relations in short waves but with disconnections that are not detected in the observed pattern (Figure 1(q)). Only run 1 of this model captures some features of the observed links in long periodicities.

In the PCM model, the 4 runs reproduce strong co-variability in short oscillations but all of them exhibit problems representing the lack of relation and the time lagged links in the longest periodicities (Figure 1(r)).

Run 1 of the UKMO-HadGEM1 model has serious problems to represent the observed interactions in all the space of variability (Figure 1(s)). Run 2 of this model reproduces strong in-phase links in oscillations of 2–6 years and disconnections in the band of 8–12 years but it has problems representing the observed time lagged pattern in the longest waves.

The analysis here presented, reveals that some models are able to reproduce the observed central-eastern tropical Pacific interactions in oscillations of 2–6 years. In fact, the observed stationary in-phase or quasi-in-phase links in such periodicities are reasonably well reproduced by runs of models CCSM3 (run 2), CNRM-CM3, CSIRO-Mk3.0 (the 3 runs), ECHAM5/MPI-OM (the 3 runs), FGOALS-g1.0 (the 3 runs), GFDL-CM2.0 (the 3 runs), GFDL-CM2.1 (the 3 runs), GISS-ER (runs 2 and 3), INM-CM3.0, IPSL-CM4, MIROC3.2 (runs 1 and 2), MRI-CGCM2.3.2 (run 4) and PCM (runs 1, 2 and 4). Some models are able to reproduce the observed disconnection between central and eastern tropical Pacific in oscillations of 8–12 years (CNRM-CM3, run 2 of CSIRO-Mk3.0, run 2 of ECHAM5/MPI-OM, run 1 of GFDL-CM2.1, IPSL-CM4, run 1 of MRI-CGCM2.3.2 and run 2 of UKMO-HadGEM1). On the other hand, all models have serious problems representing the observed links in oscillations longer than 12 years.

From the previous WTC analysis, it is clear that the studied models have deficiencies in representing the observed interactions between the SST of the central and eastern tropical Pacific Ocean. The wavelet analysis does not take into account the amplitude of the analysed oceanic time series but the atmosphere does. Therefore, as a complementary description, it is important to investigate how the models represent the interannual standard deviation of both oceanic regions which can affect the atmosphere producing different teleconnection patterns. These deviations for the observed and modelled time series are shown in Figure 2. As described by several studies, the observed variability in the EN1 + 2 region is higher than in EN3.4 (e.g., Deser *et al.*, 2010 and references therein) having magnitudes of 0.9 and 0.6 °C, respectively (Figure 2(a)). The analysed models have deficiencies in reproducing not only the magnitude of observed standard deviation in both oceanic regions but also the relations among the magnitudes. In fact, considerable variability is found in the representation of standard deviation at both the EN1 + 2 and EN3.4 regions (Figure 2(a)). In almost all runs the modelled standard deviation in the EN1 + 2 region is lower than the observed one, having models in which the simulated magnitude is 50% lower than the observed one (Figure 2(b)). The modelled standard deviation at EN3.4 region results lower or higher than the observed one depending of the model (Figure 2(a)) and there are runs in which the difference between the observed and modelled magnitudes exceeds 50% (Figure 2(b)). An important difference between the observed and modelled standard deviations for the EN1 + 2 and EN3.4 regions is the relation between the magnitudes. In the observed SSTs, the standard deviation in EN1 + 2 is higher than in EN3.4 but only the 5 runs of the ECHO-G model and the 9 runs of the GISS-ER model represent this characteristic (Figure 2(a)).

4. Conclusions

The ability of the WCRP-CMIP3 numerical models in reproducing the observed central-eastern tropical Pacific interactions has been investigated in this paper. The

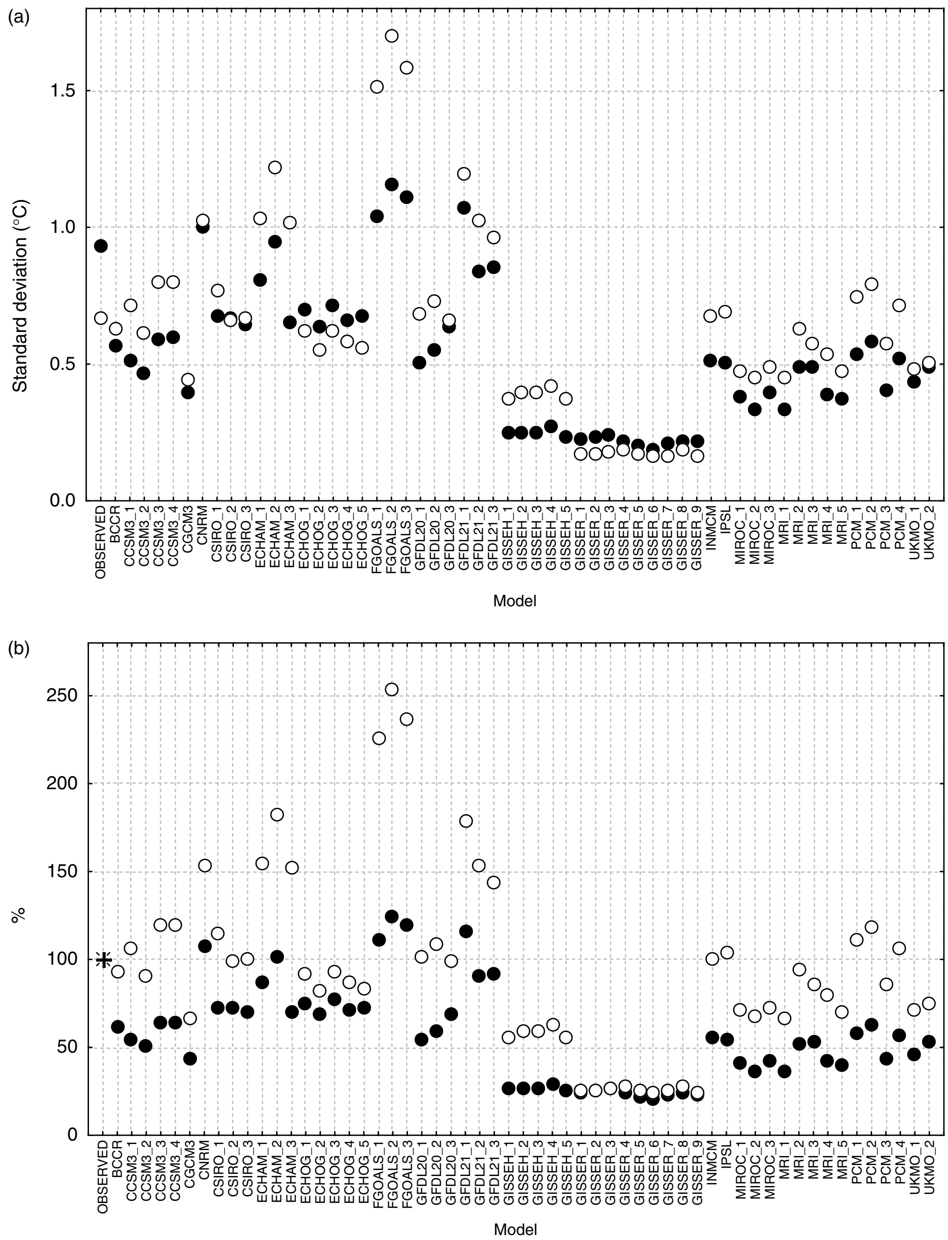

Figure 2. (a) Standard deviations of observed and modelled SST at EN1 + 2 (black circle) and EN3.4 (white circle) regions; (b) Relations between the magnitudes of observed and modelled standard deviation of SST at EN1 + 2 and EN3.4 regions expressed as percentages of the observed values (% = modelled × 100 × observed^{-1}). ●, EN1 + 2; ○, EN3.4.

analysis focused on the relationships among these oceanic regions in all time frequencies and the changes in such relationships across the time.

The observed central-eastern tropical Pacific relations during the second half of the twentieth century are mainly characterized by in-phase or quasi-in-phase links in oscillations of 2–6 years, a lack of relation in oscillations of 8–12 years and lagged time links in the longest periodicities. The analysed models show a wide variety of features describing the central-eastern tropical Pacific interactions. The in-phase or quasi-in-phase relationships in oscillations shorter than 6 years are reasonably well represented by some models and a few of them also reproduce the lack of significant relation in the band of 8–12 years. On the contrary, all models have serious problems representing the observed lagged time links in the longest periodicities.

None of the analysed simulations capture completely the observed central-eastern tropical Pacific interactions in the space of variability. Models also exhibit serious limitations in representing the amplitude of the interannual variability of SST at both tropical regions during the second half of the twentieth century. These defects of the models could be representing much more that the incapacity to reproduce conditions in the tropical Pacific. As mentioned in Section 1, several studies about ENSO events have separated the influence of the SST in the central and eastern tropical Pacific. Moreover, the location of SST anomalies over the tropical Pacific has important effect on the Southern Hemisphere atmospheric circulation and, in particular, the South American climatic variability. For southern South America, it is not clear yet the specific influence of different oceanic regions in the low-frequency climate variability. It is not either totally clear how the interactions among different oceanic regions influence the climatic variability in different bands of periodicities. Therefore, the results exposed in this paper could be showing limits of the global models in the description of important forcing of the regional climate, in particular for the South American continent.

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