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Time-varying relationships among oceanic and atmospheric modes: A turning point at around 1940

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A B S T R A C T

Oceanic and atmospheric modes play a key role in modulating climate variations, particularly on interannual and interdecadal scales, causing an indirect response of regional climate to external forcings. This study comprehensively investigated the time-varying linkages among dominant oceanic and atmospheric modes of the Pacific and Atlantic areas on different timescales using the scale space multiresolution correlation analysis. For the Pacific Ocean, the Interdecadal Pacific Oscillation (IPO) shows closer matches with the El Niño-Southern Oscillation (ENSO) than with the Pacific Decadal Oscillation (PDO). This indicates that the ENSO dominates climate variability of the whole Pacific Ocean not only on interannual but also on interdecadal scales. Interdecadal variations of the IPO appear to be more closely linked to southern Pacific Ocean climate before ~1940, but become more closely linked to northern Pacific Ocean after ~1940. The shifts on interdecadal connections among northern, tropical and southern parts of the Pacific Oceans seems to be related to the phase shifts of the IPO/PDO, which may contribute to the cooling trend from 1940s to 1970s. For the Atlantic Ocean, the Atlantic Multi-decadal Oscillation (AMO) is closely linked to the North Atlantic Oscillation (NAO) on the interdecadal scale before ~1940.

1. Introduction

Climate variation and change is caused by natural (e.g. solar and volcanic) and anthropogenic (e.g. greenhouse gas emissions and land use) forcings and modulated by internal (e.g. oceanic and atmospheric modes) feedbacks (Ruddiman, 2014; Stocker et al., 2013). Climate changes on timescales from a year to a century are hot concerns as climate changes on these timescales are closely related to socioeconomic planning. Climate changes on interannual scales describe climate changes across years (1–10 years). There are different definitions on the interdecadal scale climate change. This study employs the definition by the Climate Variability and Predictability Programme (CLIVAR) (World Climate Programme et al., 1992), which define interdecadal scales from decadal to centennial scales, i.e. 10–100 years. Internal oceanic and atmospheric modes are the key to understand climate variability and extremes particularly on interannual and interdecadal scales scales (Dai et al., 2015; Fang et al., 2014; Kosaka and Xie, 2013). This is largely because the changes of the natural and anthropogenic forcings are often less conspicuous on these timescales relative to the oceanic and atmospheric modes. For example, the orbital scale has minor influences on climate changes lower than centennial timescales. Although solar activity varies on ineterannual and interdecadal scales, these appear not sufficiently strong to directly drive climate variations on these timescales. The greenhouse gas emissions show seasonal cycles and an increasing trend since the onset of the industrial era without clear variability on timescales shorter than a century (Kosaka and Xie, 2013). In fact, on interannual and interdecadal scales, external forcings often indirectly influence regional and large-scale climate changes via modulating the oceanic and

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atmospheric oscillations (Fang et al., 2015).

The oceanic and atmospheric modes are climate patterns that encapsulate the particular state of the oceanic or atmospheric components of the climate system of certain regions and teleconnected areas, which have periodical or quasi-periodical oscillations (Mantua and Hare, 2002; Walker and Bliss, 1932). This study investigates the dominant modes of the Pacific Ocean, including the coupled oceanic and atmospheric modes of the El Niño-Southern Oscillation (ENSO), the oceanic modes of the Interdecadal Pacific Oscillation (IPO) and the Pacific Decadal Oscillation (PDO), and the atmospheric modes of the North Pacific Oscillation (NPO). We also investigate the modes of the Atlantic Ocean, including the oceanic modes of the Atlantic Multidecadal Oscillation (AMO) and the atmospheric modes of the North Atlantic Oscillation (NAO). The atmospheric modes of the middle and high latitudes (Arctic Oscillation (AO) and Antarctic Oscillation (AAO)) are also studied herein. These oceanic and atmospheric modes do not only have direct influences on local climate in their definition areas but can also impact climate in distant regions via teleconnections. For example, the ENSO not only directly modulates the climate in the tropical western and eastern Pacific Ocean but can also influence the climate of the whole earth (Ropelewski and Halpert, 1987). Teleconnections among the oceanic and atmospheric modes and climate of distant regions can be bridged by large-scale atmospheric circulations (Ding and Wang, 2005).

Due to the important roles of oceanic and atmospheric modes on climate change, numerous paleoclimate reconstructions have been conducted using proxies with high spatiotemporal resolution and climate sensitivity, such as tree rings (Li et al., 2013). However, considerable mismatches are often found among the reconstructions for the same oscillation when using different proxies from different locations. This is largely because the oceanic and atmospheric modes often interact with each other and their complex linkages are not fully understood. This study attempts to provide an overview of the oceanic and atmospheric modes and their linkages using the instrumental data. As linkages among oceanic and atmospheric modes often vary on different timescales and different periods, we paid special attention to their time-varying relationships at different timescales. These linkages revealed using instrumental data can help to assess the robustness of the paleoclimate reconstructions of oceanic and atmospheric models during their reconstruction period.

We herein introduce the data and analytical methods in section 2. Section 3 introduces the definitions of the oceanic and atmospheric modes. Section 4 studies their time-varying relationships at different timescales for Pacific area, and section 5 explores the oceanic and atmospheric modes for Atlantic area and their linkages to Pacific modes. Major findings are summarized in section 6.

2. Data and methods

2.1. Data

The existing ENSO indices are closely related to each other (Allan et al., 1996), and we herein only employed the instrumental Niño 3.4 index calculated from the HadISST dataset since 1870 (Rayner et al., 2003). The instrumental PDO since 1900 used herein was derived from the Mantua et al. (1997) ftp directory (http://jisao.washington.edu/pdo/). The instrumental record of IPO was derived from the HadISST dataset since 1870 (Henley et al., 2015). We employed a long instrumental NPO and AO data since 1899 derived from the station records and the NCEP/NCAR Reanalysis datasets (Thompson and Wallace, 2000; Trenberth and Hurrell, 1994). The long-term instrumental NAO record from the stations in Lisbon and in Reykjavik of western Iceland extends back to 1865 (Hurrell, 1995). The instrumental data used for the AMO were derived from the HadSST 3.1 dataset since 1850 (Rayner et al., 2003). The AAO data were calculated from a long station-based observational dataset spanning from 1865 to 2005 (Jones et al., 2009; Visbeck, 2009).

2.2. Analytical methods

Correlation analysis can be used to explore the linkages between the various oceanic and atmospheric modes of the Pacific and Atlantic oceans. The Pearson correlation coefficient measures linear dependence between two random variables but it is prone to several problems. The first problem is that their correlation may change over time while the Pearson correlation coefficient only measures the average correlation over the entire length of the time series. Second, different correlation structures might appear in different time scales and the Pearson correlation coefficient cannot reveal the full dependence structure of such time series. The third problem is the difficulty to make valid statistical inferences about correlation in the presence of autocorrelation. A novel solution to such problems is provided by the so called scale space multiresolution correlation analysis (Pasanen and Holmström, 2016), that takes into consideration the possibility that the correlation between two time series may not be constant in time and can have different features when viewed at different time scales.

This method was first introduced as a graphical tool to display the features of the time series in both different level of resolution, i.e. the “scale”, and different localized spaces (Chaudhuri and Marron, 1999). This method has been continuously improved and widely used as introduced by the reviews (Holmström, 2010; Pasanen and Holmström, 2016). This method has also been widely used for studies on climatology as the climate regimes often change in different periods and vary at different timescales (Godtliebsen et al., 2012). However, to our knowledge, this method has not been used to study the oceanic and atmospheric modes for the globe in instrumental period. The scale space method decomposes the two time series into several additive timescale-dependent components and then localized correlations for a range of time window widths are computed between pairs of the corresponding components. The scale space multiresolution method determines the significance of the local correlations using the Bayesian inference, which takes into account the changes in window widths, i.e. the timescales, and thus the changes in freedom at different timescales. The filtering can change the autocorrelation and thus the freedom of the time series. The Bayesian method can easily account for the changes of the autocorrelation by finding sets of time points for which the joint posterior probability of the correlations are sufficiently high (see the Appendix for more details).

Another possible approach for investigating the time-varying timescale dependent relationships between the two series is the wavelet coherence (WTC) (Chen and Li, 2004; Grinsted et al., 2004; Torrence and Compo, 1998). WTC analysis is based on wavelet analysis that decompose the time series into a time-frequency profile (Torrence and Compo, 1998). Time-varying correlation can be detected and the decomposition allows one to study the relationships between different climate modes at different timescales (Grinsted et al., 2004; Torrence and Compo, 1998). Scale space multi-resolution correlation analysis and WTC provide similar information, but the first appears to be more sensitive to the salient features of time-varying correlations and its results are arguably more interpretable (Pasanen and Holmström, 2016). The WTC analyses of the correlations between the various oceanic and atmospheric modes are included in the Appendix.

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