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Bimodality and regime behavior in atmosphere–ocean interactions during the recent climate change

Bijan Fallah*, Sahar Sodoudi*

Institute of Meteorology, Free University of Berlin, Carl-Heinrich-Becker-Weg 6-10, 12165 Berlin, Germany

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ABSTRACT

Maximum covariance analysis (MCA) and isometric feature mapping (Isomap) are applied to investigate the spatio-temporal atmosphere–ocean interactions otherwise hidden in observational data for the period of 1979–2010. Despite an established long-term surface warming trend for the whole northern hemisphere, sea surface temperatures (SST) in the East Pacific have remained relatively constant for the period of 2001–2010. Our analysis reveals that SST anomaly probability density function of the leading two Isomap components is bimodal. We conclude that Isomap shows the existence of two distinct regimes in surface ocean temperature, resembling the break and active phases of rainfall over equatorial land areas. These regimes occurred within two separated time windows during the past three decades. Strengthening of trade winds over Pacific was coincident with the cold phase of east equatorial Pacific. This pattern was reversed during the warm phase of east equatorial Pacific. The El Niño event of 1997/1998 happened within the transition mode between these two regimes and may be a trigger for the SST changes in the Pacific. Furthermore, we suggest that Isomap, compared with MCA, provides more information about the behavior and predictability of the inter-seasonal atmosphere–ocean interactions.

1. Introduction

The climate system appears chaotic but is influenced by complex and high-dimensional processes. Reoccurring climatic phenomena can have a large influence on societies, economies and human health, with extreme events potentially leading to crises of some kind. The Asian monsoon region is one of the world's most populated area, and the higher inter-seasonal fluctuations in the Asian monsoon can lead to major disasters such as floods, droughts, crop damage, *etc.* Hannachi and Turner (2013). Such complex phenomena are resulting from the interplay of different lower boundary forcings such as the oceans (Webster et al., 1998).

El Niño events are the most persistent patterns of ocean variability (Cai et al., 2014; Krishna Kumar et al., 2006) with a direct impact on rainfall's levels, duration and distribution. Cai et al. (2014) found the evidence of increasing probability of extreme El Niño events linked to climate change. The El Niño event of 1997/1998 was the strongest on record and climate models did not predict the strength of this rapid event (McPhaden, 1999). The intensity of this El Niño event may have been affected by the interplay of chaotic climate components (*e.g.*, atmosphere, hydrosphere, biosphere, *etc.*). Many studies have

* Corresponding author. Tel.: +49 30 83871181.
E-mail address: bijanf@zedat.fu-berlin.de (B. Fallah).

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investigated the feedback processes between atmosphere and Pacific ocean (Timmermann et al., 1999; Yeh et al., 2009; Collins et al., 2010; Kug et al., 2010).

According to recent Intergovernmental Panel on Climate Change (IPCC, 2013) report, the tropical rainfall enhanced over land areas during the last decade and the drying trend since mid-1970s to 1990s is reversed https://www.ipcc.ch/. The expected warming trend for the period of 1998–2012 was 0.2 °C per decade (IPCC, 2013). However, the observed global averaged warming rate was 0.04 °C per decade for this period and the climate models were unable to reproduce this hiatus. Among the possible factors (*e.g.*, atmospheric aerosols, oceans and sun) which modulate the global temperature change, equatorial Pacific accounts for the most of the hiatus (Meehl et al., 2013). According to England et al. (2014), strengthening of Pacific trade winds has a dominant impact on cooling of Central equatorial Pacific during this period and the global warming trend is likely to resume once again.

It is always a challenging work to identify the most important modes of multidimensional climate data. Dimensionality reduction techniques are recently used to detect the most important components of the data set that represent the most variability: empirical orthogonal function (EOF) analysis (Jolliffe et al., 2002), Multidimensional scaling (MDS) (Cox and Cox, 2008), Isomap (Tenenbaum et al., 2000), independent component analysis (ICA) (Comon, 1994), locally linear embedding (LLE) (Saul and Roweis, 2000), Laplacian eigenmaps (LEM) (Belkin and Niyogi, 2003). Bretheron et al. (1992) suggested several techniques for isolating the leading modes of variability between two data sets.

Previous studies indicate that there is a direct correlation between sea surface temperature anomaly (SSTA) and rainfall changes (Hastenrath and Greishar, 1993; Giannini et al., 2003; Seager et al., 2005; Hoerling et al., 2006; Krishna Kumar et al., 2006; Schubert et al., 2009). MCA can detect coupled linear atmosphere–ocean teleconnection patterns (Rayner et al., 2003; Dai, 2013). According to Tenenbaum et al. (2000), EOF analysis may be able to find a low-dimensional embedding by preserving its variances. However, many observations contain high-dimensional modes that are invisible to a linear classical dimensionality reduction method like EOF analysis. Hannachi and Turner (2013) applied Isomap to sea-level pressure anomalies to investigate the Asian summer monsoon regime behavior. They suggested that the probability density function of Asian summer monsoon is bimodal. Ross et al. (2008) concluded that Isomap presents no additional modes of climate with respect to classical principal component analysis for ENSO dynamics. Turner and Hannachi (2010) suggested further investigations using the nonlinear dimensionality reduction techniques to explain the monsoon variability.

This study investigates the global atmosphere–ocean variations during the recent climate to understand the possible feedback processes. The spatiotemporal patterns of coupled atmosphere–ocean variations are of major importance especially with respect to their relation to monsoon variability under the recent global warming. Using scale-of-the-art analysis tools will improve the understanding of such complex interactions between different components of the climate system (*e.g.*, oceans and atmosphere).

Here, MCA and Isomap are compared to investigate the most important coupled patterns between rainfall and SSTA in the observed climate. Additionally, we discuss the possible dynamics behind such relationships. To reach the highest confidence due to the increased number of observations (date-rich period), we focused on the recent period 1979–2010.

The study approach is based on the analysis of the effect of non-linearity on two different data reduction methods which are described in the next section. Section 3 contributes to the results, focusing on regime behavior in the atmosphere–ocean changes during the observation period. Discussion and conclusions are presented in Section 4.

2. Data and methods

2.1. Observations

We used monthly precipitation from GPCP Version 2.2 Combined Precipitation Data Set (Adler et al., 2003), NOAA Extended Reconstructed SST V3b (Smith and Reynolds, 2003) and 850 hPa wind from NCEP reanalysis (Kalnay et al., 1996). After removing the seasonal cycle from the data, the monthly anomalies are calculated. In addition, seven different monthly climate indices are used from Earth System Research Laboratory http://www.esrl.noaa.gov/psd/data/climateindices/list/ to define the temporal modes of MCA: Niño3.4, Trans-Niño Index (TNI) (Trenberth and Stepaniak, 2001), North Atlantic Oscillations (NAO) (Hurrell, 1995), Atlantic Meridional Mode (AMM) (Chiang and Vimont, 2004), North Tropical Atlantic Index(NTA) (Penland and Matrosova, 1998), Arctic Oscillations (AO) (Higgins et al., 2002), Pacific Decadal Oscillation (PDO) (Zhang et al., 1997). Combined Northern Hemisphere land-surface air and sea-surface water temperature anomalies (NHT) and land-surface air temperature anomalies only (NHTL) from GISS Surface Temperature Analysis (GISTEMP) are also included in our investigation. The two latter are based on the study of Hansen et al. (2010) (http://data.giss.nasa.gov/gistemp/).

2.2. MCA

MCA applies a single value decomposition (SVD) method to identify the coupled variability of the two dataset (here precipitation and SSTA). Bretheron et al. (1992) used this method to compare different climate components (*e.g.*, ocean and atmosphere). The advantage of MCA, compared with coupled EOF analysis, is that this method captures those modes