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The relationship between the Madden-Julian oscillation and the land surface soil moisture

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ABSTRACT

The impact of the Madden–Julian oscillation (MJO) on the global land surface soil moisture was explored in the study. The MJO index was calculated from long term 1997–2013 GPCP precipitation and ERA-Interim 850-hPa and 250-hPa zonal winds. The composites of soil moisture anomalies over eight MJO phases were mapped and analyzed. In order to distinguish the MJO signal with other patterns of climate variability, only MJO event days are used in the composites. In addition, the statistical significance of the anomaly composites is estimated using the Student's *t*-test. The MJO has been found to be the prominent source of the intraseasonal variation of the monsoon systems, which induces the variations of precipitation. Our results show that the variation of soil moisture between MJO phases also agrees well with the variation of the monsoon systems. In addition to the monsoon regions, the MJO also affects soil moisture over other areas such as East Africa. The relation between the soil moisture and precipitation anomaly composites across the MJO phases was also investigated. The results show that the variation of soil moisture over MJO phases is related to its connection to precipitation. In addition, large similarities were found between the GPCP-derived MJO index and the corresponding ESA CCI soil moisture composites, and ERA-Interim-derived MJO index and corresponding ERA-Interim soil moisture composites. This proves the feasibility of ERA-Interim datasets for MJO related studies. Owing to the different resolutions of the CCI and ERA-Interim soil moisture, CCI is more appropriate for regional and ERA-Interim dataset for large-scale MJO related analysis.

1. Introduction

The Madden–Julian oscillation (MJO) is the dominant mode of the tropical intraseasonal variability (Zhang, 2005, 2013). Discovered by Madden and Julian (1971, 1972, 1994), the MJO is featured by large scale convective anomalies that originate in the Indian Ocean area and propagate slowly eastward with a speed of 5–10 ms^{-1} along the equator to the Pacific Ocean. The MJO shows an intraseasonal variability with typical time scales in the order of 30 to 90 days. The MJO has nearly global impacts by influencing e.g. the EI Niño Southern Oscillation (Pohl and Matthews, 2007; Zhang and Gottschalck, 2002) and the monsoon systems (Goswami et al., 2003; Straub et al., 2006), and by teleconnections with the extratropics (Cassou, 2008; Matthews et al., 2004). Therefore, identification, forecasting and modeling of the MJO are important for the MJO related analyses. The development of the Real-Time Multivariate (RMM) MJO Index by Wheeler and Hendon (2004) makes it possible to monitor the MJO. The effects of the MJO on many weather and climate phenomena are normally described as how these events vary with MJO phases, which are characterized by convection and the associated wind fields, and are calculated based on the RMM MJO index. With the help of the RMM MJO index, the teleconnections between MJO and various weather or climate characteristics such as precipitation (Jones et al., 2004), tropical cyclones (Frank and Roundy, 2006), snow cover/depth (Barrett et al., 2015; Li et al., 2016), and surface air temperature (Yoo et al., 2011; Zhou et al., 2016) have been investigated either globally or regionally. For instance, the intraseasonal variation of precipitation due to MJO has been found over all monsoon systems (Janicot et al., 2011; Lorenz and Hartmann, 2006; Pai et al., 2011; Wheeler et al., 2009). In addition, the MJO also has influences on precipitation outside the monsoon areas and beyond monsoon seasons (Barlow et al., 2005; Pohl and Camberlin, 2006), and impacts on extreme rainfall (Jones et al., 2004; Juliá et al., 2012).

However, to the best of our knowledge, no existing research explores the relationship between the MJO and land surface soil moisture so far, despite the established connection between soil moisture and precipitation (Loew et al., 2013; Seneviratne et al., 2010; Wagner et al., 2003). Soil moisture plays a major role for vegetation and is an important variable determining energy partitioning at the land surface (D'Odorico et al., 2007; Koster et al., 2004). The role of soil moisture in the land-atmosphere system has been widely studied (e.g. Alfieri et al., 2008; Diffenbaugh et al., 2007; Koster et al., 2009; Taylor et al.,

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2007; Teuling et al., 2006) using new satellite-based soil moisture datasets (De Jeu et al., 2008; Kerr et al., 2010; Wagner et al., 2012), and recently established soil moisture measurement networks (Hollmann et al., 2013). As the prediction skill of the MJO increases (Kim et al., 2014), the knowledge of the relationship between the MJO and land surface soil moisture would provide a basis for an MJO-based soil moisture forecast system. Thus, the prediction of the MJO and the related variability of soil moisture can further help drought monitoring and forecasting, as well as agriculture management. Therefore, the objective of this study is to investigate the relationship between the MJO and land surface soil moisture. This study explores not only the areas directly affected by the MJO, but also teleconnection between MJO and soil moisture in the extra-Tropics. The latter is reasonable, because of the near-global impact of the MJO on rainfall (Donald et al., 2006) and the availability of global datasets (Hollmann et al., 2013). In the next section, the details of the data and methods used in this study are described. The results and discussion are presented in Section 3. A conclusion is given in Section 4.

2. Data and methods

2.1. Data

The data used in the present study include daily satellite-based products and reanalysis datasets, which overlap for a 17-year period (1997–2013). Each dataset is described briefly below.

2.1.1. ERA-interim reanalysis

ERA-Interim is ECMWF's state-of-the-art global atmospheric reanalysis product, which is generated with a sequential data assimilation scheme. The datasets are available on a 0.75° × 0.75° latitude/longitude spatial scale, and cover the period from 1979 until present (Dee et al., 2011). The evaluations of the ERA-Interim datasets such as soil moisture, precipitation, wind speed and air temperature have also been conducted by recent studies (e.g. Betts et al., 2009; de Leeuw et al., 2015; Peng et al., 2015b; Szczypta et al., 2011; Zhou and Wang, 2016), which show that the ERA-Interim datasets agree well with observations. In this study, we utilize precipitation, wind, and soil moisture.

2.1.2. Satellite-based products

The satellite-based products used in this study include the Global Precipitation Climatology Project (GPCP) precipitation dataset and the European Space Agency's Climate Change Initiative (ESA CCI) soil moisture product. The GPCP global precipitation dataset was established by combining multiple sources of satellite data under support of the World Climate Research Programme (Huffman et al., 1997). The GPCP daily precipitation dataset has 1° spatial resolution and spans the time period from 1996 to present (Huffman et al., 2001), which has already been widely validated and applied in many studies (e.g. Adler et al., 2003; Bolvin et al., 2009; Dinku et al., 2007; Trenberth and Shea, 2005). The CCI soil moisture represents a 36-year (1978–2014) long satellite-based dataset, which was produced within the framework of the ESA Climate Change Initiative (Liu et al., 2011). The CCI soil moisture product was generated by merging several satellite soil moisture products (Dorigo et al., 2015), and has a spatial resolution of 0.25° at daily basis. Reasonable accuracy with an average unbiased root-mean-square differences value around 0.05 $m^3\ m^{-3}$ was found by Dorigo et al. (2015), and a wide range of applications have been conducted since the release of the first version of the dataset in 2012 (e.g. Albergel et al., 2013; Hirschi et al., 2014; Miralles et al., 2014; Peng et al., 2016; Peng et al., 2015a).

2.2. Methods

This section introduces the methods used for the calculation of the MJO index and analysis of the composites. Wheeler and Hendon (2004) proposed an MJO index, which is based on the two leading principal components (PC1 and PC2) of the empirical orthogonal functions (EOF) of the combined fields of outgoing longwave radiation (OLR), 850-hPa and 200-hPa zonal wind anomalies averaged over the tropics (15°S-15°N). The MJO index and the Principal Components (PC) of the two EOFs are used to describe the amplitude and phase of the MJO. The MJO can be divided into several phases (usually eight), according to the two-dimension space constructed by the two PCs. The phases correspond to the location and the strength of the convective envelope of the MJO over the tropics (Wheeler and Hendon, 2004). Phases 1 and 2 represent periods of developing convection over the Indian Ocean, phases 3 to 5 show the propagation over the Maritime continent, while phases 6 and 8 denote the propagation over the western Pacific, with decaying convection in phase 8 (Fig. 3 (winter)). The daily MJO index is calculated by the sum of the square of the principal components of the leading pair of the EOFs: $MJO_i = PC1^2 + PC2^2$. For our analysis an index higher than one are denoted as MJO event day (Waliser et al., 2009). In this study, we calculate the multivariate EOFs of the 20–100-day bandpass filtered anomalies of precipitation and zonal winds at 850-hPa and 200-hPa, i.e. different from previous studies using OLR to calculate the EOFs, we replace OLR with precipitation. We made this choice, because little systematic differences were found between the MJOs utilizing OLR or precipitation (Crueger et al., 2013).

To explore the intraseasonal variation of soil moisture during different phases of MJO, composites of soil moisture anomalies were computed for each MJO phase. To consider the seasonal differences, the composites were made based on two seasons: winter (November–April) and summer (May–October). Composites of precipitation anomalies over land were also prepared to examine the intraseasonal variation of land precipitation that is related to the MJO, and to investigate the potential connections between the intraseasonal variation of soil moisture and that of precipitation. It should be noted that the composite anomalies of soil moisture was calculated with 2-day lags, which means 2 days after an identified MJO phase. This is, because the soil moisture usually has 1–3 days lags of precipitation (Wei et al., 2008; Williams et al., 2012). In order to explore the connections between variations of soil moisture and that of precipitation, correlation analysis between soil moisture and precipitation across the 8 phases of the MJO at each grid point were conducted. Statistical significance of the anomaly composites was estimated using the Student's *t*-test. The above-described analyses (from computation of the MJO index to the calculation of soil moisture composites) were firstly conducted based on satellite-based products including CCI soil moisture and GPCP precipitation. In addition, the same analyses have been performed purely with ERA-Interim reanalysis datasets.

3. Results and discussion

3.1. Analysis of different phases of MJO

Fig. 1 shows the leading pair of the multivariate EOFs of 20–100-day filtered 15°S-15°N averaged precipitation and zonal winds at 850-hPa and 200-hPa. Included are also the amounts of explained variance of the multivariate and the single fields. The features of the MJO can be revealed by the EOFs: 1) similar explained intraseasonal variance in the two EOFs; 2) out-of-phase relationship between zonal wind anomalies at 850-hPa and 200-hPa; 3) positive zonal wind anomalies at 850-hPa over the Indian Ocean in the early stage of the life cycle of the MJO; 4) wind anomalies more in phase with enhanced convection over the west Pacific; 5) strong precipitation anomalies only in the eastern hemisphere. The time series of the MJO index computed from the EOFs is shown in Fig. 2. The MJO index with magnitude greater than one is identified as an MJO event day. So far, the MJO analysis is based on daily data of the entire years. The MJO composites are based on two seasons, boreal winter (November to April) and boreal summer (May to October). Fig. 3 shows the composites of daily anomalies for

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