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Impact of ENSO events on the interannual variability of Hadley circulation extents in boreal winter

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Abstract

The interannual variability of the boreal winter Hadley circulation extents during the period of 1979−2014 and its links to El Niño-Southern Oscillation (ENSO) were investigated by using reanalysis datasets. Results showed that the El Niño (La Niña) events can induce the shrinking (expansion) of Hadley circulation extent in the Southern Hemisphere. For the Northern Hemisphere, El Niño (La Niña) mainly leads to shrinking (expansion) of the Hadley circulation extent in the middle and lower troposphere and expansion (shrinking) of the Hadley circulation extent in the upper troposphere. The ENSO associated meridional temperature gradients have close relationship with the Hadley circulation extents in both Hemispheres. But in the Northern Hemisphere, the ENSO associated eddy momentum flux divergence plays more important role in affecting the Hadley circulation extent than the meridional temperature gradient because of the small local Rossby number. In the Southern Hemisphere, as the ENSO induced eddy momentum flux divergence is small, the meridional temperature gradient dominates the change of the Hadley circulation extent.

Keywords: Hadley circulation; Extents; Meridional temperature gradient; ENSO

1. Introduction

Hadley circulation (HC) is a large-scale thermal driven meridional circulation in the tropics. As the HC is related to the water vapor, energy and angular momentum transport, it plays important roles in the climate system (Li et al., 2015; Hou, 1998), which has attracted a lot of focuses (Li et al., 2013; Quan et al., 2004).

Among the previous studies, HC expansion is one of the most important research aspects. It has been found that the HC suffered poleward expansion since 1979 (Fu et al., 2006; Hu and Fu, 2007; Feng et al., 2011). Subsequently, some studies focused on more evidences of the long-term widening of the HC (Seidel and Randel, 2007; Nguyen et al., 2013) and the causes (Adam and Schneider, 2014; Lu et al., 2009; Polvani et al., 2011).

Most of the above mentioned studies are focused on the long-term trends of HC width, but some studies also analyzed the interannual variability of HC width (Adam and Schneider, 2014; Nguyen et al., 2013). These studies revealed that the interannual variability of the HC extent (HCE) may reach to a deviation of 5 latitude degrees, which is even larger than the

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widening trend during last three decades. As the long-term trend of HC widening may induce expansion of subtropical drought areas (Fu et al., 2006), the interannual variability of the HCE may also cause such impacts on interannual time scale. Therefore, it is important to figure out the interannual variability of HCEs and its causes.

There are several factors affecting HCEs, such as the radiative effect caused by ozone change (Polvani et al., 2011; Waugh et al., 2015; Staten et al., 2012), the sea surface temperature (SST) change (Son et al., 2010; Adam and Schneider, 2014), and the greenhouse gas (GHG) emission (Lu et al., 2009). Among these factors, the El Niño-Southern Oscillation (ENSO) is one of the most robust interannual signals in the tropics. Many studies revealed that the changes of HC spatial structure and strength on interannual time scale are closely related to ENSO (Ma and Li, 2008; Feng et al., 2013; Feng and Li., 2013). Using diagnosing methods, Nguyen et al. (2013) pointed out that interannual variability of HCEs has close relationship with ENSO, but no further mechanism is discussed in their study. Some previous studies demonstrate that the extratropical eddy is mainly related to the HCE changes (Ceppi and Hartmann, 2013), and ENSO can influence the eddy activity (Caballero and Anderson, 2009). Thus, ENSO may be an important factor that affects HCE on the interannual time scale. At present it is not quite clear how ENSO affects HCE.

Because ENSO signals are most robust in boreal winter season (December–February, DJF), and have close links to the principal modes of DJF HC (Ma and Li, 2007, 2008). In this paper, the interannual variability of boreal winter HCEs and its relationship with ENSO will be investigated. As the remainder of this manuscript is arranged as follows: Section 2 described the reanalysis datasets and methods; Section 3 presents the results; Discussion and conclusions are given in Section 4.

2. Data and methods

The atmospheric variables employed in this work are taken from the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERAI) (Dee et al., 2011), the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (NCEP1) (Kalnay et al., 1996) and the NCEP–Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP)-II Reanalysis (NCEP2) data (Kanamitsu et al., 2002). All the reanalysis datasets have 2.5° × 2.5° horizontal resolutions. The ERAI has 37 vertical levels and the other two have 17 vertical levels. The ERAI and NCEP2 cover the period of 1979–2016 and the NCEP1 covers the period of 1948–2016. The overlapped period of 1979–2014 is chosen in this study. The SST data used in this study is from the monthly mean Extended Reconstruction of Historical Sea Surface Temperature version 3b (ERSST v3b) dataset, which has a 2.0° × 2.0° horizontal resolution and covers the period of 1854–2016 (Smith et al., 2008).

In this study, the mass stream function (MSF) is used to depict the HC. The MSF is calculated by vertically integrating the zonal mean meridional wind (Holton, 1992; Li, 2001). The HCE has several definitions, such as by using tropopause height (Seidel and Randel, 2007), the latitude of outgoing long-wave radiation (OLR) equaling to 250 W m^{-2} (Hu and Fu, 2007; Johanson and Fu, 2009), the latitude of precipitation minus evaporation equaling zero (Quan et al., 2014) and the latitude of MSF at 500 hPa equaling to zero (Hu and Fu, 2007). As the MSF $= 0$ is more commonly used to define the HCE in previous studies (Hu and Fu, 2007; Quan et al., 2014), it was also used in this study to define the HCE. The linear trends of the variables were removed in order to analyze the interannual variability.

3. Results

3.1. Interannual variability of HCE

Fig. 1 shows the changes of DJF HCE in both Hemispheres during the period of 1979–2014. It can be observed that both the northern and southern HCEs show obvious interannual variabilities, and the results from the three datasets are consistent in the variability. The correlation coefficients among the three datasets are greater than 0.85 (significant at 99% confidence level) for the Northern Hemisphere HCE and 0.66 (significant at 99% confidence level) for the Southern Hemisphere HCE. It also can be seen that the year-to-year deviation of the HCEs can reach to about 5 latitude degrees (Fig. 1b).

It is also worth noting that there are slight differences in the variances of the HCE among different datasets. Of all the datasets, the variances of HCEs in the Northern Hemisphere ranges from 0.63 to 1.34, which are larger than those in the Southern Hemisphere. The values of HCE from ERAI are systematically lower than those of NCEP1 and NCEP2 (Fig. 1b).

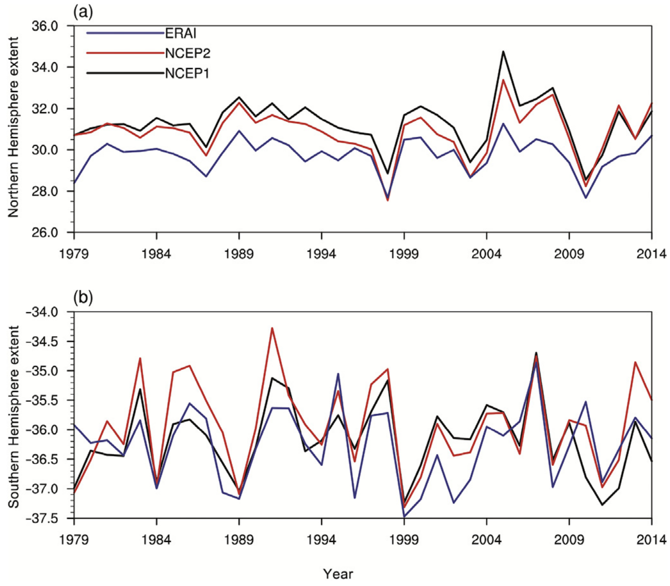

Fig. 1. Time series of the December to February Hadley circulation extent (HCE) in (a) the Northern Hemisphere and (b) the Southern Hemisphere during 1979–2014 based on ECMWF Re-Analysis (ERAI) (blue line), NCEP2 (red line) and NCEP1 (black line).