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Stratospheric control of the Indian Summer Monsoon Onset

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ABSTRACT

This paper reports a significant linkage between the seasonal timing of boreal spring stratospheric final warming (SFW) events and the onset of the Indian summer monsoon (ISM). The leading singular vector decomposition pattern reveals a significant, coupled interannual variation between the SFW-related circulation in the lower stratosphere and the ISM-related circulation in the lower troposphere, objectively confirming the intimate relationship between SFWs and the ISM. Regression and composite maps show that, associated with a late SFW, the stratospheric polar vortex and the polar jet are anomalously stronger in April to early May, which is coupled with positive anomalies of the Northern Annular Mode (NAM) and the Arctic Oscillation (AO) in the troposphere. These tropospheric NAM/AO anomalies act to pass the extratropical anomaly signals to western central Asia via a NAM-/AO-related Rossby wave train in the upper troposphere, which is initiated over the North Atlantic jet exit region and extends across Eurasia. This results in an anomalous upper tropospheric anticyclone accompanied by anomalous descent over western central Asia that in turn warms the in situ air column and results in an enhanced meridional gradient of tropospheric temperature over the land to the north of the Arabian Sea and the Indian Ocean and therefore an early onset of the ISM. In contrast, an early SFW corresponds to the negative NAM/AO phase, an anomalous upper-level low over western central Asia in the following April and May, and thus a late onset of the ISM.

1. Introduction

The onset of the Indian summer monsoon (ISM), which marks the beginning of the principle rainy season over South Asia, exhibits large interannual variability. Given the considerable socioeconomic impacts of the ISM, it has always been of great importance to fully understand the ISM's variabilities and to predict its onset (Webster et al., 1998). In recent decades, extratropical circulation variabilities have been proven to impact the ISM's variability obviously. For example, accompanied by an interdecadal change in the North Atlantic westerly jet and the related spatial pattern of the storm track, positive Arctic Oscillation (AO) or North Atlantic Oscillation (NAO) anomalies have intensified in winter in recent decades. These enhanced AO/NAO anomalies exert a stronger influence on the ISM's variability through their effects on Eurasian surface temperature (Chang et al., 2001). In agreement with this, a marked influence of the extratropical AO/NAO on the ISM's variability has been documented in numerous studies. Yang et al. (2004)

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emphasized that AO/NAO-related changes in the Middle East jet stream, which represents the variability of the 200-hPa westerlies over subtropical Asia, are highly correlated with the intensity of the ISM. Buermann et al. (2005) identified an AO-related quasi-stationary wave train that exists in the mid and upper troposphere. The wave train is oriented along a northwest–southeast axis with two nodes of the same sign over western Europe and the northern Indian Ocean, and another node of opposite sign over the Middle East. The authors emphasized a linkage between the winter AO anomalies and intensity of the ISM in the subsequent summer through this AO-related wave train. Goswami et al. (2006) argued that, compared with that in winter, the NAO anomalies in summer are more significantly correlated with the ISM's rainfall. Ding and Wang (2005) identified a circumglobal teleconnection (CGT) pattern in summer in the northern mid-latitudes. They found that a CGT-related anomalous upper-level high over western central Asia is significantly correlated with summertime precipitation over northwestern India. They further indicated that a southeastward oriented wave train over Eurasia originates from the northeastern Atlantic and contributes to the intraseasonal variability of the ISM by modifying the monsoonal easterly vertical shear and related moist dynamic instability (Ding and Wang, 2007). Syed et al. (2012) also demonstrated the importance of the CGT in the close relationship between the summer NAO and precipitation over Pakistan and northern India.

The variabilities of the AO/NAO are intimately connected with circulation anomalies in the stratosphere through stratosphere–troposphere coupling processes. Typically, geopotential height and zonal wind anomalies of one sign in the extratropical stratosphere are generally followed by corresponding anomalies of the same sign in the extratropical troposphere, manifesting in a downward propagation from the stratosphere (Baldwin and Dunkerton, 1999, 2001; Polvani and Kushner, 2002), and the dynamic coupling of the variabilities between the upper warm branch and the lower cold branch of the meridional mass circulation (Cai and Ren, 2007; Ren and Cai, 2008). The Northern Annular Mode (NAM), as a projection of the AO in the entire atmospheric layer (Thompson and Wallace, 1998; Thompson, 2000), thus always exhibits a vertically in-phase relationship during polar vortex oscillation events (NAM events, or stratospheric sudden warming events) in winter. Recently, similar vertical coupling between the stratosphere and troposphere has been identified in the spring season during stratospheric final warming (SFW) events, when the stratospheric polar vortex finally breaks down (e.g. Black et al., 2006; Black and Mcdaniel, 2007; Ayarzagüena and Serrano, 2009; Hu et al., 2014, 2015, 2018). Specifically, it has been found that the SFWs in every spring can accelerate the final collapse of the circumpolar westerly jet successively from the stratosphere to troposphere (Black and Mcdaniel, 2007). Furthermore, AO anomalies in April are found to be mostly positive when SFWs occur anomalously late (Ayarzagüena and Serrano, 2009). These studies clearly suggest that tropospheric AO anomalies in spring may be closely related with the occurrence of SFWs in the stratosphere, particularly the timing of SFW events. The existing coupling between the AO and SFWs, and the significant relationship between the AO and the ISM, may give rise to a possible relationship between SFWs and the ISM, particularly the timing of SFWs or the onset date of SFWs (SFWOD) and the onset of the ISM, both of which mark the seasonal transition from winter to summer.

The objective of this study, therefore, is to investigate the relationship between SFWs in the extratropical stratosphere and the ISM onset in the tropical troposphere and carry out a comprehensive diagnosis aimed at revealing the possible dynamical processes mainly responsible for that linkage. This study will demonstrate the spatiotemporal patterns that act to link the seasonal timing of SFWs to the variabilities of the ISM onset. By providing a complete physical picture of the SFW–ISM relationship, the results will benefit our understanding of the extratropical influences on the interannual variability of the ISM, and will be helpful in improving our current ability to predict the onset of the ISM.

The rest of the paper is organized as follows. Section 2 describes the data and method. Section 3 demonstrates the coupled interannual variabilities of the circulation patterns between the stratosphere and troposphere, associated with the SFW–ISM relationship. In section 4, we reveal the dynamical processes mainly responsible for the SFW–ISM linkage. In particular, we demonstrate the critical role of the SFW-related NAM/AO anomalies in bridging the SFWs to the ISM. Section 5 provides concluding remarks.

2. Data and methods

The daily and monthly data fields including wind, temperature and geopotential height on 2.5° × 2.5° grids and at 17 standard pressure levels from 1000 to 10 hPa used in this study were derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis 1 (R1) dataset covering the period from January 1979 to December 2010 (Kalnay et al., 1996). This dataset has sufficient accuracy in characterizing the interannual variability and long-term trend of the Northern Hemisphere stratospheric polar vortex, which has been widely used in the studies on the stratospheric sudden warming events and SFWs (e.g., Black et al., 2006; Langematz and Kunze, 2006; Charlton and Polvani, 2007). Monthly averages of the outgoing long wave radiation (OLR) data and the Global Precipitation Climatology Project precipitation data on 2.5° × 2.5° grids were obtained from the National Oceanic and Atmospheric Administration datasets (http://www.esrl.noaa.gov/psd/data/gridded/). The monthly AO index from January 1979 to December 2010 was from the Climate Prediction Center website, http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/, where the loading pattern of the AO is defined as the first leading mode of an empirical orthogonal function (EOF) analysis of the year-round monthly mean 1000-hPa geopotential height anomalies poleward of 20 °N. The daily NAM index from 1000 hPa to 10 hPa and from 1 January 1979 to 29 July 2006 was downloaded from the website http://www.nwra.com/resumes/baldwin/nam.php using the algorithm of Baldwin and Dunkerton (2001). The NAM pattern for each pressure altitude was defined as the regression between the leading EOF time series and the geopotential height used in the EOF analysis of November to April data only, from 20 °N to the North Pole. Daily values of the NAM index were calculated by projecting daily geopotential anomalies onto the leading EOF patterns. We then obtained the monthly NAM index by averaging the daily values for each corresponding month. For a period of 28 years from 1979 to 2006, we confirmed that the correlation between the AO index