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Relative contribution of the anthropogenic forcing and natural variability to the interdecadal shift of climate during the late 1970s and 1990s

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Abstract Global warming accelerated after the late 1970s and slowed down after the late 1990s, accompanying the significant interdecadal changes in the regional climate. We hypothesized that the interdecadal changes linearly consisted of two independent components, anthropogenic forcing and natural decadal variability, which can be represented simply by the radiative forcing effect of carbon dioxide (RF_{CO_2}) and the Pacific Decadal Oscillation (PDO), respectively. The combined effect of the RF_{CO_2} and PDO could explain the majority of the surface temperature changes during the late 1970s and 1990s, but the magnitudes of the relative contribution of the RF_{CO_2} and the PDO are inconsistent in different regions. For both the surface temperature and geopotential height, the RF_{CO_2} could induce significantly positive anomalies over almost the entire globe for these two shifts, exhibiting a larger magnitude in the mid–high latitudes and in the late 1990s shift. The PDO could induce opposite anomalies for the two interdecadal shifts due to its phase transitions (negative-positive–negative). Furthermore, for the shift in the late 1970s, both the RF_{CO_2} (53.7 %–66.7 %) and the PDO (33.3 %–46.3 %) were important in regulating the tropical geopotential height, whereas the RF_{CO_2} dominated the changes in the mid-latitudes. For the western Pacific subtropical high, the RF_{CO_2} (PDO) could explain 52.3 %–62.1 % (37.9 %–47.7 %) of the change. The negative effect of the PDO counteracted most of the RF_{CO_2} effects for the late 1990s shift.

Keywords Anthropogenic forcing · Natural decadal variability · Global warming · Surface temperature · Geopotential height

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1 Introduction

Climate variations at different timescales, such as intraseasonal, interannual, interdecadal, and longer timescale variations, intertwine together to form real climate changes on the earth. Interdecadal climate variation is an important contributor to climate variability. Since the late twentieth century, its influences on short-term climate prediction abilities have become a focus of climate research [e.g., 1, 2]. Climate variation and prediction on an interdecadal timescale are also major objectives of some international research projects, such as the Climate Variability and Predictability (CLIVAR) project conducted by the World Climate Research Programme and the ENSEMBLES project supported by the European Commission's 6th Framework Programme.

Two prominent interdecadal changes were observed in the global mean surface temperature since the 1970s. One was the acceleration of global warming after the late 1970s; the other was the slowdown of global warming after the late 1990s (IPCC, 2013), which is well known as the global warming hiatus in recent years.

The significant interdecadal climate shift in the late 1970s occurred in many regions, particularly over East Asia. Lots of studies have investigated the features and physical mechanisms of the interdecadal shift in the East Asian summer climate. Since the late 1970s, the East Asian summer monsoon has weakened [3], and the northern boundary of the monsoon has receded more southward. At the same time, the western Pacific subtropical high (WPSH) was strengthened and expanded to the west and the south, and the East Asian westerly jet stream (EAWJS) became stronger and moved toward the equator. As a result, the rainfall in the lower reaches of the Yangtze (Yellow) River valley significantly increased (decreased) [4–11].

Different mechanisms have been proposed for this interdecadal change, and each generally attempted to explain the phenomena from two kinds of mechanisms: one kind is the natural variability of climate system that includes internal variability and natural forcing (such as volcano eruptions) that induced variability [12, 13]. The boundary conditions are important drivers for the atmospheric circulation changes, including the global sea surface temperature (SST) [4, 14–20]; Arctic sea ice and Eurasian snow [21, 22]; and increased snow over the Tibetan Plateau [23].

The other kind is the external anthropogenic forcing for the climate system. Anthropogenic greenhouse gases could explain the largest proportion of global warming in the past decades [24]. Moreover, anthropogenic aerosols could play an important role in the interdecadal shift of the late 1970s [e.g., 25, 26], although the magnitude of forcing by aerosols was reduced relative to IPCC AR4 [24]. Wang et al. [27] revealed that anthropogenic agents, including the aerosols and greenhouse gases, were prime drivers in the shift of East Asian summer rainfall in the late 1970s. Moreover, strong tropical volcanic eruptions may also result in a weakened East Asian summer monsoon [28].

The recent global warming hiatus since the late 1990s has been attributed to the phase change of the Pacific Decadal Oscillation (PDO) to negative, which can induce more ocean heat content in the eastern tropical Pacific and less heat flux into the atmosphere [29–32]. At the same time, the East Asian summer monsoon experienced a new interdecadal shift [33–36], with ascending anomalies and increased rainfall in the Huang-Huai River valley (HRV). The EAWJS has become stronger and more poleward since the late 1990s, but the WPSH has shown very little changes. Through diagnostic analysis and numerical experiments, Zhu et al. [33, 36] suggested that the PDO phase transition significantly contributed to this interdecadal shift.

It is presumably common sense that the observed long-term interdecadal changes are the combined results of both external anthropogenic forcing and natural variability; however, to what extent the two factors contributed to the interdecadal changes of the climate variables (such as the surface temperature and geopotential height), both globally and regionally, remains an outstanding question. Moreover, the geopotential height is an important variable related to large-scale atmospheric circulation. Furthermore, there is much debate on change of the WPSH in the late 1970s. Some scientists revealed a stronger and more southwestward WPSH and attributed it to tropical Indo-Pacific warming [e.g., 27, 37]. However, Huang et al. [38, 39] used eddy geopotential height to identify an eastward-shifted WPSH. Therefore, to better understand the WPSH change, in this study, we attempt to approximate the contribution of anthropogenic forcing and natural variability to the two interdecadal shifts in the surface temperature and the 500 hPa geopotential height by simply regressing the radiative forcing effect of the carbon dioxide (RF_{CO_2}) and PDO (one of the dominant natural decadal modes in the climate system) indices onto the geopotential height, respectively.

2 Method and data

In this study, we used three different reanalyses, including the NCEP/NCAR reanalysis (NCEP for short) [40], the JRA-55 reanalysis (JRA for short) [41], and ERA data merging the ERA-40 (1958–2002) and ERA-interim (1979–present) reanalyses (ERA for short) [42] from ECMWF (European Centre for Medium-Range Weather Forecast). The climatological difference between ERA-40 and ERA-interim during 1979–2002 was added to the ERA-40 data, and one dataset covering the period of 1958–present was thus obtained by concatenating ERA-40 during 1958–1978 and ERA-interim during 1979–present. The annual mean concentration of CO_2 at Mauna Loa was from the National Oceanic and Atmospheric Administration. The Jones (Climatic Research Unit, CRU for short) air and marine temperature anomalies (HadCRUT4) from NOAA were also used. The global mean surface temperature index from CRU was also used.

To ensure that our results are easily understood, we made some simplifications and approximations. Because the CO_2 effect dominates the radiative forcing (RF, unit: W/m^2) caused by well-mixed greenhouse gases, the RF of