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Changes of climate regimes during the last millennium and the twenty-first century simulated by the Community Earth System Model

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ABSTRACT

This study examines the shifts in terrestrial climate regimes using the Köppen–Trewartha (K–T) climate classification by analyzing the Community Earth System Model Last Millennium Ensemble (CESM-LME) simulations for the period 850–2005 and CESM Medium Ensemble (CESM-ME), CESM Large Ensemble (CESM-LE) and CESM with fixed aerosols Medium Ensemble (CESM-LE_FixA) simulations for the period 1920–2080. We compare K–T climate types from the Medieval Climate Anomaly (MCA) (950–1250) with the Little Ice Age (LIA) (1550–1850), from present day (PD) (1971–2000) with the last millennium (LM) (850–1850), and from the future (2050–2080) with the LM in order to place anthropogenic changes in the context of changes due to natural forcings occurring during the last millennium. For CESM-LME, we focused on the simulations with all forcings, though the impacts of individual forcings (e.g., solar activities, volcanic eruptions, greenhouse gases, aerosols and land use changes) were also analyzed. We found that the climate types changed slightly between the MCA and the LIA due to weak changes in temperature and precipitation. The climate type changes in PD relative to the last millennium have been largely driven by greenhouse gas-induced warming, but anthropogenic aerosols have also played an important role on regional scales. At the end of the twenty-first century, the anthropogenic forcing has a much greater effect on climate types than the PD. Following the reduction of aerosol emissions, the impact of greenhouse gases will further promote global warming in the future. Compared to precipitation, changes in climate types are dominated by greenhouse gas-induced warming. The large shift in climate types by the end of this century suggests possible wide-spread redistribution of surface vegetation and a significant change in species distributions.

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1. Introduction

There is a general consensus that the global surface temperature has risen significantly during the twentieth century and the anthropogenic global warming trend has accelerated in the last fifty years (Karl et al., 2009; IPCC, 2013). This warming has had a tremendous impact on global and regional hydrologic cycles as well as the distribution of precipitation (Huang et al., 2016), which led to more frequent and more intense extreme weather, including heat waves, droughts and floods (Dole et al., 2011; Houze et al., 2011; Min et al., 2011; Schubert et al., 2011; Lau and Kim, 2012; Dai, 2013; IPCC, 2013; Feng et al., 2016, 2017). The warming has had a more direct impact on glaciers and high-latitude sea-ice loss (Stroeve et al., 2007; Perovich and Richter-Menge, 2009; Yao et al., 2012). The impacts of global warming and associated extreme weather are therefore already evident in many different sectors (e.g., the environment and ecosystems). It is extremely likely that this recent warming is a result of human activities, predominantly the burning of the fossil fuels (IPCC, 2013).

In addition to the Current Warm Period (CWP), numerous independent lines of evidence confirm that in the past, the global climate has been characterized by episodic warm/cold periods. During the past millennia, the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) have been the most important anomalous climate periods globally, and they have received extensive

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attention in recent decades (Mann et al., 2009; PAGES 2k Consortium, 2013). Noticeable hydroclimatic changes on regional and continental scales between the MCA and LIA were identified (e.g., Newton et al., 2006; Cook et al., 2007; Seager et al., 2007; Feng et al., 2008; Chen et al., 2010, 2015; Graham et al., 2011). The regional surface vegetation (e.g., pollen assemblage) between the MCA and LIA was also quite different (e.g., Chen et al., 2006; Kaniewski et al., 2011; Quamar and Chauhan, 2014; Heusser et al., 2015). These changes in hydroclimate and ecosystems were likely caused by natural factors because both the MCA and LIA occurred in a period during which anthropogenic activities had a fairly limited influence. The questions therefore arise, how have ecosystems responded to climate changes caused by natural and anthropogenic forcings during the past millennia? Have ecosystems exhibited any responses that are different from those due to accelerated anthropogenic global warming? Answering these questions may lead to a better understanding of how ecosystems will respond to a warmer climate in the future.

Different approaches with varying degrees of complexity have been used to assess the impact of climate change on ecosystems (e.g., McCarty, 2001; Leemans and Eickhout, 2004; Liu et al., 2017). Among them, climate classifications (e.g., the Köppen classification) have frequently been used to investigate the potential broad-scale impacts of the past and projected future climate on ecoregions on global or regional scales (e.g., Fraedrich et al., 2001; Wang and Overland, 2004; Kottek et al., 2006; de Castro et al., 2007; Peel et al., 2007; Roderfeld et al., 2008; Baker et al., 2010; Rubel and Kottek, 2011; Feng et al., 2012). The climate classifications combine temperature, precipitation and their seasonality into one matrix to understand the interactions between many of Earth's physical and biological systems, including biota, soils and water. The Köppen classification and its subsequent modification, the Köppen–Trewartha (K–T) system (Köppen, 1936; Trewartha and Horn, 1980), were constructed on the basis of vegetation types. Therefore, each climate type is closely associated with certain prevalent species of vegetation. The changes in climate types may subsequently be used to investigate ecoregion changes. Based on the K–T climate classification, it was found that global warming would cause the climate to shift towards warmer and drier types (Kalvová et al., 2003; de Castro et al., 2007; Feng et al., 2012, 2014; Hanf et al., 2012; Chen and Chen, 2013). Specifically, it is projected that the polar, sub-polar and subtropical climate types would contract, whereas the tropical, temperate and dry climate types would expand (Feng et al., 2014). However, previous studies using the Köppen or K–T classification mostly focused on climate regimes changes during the instrumental period or in the future. To date, no attempts have been made to analyze the shifts in climate regimes during the past millennia (e.g., the MCA and LIA) and compare these changes with the CWP and future. In addition, no attempts have been made to segregate the impacts of greenhouse gases, aerosols and other climate forcings on climate regimes during the last millennium and the future.

The Community Earth System Model Last Millennium Ensemble simulations (CESM-LME) for the period 850–2005 recently became available to the community (Otto-Bliesner et al., 2016). These ensemble runs include simulations forced by the transient evolution of solar intensity, volcanic emissions, greenhouse gases, aerosols, land use conditions and orbital parameters, both together and individually. Besides CESM-LME, new CESM simulations during the instrumental period and the future under various scenarios were also became available in recent years (Kay et al., 2015; Sanderson et al., 2015). These new simulations provide a unique opportunity to understand the responses of temperature and moisture variations to internal variability and external forcings (both natural and anthropogenic) during the last millennium and the future. Specifically, this study compares K–T climate types of the MCA (950–1250) with the LIA (1550–1850), the present day (PD) (1971–2000) with the last millennium (LM) (850–1850) and the future (2050–2080) with the LM. Through these comparisons, this study places anthropogenic changes in the context of changes due to natural forcing occurred during the last millennium.

2. Data and methods

2.1. Data

We used simulations from the CESM-LME for the period 850–2005. The model was spun up for an 1850 control simulation of 650 year, from which an 850 control simulation was branched and run for an additional 1356 year. All CESM-LME simulations were started from year 850 of the 850 control simulation (Otto-Bliesner et al., 2016). These datasets include nine simulations with full forcings and twenty simulations with individual forcings. The individual forcings include four simulations forced with solar activity, five forced with volcanic eruptions, three forced with orbital changes, three forced with land cover land use, three forced with greenhouse gas concentrations and two forced with tropospheric ozone and aerosols, respectively. The simulations forced by anthropogenic aerosols and anthropogenic-induced ozone changes are only available for the period 1850–2005. This study mainly focused on simulations with full forcings, albeit the simulations of individual forcings were also analyzed to decipher the impacts of individual factors on climate regimes. Comparing the model simulations with the observational and proxy data suggests that the CESM-LME can reasonably reproduce the variability of surface temperature, drought occurrence and the El Niño–Southern Oscillation (Otto-Bliesner et al., 2016). Besides the CESM-LME, simulations from the CESM Large Ensemble (CESM-LE) (Kay et al., 2015), CESM Medium Ensemble (CESM-ME) (Sanderson et al., 2015) and CESM Medium Ensemble with fixed aerosols (CESM-LE_FixA) (Kay et al., 2015) are also used. CESM-LE was began with a multi-century 1850 control simulation with constant preindustrial forcing (Kay et al., 2015) and the CESM-ME ensemble members were each initialized from the corresponding historical simulation in CESM-LE (Sanderson et al., 2015). The CESM-LE has thirty ensemble simulations. These simulations include both natural external and specified historical anthropogenic forcings during the period 1920–2005 and exhibit changes in anthropogenic and greenhouse gases following the representative concentration pathway 8.5 (RCP8.5) during the period 2006–2080. All thirty ensemble simulations use the same model configuration and the same external forcings except the initial conditions were different. In the RCP8.5 scenario, the aerosol emissions are proposed to reduce abruptly. To understand the impacts of aerosol emissions and tropospheric oxidants in the future, the fixed aerosols simulations (CESM-LE_FixA) were also analyzed. The CESM-LE_FixA used the same forcing as CESM-LE except that 1) all aerosol emissions and tropospheric oxidants are fixed at the 2005 levels, and 2) it only has fifteen ensemble simulations. Comparison of the CESM-LE and CESM-LE_FixA allows up to evaluate the relative contributions of aerosols and GHGs to future climate regime shifts.

The CESM-ME is similar to CESM-LE except that it has fifteen ensemble simulations under the RCP4.5 scenario during 2006–2080. The CESM-LME, CESM-LE, CESM-ME and CESM-LE_FixA employ the same model. The only difference is the resolution of the atmosphere and land components. Specifically, the CESM-LE, CESM-ME and CESM-LE_FixA use ~1° horizontal resolution in all model components. The CESM-LME uses ~2° horizontal resolution in atmosphere and land components and ~1° resolutions in all other model components. Additionally, the CESM-LME, CESM-

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