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Warmer and wetter or warmer and dryer? Observed versus simulated covariability of Holocene temperature and rainfall in Asia

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A B S T R A C T

Temperatures in Asia, and globally, are very likely to increase with greenhouse gas emissions, but future projections of rainfall are far more uncertain. Here we investigate the linkage between temperature and precipitation in Asia on interannual to multicentennial timescales using instrumental data, late Holocene paleoclimate proxy data and climate model simulations. We find that in the instrumental and proxy data, the relationship between temperature and precipitation is timescale-dependent. While on annual to decadal timescales, negative correlations dominate and thus cool summers tend to be rainy summers, on longer timescales precipitation and temperature are positively correlated; cool centuries tend to be dryer centuries in monsoonal Asia. In contrast, the analyzed CMIP5/PMIP3 climate model simulations show a negative correlation between precipitation and temperature on all timescales. Although many uncertainties exist in the interpretation of the proxy data, there is consistency between them and the instrumental evidence. This, and the persistence of the result across independent proxy datasets, suggests that the climate model simulations might be considerably biased, overestimating the short-term negative associations between regional rainfall and temperature and lacking long-term positive relationships between them.

1. Introduction

The Asian summer monsoon winds transfer moisture from the tropical oceans onshore and release it as they cool while traveling inland, driven mainly by the thermal gradient between the surrounding oceans and the land surface (Fig. 1 and Turner and Annamalai, 2012). The state and fate of the monsoon is of particular importance to the agricultural economies across Asia, yet, globally and across Asia, precipitation projections are far more uncertain than those for temperature (IPCC, 2013).

Simulations of future precipitation in the Coupled Model Intercomparison Project Phase 3 (CMIP3, Meehl et al., 2007) showed no consistent response in Asia to increasing temperatures. The models in the more recent CMIP5 ensemble (Taylor et al., 2012) largely agree on an increase in rainfall amount and variability (Menon et al., 2013; Sperber et al., 2012). Nevertheless, the skill of the models in representing key features of the Asian summer monsoon, such as its onset timing, duration and intensity has not improved significantly from CMIP3 to CMIP5 (Menon et al., 2013; Sperber et al., 2012). Improved consistency across models therefore does not guarantee improved future prediction skill, as many models have difficulties in simulating monsoon rainfall and variability (Levine et al., 2013; Turner and Annamalai, 2012).

In theory, global rainfall is likely to increase in a warmer world, as the partial pressure of water vapor at saturation increases by ∼7% per 1 °C temperature increase, following the Clausius–Clapeyron relationship (IPCC, 2013). Locally, precipitation responses are difficult to project, as it is unclear if the atmospheric pathways which relay evaporated oceanic moisture onto the continents remain the same in a warmer atmosphere with greenhouse gas, aerosol load, regional vegetation and land use changes. Analyzing trends of the last 50 yr showed a warming but no consistent precipitation change across Asia (Turner and Annamalai, 2012). The thermal response to greenhouse gas forcing is better known than the hydrological response. Thus, complementary information on future rainfall can be gained by analyzing the relationship of precipitation and temperature (T–P relationship) on observational datasets. Direct extrapolation of results based on largely naturally forced past temperature variability onto a future where temperature changes are dominated by anthropogenic forcing, however, needs to be treated with caution, as the monsoon circulation response may also be specific to the forcing, rather than temperature changes.

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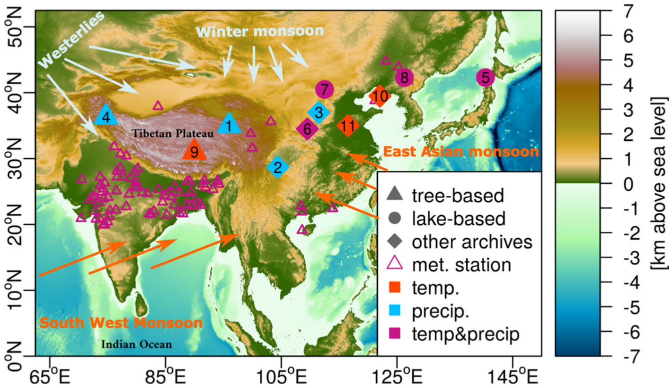

Fig. 1. Overview of the study area and the dominant summer (orange) and winter (light blue and yellow) wind systems. Symbols show the paleoclimate proxy data sites and meteorological stations for which Table 1 and Supplementary Table 2 give more details. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

On daily to interannual timescales, negative correlations between local temperatures and precipitation in Asia were estimated from satellite and station data as well as from model simulations (Trenberth, 2005; Adler et al., 2008; Berg et al., 2015; Williams et al., 2012). This evident negative correlation between local temperature and precipitation roots in fundamental aspects of the hydrological cycle: rainy days tend to have a higher cloud cover and soil moisture, and thus lower temperatures through insolation shielding and evaporative cooling, hot days are more likely to be dry (Berg et al., 2015; Williams et al., 2012, and references therein). Over land, this anticorrelation was found to be strongest in the summer months but persisted throughout the year. On daily timescales, Williams et al. (2012) observed differences to the monthly analysis of Trenberth (2005) and concluded that a timescale dependency of processes influencing the T–P relationship is already relevant between daily and monthly scales. Due to the shortness of the observational record, however, station- or satellite-based correlation studies are mostly limited to shorter than decadal timescales.

Within monsoonal Asia, slow processes acting on interannual to centennial scales are likely to modify the boundary conditions for the monsoon circulation, modulating its intensity, duration and distribution. Most of them result in a positive association between regional temperatures, and rainfall amounts: On the oceanic side, interannual to centennial precipitation changes in monsoonal Asia have been attributed to warmer surface temperatures in the subtropical Pacific and the Indian Ocean, the source areas of monsoonal moisture (Trenberth, 2005). In the atmosphere, reducing (increasing) the albedo of the Tibetan Plateau by lower (higher) snow cover in a warming scenario, was proposed to increase (decrease) monsoonal intensity by damping (strengthening) its role as an amplifying elevated heat source (Zhang et al., 2004). On centennial timescales, proxy data suggests a wetter summer monsoon during the warm Medieval Climate Anomaly, and a weakening during the cold period thereafter (e.g. Chen et al., 2015; Rehfeld et al., 2013; Zhang et al., 2008). This is consistent with the notion that the Intertropical Convergence zone extends further north in warm periods than in cold periods (Schneider et al., 2014).

On timescales of decades to centuries the nature and timescale-dependency of the T–P relationship within Asia and beyond is far from being understood. Here, we provide a systematic investigation of the T–P interdependence from decadal to multicentennial timescale. Therefore, we employ paleoclimate proxy data, instrumental datasets and model simulations to obtain a comprehensive view of the relationship between temperature and precipitation changes across Asia.

2. Data

2.1. Paleoclimate data

We identified eleven suitable Holocene paleoclimate proxy reconstructions for temperature and/or precipitation in the region 60–150°E and 5–50°N after a quality screening of available data. The datasets cover multiple proxies, reconstruction techniques and resolutions in the area depicted in Fig. 1.

We only included proxy records which were interpreted as temperature and/or precipitation sensitive by the original authors. Locations, archive and proxy type, seasonal coverage and reconstruction methods of the datasets are given in Table 1. In addition, Table 1 also gives the temporal resolution and the temporal span over which the records were evaluated. The datasets had to cover more than 400 yr of the Holocene, between 10 000 BP and present day, and had to have sufficient overlap with at least one other complementary record. Note that we did not consider individual speleothem δ^{18}O time series for our analyses, as the attribution to precipitation or temperature may be ambiguous on long timescales (Caley et al., 2014). Preliminary analyses indicated that individual cave speleothem time series correlated more strongly with the temperature reconstructions in the set of reconstructions, than with the rainfall reconstructions (not shown). Some speleothem oxygen isotope time series were included in the precipitation reconstruction of Tan et al. (2011).

Reconstruction methods may strongly influence the character and trends of quantitative paleoclimate reconstructions, especially when multiple climate variables are derived based on the same proxy data (Juggins, 2013; Telford and Birks, 2011). One temperature dataset had to be excluded, because it was *by construction* negatively correlated to the simultaneous precipitation reconstruction (Number 3 in Table 1, Yi et al., 2011). These climate variables were based on tree-ring and historical drought/flood observation data, and then processed by principle component analyses. Significant axes were combined positively for precipitation, and negatively for temperature. As the temperature reconstruction showed considerably lower skill than that for precipitation (Yi et al., 2011) we only retained the summer precipitation time series in the database.

Two proxy datasets were considered regionally consistent and comparable, if they both stem from the South-West-Summer-Monsoon (SWSM) domain, west of 100°E, or the East Asian Summer Monsoon (EASM) domain (Fig. 1). A comparison between SWSM domain records and EASM records would not be appropriate, as the monsoon systems may act independently and asynchronously. An independent verification of all proxy reconstructions with meteorological observations is, unfortunately, not possible, as many reconstructions do not cover the instrumental era at a sufficient resolution – or at all.

2.2. Model data

We analyze the climate model simulations from the Coupled Model Intercomparison Project phase 5 (CMIP5) of the last millennium (past1000, 850–1850 AD) forced with reconstructed solar, volcanic, GHG and aerosol forcing, and partly land use changes (Taylor et al., 2012). These nine millennium simulations, for which complete surface temperature and precipitation output was available, allow us to investigate the modeled relationship $r_{(t,p)}$ in response to largely natural forcing from annual to multidecadal timescales. If multiple ensemble members were available, only the first ensemble member was analyzed. To extend our analysis to centennial timescales we employ an orbital only forced 6000-yr ECHAM5-MPIOM simulation (by Fischer and Jungclaus, 2011, denoted "orbital" in the following). To cover shorter timescales, and thus to provide a link to the instrumental record, we employ the