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Increased Eurasian-tropical temperature amplitude difference in recent centuries: Implications for the Asian monsoon

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[1] A warmer Eurasian continent and stronger land/sea temperature gradient between Eurasia and the tropical oceans contribute to an intensified summer monsoon. We evaluate changes in the temperature difference between Eurasia and the tropics over 250 years using proxies of Eurasian surface air temperatures (tree rings) and tropical sea surface temperatures (Indo-Pacific corals). These records show low-frequency correspondence with each other over this interval, and with other temperature and precipitation-sensitive proxies from the Asian monsoon regime. Greater warming is estimated for Eurasia (amplitude = 1.70 ± 0.28°C; 1801–20 vs 1976–95) relative to the tropics (0.61 ± 0.29°C; 1806–25 vs 1937–56). The amplitude change from the 18th to 20th centuries is thus estimated to be about three times (1.5–6) greater over Eurasia than the tropics. This change may have contributed to an intensified Asian monsoon system over recent centuries, and to a decoupling of the monsoon and El Niño-Southern Oscillation in recent decades. **Citation:** D'Arrigo, R., R. Wilson, and J. Li (2006), Increased Eurasian-tropical temperature amplitude difference in recent centuries: Implications for the Asian monsoon, *Geophys. Res. Lett.*, *33*, L22706, doi:10.1029/2006GL027507.

1. Introduction

[2] Since the time of *Blanford* [1884], linkages have been postulated between the climate of Eurasia and the Northern Hemisphere (NH) as a whole and the variability of the Asian monsoon. These relationships have been utilized in monsoon prediction efforts with varying success [e.g. *Rajeevan*, 2001]. Warmer Eurasian surface air temperatures favor an enhanced meridional land-sea temperature gradient, conducive to a strong monsoon [e.g. *Kumar et al.*, 1999; *Liu and Yanai*, 2001; *Pai*, 2004]. Greater warming over Eurasian and NH land areas relative to that of tropical oceans may have contributed to an overall intensification of the Asian monsoon system over the past few centuries [*Anderson et al.*, 2002], and to a weakening of the ENSO-monsoon relationship over recent decades [*Kumar et al.*, 1999; *Ashrit et al.*, 2001]. Despite these observations, there is still considerable uncertainty regarding the extent to which large-scale warming impacts monsoon variability, as the Asian monsoon is spatially and temporally complex [*Kripalani et al.*, 2003; *Robock et al.*, 2003].

[3] A greater understanding of the low-frequency Eurasian climate-Asian monsoon link is limited by the absence of long instrumental or proxy records for remote areas of Eurasia and the tropics. Here we use a temperature-sensitive ring-width composite to infer annual surface air temperatures for Eurasia spanning the past ~1000 years [*D'Arrigo et al.*, 2006], and a 250-year coral-based reconstruction of annual tropical sea surface temperatures (SSTs [*Wilson et al.*, 2006]) to estimate respective changes in land/sea temperatures over their common 250-year period. We also compare these two series with other proxies ranging in location from northern Asia to the lower-latitude Asian monsoon regime. Results reveal common low frequency climate signals, suggesting that Eurasian and NH temperatures have covaried with conditions over areas of monsoon Asia and the tropics at low-frequency (multidecadal to centennial) time scales over recent centuries.

2. Data and Analysis

[4] The Eurasian composite record is based on an average of seven regional composite temperature-sensitive ring-width series from latitudinal and elevational treeline sites (Figure 1) [*D'Arrigo et al.*, 2006]. These series, and similar records for North America (Figure 1), were previously merged to develop a well-verified, millennial, high resolution temperature record for the NH [*D'Arrigo et al.*, 2006]. Based on comparisons with instrumental records, as well as ecological considerations, the Eurasian ring-width series are primarily considered to reflect summer temperatures but may also integrate conditions throughout the year [*D'Arrigo et al.*, 2006]. Processed to retain low-frequency (multidecadal to multi-centennial) trends, the Eurasian composite chronology is reasonably correlated with surface air temperatures for the continent, and was used to infer information on past natural climate variability relative to 20th century warming [*D'Arrigo et al.*, 2006].

[5] Here, the Eurasian composite tree-ring width record, which has not previously been calibrated with temperature, is scaled (adjusted for mean and variance) against instrumental annual surface air temperature data averaged over 30–60°N, 10°W–160°E (CRUTEM3 [*Brohan et al.*, 2006]). Correlation with the Eurasian tree-ring series is r = 0.38 (p = 0.0001), 1850–1995 for unfiltered data and r = 0.82 (p = 0.0457), 1853–1992 after smoothing with a 20-year smoothing spline. These p values were calculated after the degrees of freedom had been adjusted for autocorrelation in the series [*Dawdy and Matalas*, 1964].

[6] The reconstruction of annual (Jan-Dec) tropical SSTs of *Wilson et al.* [2006] is calibrated over 30°N–30°S (HadISST [*Rayner et al.*, 2003]). Correlation between the coral reconstruction and SSTs is r = 0.83 (p = 0.0000),

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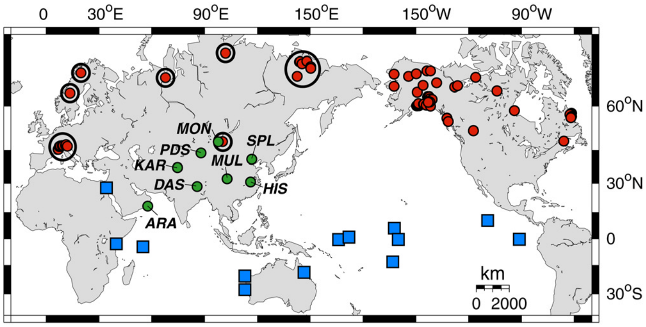

Figure 1. Tree-ring (red circles; 7 sites outlined in black were included in Eurasian composite) and coral (blue squares) records utilized by *D'Arrigo et al.* [2006] and *Wilson et al.* [2006], and individual proxies (green circles) investigated for this study: a Mongolia (MON) composite chronology [*D'Arrigo et al.*, 2000], a China PDSI (PDS) reconstruction [*Li et al.*, 2006], a historical China temperature record (HIS [*Ge et al.*, 2003]), a speleothem record from Beijing (SPL [*Tan et al.* 2003]), a multiproxy temperature record for all of China (MUL [*Yang et al.*, 2002]), the Dasuopu (DAS) δ^{18}O ice core series [*Thompson et al.*, 2000], a Pakistan δ^{18}O record (KAR) [*Treydte et al.*, 2006], and an Arabian Sea (ARA) sediment record of monsoon wind strength [*Anderson et al.*, 2002].

1870–1997 for unfiltered data and r = 0.93 (p = 0.0700), 1873–1994 after smoothing with a 20-year smoothing spline). Although this is a reconstruction of zonal temperatures, it is based on 13 coral skeletal δ^{18}O and 1 fluorescence series for the tropical Indian and Pacific Oceans, with a greater emphasis on the Pacific (Figure 1) [*Wilson et al.*, 2006]. Both oceans have highly significant, but varying, impacts on the Asian monsoon [*Kumar et al.*, 1999; *Wang et al.*, 2006]. This is the first coral-based reconstruction of SSTs for the entire tropics and represents past SST variability at annual to centennial time-scales [*Wilson et al.*, 2006]. The reconstruction is less robust prior to ~1850, but still shows reasonable fidelity back to 1751 [*Wilson et al.*, 2006]. Ambiguities in the low frequency domain of the δ^{18}O coral records (e.g. from possible competing signals related to salinity) were partially overcome by pooling together series from different tropical locations. Further details on the Eurasian tree-ring and tropical coral records and their validation as large-scale temperature proxies are given by *D'Arrigo et al.* [2006] and *Wilson et al.* [2006].

[7] We compare the Eurasian and tropical temperature proxies to eight proxy records from sites within a broadly defined Asian monsoon regime (Figure 1). These examples were selected because they are indicators of either temperature and/or monsoon precipitation from sites within or at the edge of monsoon Asia. All indicate intensified conditions (i.e. warming, increased precipitation or both) during the 20th century, consistent with the increase in Eurasia-tropical temperature differential computed below. The first is a temperature-sensitive elevational treeline ring-width composite record for Mongolia (MON) [*D'Arrigo et al.*, 2000], independent of that used by *D'Arrigo et al.* [2006]. The second is a reconstruction of the Palmer Drought Severity Index (PDSI) for northwestern China based on ring width data (PDS [*Li et al.*, 2006]). This record appears to have a mixed moisture and temperature response and, like the Mongolia record, is on the northern edge of the zone of monsoon influence [e.g. *Wang and LinHo*, 2002; *Wang and Zhou*, 2005]. It correlates positively with Arabian Sea SSTs, which are closely related to the southwest Asian monsoon [*Wang et al.*, 2006; J. Li et al., manuscript in preparation, 2006]. The third series is an δ^{18}O ice core record for Dasuopu (DAS), Tibetan Plateau [*Thompson et al.*, 2000], obtained at decadal resolution (NOAA Paleoclimatology, http://www.ncdc.noaa.gov/paleo/paleo.html). It is considered to be a temperature, rather than a precipitation proxy, although this interpretation is controversial [*Thompson et al.*, 2000]. It covaries with instrumental Tibetan Plateau temperatures over recent decades; and with instrumental NH temperatures since 1860 (r^2 = 0.37, 5-yr avg., 0.001 level). It also reflects the Asian monsoon, showing evidence for major monsoon failures in the 1790s and 1877–78 [*Thompson et al.*, 2000]. On longer time scales, however, the temperature relationship is considered dominant [*Thompson et al.*, 2000]. The fourth record is a sediment upwelling record of Arabian Sea southwest monsoon winds (ARA) (~10-yr resolution, NOAA website [*Anderson et al.*, 2002]). It correlates well with reconstructed NH temperatures for the past millennium [*Mann et al.*, 1999], a finding that was used to link large-scale warming to intensification of the monsoon over the past four centuries [*Anderson et al.*, 2002]. The fifth proxy is a precipitation reconstruction for northern Pakistan based on tree ring δ^{18}O measurements from sites on the western edge of the Asian monsoon region (KAR [*Treydte et al.*, 2006]). It shows an unprecedented intensification of the Asian hydrological cycle in the 20th century relative to the past millennium, attributed to anthropogenic warming. The sixth is a cold season (October to April) temperature reconstruction based on phenological events described in historical and documentary records (HIS [*Ge et al.*, 2003; see also *Ge et al.*, 2005]). The seventh is a multiproxy temperature reconstruction derived from combining ice core, tree ring, lake sediment and historical documentary records (MUL [*Yang et al.*, 2002]). The final record is a reconstruction of summer temperatures derived from thickness variations in annual layers of a stalagmite near Beijing (SPL [*Tan et al.*, 2003]); these latter three series are for China.

3. Eurasian and Tropical Temperatures

[8] Figure 2 compares the Eurasian surface air temperature and tropical SST proxies over their ~250-year common period. For both proxies, when compared to instrumental data, temperatures since the late 20th century have been at their highest levels over their respective lengths of record. The amplitude of temperature change – defined as the difference between the warmest and coldest 20-year periods – is much greater for Eurasia (1.70 ± 0.28°C) compared to the tropics (0.61 ± 0.29°C, Figure 2). The amplitude of temperature change from the 18th to 20th centuries is thus estimated to be about three times greater over Eurasia than the tropics (although this value varies from 1.5–6 due to the

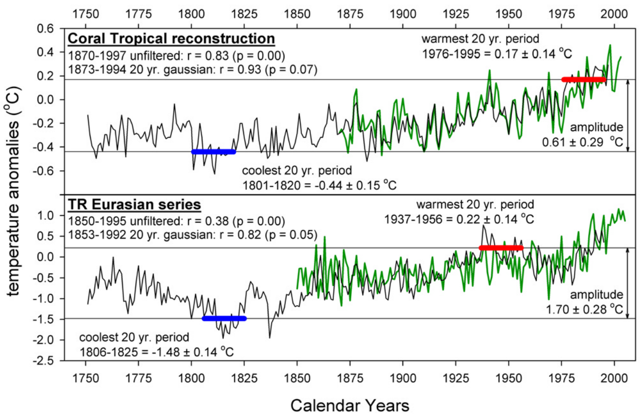

Figure 2. Coral-based tropical [*Wilson et al.*, 2006] and tree-ring based Eurasian [*D'Arrigo et al.*, 2006] temperature reconstructions (black lines). Green lines are the instrumental temperatures. Both series were scaled to their respective instrumental data over the common 1870–1995 period. The amplitude of warming is estimated by the difference between the warmest (red) and coolest (blue) 20-year periods in each record. The 2 sigma error ranges for the bi-decadal and amplitude estimates are also provided. The error ranges for these average values were calculated from the standard error of the estimate (i.e. calculated from the calibration period) derived from scaling 20-year smoothed low passed versions of the proxies with similarly smoothed instrumental data. The standard deviation of the residual difference between the two series is defined as the standard error (SE). The resulting amplitudes (with 2 sigma error ranges – i.e. 1.96*SE) for the coral and TR Eurasian proxies are 0.61 ± 0.29°C and 1.70 ± 0.28°C respectively.

error ranges of the amplitude estimates), a change which may have intensified low-frequency Asian monsoon variability over the past ~200 years. Similar results would be obtained using the *D'Arrigo et al.* [2006] NH temperature reconstruction. Conversely, monsoon strength may have weakened [e.g. *Anderson et al.*, 2002] along with the cooling in the early-middle 1800s seen in some NH temperature reconstructions [e.g. *Esper et al.*, 2002; *D'Arrigo et al.*, 2006]. This apparent weakening may be attributable to shifts in volcanic and solar forcing, with resultant cooling in the tropics as well as higher latitudes [*Chenoweth*, 2001; *Anderson et al.*, 2002; *Wilson et al.*, 2006].

4. Comparison With Asian Monsoon Proxies

[9] Figure 3 compares the tropical and Eurasian temperature series to proxy records from within the Asian monsoon regime. Some common low-frequency trends are evident which reflect those observed in hemispheric-scale temperature reconstructions over recent centuries [e.g. *Mann et al.*, 1999; *Esper et al.*, 2002; *D'Arrigo et al.*, 2006] (D'Arrigo et al.'s study is included in Figure 3). Yet there are also differences and the inter-proxy correlations are quite variable (Table 1) with all values being non-significant after adjusting the degrees of freedom for 1st order autocorrelation. However all indicate anomalous warming and/or intensified monsoon-related conditions during the 20th century. Both the *Treydte et al.* [2006] and *Li et al.* [2006; J. Li et al., manuscript in preparation, 2006] (primarily) precipitation-sensitive series show more low-frequency information than is usually found in precipitation-dominated records [*New et al.*, 2001]. *Treydte et al.* [2006] also presented similarities with other monsoon related proxies for Asia, and with warming over the past ~150 years. Similarly, *Brauning and Mantwill* [2004] used tree-ring temperature and precipitation reconstructions to conclude that recent increased monsoon rainfall over the Tibetan Plateau was unprecedented over the past four centuries. The recent low-frequency trends in these temperature and precipitation-sensitive proxies may be causally linked, as Eurasian and NH warming can lead to increased moisture-holding capacity in the atmosphere over the monsoon Asian region. The apparent connection between Eurasian temperatures and the monsoon is supported by studies that suggest that Eurasian warming has had profound impacts on the state

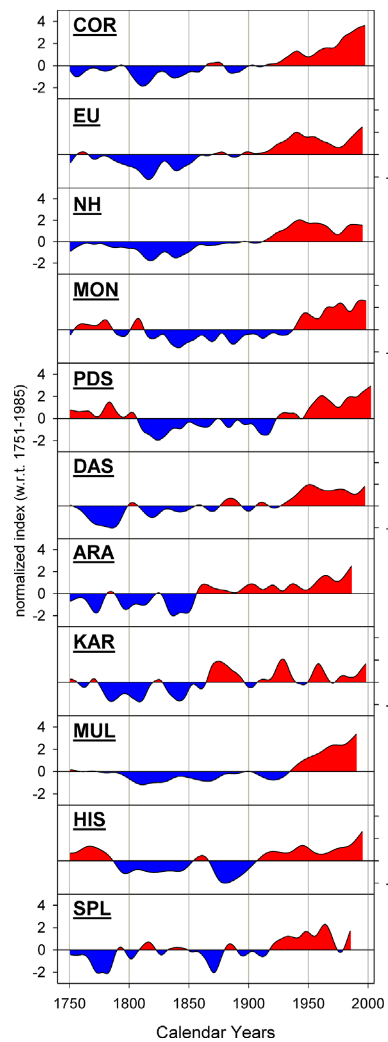

Figure 3. Proxy time series showing similar low-frequency trends. EU is the Eurasian composite; NH is the Northern Hemisphere reconstruction of *D'Arrigo et al.* [2006]. Series have been smoothed with a 20-year spline and normalized over the 1751–1985 common period. See text for proxy codes.

Table 1. Correlation Matrix (1751–1985) of the Proxy Time-Series[a]

	EU	NH	MON	PDS	DAS	ARA	KAR	MUL	HIS	SPL
COR	0.82	0.84	0.65	0.63	0.65	0.76	0.49	0.85	0.56	0.44
EU		0.96	0.52	0.57	0.65	0.73	0.59	0.66	0.63	0.44
NH			0.63	0.64	0.72	0.72	0.53	0.72	0.64	0.56
MON				0.74	0.49	0.48	0.07	0.81	0.65	0.29
PDS					0.35	0.38	0.16	0.77	0.55	0.24
DAS						0.60	0.45	0.65	0.25	0.71
ARA							0.58	0.59	0.36	0.39
KAR								0.26	0.12	0.23
MUL									0.54	0.47
HIS										0.18

[a]None of the correlations are significant after the degrees of freedom had been adjusted for autocorrelation in the series [*Dawdy and Matalas*, 1964].

of the Asian monsoon and related ecosystems [*Goes et al.*, 2005].

5. Discussion and Conclusions

[10] We have presented proxy reconstructions of Eurasian surface air temperatures and tropical SSTs, and used these proxies to determine that the rate of temperature increase since the early 19th century was about three times greater over Eurasia than the tropics (Figure 2). This increase is a result of the greater warming reconstructed for the Eurasian land mass than over the tropical oceans, and suggests an overall intensification of the Asian monsoon climate system. This finding is consistent with those of the other studies discussed herein (Figure 3). *Treydte et al.* [2006] cite additional studies for Eurasia that indicate enhanced pluvial conditions in the 20th century consistent with large-scale anthropogenic warming. Caveats include various uncertainties in the proxy estimates of large-scale temperature stated herein, and the annual to decadal, rather than seasonal, resolution of some of the proxies. This latter point is not critical as we were primarily interested in low-frequency changes in this paper.

[11] There are, of course, additional potential sources of low-frequency monsoon variability in addition to the Eurasian-tropical temperature gradient. The common low frequency signals observed between the temperature proxies for Eurasia and the tropics, and the other proxy series from monsoon Asia (which indicate warmer, wetter conditions) imply either cause and effect relationships, or a response to common forcings [*Anderson et al.*, 2002]. In addition to external factors (solar, volcanic, anthropogenic) that might simultaneously impact climate over the regions represented by these proxies, the circulation of the North Atlantic is one potential teleconnected source of monsoon variability, possibly via its downstream effects on conditions over Eurasia [*Chang et al.*, 2001; *Robock et al.*, 2003; *Goswami et al.*, 2006].

[12] Our utilization of large-scale temperature proxies to estimate the relative change in Eurasian land/tropical ocean temperatures is only one approach for inferring past monsoon variability [*Pai*, 2004; *Goswami et al.*, 2006]. There is no single record that is representative of the Asian monsoon, which is a highly complex and non-stationary feature of global climate [e.g. *Kumar et al.*, 1999; *Robock et al.*, 2003]. On the time scale of most interest to this study (decades to centuries), monsoon variability is perhaps the least understood, but of the most interest to human populations. Improved understanding of the monsoon will require additional proxy records for Eurasia as well as the tropics. Global circulation model studies indicate that intensified monsoon conditions can result from stronger warming of land compared to tropical oceans [e.g. *Ashrit et al.*, 2001]. Such models can be used to test the relationships between Eurasian and tropical climate observed in the proxy data.

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