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On the long-term interannual variability of the east Asian winter monsoon

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[1] The East Asian Winter Monsoon (EAWM) and Siberian High (SH) are inherently related, based on prior studies of instrumental data available for recent decades (since 1958). Here we develop an extended instrumental EAWM index since 1871 that correlates significantly with the SH. These two indices show common modes of variation on the biennial (2–3 year) time scale. We also develop an index of the pressure gradient between the SH and the Aleutian Low, a gradient which critically impacts EAWM variability. This difference series, based on tree-ring reconstructions of the SH and the North Pacific Index (NPI) over the past 400 years, shows that the weakening of this gradient in recent decades has not been unusual in a long-term context. Correlations between the SH series and a tree-ring reconstruction of the El Niño-Southern Oscillation (ENSO) suggest a variable tropical-higher latitude teleconnection. **Citation:** D'Arrigo, R., R. Wilson, F. Panagiotopoulos, and B. Wu (2005), On the long-term interannual variability of the east Asian winter monsoon, *Geophys. Res. Lett.*, *32*, L21706, doi:10.1029/2005GL023235.

1. Introduction

[2] The East Asian Winter Monsoon (EAWM) strongly impacts winter climate over East Asia, and interacts with the larger-scale Asian monsoon system and with global climate [*Zhang et al.*, 1997; *Jhun and Lee*, 2004]. Strong EAWMs are linked to cold winter conditions over much of East Asia [*Jhun and Lee*, 2004]. The interannual variability of the EAWM depends largely on the behavior of the Siberian High (SH) pressure cell [*Gong and Ho*, 2002]. During strong EAWM and SH conditions, dramatic drops in temperature (cold surges) originating in the SH source region penetrate eastern China, and as far south as Australia [*Gong and Ho*, 2002; *Jhun and Lee*, 2004]. The EAWM appears to have weakened in recent decades [*Nakamura et al.*, 2002], along with the intensity of the SH [*Panagiotopoulos et al.*, 2005]. Another climate feature that critically impacts the EAWM is the Aleutian Low (AL) pressure cell, via the zonal pressure gradient between the AL and SH and the processes that control it [*Nakamura et al.*, 2002; *Jhun and Lee*, 2004; *Panagiotopoulos et al.*, 2005].

[3] Several EAWM and SH indices have been defined in the literature [e.g., *Wu and Wang*, 2002; *Jhun and Lee*, 2004]. The instrumental SH and EAWM sea-level pressure (SLP) indices of *Wu and Wang* [2002] (hereafter SHI and EAWMI) correlate at r = 0.8 over 1958–2000. A wind-based EAWMI, distinct from that of *Wu and Wang* [2002], correlates significantly with the SH (r = 0.68) and the North Pacific Index (NPI, an index of AL intensity; *Trenberth and Hurrell*, 1994; r = −0.48) [*Jhun and Lee*, 2004]. However, other atmospheric circulation indices investigated by *Jhun and Lee* [2004] over 1958–2000 (including the North Atlantic Oscillation (NAO), and Niño-3.4 sea surface temperatures (SST)) did not correlate significantly with the EAWMI on interannual time scales. On decadal time scales additional features, such as the Arctic Oscillation [*Gong and Ho*, 2002; *Jhun and Lee*, 2004], impact EAWM variability.

[4] There is still considerable uncertainty in our understanding of the nature and mechanisms of the EAWM [*Wu and Chan*, 2005]. In this paper we develop an extended instrumental index of the EAWM from 1871–1994. We evaluate a 400-year tree-ring reconstruction of the SHI [*D'Arrigo et al.*, 2005a] for its relationship to the EAWM, and compare it to two other tree-ring reconstructions: of the NPI, and of the El Niño-Southern Oscillation (ENSO). Relative changes in these proxy series over time are shown to provide information on past EAWM variability and its teleconnections.

2. Data and Analyses

2.1. Instrumental Data

[5] The EAWMI of *Wu and Wang* [2002] is based on the sum of normalized zonal SLP differences (110°E–160°E) computed at 5 degree intervals over 20–70°N. It represents the boreal winter [Dec–Feb] meridional wind component over the coast of East Asia associated with the EAWM (Figure 1). Because this record is very short, based on NCEP-NCAR data beginning in 1958, we have applied the formula of *Wu and Wang* [2002] to a global mean SLP data set (GMSLP; V. 2.1f; UK Met Office-Hadley Centre, 5° × 5°; a blend of existing gridded and observed data) [*Basnett and Parker*, 1997] in order to extend this record from 1871–1994. For computing the EAWMI, we used the same latitude band (40–65°N) typically employed to define the SHI [*Panagiotopoulos et al.*, 2005]. The resulting extended EAWMI (Figure 1) correlates with a version based on the 20–70°N gridcell (the same latitude band employed by *Wu and Wang* [2002]) at r = 0.89 over 1871–1994. Correlation of this EAWMI with the SHI, based on SLP averaged over 40–65°N, 80–120°E (Figure 1), improves from 0.65 (using the 20–70°N EAWMI) to 0.74 (using the 40–65°N EAWMI) over this extended period.

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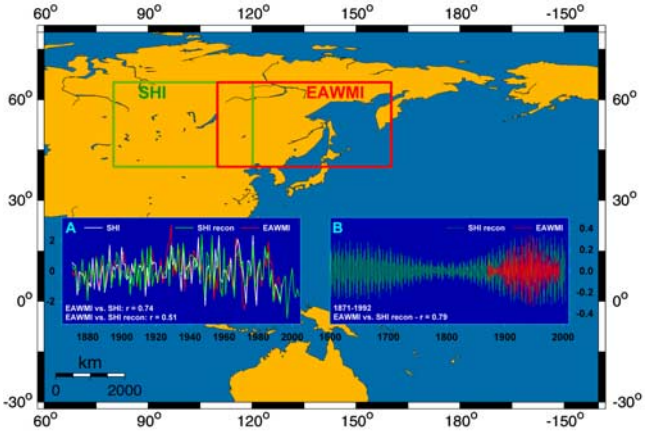

Figure 1. Map showing locations of gridcells used to define the EAWMI (red grid; 40–65N, 110–160°E) and SHI (green grid; 40–65°N, 80–120°E). (a) Comparison between extended EAWMI (red line), instrumental SHI (white line) and reconstructed SHI (green line [*D'Arrigo et al.*, 2005a]) from 1871–1994. (b) Dominant oscillatory modes of biennial variability (~2.4 yr) extracted using SSA. Relevant biennial modes were summed for each series. Biennial modes for the extended EAWM (1871–1994) and SHI reconstruction (1599–2003; r = 0.79 over 1871–1994) are shown.

2.2. Proxy Data

[6] The Dec–Feb SHI reconstruction (1599–2003) is based on Eurasian and northwestern North American tree-ring records [*D'Arrigo et al.*, 2005a]. The NPI reconstruction (1606–2003) includes northwestern North American tree-ring data that are largely independent of those used to reconstruct the SHI [*D'Arrigo et al.*, 2005c], with only one chronology in common between these two series. Correlations between the SH and NPI reconstructions are not significant (Figure 2), which is also the case for the instrumental SHI and NPI: r = −0.25 for 1958–2000 [*Jhun and Lee*, 2004). As we were most interested in the interannual variability of the EAWM, persistence was removed by autoregressive modeling of the tree-ring data used in both the SHI and NPI reconstructions, which eliminated any decadal and longer-term climatic information [*Cook and Kairiukstis*, 1990]. The NPI reconstruction utilized herein has been modified from the Nov–May version described in *D'Arrigo et al.* [2005c] to cover a cold season (Dec–Mar) more consistent with the Dec–Feb EAWMI. We also compare the EAWMI and SHI to a reconstruction of Niño-3 SSTs based on tree-ring records from the southwestern USA [*D'Arrigo et al.*, 2005b] in order to evaluate the relationship of these higher latitude indices to ENSO.

3. East Asian Winter Monsoon and Siberian High

[7] The extended EAWMI correlates significantly with the SHI reconstruction at r = 0.51, and with the instrumental SHI at 0.74, as noted above, over 1871–1994 (Figure 1a). Previous spectral analyses of both the instrumental EAWMI [*Li et al.*, 2001] and instrumental SHI [*D'Arrigo et al.*, 2005a] showed statistically significant (95% level) peaks at 2–3 years. Spectral peaks at 2–3 years are also observed in the extended version of the EAWM (not shown). A significant (99% level) peak at ~2.4 years found previously in the SHI reconstruction is the strongest in this 400-year record [*D'Arrigo et al.*, 2005a]. Singular spectrum analysis (SSA), a data adaptive method for extracting signals from noise in time series [*Vautard*, 1995], was performed on the EAWMI and SHI reconstruction in order to identify important oscillatory modes and their fluctuations over time. Both the EAWMI and SHI reconstruction show dominant waveforms at ~2.4 years (Figure 1b), consistent with the peaks identified in the previous spectral analyses. They are also consistent with the time scale of the Tropospheric Biennial Oscillation (TBO; *Meehl and Arblaster*, 2002), defined as the tendency for strong and weak monsoons to occur in alternate years. The ~2.4 year modes in the EAWMI and SHI are highly correlated at r = 0.79 (Figure 1b). Over the full length of the SHI reconstruction, its biennial mode varies in intensity, with relatively high amplitude prior to ~1750, low amplitude from ~1750 to 1850, and higher amplitude centered around the early to middle 1900s (Figure 1b).

4. Comparison With Other Proxy Records

[8] The SH and AL, and the zonal pressure gradient between them, account for much of the interannual variability in the EAWM (Figure 2) [e.g., *Jhun and Lee*, 2004]. A strong EAWM is associated with a strong (positive) SHI and a more intense AL (negative NPI) [*Trenberth and Hurrell*, 1994; *Jhun and Lee*, 2004]. We computed the difference time series between the normalized SHI and NPI reconstructions over their common period (1606–2003) in order to estimate the zonal pressure gradient between the SH and AL, and thus the intensity of the

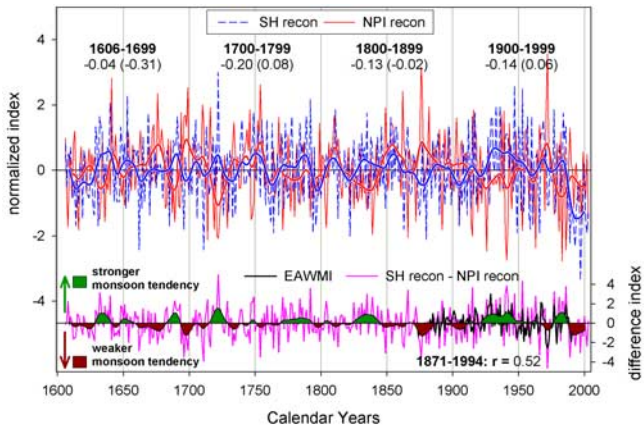

Figure 2. (top) Time series of the normalized Dec–Feb Siberian High and the Dec–March NPI (an index of Aleutian Low intensity; *Trenberth and Hurrell*, 1994) reconstructions over their common period from 1606–2003. Correlations shown for different subperiods. Low-pass filtered correlations in parentheses. Although correlation of the EAWMI is stronger with the instrumental Dec–Feb NPI (−.48) versus Dec–March (−.39), the Dec–March season provides a better tree-ring model. (bottom) The normalized SH-AL difference series, compared to the EAWMI for 1871–1994. A stronger (weaker) pressure gradient is linked to a stronger (weaker) monsoon tendency, as indicated by arrows.

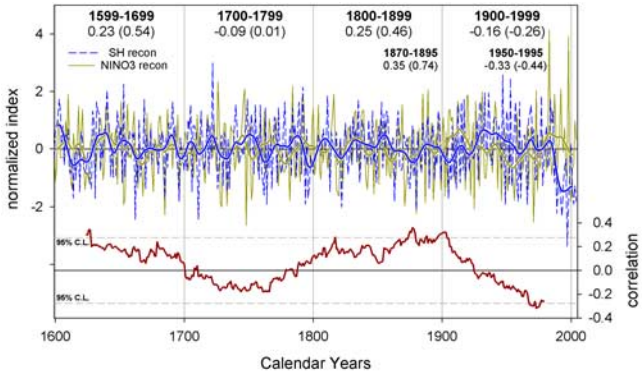

Figure 3. Comparison of SHI reconstruction with a reconstruction of Niño-3 SSTs (common period 1599–2003) [*D'Arrigo et al.*, 2005b]). Correlations for different subperiods are shown for the two series. Correlations for subintervals identified by *Robock et al.* [2003] are also indicated (see text for details; some of the tree-ring records included in the SHI reconstruction are also sensitive to the NAO). Correlation between the instrumental EAWMI and Niño-3.4 SSTs is −0.25, not significant over 1958–2000 [*Jhun and Lee*, 2004]. Lower panel shows 51-year running correlations.

EAWM, over time (Figure 2) [*Nakamura et al.*, 2002; *Jhun and Lee*, 2004]. This difference series is significantly correlated with the EAWMI at r = 0.52 over 1871–1994. The EAWMI and NPI reconstruction are correlated at r = −0.29; and at −0.39 with the instrumental Dec–Mar NPI over 1871–1994. The recent declines in the pressure gradient and inferred EAWM [*Nakamura et al.*, 2002] do not appear to be unique in the context of the past four centuries (Figure 2).

[9] Evidence for a varying tropical-extratropical connection is presented in Figure 3, which compares the SHI reconstruction to a tree-ring reconstruction of Niño-3 SST [*D'Arrigo et al.*, 2005b]. Figure 3 indicates an alternation in the strength and sign of the relationship between the SHI and ENSO approximately every 100 years. Interestingly, *Robock et al.* [2003] found that the NAO index (like the SHI, an indicator of Eurasian climate) correlates with an Indian monsoon rainfall index (like the Niño-3 SST index, an indicator of tropical climate) for only two intervals in the instrumental period: 1870–1895 and 1950–1995. Correlations between the SHI and ENSO reconstructions are also significant, suggesting an intensified tropical-extratropical connection during these two intervals (Figure 3).

5. Discussion and Conclusions

[10] We have presented an extended instrumental-based index of the EAWM that correlates significantly with instrumental and tree-ring records of the SHI, confirming previous studies based on much shorter data sets [e.g., *Wu and Wang*, 2002]. Singular spectrum analysis of the SHI and EAWMI records shows well-correlated common variability (~2.4 years) consistent with the time scale of the TBO, an important but poorly understood feature of Asian monsoon climate [*Meehl and Arblaster*, 2002]. The biennial mode in the full SHI reconstruction varies in intensity, with low amplitude from ~1750–1850. A difference series of the SH and AL, two of the most critical climate features known to impact the interannual EAWM [e.g., *Jhun and Lee*, 2004], provides an estimate of interannual changes in EAWM intensity over the past four centuries. Recent declines in the SH-AL gradient and EAWM (Figure 2) do not appear to be unique in this long-term context, although a decline in the strength of the SH alone appears to be unprecedented over the past four centuries [*D'Arrigo et al.*, 2005a].

[11] Previous studies have shown close relationships between the EAWM and tropical climate. *Yasunari* [1989] suggested that the EAWM and TBO are linked through a strong negative correlation between the Indian summer monsoon and SST anomalies in the South China Sea. The SH, EAWM, and convective activities over the western tropical Pacific are inherently related. Generally, a stronger than normal EAWM results in active convection over the western tropical Pacific. An anomalous lower-tropospheric anticyclone (cyclone) in the western North Pacific is the key system bridging warm (cold) events in the equatorial eastern Pacific with a weak (strong) EAWM [*Wang et al.*, 2000]. Formation of an anomalous Philippine Sea anticyclone coincides with an abnormal deepening of the East Asian trough. Its development may be attributed to the combined effects of ENSO, tropical-extratropical interaction, and monsoon-ocean interaction [*Wang and Zhang*, 2002]. We have shown herein that there appears to be a variable relationship between the EAWM, SH and tropical climate (ENSO) over the past four centuries.

[12] Using extended instrumental and proxy records, our results support the hypothesis that there are long-term relationships between the SH and EAWM on interannual time scales [e.g. *Li et al.*, 2001; *Wu and Wang*, 2002; *Jhun and Lee*, 2004]. Although the biennial modes identified herein are intriguing, we caution that they approach the limit of resolvability for tree-ring data [*Cook and Kairiukstis*, 1990]. We observe a variable tropical-extratropical interaction related to the EAWM and SH over the past several centuries. However, additional proxy data and analyses, from both Asia and the tropics, are needed to further clarify the complex roles of these important features of the Asian monsoon system.

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