GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L01705, doi:10.1029/2007GL032409, 2008

Variability of the low-level cross-equatorial jet of the western Indian Ocean since 1660 as derived from coral proxies

Dao-Yi Gong[1] and Jürg Luterbacher[2,3]

Received 19 October 2007; revised 15 November 2007; accepted 20 November 2007; published 11 January 2008.

[1] Using monthly-seasonally resolved coral proxies from the Indian Ocean basin, we statistically reconstruct the June–July–August (JJA) low-level jet in western Indian Ocean from 1660–1957 with skillful estimates for high- and low-frequencies. The El Niño/Southern Oscillation (ENSO) signals are reasonably captured. The strength of the jet significantly increases from the late 17th century to late 19th century. The decreasing in reconstructed jet in 20th century disagrees with previous studies which indicated an enhancement of Southern Asian summer monsoon (SASM) in association with the rapid global warming. The jet reconstructions are useful for understanding of SASM variability and the validation of historical monsoon simulation. **Citation:** Gong, D.-Y., and J. Luterbacher (2008), Variability of the low-level cross-equatorial jet of the western Indian Ocean since 1660 as derived from coral proxies, *Geophys. Res. Lett.*, *35*, L01705, doi:10.1029/2007GL032409.

1. Introduction

[2] Much recent effort has been aimed at monsoon precipitation reconstruction in the late Holocene using proxies from ice cores in Tibetan Plateau [*Thompson et al.*, 2000; *Duan et al.*, 2004; *Yang et al.*, 2007], stalagmites from Oman and India [*Burns et al.*, 2002; *Fleitmann et al.*, 2004; *Yadava et al.*, 2004], and tree-rings from South/East Asia [*Buckley et al.*, 2007]. The consistency of these reconstructions often weakens when records from widely separated sites or from different proxies are compared [*Ramesh*, 2001], due to the regionality of monsoon climates, data resolution, and the complicated monsoon-proxy relations. These would make SASM signals in any individual proxy time-series weak. The usage of multi-proxies (rather than the analysis of single records) and to reconstruct the large-scale circulation system (rather than to reconstruct the local climates) are important to reduce the uncertainties in SASM reconstruction. In Western Indian Ocean and east Africa the prevailing air-flow in lower troposphere forms the cross-equatorial lower level jet (Figure 1), an important indicator of the large-scale SASM system [*Findlater*, 1969]. Here we present the statistical reconstruction of the jet for JJA since 1660 based on season-resolved proxies in coral network from the Indian Ocean basin.

2. Data and Methods

[3] The jet is defined as the regional mean meridional wind at 850 hPa level (V850) in area 5°S–5°N and 37.5°E–60°E based on ERA40 reanalysis data sets. During the data period 1958–2002 the jet location is stable, while it changes notably in strength (mean = 7.9 m/s, σ = 0.38 m/s). Eight high-resolution coral proxies used in the study are selected from published works (Table 1 and Figure 1). For site Xisha (Southeast Asia) the proxy is the strontium content and for the other seven are δ^{18}O. The monsoon circulation related δ^{18}O anomalies are of large-scale in Indian Ocean basin [*Vuille et al.*, 2005], in association with the regional sea surface temperature(SST)/precipitation-atmosphere interaction and teleconnections [*Charles et al.*, 1997, 2003; *Cole et al.*, 2000; *Abram et al.*, 2007]. Therefore the usage of coral records in Indian Ocean and western Pacific are expected to improve the reconstruction skills.

[4] Prior to calibration, we screened all time-series to find the maximum connection between JJA V850 and proxies using the raw data, and a couple of months time-lags were identified (Table 1). Proxies in these months are averaged to obtain a single proxy time-series for each coral site, and used as the predictors in validation and reconstruction procedure. The averaging over multi-months also reduces the influence of the dating error (about 1–2-month) caused by ascribing local maxima in the proxy record to a prescribed calendar month during the coral dating procedure [*Charles et al.*, 1997]. We checked the high-frequency components (<10 yr) that are obtained from a Butterworth filter. All eight proxies listed in Table 1 are significantly correlated with V850 at high-frequencies. Therefore, the eight high-pass filtered proxies are used to reconstruct the high-frequency components of V850. When reconstructing the climatic low-frequencies it is important to carefully choose proxies since the correlations at long-term fluctuations in proxies might conceal the lack of a physical link thus bias the estimates for low-frequencies. We found that the raw data in NIN, HOU and REU show the strongest trends in all eight proxies, significant at the 0.01 level. The decreasing trends in HOU and REU are mainly caused by the jump-like drops in time series (e.g., abrupt drops in 1842/43, 1867/68 in HOU; 1903/04 in REU). No substantial evidence supports that these jumps in HOU and REU and remarkable trend in NIN are climate-related. To avoid overestimating the low-frequencies and trends in the jet reconstruction, we used only five un-filtered proxies (IFA, SEY, BAL, XIS and BUN) for the raw reconstruction (Table 1).

[1]State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Resources Science and Technology, Beijing Normal University, Beijing, China.

[2]Oeschger Centre for Climate Change Research and National Centre of Competence in Research on Climate (NCCR), University of Bern, Bern, Switzerland.

[3]Institute of Geography, Climatology and Meteorology, University of Bern, Bern, Switzerland.

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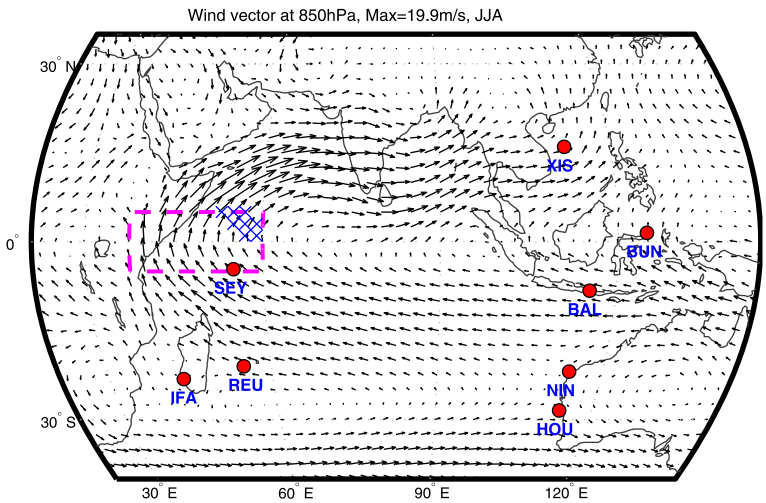

Figure 1. Locations of coral proxies are shown in solid circles (see Table 1). Crosses indicate COADS grids where missing July wind are less than 15% before 1957. Vectors are ERA40 climate wind at 850 hPa level in JJA over the 1958–2002 period. The mean meridional wind in the box in western Indian Ocean is defined as the cross-equatorial jet.

[5] By applying multivariate regression method the V850-proxy relations were calibrated and cross-validated based on the period of 1958–1989/93/94, using raw data of five proxies (designed for the low-frequency components reconstruction) and the high-pass filtered data of all eight corals (designed for high-frequency reconstruction), respectively. Then regressions were applied to compute the V850 in 1660–1957. In verification procedure we checked the explained variance, standard error (SE), and the reduction of error (RE). The cross-validation was performed by applying a leave-one-out validation method (Table 2).

3. Results and Discussion

[6] Reconstructions are shown in Figure 2. For raw-reconstruction, the explained variance of the low-level jet increases from 37% in 1660–1781 when only one predictor is used up to 41% in the recent period when all five coral proxies are included. During period 1660–1957 the explained variance remains relatively stable with an average of approximately 39% (Table 2). At the same time the SE varies little with time (0.28–0.30 m/s). The REs before 1860 are all above +0.2 and +0.13 in 1906–1957. Note that higher REs do not appear in periods when there are more coral data available, suggesting the local influence on the estimates of low-frequency. For future studies, more skillful proxies would be helpful to reduce the uncertainties in the low-frequency reconstruction. Generally, the positive RE values are indicative of reliable reconstruction. For the high-frequency reconstruction, the explained variance notably changes with time, being 28% during 1660–1781 and increasing up to 74% after 1879. Also, the RE changes between +0.17–+0.37 during 17th –mid-19th centuries and reaches value of +0.54 in 1879–1905. These statistics indicate that both raw- and high-frequency reconstructions point to relatively skillful estimates for approximately the last 340 years.

[7] The raw-reconstruction shows a linear trend of +0.05m/s/100yr for the 1660–2002 period, significant at the 0.01 level. Within this period a three times stronger trend is found from the mid-17th to 19th centuries. However, the trend in the 20th century (–0.001 m/s/100 yr, not

Table 1. Pearson Correlation (*r*) Between JJA V850 and Coral Proxies Within the Second Part of the 20th Century[a]

Coral Site	Resolution	*r* (Unfiltered Data)	*r* (High-pass Filtered Data)	*r* Period	Proxy Season for *r*	Data Length	References
IFA(Ifaty)	bi-monthly	–0.61[b]	–0.53[b]	1958–1994	Aug–Dec	1660–1994	*Zinke et al.* [2004]
SEY (Seychelles)	monthly	+0.21	+0.48[b]	1958–1993	Nov–Jan	1847–1994	*Charles et al.* [1997]
NIN (Ningaloo)	bi-monthly	[+0.11]	+0.28[c]	1958–1994	Oct–Dec	1879–1994	*Kuhnert et al.* [2000]
HOU(Houtman)	bi-monthly	[+0.25]	+0.42[b]	1958–1993	Aug–Oct	1795–1993	*Kuhnert et al.* [1999]
REU (Réunion)	bi-monthly	[+0.25]	+0.31[c]	1958–1994	Oct–Dec	1832–1994	*Pfeiffer et al.* [2004]
BAL (Bali)	monthly	+0.01	–0.36[d]	1958–1989	Aug–Oct	1782–1989	*Charles et al.* [2003]
XIS (Xisha)	monthly	+0.33[d]	+0.28[c]	1958–1992	Oct–Jan	1906–1993	*Sun et al.* [2004]
BUN (Bunaken)	monthly	–0.13	–0.61[b]	1958–1989	Jul–Dec	1860–1989	*Charles et al.* [2003]

[a]All proxies listed were used in high-frequency reconstruction, and those indicated by brackets were excluded from raw-reconstruction. For locations of proxies, see Figure 1.
[b]Significant at the 0.01 level.
[c]Significant at the 0.1 level.
[d]Significant at the 0.05 level.

Table 2. Statistics for the Calibration and Verification[a]

Raw Reconstruction					High-Frequency Reconstruction				
Proxy Number	Period	r^2, %	SE, m/s	RE	Proxy Number	Period	r^2, %	SE, m/s	RE
5	1906–1957	41	0.29	0.13	8	1906–1957	74	0.14	0.46
4	1860–1905	40	0.29	0.20	7	1879–1905	74	0.14	0.54
3	1847–1859	39	0.30	0.24	6	1860–1878	63	0.16	0.37
2	1782–1846	38	0.30	0.26	5	1847–1859	59	0.17	0.30
1	1660–1781	37	0.28	0.30	4	1832–1846	53	0.18	0.27
					3	1795–1831	48	0.19	0.22
					2	1782–1794	35	0.22	0.17
					1	1660–1781	28	0.21	0.19
Mean		39.0	0.29	0.23	Mean		54.3	0.18	0.32

[a]See text for details.

significant) is inconsistent with previous proxy data. The surface wind derived from the abundance of *G. bulloides* in ocean sediment in western Arabian Sea shows continuously strengthening since ∼1600, with a strong positive trend within the 20th century [*Anderson et al.*, 2002]. Whereas this increasing trend is neither supported by precipitation proxies nor by observations [*Burns et al.*, 2002; *Fleitmann et al.*, 2004; *Kaspari et al.*, 2007]. The puzzling long-term trend of SASM in the 20th century remains an open question. Different resolution of proxies may be one reason, because *Anderson et al.* [2002] data are annual or multi-annual while we are dealing with JJA means. In annually resolved data it is hard to identify the winter-summer climate contrast which is a dominant feature of monsoon. To clarify the fidelity of the reconstructed trend in the 20th century we analyzed the observed surface wind using Comprehensive Ocean-Atmosphere Data Set (COADS) data and simulated V850 since the late 19th century. Due to limited data availability we only checked surface wind speed in July (Figure 3a). The surface wind speed has an observable decrease during the first half of the century and followed by a slight increase during the recent couple of decades. The low-frequency tendency is generally comparable with the reconstructed JJA jet, raising somewhat confidence in the trend of reconstruction. Then, we analyzed 20 simulations of the 20th century climate (IPCC AR4 20C3M) forced by the observed anthropogenic and natural forcings (for details see: http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php). The mean jet of 20 ensembles shows no increasing trend during the 20th century as the globe and region warms [e.g., *Zhou and Yu*, 2006], and the trend since the late 19th century bears somewhat similarity to our reconstruction and observations (Figure 3b). We also compared the long-term modeling of 850 hPa and surface cross-equatorial jet winds in ECHO-G simulations of the past millennium, which was forced with prescribed natural and anthropogenic forcings [*González-Rouco et al.*, 2003; *Zorita et al.*, 2005], and found that the simulation displays

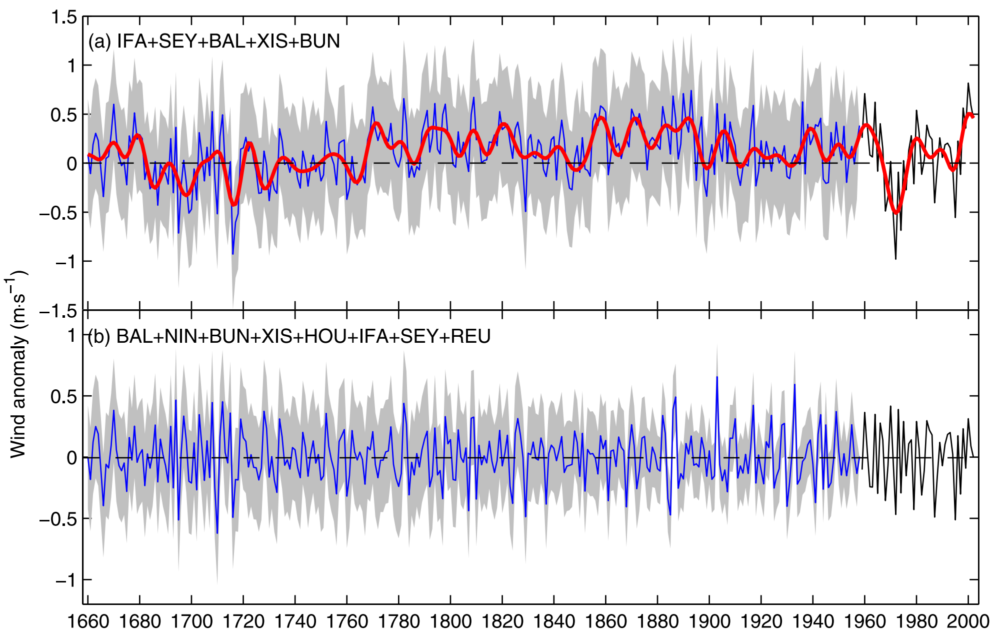

Figure 2. Reconstructed jet given as anomalies (in m/s, w.r.t. 1961–1990). (a) Raw reconstruction based on five unfiltered coral proxies, and smooth line is the low-frequency (>10 yr) variations from a Butterworth filter. (b) The high-frequency reconstruction derived from eight filtered coral proxies. Shading indicates the range of ±2 × SE derived from unresolved variance in the calibration period.

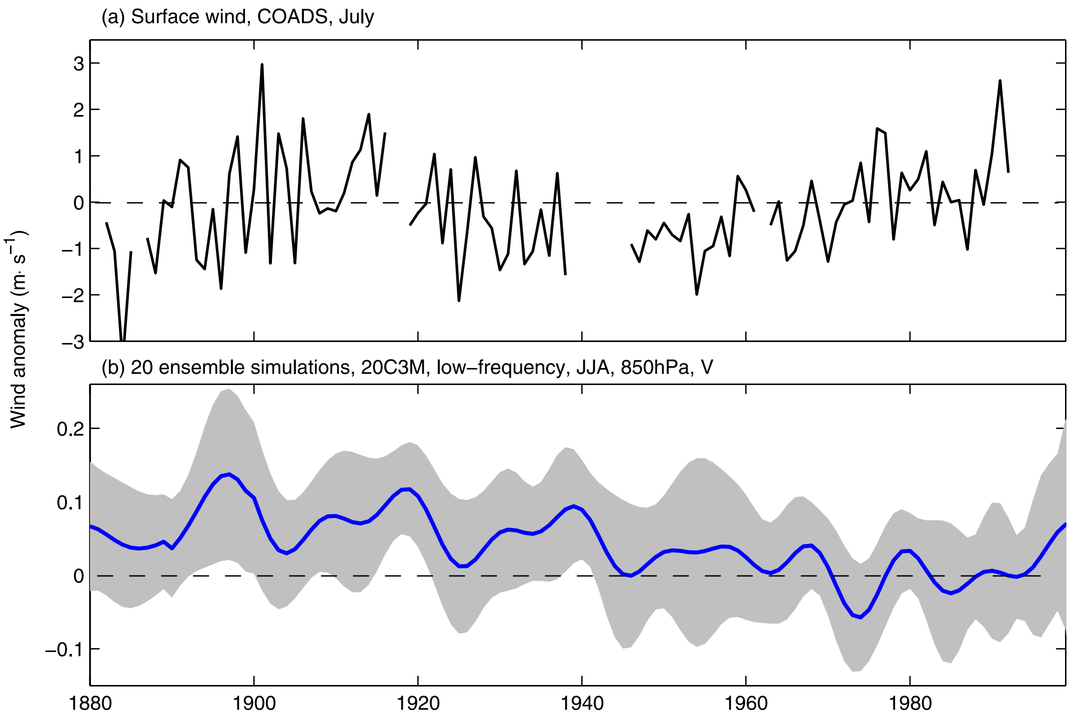

Figure 3. (a) COADS July surface wind speed anomaly (w.r.t. 1961–1990) as the average from eight grids shown in Figure 1. Years with more than 2 missing grids are omitted. (b) Simulated jet in IPCC AR4 20C3M, shown as the mean of 20 ensembles. In Figure 3b the shading indicates the range of ±2 × SE of the ensemble means, and only the >10 yr components from a Butterworth filter are presented.

similar decadal frequencies as our reconstructions during 1660–1990 (figure not shown). The simulated 850 hPa jet shows weak positive trend in the periods 1660–1900 and 1900–1990. However, the trends are not statistically significant. The study of *Hu et al.* [2000] shows a clear intensification of the monsoon in the warmer 21st century. This indicates that the model monsoon is quite sensitive to anthropogenic forcing. *Zickfeld et al.* [2005] indicated that any given boundary forcing may lead to altering between multi-equilibrium states of SASM, suggesting complex responses of SASM to global climate. Multi-model ensemble simulations backward to 1660 would be very valuable for assessment of the centennial trends in SASM and its response to global climate.

[8] Superimposed upon the long-term trend there are evident decadal variations in the raw reconstruction. We checked all decadal averages and their differences from the climate means using two-tailed *t*-test, and identified seven significant (at the 0.05 level) anomalous decades. The largest positive decades are 1790s (+0.35 m/s), 1870s (+0.32 m/s), and 1880s (+0.31 m/s), and the largest negative decades occur in 1970s (−0.23 m/s), 1710s (−0.20 m/s), 1690s (−0.16 m/s), and 1760s (−0.08 m/s). Interestingly, the decadal-scale dips of the jet generally correspond to drought events as reconstructed from different proxies [e.g., *Buckley et al.*, 2007], suggesting monsoon weakening at these periods.

[9] Power spectral analysis of the raw reconstruction shows significant inter-annual timescale variations of ~8.3, ~2.3, ~2.9 and ~3.9 years. Similar inter-annual variations between 2–8 years are also found in the high-frequency reconstruction, likely suggesting the jet association with ENSO. To check the ENSO-monsoon connection in our reconstructions, we computed the correlation between V850 and observed JJA Niño3 SST. During the reconstruction period (1856–1957), Niño3 SST is significantly correlated with the jet at −0.34 and −0.41 for raw and high-frequency reconstructions, agreeing well with instrumental observation that during El Niño conditions the SASM tends to be weaker than normal. This suggests that the ENSO signals are reasonably captured in reconstructions. In addition, the periodicities of ~12, ~22 years are also outstanding. These frequencies are widely documented in climate proxies in Indian Ocean and neighboring regions too [*Charles et al.*, 1997; *Cole et al.*, 2000; *Burns et al.*, 2002]. The mechanisms for the decadal variations, however, are not well understood. *Charles et al.* [1997] speculated that the source of this decadal variability lies in the coupling between SASM and Indian Ocean. Note that this is a phenomenon in global tropics [*Cole et al.*, 2000], planetary scale forcings such as the solar radiation may play an important role [*Burns et al.*, 2002; *Fleitmann et al.*, 2003]. *Kodera* [2004] explained that the solar signals originating from the stratosphere modulates the upwelling in the tropical atmospheres, and subsequently influencing the SASM and precipitation. Therefore it is very likely that the decadal variation in reconstructed jet is a dynamical response to solar influence, though other mechanisms such as air-sea interaction have contributed as well. The robustness of the reconstructed high-frequency is also supported by the V850- precipitation connection. Observation of all-Indian monsoon precipitation in June to September [*Pathasarathy et al.*, 1994] experiences dominant inter-annual variation that accounts for 82% of the total variance

(1871–2000). We checked the consistency between the Indian precipitation and the reconstructed jet. For the raw data we found $r = +0.33$ for both the calibration period (1958–2000) and the reconstruction (1871–1957). For high-frequency data in the observation and reconstruction periods the correlations are +0.42 and +0.37, respectively. With respect to the jet's consistency with ENSO and Indian monsoon precipitation, we conclude that the inter-annual variations are reasonably presented in reconstructions.

4. Conclusions

[10] We statistically reconstructed the cross-equatorial low-level jet back to 1660 using a coral proxy network in Indian Ocean basin, and found skillful estimates for both the high and low frequency domains. The raw reconstruction shows an evident increasing trend from the late 17th century to the late 19th century. From the late 19th century to the middle 20th century the jet slightly weakened and followed by an increase after the middle 1970s. The decades with largest significant positive jet anomalies occur in 1790s, 1870s, and 1880s, suggesting strengthening of the monsoon at these periods. The largest negatives appear in 1970s, 1710s, 1690s, and 1760s, suggesting weakening of the SASM. On the interannual timescale, ENSO signals are reasonably captured in the reconstructions. The jet slightly decreased in the 20th century, being generally in agreement with the surface wind observations and the IPCC-AR4 simulations. However, this trend is apparently different from previous proxy studies that indicated a stronger wind. Elaborate analysis of season-resolved wind proxies and ensemble simulations of historical climate are needed to clarify this puzzle. Our results may have hydrological, economical and social implications in densely populated South/East Asia.

[11] **Acknowledgments.** DYG was supported by the Sino-Swiss Cooperation Research Fellow program. This study was supported by grant NSFC40675035, PE07030, and the 111 Project (B06004). JL was supported by the Swiss NSF through the NCCR Climate. Authors thank Tianjun Zhou for help in processing 20C3M data and Eduardo Zorita and Fidel González-Rouco for providing ECHO-G simulations. We thank the reviewers for helpful suggestions and constructive criticism that helped improve the quality of the paper.

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D.-Y. Gong, State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Resources Science and Technology, Beijing Normal University, Beijing 100875, China. (gdy@bnu.edu.cn)

J. Luterbacher, Institute of Geography, Climatology and Meteorology, University of Bern, CH-3012 Bern, Switzerland. (juerg@giub.unibe.ch)