Chapter 8

THE PACIFIC SECTOR HADLEY AND WALKER CIRCULATION IN HISTORICAL MARINE WIND ANALYSES

Potential for Reconstruction from Proxy Data

Michael N. Evans[1] and Alexey Kaplan[2]
[1]*University of Arizona, Laboratory of Tree-Ring Research, Tucson, Arizona 85721 U.S.A.*
[2]*Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964 U.S.A.*

Abstract

We investigate the historical variation of the wintertime Pacific marine sector meridional atmospheric circulation, using simple diagnostics calculated from a statistical analysis of 140 years of surface wind data. Intensity of the wintertime expression of the Hadley circulation, as expressed by a wind divergence index, varies interannually and secularly. In agreement with previous studies, interannual variation is associated with variations in the Walker circulation; e.g., El Niño/Southern Oscillation (ENSO) activity. The secular variation, most likely affected by systematic measurement biases, is nevertheless consistent with results from simulation of the Indo-Pacific-sector Hadley circulation variability in the NCEP/NCAR reanalysis (see Chapter 3, “Change of the Tropical Hadley Cell since 1950,” Quan et al., this volume; and Chapter 5, “Interannual to Interdecadal Variations of the Hadley and Walker Circulations,” Minobe, this volume) and model simulations of the global atmospheric response to anthropogenic forcing (see Chapter 14, “The Response of the Hadley Circulation to Climate Changes, Past and Future,” Rind and Perlwitz, this volume; and Chapter 17, “Mechanisms of an Intensified Hadley Circulation in Response to Solar Forcing in the Twentieth Century,” Meehl et al., this volume). A proxy network tracking Hadley intensity as mirrored in sea surface temperature (SST), precipitation, surface winds, and/or ocean upwelling might be used to further study processes underlying long-term variability in the Hadley circulation over the past several hundred years.

1. INTRODUCTION

How steady is the zonal mean tropical atmospheric circulation in the presence of internal and external forcing? The mean circulation of the atmosphere is now well described by the large number of observational sites established in the past 50 years and the development of remote-sensing instruments in the satellite era. One of the most prominent features of the general circulation is the thermally direct, seasonally varying tropospheric circulation system now known as the Hadley circulation. It is well established that interannual variability in the Hadley circulation is strongly tied to El Niño/Southern Oscillation (ENSO) activity (Bjerknes 1966; Bjerknes 1969; Oort and Yienger 1996). However, it is also increasingly clear that the past century may also be one of change and reorganization in the tropical Pacific component of the climate system on decadal to centennial time scales (e.g., Cane et al. 1997). Whether the observed variability on these longer time scales is due to processes internal to the natural climate system, or is related to external factors such as anthropogenically driven change in atmospheric trace gas composition, or reflects some combination of these influences, remains a matter of debate.

There are at least two means by which the question may be addressed. We can build models that simulate the relevant aspects of the climate system, and perform experiments with and without hypothesized or known forcing. Or we can develop estimates of past variability of the meridional tropical circulation from historical data and/or from localized responses to change in the general circulation, which are preserved in proxy data from geological or biological archives. Although there are well-known strengths and weaknesses to each of these approaches (Bradley 1999; Meehl et al. 2000), intercomparison of observational and model results provides mostly independent support for the conclusion that the results are not tool-specific. Due to its intermediate spatial and temporal coverage, historical observational data are the link often used to tune or calibrate both models of climate and proxy data, and form the basis for the present investigation.

As a precursor to paleoclimatic reconstruction of the Hadley circulation, we seek an index of the surface expression of the Hadley circulation in the Pacific sector from multidecadal, marine historical observations. The zonally averaged solstitial surface divergences from the International Comprehensive Ocean-Atmosphere Data Set (I-COADS; Woodruff et al. 1998) climatology for the Pacific marine sector are illustrated in Figure 8-1. These divergences were computed from surface wind components u and v as

$$D(y) = \left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right]_{150^{o}W-90^{o}W}$$

where the square brackets indicate zonal averaging over the indicated interval, and the meridional averaging is as described in Section 2.2. These sectorial divergences are consistent with but not analogous to the globally averaged winter meridional overturning stream functions for the Northern and Southern Hemispheres, respectively (e.g., Peixoto and Oort 1992, Fig. 7.19). For instance, Figure 8-1a shows maximum tropical convergence, implying rising motion above, from approximately 2°S to 10°N and divergence, implying subsidence, from about 18°N to 30°N, during Northern Hemisphere winter. Similarly, Figure 8-1b shows convergence, implying rising motion, from approximately 8°N to 16°N, and divergence, implying descent, from about 12°S to 8°N, during Southern Hemisphere winter. Consequently our approach to paleoclimatic reconstruction is to first develop a diagnostic index from surface wind divergences, which in turn might ultimately be mirrored in paleoproxy observations. Although interpretation of historical data sets is limited due to spatiotemporal heterogeneities in observational coverage and poorly known biases, recent analyses of such data, using modern statistical techniques, may permit reconstruction of large-scale climatic phenomena from, for example, historical marine data sets (Kaplan et al. 1997, 1998, 2000). We might also be able to reconstruct such features from the growing observational network of seasonal to annual resolution proxy climate observations using similar techniques (Evans et al. 2002).

Reconstruction of interannual and longer-term variability from spatiotemporally heterogeneous historical observations and proxy climate data is limited by observational density and poorly understood biases. In addition, our understanding of the controls on the long-term variation of proxy climate observations is limited and may not be independent of frequency (for example, see Evans et al. 2002). Furthermore, resolution of the large-scale meridional circulation may only be weakly approximated by limited availability of proxy climate observations. Hence, potential application of proxy data to this problem must make use of the ability of such data to integrate conditions over large ranges of space and/or time, yet also resolve seasonal differences. Toward this goal, multiple data sources should be used to identify and minimize errors in the proxy data, and intercomparison with modeling efforts should be used to interpolate between the sparse paleoproxy data network.

Here we investigate the potential for reconstruction of the Pacific marine sector meridional overturning circulation using surface historical and proxy climate data. The basis for this study is the development of analyzed historical surface climate data products (Kaplan et al. 2004) derived from the I-COADS project (Woodruff et al. 1998). We describe the analyzed wind product and the construction of a surface winds–based index in Section 2. Discussion of the behavior of the index over the past 140 years and some implications for reconstruction of Hadley circulation variability from paleo-proxy data are discussed in Section 3. A summary is given in Section 4.

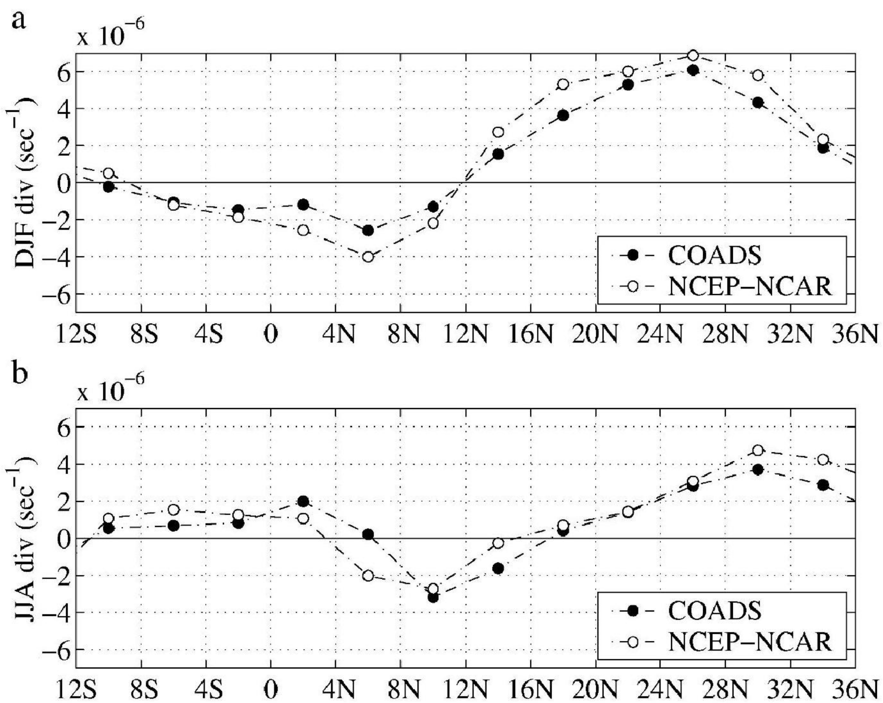


Figure8-1. **a:** Average (1951–80) December–February (DJF) divergences, zonally averaged over the Pacific basin (150°E–120°W), from I-COADS (solid circles) and NCEP/NCAR (open circles). Data are gridded as 4° x 4° averages centered between the latitude ticks indicated on the x-axis of the plot. Units are x 10^{-6} sec^{-1} as shown. **b:** As above, except for June–August (JJA) averages.

2. A SURFACE WINDS–BASED MERIDIONAL CIRCULATION INDEX

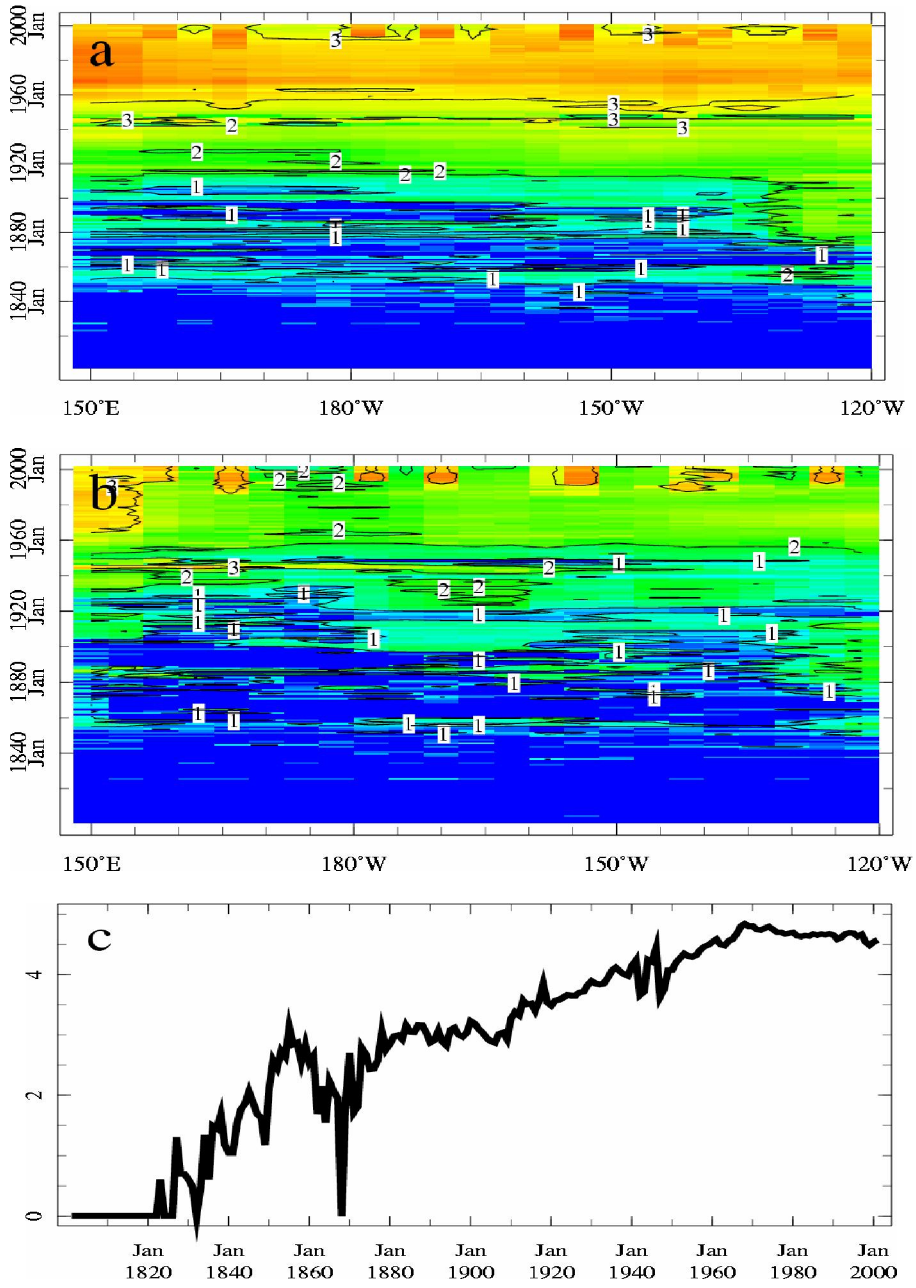
2.1. Analyzed Historical Wind Fields

Our source of historical surface wind data is the recently produced analysis (Kaplan et al. 2001, 2004) of the I-COADS gridded marine climate data set (Woodruff et al. 1987, 1998; Diaz et al. 2002). This analysis derives from the family of reduced space objective analysis procedures, which have now been used to describe and reconstruct large-scale features in sea level height, sea surface temperature (SST), and sea level pressure (SLP) from sparse gridded historical observations (Cane et al. 1996; Kaplan et al. 1997, 1998, 2000, 2003). The mechanics of the optimal interpolation analysis described here are identical to those described in detail in these preceding references.

The key to such analyses is the statistical definition of the large-scale space-time patterns of field variability from a well-observed modern period using empirical orthogonal function (EOF) analysis and filtering. The leading EOFs represent a model for the large-scale spatial and/or temporal covariance of the observations. Together with estimates of the observational and model errors, the simultaneous least-squares fit to historical observations and the model produces data field and error estimates for all locations for which the model can be defined and for all times for which observational data exist. Key prior assumptions include proper estimation of the statistical model, including its dimensionality, and accurate definition of errors in the statistical model and in the historical observations. Analysis results must be tested *a posteriori* to ensure that key prior assumptions are satisfied. These may include checking the consistency of prior and posterior error estimates (e.g., Kaplan et al. 1997) and comparison with withheld or independent observations (e.g., Evans et al. 2002).

In the case of the I-COADS winds analysis, only a spatial covariance model can be reliably defined (Kaplan et al. 2004), so the wind product is developed by using reduced space optimal interpolation (Kaplan et al. 1997). No bias corrections were applied to the I-COADS data set prior to analysis. No balanced friction force corrections (Ward and Hoskins 1996) or linear detrending to remove observational bias (Cardone et al. 1990) was used in this product. Hence in the absence of further information any interpretation of secular variability in the winds analysis or derived indices must be interpreted with caution.

The Kaplan et al. (2001, 2004) analysis of I-COADS winds potentially spans the period January 1800 to September 2001. However, severe data limitations are evident throughout the observational period in the tropical Pacific (Fig. 8-2). Data are generally fewer for the deep tropics and south of the equator; $O(10^2–10^3)$ observations per area denoted by Figures 8-2a and 8-2b are reached only in the 1850s and later, with scarcely any observations prior to the 1820s. In our opinion, severe levels of missing data preclude much use of the data or analysis for forming large-scale winds indices before about 1860 (Fig. 8-2). Intercomparison of the independent analyses of I-COADS winds, SST, and SLP for the tropical Pacific support this limitation; the three fields are tightly coupled as expected from tropical Pacific ocean-atmosphere dynamics, back to about the 1870s (Fig. 8-3).



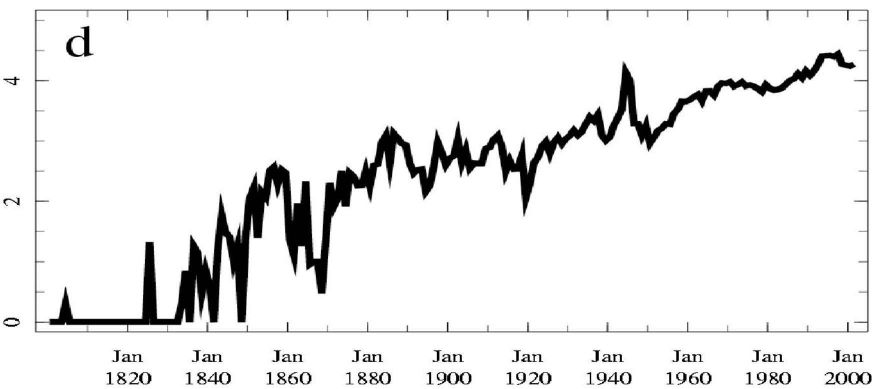


Figure 8-2. I-COADS historical meridional winds observations as a function of time (time increasing upward) and space (see Section 2). **a:** DJF averages for 150°E–120°W, 2°S–30°N, corresponding to the region over which the surface expression of the Pacific marine sector wintertime Northern Hemisphere Hadley circulation is developed (Section 2.2). **b:** JJA observations for 150°E–120°W, 12°S–16°N, corresponding to the region over which the surface expression of the Pacific marine sector wintertime Southern Hemisphere Hadley circulation is developed. **c:** DJF observations vs. time for region in panel a. **d:** JJA observations vs. time for region in panel b. In all panels, observational frequency is given on a logarithmic scale.

2.2. Pacific Marine Sector Hadley Circulation Indices

We seek a description of the surface expression of the thermally direct, zonally averaged atmospheric circulation that can be resolved in coarsely gridded historical surface marine observations and perhaps even in proxy climate observations. As a target we develop an index of the Hadley circulation over the tropical Pacific (150°E–120°W) based on the zonally averaged divergence for this region (Fig. 8-1). We define a Pacific basin, zonal mean Hadley circulation index (hereafter abbreviated HCI) for boreal and austral winters as:

$$HCI(DJF) \equiv [D]_{18^\circ N-30^\circ N} - [D]_{2^\circ S-10^\circ N}$$
$$HCI(JJA) \equiv [D]_{12^\circ S-8^\circ N} - [D]_{8^\circ N-16^\circ N}$$

where D is as defined earlier (Section 1) and averaged over December–February and June–August, respectively. It is important to note that this choice of area-averaged index is subjectively chosen to reflect the meridional circulation over the Pacific marine sector (Fig. 8-1); it may not represent a closed atmospheric circulation cell (as is guaranteed by a complete zonal average), and is therefore not analogous to the canonical zonal mean Hadley circulation (e.g., such as is described in Peixoto and Oort [1992]).

The index computed by using the analyzed I-COADS winds is denoted as "HA," for historical analysis. To assess the uncertainty in the index calculations due to temporal changes in observational coverage (Figs. 8-2, 8-3), we also compute indices using the unanalyzed I-COADS observations. We also compare the Hadley circulation index computed by using analyzed I-COADS data to that computed by using NCEP/NCAR 50-year Reanalysis Version 1 winds, available for 1949 to the present, denoted as "RA"-derived indices (Kalnay et al. 1996; Kistler et al. 2001).

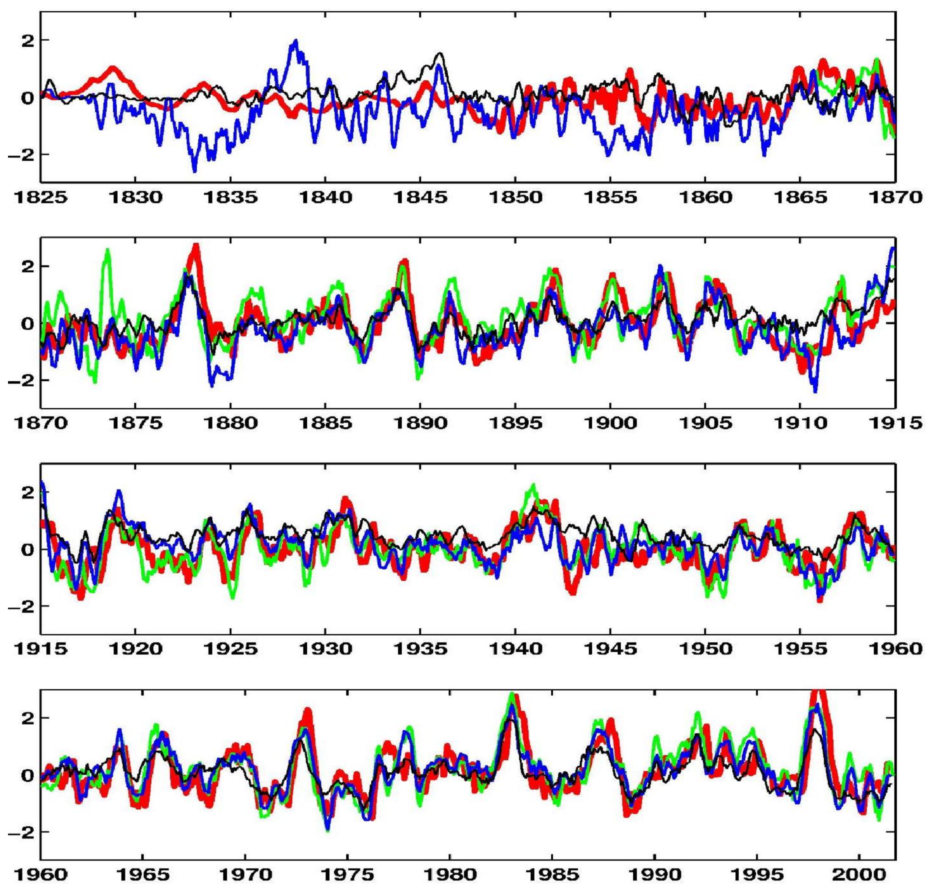


Figure 8-3. Intercomparison of I-COADS analyzed tropical Pacific historical marine data set diagnostics. Black: zonal wind averaged over the central equatorial Pacific. Blue: Darwin grid point sea level pressure. Red: NINO3 (150°W–90°W, 5°N–5°S area average) sea surface temperature anomaly. For comparison with independent observations, the green line shows Darwin station sea level pressure from Allan et al. (1991).

Scatter plots of the HC indices derived from HA and RA products are shown in Figure 8-4. In accordance with climatological observations (Fig. 8-1), the boreal circulation index is stronger than the austral circulation index. Correlation between linearly detrended HA and RA series is 0.94 and 0.82 for the 1950–2001 comparison period for DJF and JJA indices, respectively (Fig. 8-4). This is expected because COADS data are an input to the NCEP/NCAR reanalysis. However, mean differences between indices relatively to HA are 34% and 50% for DJF and JJA indices, respectively (Fig. 8-4). In addition, relative to HA, the DJF RA index is about 15%–25% larger in amplitude (Fig. 8-4a), although the JJA RA index is of comparable amplitude to the JJA HA index. Similar biases in Hadley circulation diagnostics from NCEP/NCAR reanalysis data were found by Waliser et al. (1999), and Wu and Xie (2003) argued that the NCEP/NCAR reanalysis contained seasonally dependent biases in winds for the tropical Pacific relative to COADS (see also differences between COADS and NCEP/NCEP divergence climatologies evident in Fig. 8-1).

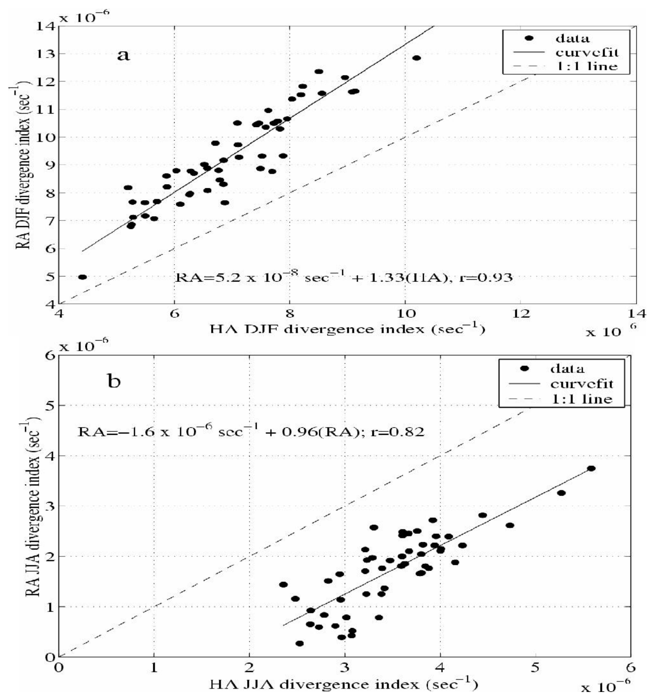


Figure 8-4. **a:** Regression of RA divergence index on HA divergence index, DJF averages, 1950–2001. Mean difference between indices is –2.4 x 10^{-6} sec^{-1}. **b:** As in panel a, except for JJA averages. Mean difference between indices is 1.8 x 10^{-6} sec^{-1}.

Following the results of Dima and Wallace (2003), we find the interannual variability evident in the boreal and austral winter indices is reasonably correlated across seasons: r = 0.49 for correlation of the DJF HA index with the JJA HA index over 1860–2001 (Fig. 8-5). We use this result to construct a combined seasonal Hadley circulation index over the marine Pacific sector by calculating the variance-weighted sum of the boreal and austral indices, and standardizing the result.

Time series of the DJF, JJA, and combined HC indices are shown in Figure 8-6. As is suggested by Figure 8-2, the drop in observational coverage results in greater noise in the I-COADS wind data, especially prior to 1870 and 1920. By general property of least-squares analysis (Kaplan et al. 2003), the wind analysis gives lower weight to scarce, noisy observations, relying more heavily on large-scale structures identified in the statistical model and producing estimates with lower variance and greater estimated uncertainty.

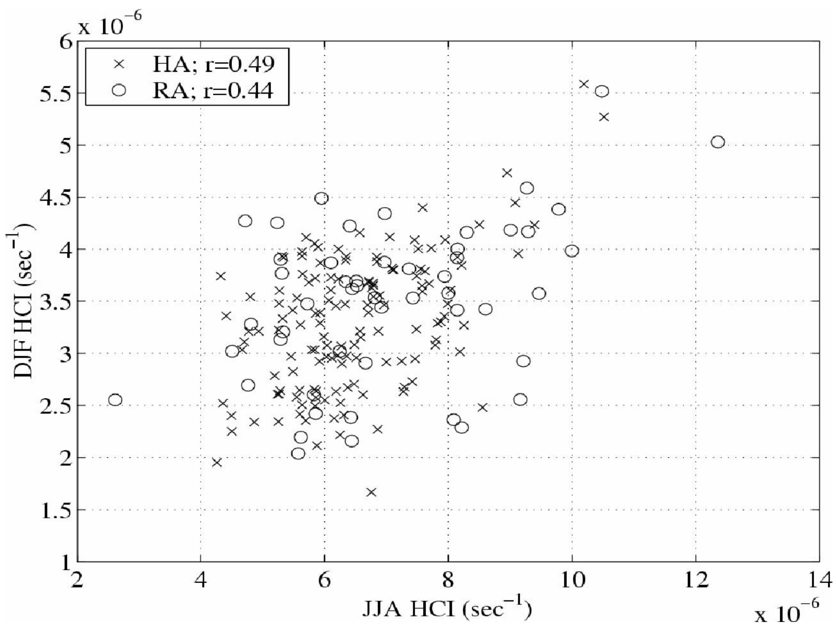


Figure 8-5. Scatter plot of DJF vs. JJA HC indices. Crosses: HA. Circles: RA. Correlations between DJF and JJA indices are 0.49 and 0.44, and are significant at the $\alpha \leq 0.01$ and 0.05 levels, respectively.

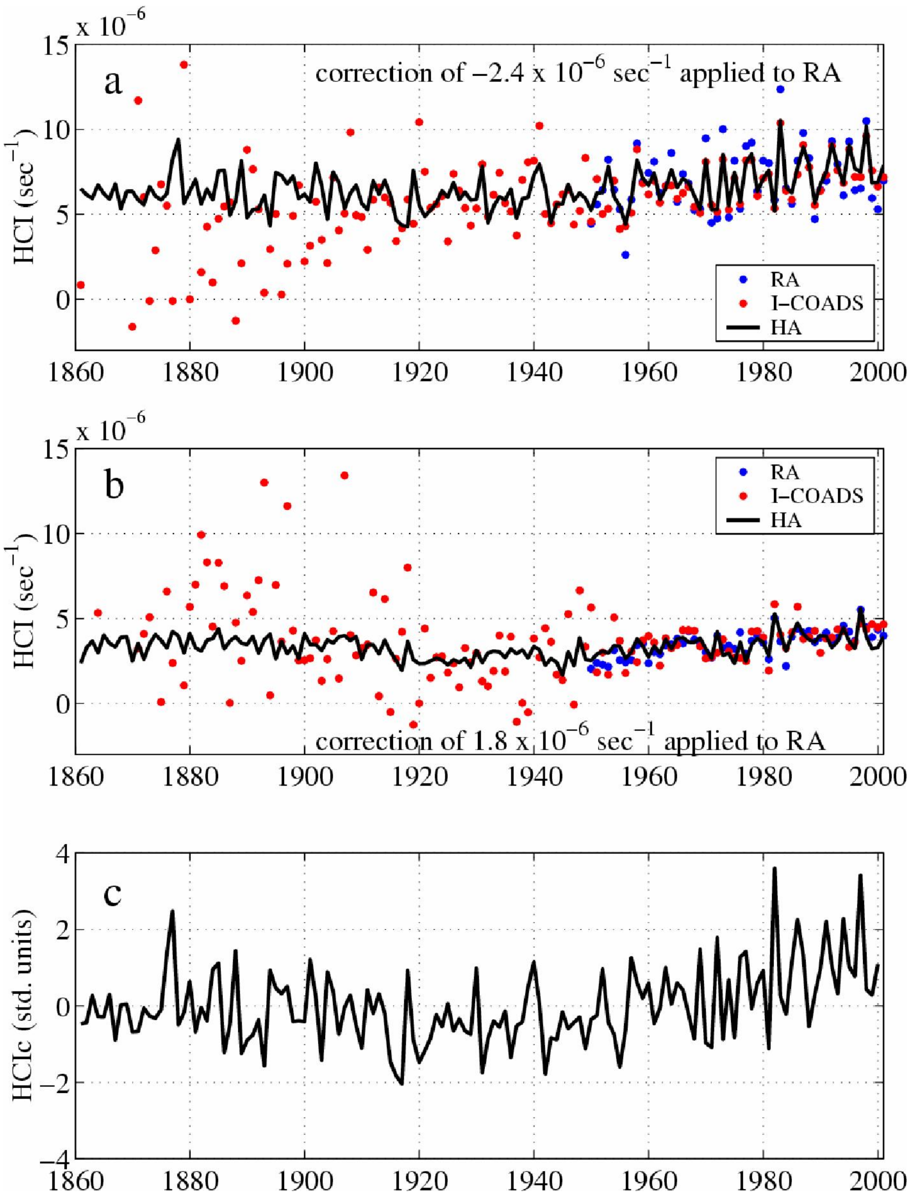


Figure8-6. **a:** Time series of HA- (solid line) and RA-derived HC indices (open circles) for the DJF season. HC indices constructed from I-COADS observations are shown as unconnected filled circles. **b:** As in panel a, except for JJA averages. **c:** The combined Hadley circulation index (HCIc), composed of the standardized, variance-weighted sum of the boreal and austral indices shown in panels a and b.

Longer-term variability is also evident in both boreal and austral indices (Fig. 8-6). This variability appears not to be an artifact of the change in observational coverage over time (Figs. 8-2, 8-6). However, since we have made no bias corrections to the I-COADS data prior to objective analysis, and no corrections were made to the COADS winds prior to assimilation into the NCEP/NCAR reanalysis, we cannot determine that the HA and RA trends since the 1940s are not due to changes in the height and manner in which wind measurements were made (see discussion by Ward and Hoskins [1996] for a review of wind bias corrections.) In addition, if some portion of the lower-frequency variation over the full period is climatic, we also cannot determine from our analysis whether this reflects a change in intensity of the Pacific marine sector Hadley circulation, a change in the position of the net convergence and divergence regions, or a combination of these two effects.

3. DISCUSSION

3.1. Interannual and Secular Variability: 1860–2000

Variability in the Pacific marine sector of the meridional overturning circulation, as reconstructed here from analyzed historical surface wind observations, is observed to negatively covary with the strength of the Walker circulation over the tropical Pacific on interannual time scales associated with ENSO (Fig. 8-7). The correlation between indices of the Hadley and Walker circulations is highly significant at interannual time scales. This result is consistent with previous analyses comparing upper air wind data to sea surface temperatures in the eastern equatorial Pacific (Oort and Rasmusson 1970; Oort and Yienger 1996; Chapter 6, "ENSO, Atlantic Climate Variability, and the Walker and Hadley Circulations," Wang, this volume), and further validates interpretation of the interannual variation in the HC indices presented here into the late nineteenth century. This result also links the meridional overturning circulation above the marine boundary layer (MBL) to surface observations, which may in turn be mirrored in proxy climate observations (see below for discussion). Correlation of the low-pass series is still significant, but there are very few effective degrees of freedom in the series (Trenberth 1984), so this correlation must be interpreted with caution. However, longer-term coherence in these indices of the Pacific sector Hadley and Walker circulations may be found in similar amplitude modulation on decadal time scales (Figure 8-8). More variance is found in the high-pass filtered series for both indices in the most recent few decades and in the late nineteenth century. Although these variance estimates will be sensitive to uncertainty and to the averaging interval chosen, and are not likely to be significantly different from the mean variance over this period, this result is consistent with previous studies of ENSO for this interval using historical data (Trenberth and Shea 1987; Trenberth and Caron 2000) and coral-based proxy observations (Cole et al. 1993).

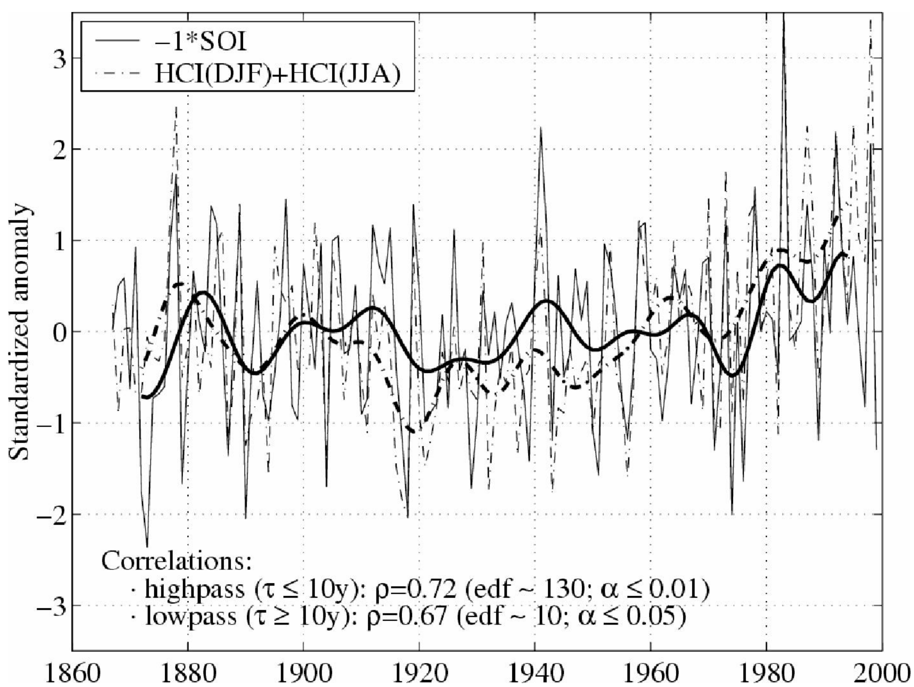


Figure 8-7. Time series plot of combined DJF + JJA HC indices (solid line) vs.–1*Southern Oscillation Index (SOI; dashed line). Thickened solid and dashed lines give respective low-pass (period (τ) ≥ 10 year) filtered data series. Correlations (ρ) and significance estimates (α) for low-pass and high-pass time series (data shown in Fig. 8-8) are indicated.

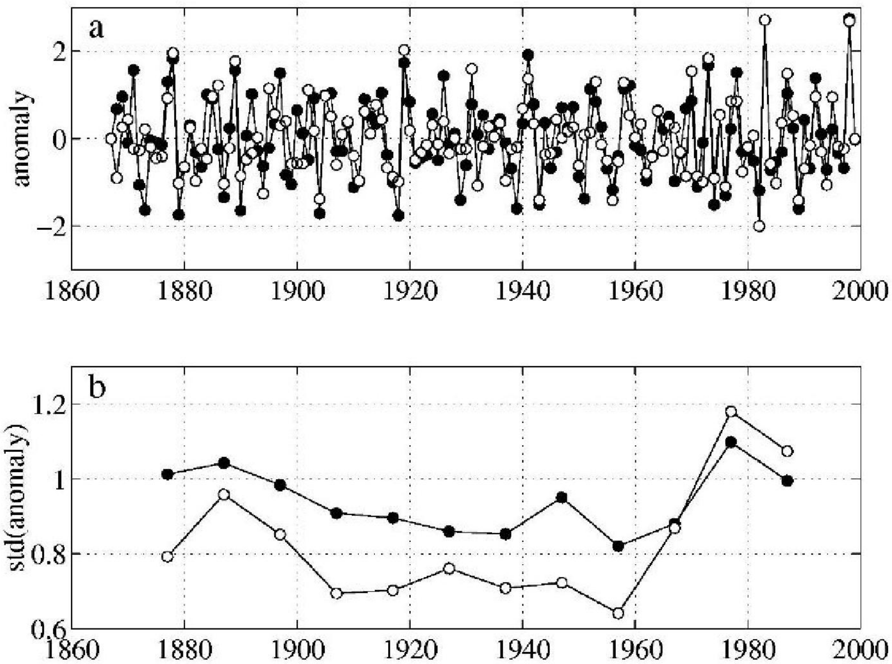


Figure 8-8. a: Time series plot of high-pass filtered combined DJF + JJA HC indices (open circles) vs. high-pass filtered–1*Southern Oscillation Index (closed circles). Correlation between series is 0.72 (Fig. 8-7). b: Estimated standard deviation of anomalies in panel a for independent 21-year windows (circles show center years).

Interpretation of the secular variability evident in the Hadley circulation indices (Fig. 8-7) must be treated with caution because assessment and correction for systematic measurement biases is difficult if not impossible (Section 2). The most likely explanation of the secular variation is in systematic measurement bias (Cardone et al. 1990; Ward and Hoskins 1996; Wu and Xie 2003). On the other hand, the tropical Pacific has shown ENSO-like variability on decadal time scales (Garreaud and Battisti 1999), so it would not be unreasonable to presume that similar interdecadal shifts in strength and/or position of the Pacific-region Hadley circulation might have also occurred (Oort and Yienger 1996). There is significant correlation with SST anomalies in the central and eastern equatorial Pacific on interannual time scales, but only a weak, nonsignificant, ENSO-like pattern on decadal time scales (Fig. 8-9).

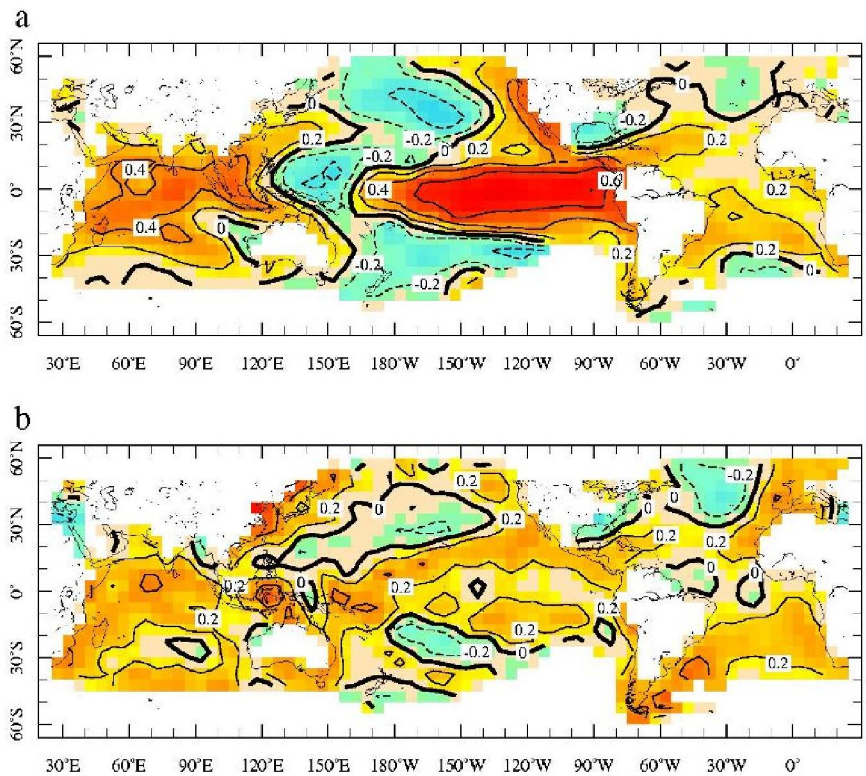


Figure 8-9. a: Pattern correlation of the high-pass ($\tau \leq 10$y) component of the combined DJF and JJA HC indices with the analyzed historical gridded SST field from Kaplan et al. (1998). Correlations of ≥ 0.2 are significant at the 95% confidence level assuming 130 degrees of freedom. b: As in panel a except for the low-pass component ($\tau \geq 10$y) of the combined DJF and JJA HC indices. Correlations of ≥ 0.6 are significant at the 95% confidence level assuming 8 effective degrees of freedom.

If some component of the trends evident in the HC indices is climatically driven, Figure 8-9 indicates that strengthening of the wintertime meridional overturning circulations has occurred over the past 50 to 80 years, which is associated with variation in the Walker circulation over the Pacific. These results appear to be consistent with model simulations reported by others in this volume. Quan et al. (Chapter 3, “Change in the Tropical Hadley Cell since 1950) has shown that the trend in a zonally averaged 850–200 hPa meridional wind index calculated from NCEP/NCAR reanalysis data is reproduced by forcing an atmospheric general circulation model (AGCM) with observed sea surface temperatures over the past 50 years. Half of the trend was attributed to an increased amplitude of ENSO activity in the most recent decades; the other half was attributed to a trend in SSTs in the tropical Indian and western Pacific Ocean. Rind and Perlwitz (Chapter 14, "The Response of the Hadley Circulation to Climate Changes, Past and Future," this volume) observed that simulated increases in the strength of the Hadley circulation in $2xCO_2$ experiments were most tightly linked to increases in the tropical-subtropical SST gradient and associated precipitation increases in the tropics. Indeed, the correlation of the combined boreal and austral HC indices with the SST field shows the variability in the HC indices is associated with more vigorous ENSO activity (Figs. 8-7 through 8-9). This was also observed in a separate study of vertical structure of the NCEP/NCAR wind fields by Minobe (Chapter 5, "Interannual to Interdecadal Variations of the Hadley and Walker Circulations," this volume), who tied Hadley circulation variability on interdecadal time scales to the signature of the Pacific Decadal Oscillation (PDO) in the central tropical Pacific (also see Fig. 8-9b). Meehl et al. (Chapter 17, "Mechanisms of an Intensified Hadley Circulation in Response to Solar Forcing in the Twentieth Century," this volume) showed that a coupled ocean-atmosphere general circulation model run with realistic solar, greenhouse, aerosol, and ozone forcings over the past century produces an enhancement of the modeled intensity of both the Hadley and Walker circulations.

3.2. Potential for Paleo-Reconstructions Using Proxy Data

Further studies of long term changes in the strength and/or position of the Hadley circulation might be made using paleoclimatic proxy data. Ideally we would seek to reconstruct a measure of the zonal mean ascending and subsiding branches of the tropical atmospheric circulation from a zonally extensive network of seasonally resolved surface proxy observations. Such results might be used to further test the hypothesis that some of the change in intensity of the meridional overturning circulation is due to anthropogenic forcing, or to assess the thermodynamical and dynamical effects of changes in the seasonality of radiative forcing at various times during the Holocene.

A direct proxy-based Hadley circulation reconstruction may never be possible, because the likelihood of obtaining a dense, globally extensive network of observations is low, and the signal is relatively subtle. However, such proxies might be derived from geobiological archives influenced by related SST, precipitation, surface winds, and upwelling phenomena. The results presented here (e.g., Figs. 8-9, 8-10) suggest that proxies for the Pacific marine sector Hadley circulation, as delineated in this chapter, may be derived from the oceanographic signature of Hadley circulation variability in central and eastern tropical Pacific SST. For example, the NINO3 index calculated from reconstruction of the Pacific SST field based on statistical analysis of 65 coral proxy climate data series (Evans et al. 2001b, 2002) should reflect Hadley circulation variability, via modulation of ENSO frequency or amplitude (Evans et al. 2001a). The reconstructed NINO3 index based on the coral data is significantly correlated on interannual time scales, and shows a similar trend over the past 50–80 years (Fig. 8-10). But since the reconstruction is based on limited proxy observations and contains a time-dependent variance bias, further analysis will require additional data and intercomparison with complementary proxies (Evans et al. 2002).

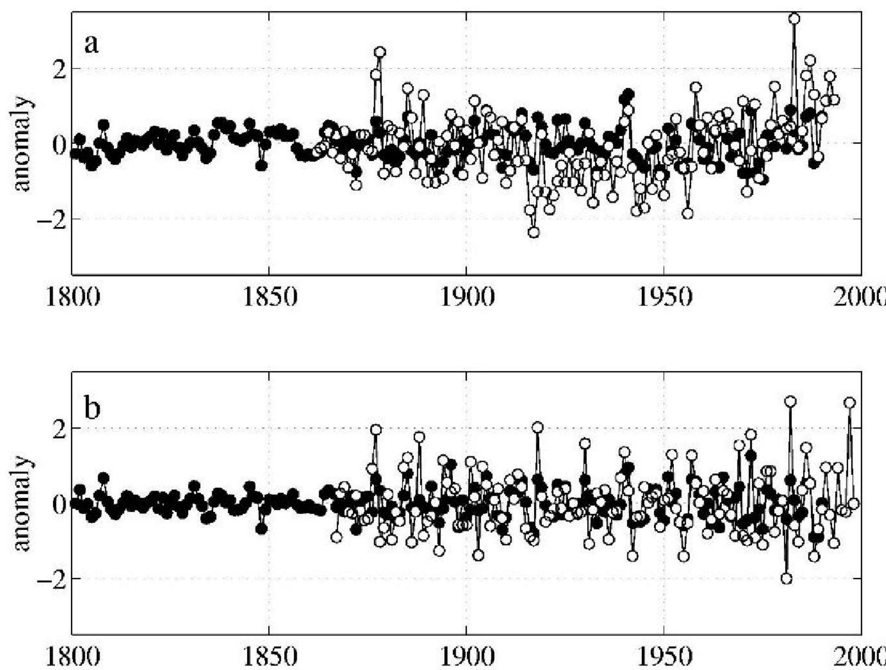


Figure 8-10. Time series intercomparison of the combined DJF + JJA HC indices (open circles) with April–March average NINO3 SST reconstructed from coral-derived proxy observations (closed circles) (Evans et al. 2001b, 2002). a: Raw series; correlation is 0.39, significant at the 95% level with 130 degrees of freedom. b: High-pass filtered series (as in Fig. 8-8); correlation is 0.59, significant at the 99% level with 130 degrees of freedom.

4. SUMMARY

We have employed a new analyzed historical surface wind product to develop proxy estimates of the boreal and austral wintertime meridional overturning circulations over the central and eastern Pacific marine sector for the past 140 years. The combined indices are negatively and significantly correlated with indices of variation in the Walker circulation—in other words, with the ENSO phenomenon—and possibly with its amplitude modulation. A trend in the HC indices is most probably due to the presence of systematic wind measurement bias. However, the secular variation over the past 50–80 years is not inconsistent with results from a number of modeling simulations described in this volume, which link an intensification of the Hadley circulation over the past 50–100 years to greenhouse and solar forcing via an enhanced tropical-subtropical SST gradient. Interdecadal shifts in Hadley circulation strength might be resolved by a network of seasonally resolved proxy observations of SST, ocean upwelling, zonal wind strength, and precipitation that describe tropical-subtropical divergence gradients and variations.

5. ACKNOWLEDGMENTS

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