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Reduction in Himalayan snow accumulation and weakening of the trade winds over the Pacific since the 1840s

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[1] In 1884, Blanford suggested that summer rainfall over Northwest India was anti-correlated with snow cover during the preceding winter and spring in the western Himalaya. Walker elaborated on this suggestion in his seminal work on predictors of the Indian summer monsoon, a body of work that forms the basis of our understanding of how Eurasia influences this monsoonal circulation. Recently, a number of studies have questioned the existence of this relationship or have proposed a more complex coupling between Eurasian snow cover, including the Himalaya, and the Indian summer monsoon. Here, we present a 196-year record of snow accumulation from a Himalayan ice core that contains a decreasing trend in accumulation that began in the 1840s. Indian summer monsoon rainfall shows no evidence of such a trend and we argue that this reduction in snow accumulation is associated with a long-term weakening of the trade winds over the Pacific Ocean.
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1. Introduction

[2] The Asian summer monsoon is one of the most important components of the global climate system and has a direct impact on the livelihood of over half of the world's population [*Shukla and Paolino*, 1983; *Webster et al.*, 1998]. Given the importance of this circulation system and its large inter-annual variability, attempts to forecast its intensity have been ongoing for over a century [*Kumar et al.*, 1995]. In the first quantitative analysis, *Blanford* [1884] suggested an inverse relationship existed between summer rainfall over Northwest India and snow cover during the preceding winter and spring in the western Himalaya. *Walker* [1910] extended Blanford's analysis and employed spring Himalayan snow cover as a predictor for the intensity of the following Indian summer monsoon (ISM). The basic mechanism being that extensive snow cover during the winter reduces the heating that occurs in the spring and summer, thereby acting to eliminate the land-sea thermal contrasts that drive the monsoon [*Yasunari and Seki*, 1992; *Vernekar et al.*, 1995]. This anti-correlation appeared to break down in the middle of the 20th century [*Kumar et al.*, 1995]. In recent years, numerous studies have re-examined the relationship between the ISM and Eurasian snow cover [*Bamzai and Shukla*, 1999; *Kripalani et al.*, 2003; *Robock et al.*, 2003; *Fasullo*, 2004; *Zhao and Moore*, 2004]. In particular, *Bamzai and Shukla* [1999] found a positive correlation between the snow cover over Tibetan plateau and ISM, a result opposite to that of Blanford. However, the correlation was not significant at 95% confident level. In addition, *Robock et al.* [2003] identified statistically significant positive anomalies in the snow cover over Tibetan plateau associated with heavy ISM rainfall. Others have proposed that the relationship between the ISM and Eurasian snow cover is modulated by other modes of climate variability [*Fasullo*, 2004; *Zhao and Moore*, 2004]. Interest in this relationship has been recently heightened by the observation that over the past decade, there has been an intensification of the summer monsoon winds over the Indian Ocean and a concomitant reduction in Eurasian snow cover [*Goes et al.*, 2005]. However, their snow cover time series is very short (9 years) and concerns have been raised that changes in the processing of the satellite data used to generate the snow cover dataset may have introduced a bias [*Robinson*, 2003].

[3] The relatively short length of the instrumental datasets in the region and the binary nature of snow cover restrict the study of the variability within the climate system including the ISM [*Bamzai and Shukla*, 1999; *Wunsch*, 1999]. In 1997, three ice cores were drilled at the site of 7200 m above sea level from the Dasuopu Glacier (28°23′N, 85°43′E) on Shishapangma (Xixiabangma) in southern Tibet. The Dasuopu site is located within the footprint of the ISM and it has been proposed that the ice core data from the site is a suitable proxy to study its variability [*Thompson et al.*, 2000]. This interpretation has been questioned, as there exists no statistically significant correlation between the snow accumulation from one of these ice cores and the ISM rainfall over the past 38 years [*Zhao and Moore*, 2002]. Rather, *Zhao and Moore* [2002] presented evidence that the Pacific Ocean is a source of moisture for the snow that accumulates at the site.

[4] Here, we make use of the annual snow accumulation (DSA) time series averaged from the other two, longer, ice cores covering the 196-year period from 1801 to 1996 [*Thompson et al.*, 2000; *Davis et al.*, 2005] to discuss the connection between Himalayan snow cover, the Indian summer monsoon and the strength of the trade winds over the Pacific Ocean.

2. Reduction in the Himalayan Snow Accumulation

[5] Figure 1 shows the DSA time series over the period 1801–1996. Also shown is a low-pass filtered DSA time series that retains variability on time scales greater than 30 years. In addition to variability on inter-annual and

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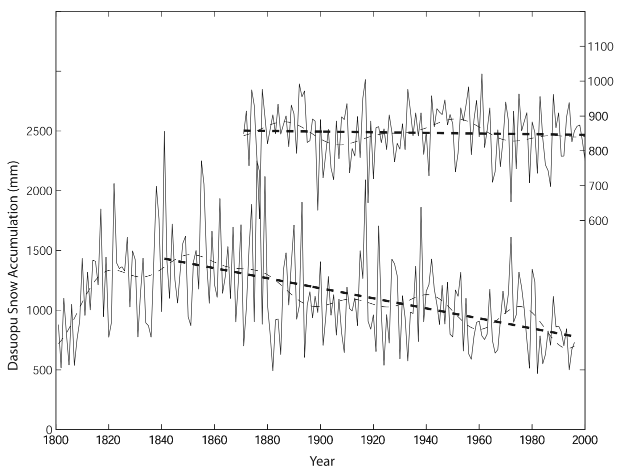

Figure 1. The averaged annual snow accumulation (DSA) from Cores 2 and 3 at Dasuopu site over 1801–1996 and the All Indian Summer Monsoon Rainfall (AIMR) over 1871–2000. The dashed curves are the 30-year low-pass filtered time series and the thick dashed lines indicate trends.

inter-decadal time scales, the DSA time series clearly indicates that snow accumulation at the site has been decreasing since the middle of the 19th century. Also shown in Figure 1 is the All Indian Summer Monsoon Rainfall (AIMR) time series over the 130 year period from 1871–2000, the longest and most widely used instrumental record of the ISM [*Parthasarathy et al.*, 1992]. Although this time series also exhibits variability on a number of time scales, there is no evidence of a trend like that contained in the DSA time series.

[6] To assess the statistical significance of the trend in the DSA time series, we tested the validity of the null hypothesis that this trend was indistinguishable from zero with the least-squares method. Because of geophysical time series typically exhibit elevated power at low frequencies, we assumed that the regression residuals are temporally correlated [*Santer et al.*, 2000]. As a result, we used a reduced number of degrees of freedom that is a function of the lag-1 (year) autocorrelation of the regression residuals in the test of the statistical significance [*Santer et al.*, 2000; *Moore et al.*, 2005]. The test showed that for all starting dates in the middle of the 19th century, the trend in the DSA time series is statistically significant at 99% level. A similar test indicated that the trend in the AIMR time series over the period 1871–2000 was not statistically significant even at the 75% level, a result consistent with *Kripalani and Kulkarni* [2001]. In addition, the correlation coefficient between the DSA and IMR time series over the period of their overlap, 1871–1996 is 0.04, a result that was not statistically significant even at the 75% level. These results support the contention that although the ice core site is within the footprint of the ISM, the extreme height of the ice core site effectively decouples it from the circulation responsible for Indian summer monsoon rainfall [*Zhao and Moore*, 2002].

[7] The conclusions drawn from Figure 1 are confirmed in Figure 2, where the power spectra of the DSA and AIMR time series are shown as computed with the multi-taper method with an assumed red noise model [*Mann and Lees*, 1996]. Both time series contain statistically significant power on inter-annual time scales. With regard to the AIMR, our results are consistent with previous work [*Mooley and Parthasarathy*, 1984; *Meehl*, 1997]. In contrast to the results of *Krishnamurthy and Goswami* [2000], we identify no statistically significant power in the AIMR on inter-decadal time scales. It appears that the result of *Krishnamurthy and Goswami* [2000] is an artefact of the application of an 11-year running mean that serves to amplify power on these time scales. Unlike the AIMR, the DSA time series contains low-frequency power (larger than 70 years) that is statistically significant at levels in excess of 99%.

3. Weakening of the Trade Winds Over the Pacific

[8] To identify the spatial pattern of the climate signal contained in the DSA time series, we present in Figure 3 the regression of the annual mean sea-level pressure (SLP) field [*Kaplan et al.*, 2000] against it. Please note that although snowfall at the site is assumed to occur most often during the summer months [*Thompson et al.*, 2000], there is evidence that synoptic-scale disturbances during the cool season may also contribute to the annual snow accumulation [*Das et al.*, 2003; *Moore*, 2004]. In the absence of definitive knowledge as to the seasonality of the snow accumulation at the site, we have chosen to consider annual mean fields in our analysis. Similar results were obtained with winter and summer mean fields. Also shown is the trend in this field over the period 1855–1992. The regression pattern in the SLP associated with the DSA time series (Figure 3a) is dominated by a tri-polar structure in the Pacific Ocean with a negative region centered on the equator near 120°E and two positive regions, one in the sub-tropics of each hemi-

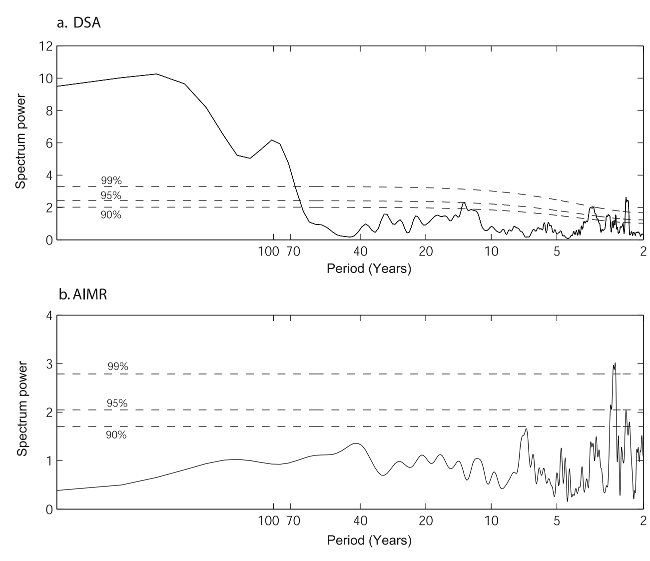

Figure 2. Multitaper power spectra of (a) the DSA time series for the period 1801–1996 and (b) the AIMR time series for 1871–2002. Significance levels are shown by dashed curves based on AR(1) noise model.

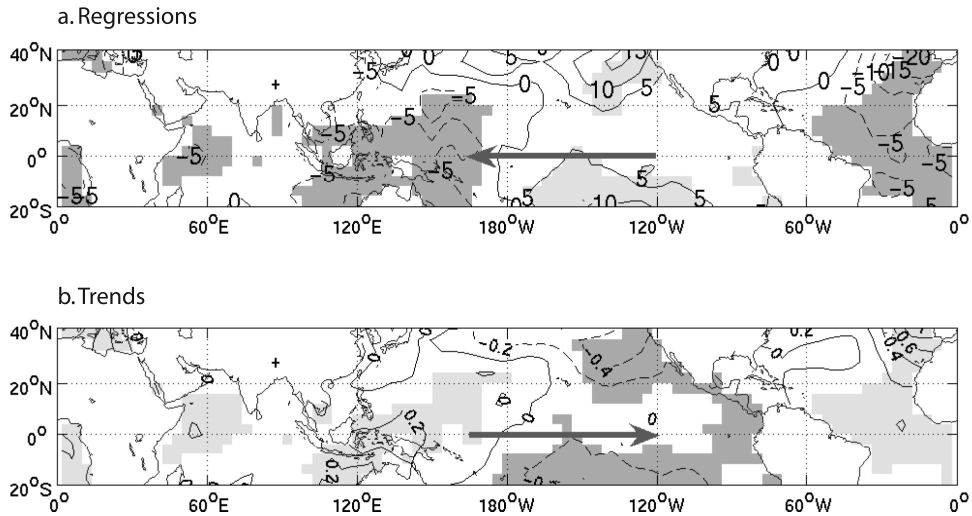

Figure 3. (a) Regressions of the annual mean SLP against the DSA over the period 1855–1992; (b) Trend (mb/century) in the annual mean SLP at every grid point over 1855–1992. Shaded regions indicate statistical significance at 90% level using a Student's t-test with a reduced number of degrees of freedom. Arrows indicate the direction of anomalous trade winds.

sphere, near 120°W. There are also signals in the Atlantic and Indian Oceans. The regression pattern in the Pacific indicates that heavy snow accumulation at the Dasuopu site is associated with an intensification of the easterly trade winds across the equatorial Pacific Ocean as the result of a positive pressure gradient orientated from the eastern to the western equatorial Pacific Ocean.

[9] The spatial trend in the SLP field (Figure 3b) is very similar to the regression against the DSA time series (Figure 3a) but with a reversal in sign. This implies that there has been a tendency for a weakening of the easterly trade winds along the equatorial Pacific since the middle of 19th century. This weakening of the trades may have resulted in a reduction in the westward transport of moisture towards Asia thereby contributing to the decreasing snow accumulation at the Dasuopu site (Figure 1). The spatial pattern in the SLP identified in Figure 3b is consistent with the low-frequency mode of spatial variability that has been identified in this field [*Kaplan et al.*, 2000].

[10] There are concerns that the SLP dataset used in Figure 3 may have limited validity in the early part of its record due to the sparse nature of observations that forms its

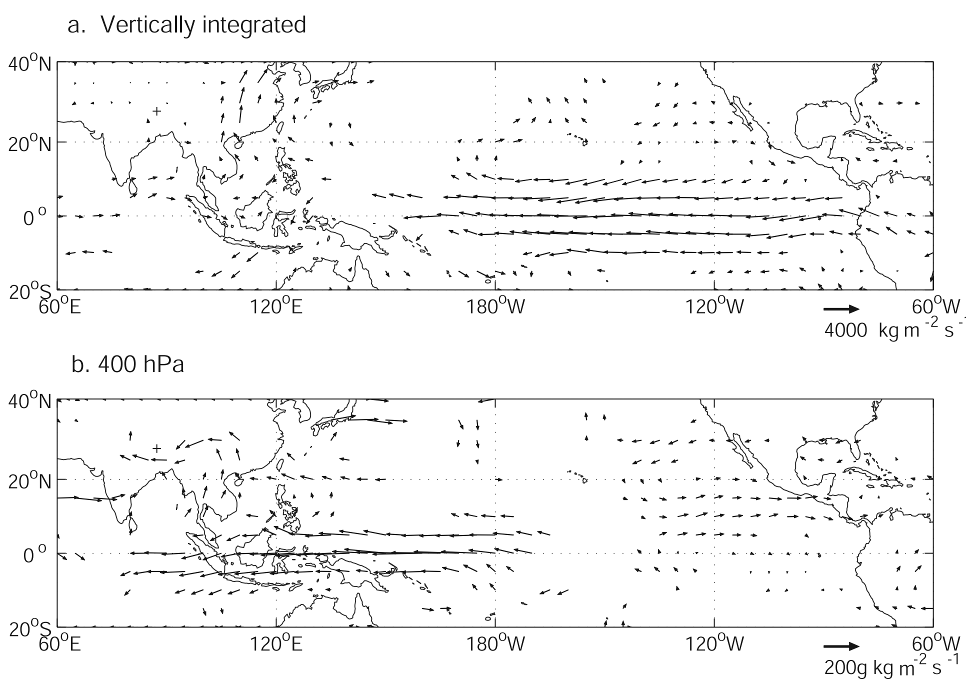

Figure 4. Regressions of annual mean (a) vertically integrated; (b) 400 hPa water vapour transport field against the Dasuopu Snow Accumulation over the period 1956–1993. The vector fields are only shown at those grid points where at least one of the components is significant at 95% level using the Student's t-test.

basis [*Kaplan et al.*, 2000]. One of the longest instrumental surface pressure time series in the region is from Jakarta Indonesia and covers the period from 1841–1999 [*Smith et al.*, 2003]. This time series contains an expression of the Southern Oscillation and the Walker Circulation, the zonal overturning circulation in the tropical Pacific that includes the easterly trade winds as its low-level branch. In particular, the Jakarta surface pressure time series is inversely correlated with the Southern Oscillation and as such higher pressures are associated with the negative phase of the oscillation, a weaker Walker Circulation and weaker trade winds [*Konnen et al.*, 1998]. This SLP time series (not shown) displays a trend towards higher pressure over the period 1841–1999. This trend is statistically significant at the 95% for this period, using a t-test with the reduction in the degrees of freedom that follows from time series' temporal auto-correlation, and is consistent with our hypothesis regarding a weakening of the trade winds over the Pacific.

[11] The water vapour transport field has been shown to be useful in diagnosing the climate signals contained in high elevation ice cores [*Moore et al.*, 2002; *Zhao and Moore*, 2002]. With global meteorological fields like those contained in the NCEP reanalysis, it is possible to reconstruct this field since the mid 20th century. Figure 4 shows the regressions of the annual mean vertically integrated water vapour transport field as well as the annual mean water vapour transport at 400 hPa, the approximate height of the ice core site, against the snow accumulation from three Dasuopu ice cores averaged over their period of overlap, 1956–1993. As can be seen from the regression against the vertically integrated field (Figure 4a), snow accumulation at the site is positively correlated with easterly transport over the much of the eastern and central tropical Pacific. The vertically integrated water vapour transport is heavily weighted towards the surface and so may not contain information on the transport near the ice core site at 7200 m [*Zhao and Moore*, 2002]. The regression against the water vapour transport at 400 hPa (Figure 4b) indicates that snow accumulation is positively correlated with easterly transport over the western equatorial Pacific directed towards the ice core site. This upper-level meridional transport may be associated with the regional Hadley circulation [*Zhao and Moore*, 2002]. The transition identified in Figure 4 from lower-level transport over the eastern and central tropical Pacific to upper-level transport over the western equatorial Pacific may be associated with the rising motion associated with the Walker Circulation [*Krishnamurthy and Goswami*, 2000].

4. Summary

[12] In this paper, we have presented evidence of a long-term reduction in snow accumulation at the Dasuopu Glacier in southern Tibet. This reduction appears to have begun around the middle of the 19th century and thus corresponds to the period of time when the Little Ice Age is generally thought to have ended [*Free and Robock*, 1999; *Hendy et al.*, 2002]. Other studies have indicated that during the Little Ice Age, the trade winds across the tropical Pacific were stronger than today and that the middle of the 19th century was the period when they weakened attaining more modern values [*Thompson et al.*, 1986; *Hendy et al.*, 2002]. In addition, data from an ice core from a high elevation site in the Gulf of Alaska region indicates that an increase in snow accumulation began around the middle of the 19th century [*Moore et al.*, 2002]. This increase was also attributed to a reduction in the strength of the trade winds in the Pacific and a concomitant increase in the meridional circulation in the region that lead to an increase in planetary wave activity resulting in an increase in the moisture flux towards the Gulf of Alaska [*Moore et al.*, 2005]. These trends appear to be associated with long-term changes in the atmospheric circulation associated with the end of the Little Ice Age, although it is difficult to distinguish these changes from anthropogenic impacts associated with an increase in atmospheric carbon dioxide [*Vecchi et al.*, 2006]. This result suggests that the dramatic retreat of glaciers in the region that is cause of recent concern may have been ongoing since the middle of the 19th century [*Qin et al.*, 2000; *Richardson and Reynolds*, 2000]. In addition, our results do not support the hypothesis of a relationship between snow cover in the Himalaya and the ISM. Nevertheless recent changes in relationship between the monsoonal circulation, the trade winds and Himalayan snow cover suggest that we may now be entering a different climate regime [*Clarke and Lebedev*, 1996; *Kumar et al.*, 1999; *Goes et al.*, 2005].

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