Periodic temperature-associated drought/flood drives locust plagues in China

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Global warming is currently of great concern. Yet the ecological effects of low-frequency climate variations remain largely unknown. Recent analyses of interdecadal variability in population abundance of the Oriental migratory locust (*Locusta migratoria manilensis*) in China have revealed negative associations with temperature and positive associations with Yangtze drought and flood frequencies during the past millennium (AD 957–1956). In order to shed new light on the causal relationships between locust abundance, floods, droughts and temperature in ancient China, we used wavelet analysis to explore how the coherencies between the different variables at different frequencies have been changed during the past millennium. We find consistent in-phase coherencies between locusts and drought/flood frequencies, and out-of-phase coherencies between locusts and temperature and between drought/flood and temperature at period components of 160–170 years. Similar results are obtained when historical data of drought/flood frequencies of the Yangtze Delta region are used, despite flood data showing a weak and somewhat inconsistent association with other factors. We suggest that previously unreported periodic cooling of 160–170-year intervals dominate climatic variability in China through the past millennium, the cooling events promoting locust plagues by enhancing temperature-associated drought/flood events. Our results signify a rare example of possible benign effects of global warming on the regional risk of natural disasters such as flood/drought events and outbreaks of pest insects.

Keywords: Oriental migratory locust (*Locusta migratoria manilensis*); global warming; droughts; floods; disaster; temperature-associated climate

1. INTRODUCTION

The Oriental migratory locust (*Locusta migratoria manilensis*) has been one of the most damaging agricultural pests throughout the Chinese history (Chen 1936, 1939). The Oriental migratory locust is widely distributed in the eastern parts of China (Chen 1999). The main sources of locust plagues are marshland habitats associated with the overflow channels and flood lakes connecting the lower parts of the river systems (Ma 1958). Earlier studies have suggested that temperature and moisture are key factors affecting reproduction and survival of the locust (Ma *et al.* 1965; Chen 1999). For the period 1913–1962, Ma *et al.* (1965) reported that large occurrences of locusts in the Hongze Lake region were closely associated with warm and dry weather. The causal factor was assumed to be temperature that was affecting the survival of the locusts.

For the periods 200 BC to AD 1900 (Tsao 1950) and AD 957–1956 (Tsao 1950; Ma 1958, 1965), locust outbreaks were typically found to occur during drought years or in years immediately following flood years. It was suggested that the mechanisms behind the drought and flood impacts are direct and delayed effects on the breeding habitat of the locusts.

By using a regression model and spectral analysis, we recently demonstrated that decadal mean locust abundance is negatively correlated with temperature during AD 957–1956 (Stige *et al.* 2007). This finding challenges the traditional view that, on an annual scale, locust plagues are associated with warm temperatures (Ma *et al.* 1965). Based on further analysis, we hypothesized that the negative temperature effect may be explained by a low-frequency association between the temperature and the frequencies of droughts and floods in the Yangtze Delta (Stige *et al.* 2007). Locust abundance was the highest during decades with high frequencies of both floods and droughts, and high flood and drought frequencies tended to occur during cold periods (Jiang *et al.* 2005; Stige *et al.* 2007). The previous results demonstrated pairwise

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associations between all three time series (i.e. locust, drought/flood and temperature). However, using traditional methods such as regression and spectral analysis it was not possible to test if higher locust abundance, higher drought/flood frequency and lower temperature occur at the same frequency and time spaces. If associations between different pairs of variables occur at different time and/or frequency bands, a multiple-variable-linked hypothesis is not supported (in our case: temperature→drought/flood→locust). Furthermore, it was not possible to test whether the associations between the variables were persistent through the millennium. If an association between two variables is only apparent for parts of the period, it may suggest that the relationship between the variables is either spurious or dependent on a third, possibly unknown, variable. Finally, the data had to be transformed by differencing in order to obtain approximate stationarity (constant statistical properties such as mean and variance)—a prerequisite for doing spectral analysis. Differencing may, however, change the periods or frequencies of the original time series, making the periodicity estimation less precise.

Ecological systems are typically noisy, complex and non-stationary (Stenseth & Chan 1998; Turchin 2003; Ranta *et al.* 2006). Indeed, an increasing number of studies emphasize the non-stationary features of ecological dynamics (Hare & Mantua 2000; Hastings 2001; Benton *et al.* 2006; Cazelles & Hales 2006). Wavelet analysis is ideally suited for investigating time-series data from non-stationary systems and the causal links within such systems (Grinsted *et al.* 2004; Klvana *et al.* 2004; Cazelles *et al.* 2008). Wavelet analysis measures association (coherency) between two variables at every frequency (period) band and at every time-window period, and does not require the time series to be stationary. Wavelet analysis is particularly suitable to explore a multiple-variable-linked hypothesis because it gives a two-dimensional mapping of the associations between every two variables.

Using the same data as Stige *et al.* (2007), together with additional data on flood and drought covering entire China (Chen 1939), we apply wavelet analysis to explore how temperature, drought/flood and locust abundance are associated with each other at both frequency and time spaces and to reveal the periodic climatic components that drive locust dynamics. The method allows the detection of non-stationary processes, thereby enabling us to explore how the links between locusts, droughts, floods and temperature change temporally. This new analysis of ours supplements our previous analysis by showing associations of locust plagues, temperature, flood and drought in two-dimensional frequency-time space, thus shedding new light on the causal mechanisms behind the locust-climate association.

2. MATERIAL AND METHODS
(a) *Locust data*
Decadal locust abundance data for AD 950s–1950s are the same as Stige *et al.* (2007), annual locust abundance data for the period of AD 957–1956 were extracted from figure 9*a* of Ma (1958) and used to calculate decadal-mean values. Ma (1958) obtained the data from various sources of the older Chinese literature (Chen 1936, 1939). The locust index

is assumed to refer only to the subspecies *L. m. manilensis* (Ma 1958). The index used by Ma (1958), was derived by referring to the reported intensity and spatial extent of locust outbreaks based on locust reports and/or damages in China.

(b) *Flood/drought frequency data*
Decadal records of flood and drought frequencies for the Yangtze Delta in south-eastern China for AD 1000s–1950s were obtained from Jiang *et al.* (2005). Decadal frequencies of floods and droughts covering entire China from BC 246 to AD 1913 were compiled by Chen (1939), by referring to several historic sources, including the Zizhitongjian, Ming History, Qing History and 25 History Books. The frequency of flood/drought was calculated as the number of flood/drought records for each decade within the dynasties, including Qin and Han Dynasties (BC 246–AD 24), Eastern Han Dynasty and Three Kingdoms (AD 25–264), Jin Dynasty (AD 265–419), Southern and Northern Dynasties (AD 420–588), Sui and Tang Dynasties (AD 589–906), Five Dynasties and Ten Kingdoms (AD 907–959), Song Dynasty (AD 906–1279), Yuan Dynasty (AD 1276–1367), Ming Dynasty (AD 1368–1643) and Qing Dynasty (AD 1644–1913). Since the time scales for the flood/drought frequencies reported by Chen (1939) do not match exactly with those of the other time series (being calculated from the first year of each dynastic period), the data were re-calculated by weighted averaging of the frequencies of the neighbouring two decades for best matching the time scale AD 950s–1900s. The drought/flood data representative for entire China may be more appropriate than data for the Yangzte Delta region for analysing associations with locust and temperature in entire China.

(c) *Temperature data*
Decadal mean temperature records for AD 950s–1950s were obtained from Yang *et al.* (2002). The temperature time series was reconstructed by combining multiple area weighted palaeoclimatic proxy records obtained from ice cores, tree rings, lake sediments and historic records. Before further calculations, the individual proxy records were normalized to zero mean and unit variance, thus yielding a dimensionless temperature index expressed in sigma units. In total, three temperature reconstructions were calculated with different time frequency characteristics and different spatial coverage: (i) the 'high-resolution' time-series was derived by averaging only available high-resolution proxy records, (ii) the 'complete' time series was derived by directly averaging all nine proxy records, and (iii) the 'weighted' time series was formed by combining area weighted regional proxy records. This weighted temperature reconstruction is representative for entire China and shows good agreement with north Hemisphere temperature variations (Yang *et al.* 2002). In this study, the weighted temperature reconstruction for AD 950s–1950s was used.

(d) *Statistical analysis*
Among the various approaches developed to study non-stationary data, wavelet analysis is probably the most efficient. In particular, the continuous wavelet transform (CWT) that decomposes the time series into both a time domain and a frequency space gives the possibility of investigating and quantifying the temporal evolution of time series with different rhythmic components and also the transient relationships between two time series (Grinsted *et al.* 2004;

Cazelles *et al.* 2008). Here, the Morlet wavelet was used for wavelet decomposition. This wavelet has the advantage of being very well localized in frequencies and of being a complex wavelet that provides the possibility to compute the phase and then to give more quantitative information about interactions between two time series. With the wavelet decomposition, the distribution of variance between periodic or frequency bands and different time locations can be estimated. This is known as the wavelet power spectrum.

Cross-wavelet analysis was used to identify coherencies in both time and frequency space. From the wavelet power spectrum of two time series, wavelet coherence is constructed, which shows the significant coherences at different periods or frequency bands. Such cross-wavelet analysis is a powerful tool in revealing the significant associations at specific periods (frequencies). In complement to wavelet analysis, we can use phase analysis to characterize phase shifts between two time series. Based on these phase shifts, we determined in-phase or out-of-phase associations and the time lag between two time series. The arrows in wavelet coherence figures indicate the relative phase relationship (with in-phase pointing right, out-of-phase pointing left).

Bootstrap methods were used to quantify the statistical significance of the computed patterns. The significance levels were computed based on 1000 'Beta-Surrogate' series (Rouyer *et al.* 2008). The significance level was set at $p < 0.05$. These bootstrapped series used $1/f^{\beta}$ spectrum models to take the highly auto-correlated nature of the environmental time series into account (Rouyer *et al.* 2008).

Wavelet analysis is particularly suited to study non-stationary data—whether the non-stationarity is observed in the mean, the variance or both. Nevertheless, to highlight the results in numerous cases, some rescaling of the variance distribution is performed (Cazelles *et al.* 2008). The original time series of locust abundances, temperature and flood/drought frequencies were thus detrended through the removal of the low-frequency components (more than 350 years) computed by a classical 'low-pass filter' (Shumway & Stoffer 2000). This allows us to highlight the evolution of these periodic components that were present but masked by the trend. The detrended time series are displayed in figure 1. Before the wavelet analyses, the time series were standardized to zero mean and unit s.d.

3. RESULTS

Using data representative for entire China, the CWT analysis demonstrated that for locust abundance, consistent and significant oscillating components occur at period bands of 80–170 years that diverged to 80–120 years and 160 years at approximately AD 1400s (figure 2a). For temperature, the most significant oscillating component was approximately 160 years (figure 2b). Finally, for flood frequency, the variance was mainly at 120–160 years before 1600s (figure 2c), and for drought frequency the dominant oscillating components were approximately 160–180 years after AD 1100s (figure 2d). Cross-wavelet analysis showed that at bands of approximately 160–170 years, strong and consistent significant coherencies occur between locusts and temperature (figure 3a), between locusts and droughts (figure 3b) and between locusts and flood frequencies (figure 3c).

The periodic components of the locust and the temperature series were generally out-of-phase (all arrows

point left, see figures 3a and 4a), while those of the locust and the drought/flood series tended to be in-phase (all arrows point right, see figures 3b,c and 4b,c). We also found significant and consistent out-of-phase associations between drought frequencies and temperature at bands of approximately 160–170 years (figure 3d) and between flood frequencies and temperature (figure 3e; all arrows point left). Interestingly, flood and drought frequencies were significantly and consistently in-phase (figure 3f; all arrows point right). All these associations were generally consistent in the 160–170 years band, despite of other significant bands that occur more scattered (e.g. at bands of 60–80 years during AD 1100s–1400s in figure 3d; at a 120-year band during AD 1500s–1800s in figure 3e). These results suggested that locust abundances were positively associated with low-frequency flood and drought events. In turn, the flood and drought events were negatively associated with temperature, predominantly at bands of 160–170 years.

Using flood and drought data representative only for the Yangtze Delta region, we obtained generally similar results as if using the data representative for entire China (figures S1, S2 in the electronic supplementary material). Nevertheless, some differences in the cross-wavelet spectrum may also be observed. The first difference is that at bands of 160–170 years, the associations between locust and flood frequencies and between flood frequencies and temperature are inconsistent (figure S2b,e in the electronic supplementary material). The second difference is that the association between locust and flood frequencies in the same frequency band is out-of-phase (arrows point to left, figure S2c in the electronic supplementary material), as is the association between flood and drought frequencies (figure S2f in the electronic supplementary material). The in-phase flood–temperature-relationship in Yangtze Delta region (figure S2e in the electronic supplementary material) is different from that (out-of-phase) for entire China (figure 3d).

4. DISCUSSION

Our results clearly indicate that locust outbreaks, drought and flood frequencies and temperature in China during the past millennium are consistently and strongly associated with periods of approximately 160–170 years, suggesting that the three variables may be causally interlinked. These results strongly support our previous hypothesis that the negative low-frequency association between temperature and locust plague is mediated by climatic forcing of floods and droughts (Stige *et al.* 2007). As our earlier regression analyses have demonstrated, locust plagues are affected by a multiplicative effect of drought and flood frequencies in the Yangtze Delta region. In the present paper, data were log-transformed and drought and flood effects would be expected to be additive. This allowed us to explore the effects of drought and flood on locust dynamics separately. The new results reported here document significant associations between locusts and temperature on one hand and Yangtze droughts, but not floods, on the other hand. However, using flood and drought data representative for entire China, we found significant associations also with floods. The temperature→drought→locust link is thus consistent in all analyses, while the
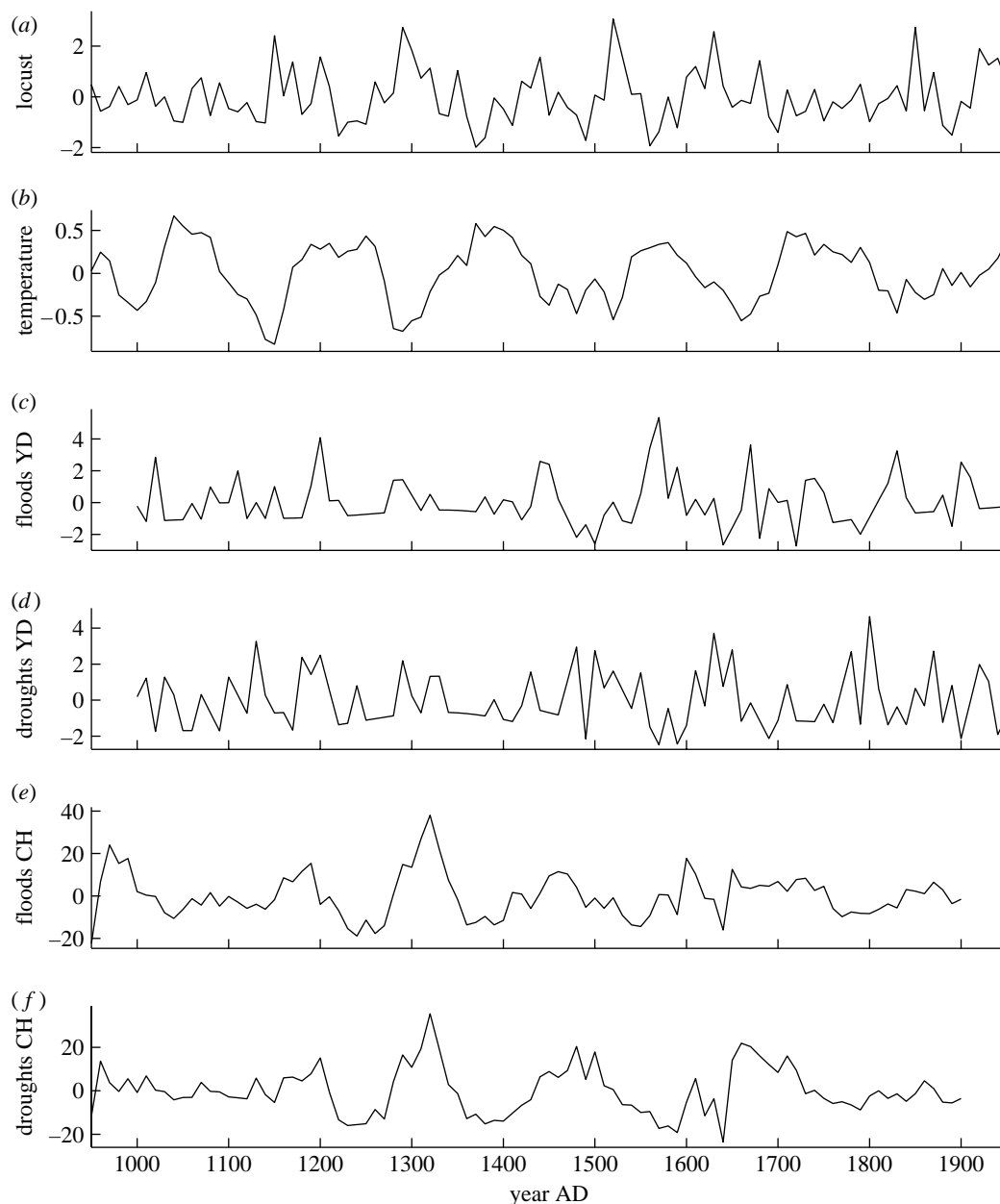
Figure 1. Analysed time series: (*a*) locust abundances, (*b*) temperature, (*c*) flood frequencies, and (*d*) drought frequencies in the Yangtze Delta (YD) of southern China during AD 1000s–1950s; (*e*) flood frequencies, and (*f*) drought frequencies in entire China (CH) during AD 950s–1900s. All these series were detrended through the removal of the low-frequency components computed by a classical 'low-pass filter'. Before the wavelet analyses the time series were standardized.

temperature→flood→locust link is not. This suggests that Yangtze flooding, although possibly affecting locust abundance in China (Stige *et al.* 2007), is unlikely to be a mediating factor behind the locust-temperature association in the 160–170 years band. Our findings further suggest that temporal variability and climatic forcing of droughts is consistent at larger geographical scales than those for floods, the occurrence of floods being more regional in character.

In our previous work, we found locusts, precipitation or drought/flood and temperature were closely associated with each other, but we only calculated coherency spectra of locusts with temperature (maxima at periods of approx. 50, 70 and 200 years) and of locusts with the product of temperature and precipitation (maxima at periods of approx. 30, 50 and 200 years) (Stige *et al.* 2007). The coherency spectra of locust or temperature with drought/flood were not calculated. The new results using

cross-wavelet analysis demonstrate that only the coherence at the highest period band (here found to be approx. 160–170 years) is consistent throughout the millennium (figures 3*a* and 4*a*; figure S2*a*, S3*a* in the electronic supplementary material). Note that the presently estimated periods are likely to be more precise than the estimates from our previous analysis, as differencing was not required for wavelet analysis. Further significant coherencies were detected at periodical bands of approximately 40–60 years and 60–80 years, but only for limited time periods (figure 3*a*; figure S2*a* in the electronic supplementary material). These coherencies at 40–80 years bands were not consistent among locust, drought/flood and temperature at the same frequency-time space, and thus they are not relevant in explaining the temperature→drought/flood→locust causal links (figure 3).

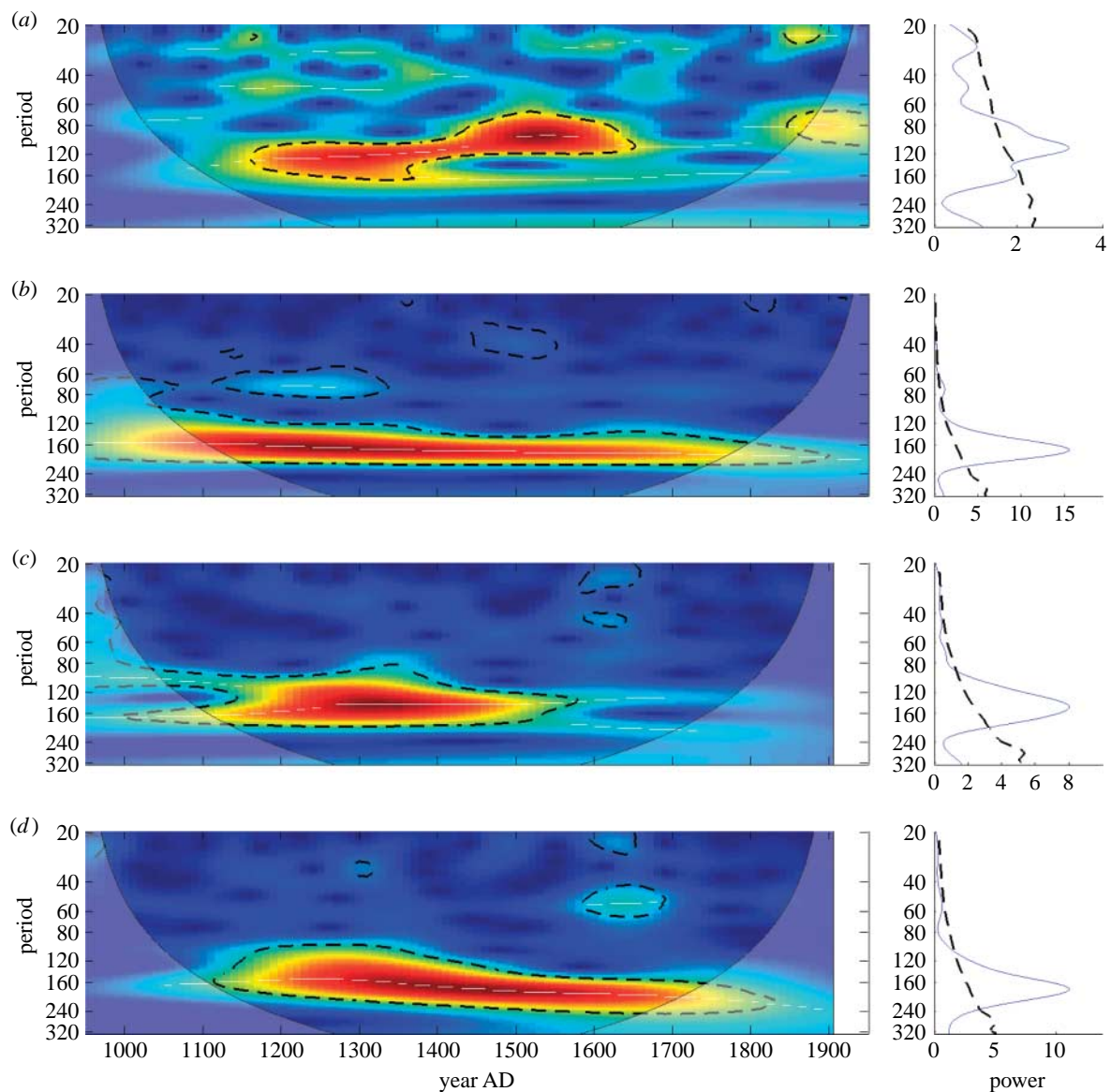Using historical data of drought and flood for entire China, we have thus found that drought as well as flood

Figure 2. (*a*) The continuous wavelet power spectrum of locust abundance, (*b*) temperature, (*c*) frequencies (number/decade) of floods, and (*d*) frequencies of droughts in entire China during AD 950s–1950s. The colour codes for power values from dark blue (low values) to dark red (high values). The dotted white lines show the maxima of the undulations of the wavelet power spectrum. The cone of influence where edge effects might distort the picture is shown in a lighter shade. The graphs on the right represent the average wavelet power spectrum computed based on the corresponding left graph. On the left and right graphs, the thick dashed lines show the $\alpha = 5\%$ significance levels computed based on 1000 'Beta-Surrogate' series (Rouyer *et al.* 2008).

frequencies during the last millennium were coherently associated out-of phase with temperature at period bands of approximately 160–170 years. Although climatic oscillations at an 80-year period in China is well established (e.g. Wang *et al.* 1981; Shen *et al.* 2006), it should be noted that our study, to our knowledge, is the first to report temperature-driven climatic patterns with a predominant period of 160–170 years in China, a periodic climatic pattern that also drives locust dynamics. Our results suggest that China experienced more droughts and floods in the colder periods than in the warmer periods, but that the association between floods and temperature may vary regionally. Specifically, we found positive associations between flood frequency and temperature in the Yangtze Delta region. How do these findings relate to what is known regarding large-scale climate variability in south-east Asia?

Paleoclimatic studies using ice core records in the Kunlun Mountains (Yao *et al.* 2000), pollen profiles from Qinghai Lake (Kong *et al.* 1992) or tree rings in the north-eastern Tibetan Plateau (Liu *et al.* 2006) documented a positive correlation between precipitation and temperature in China over the past one or two millennia. Global warming may increase precipitation in China through enhanced land–ocean water circulation by intensifying the land–sea thermal gradient during boreal summer (Webster *et al.* 1998). Precipitation in China is largely determined by the intensity and duration of the Indian summer monsoon (ISM) and East Asian summer monsoon (EASM). Climate modelling studies show that summer monsoon rainfall in Asia increases significantly with global warming (Ueda *et al.* 2006). The primary cause is an enhanced moisture transport from the surrounding oceans to the Asian continent (Jiang *et al.* 2005).
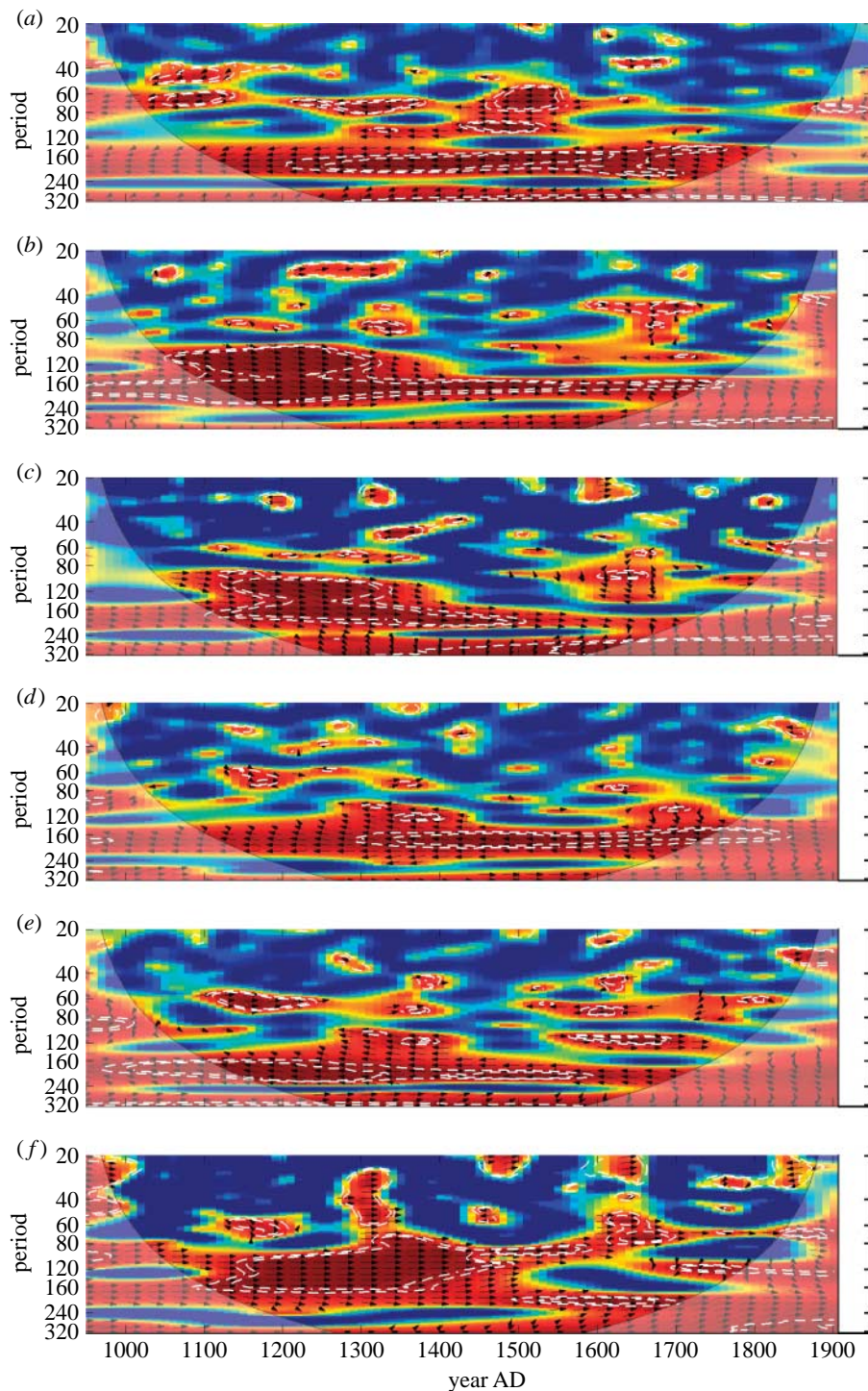
Figure 3. (*a*) Wavelet coherences between locust abundances and temperature, (*b*) between locust abundances and drought frequencies, (*c*) between locust abundance and flood frequencies, (*d*) between drought frequencies and temperature, (*e*) between flood frequencies and temperature, and (*f*) between flood frequencies and drought frequencies in China during AD 950s–1950s. The colour codes for coherence values from dark blue (low values) to dark red (high values). The 5% significance levels computed based on 1000 'Beta-Surrogate' series (Rouyer *et al.* 2008) are shown as thick white contour dashed-lines. The cone of influence where edge effects might distort the picture is shown in a lighter shade. The arrows indicate the relative phase relationship (with in-phase pointing right, out-of-phase pointing left). A complementary illustration of the phase evolution in the 160–170 years period band is done on figure 4.

Another large-scale forcing factor determining monsoon variability in Asia is the Himalayan/Eurasian winter snow cover extent (Kumar *et al.* 1999). Many studies have shown that EASM and ISM rainfalls are negatively correlated with winter snow cover over the Himalaya or over Eurasia (Blanford 1884; Hahn & Shukla 1976; Dickson 1984; An *et al.* 1991; Liu *et al.* 2004, 2006;

Ye & Bao 2005; Zhang *et al.* 2007). It is likely that the reduced EASM and ISM rainfalls in cold periods would increase the frequency of droughts for entire China. The finding that the frequency of floods in China as a whole also increases in cold periods is somewhat surprising. This is probably caused by more typhoon rainstorms in southern China in cold periods (see Liu *et al.* 2001;
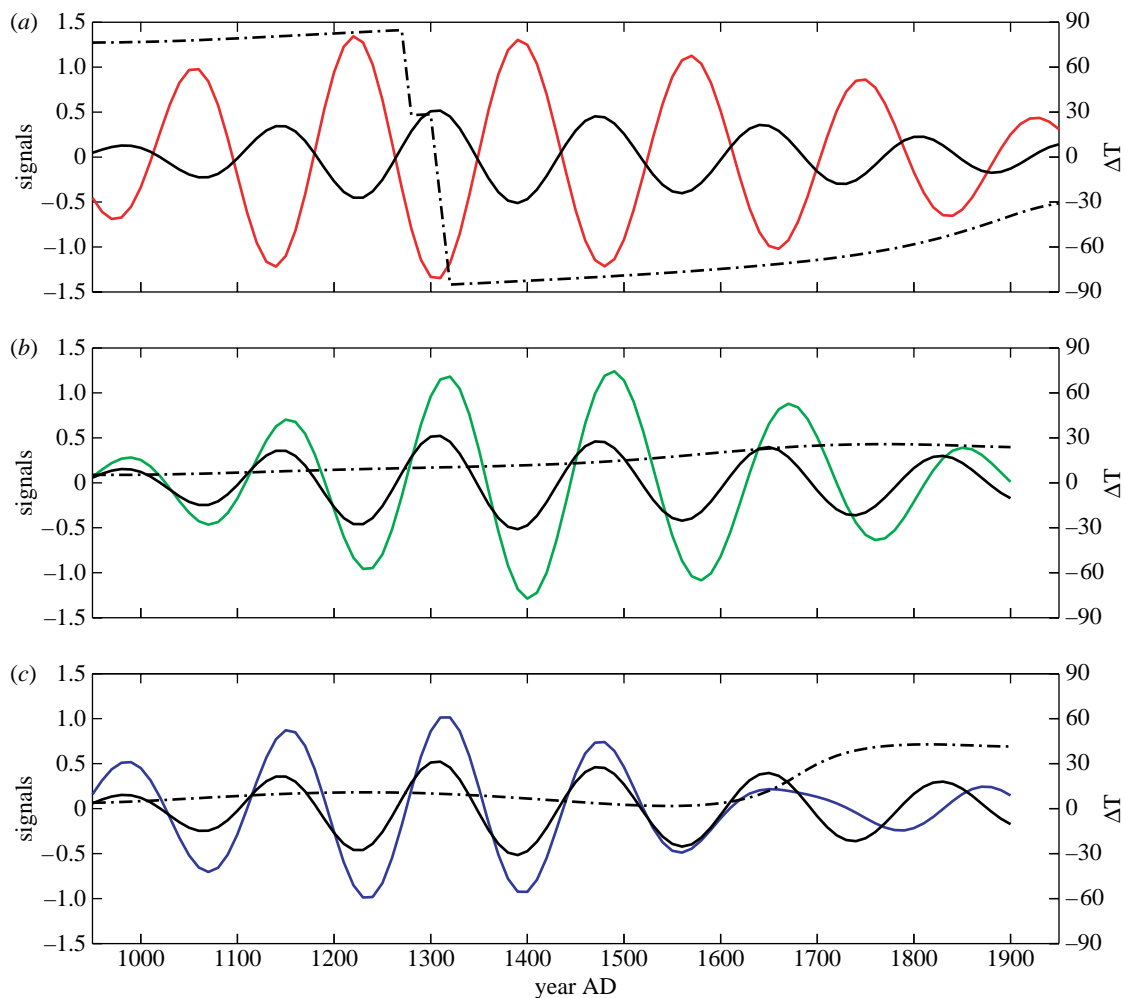
Figure 4. Oscillating components in the 160–170 years period band for the locust abundance (black curve), temperature (red), frequencies of droughts (green) and frequencies (number/decade) of floods (blue), in China during AD 950s–1950s. (*a*) The dotted-dashed lines show the instantaneous time delay (in years) between these oscillation components for the locust abundance and temperature, (*b*) for the locust abundance and frequencies of droughts, and (*c*) for the locust abundance and floods. For the computation of the instantaneous time delay see Cazelles *et al.* (2005).

Leung *et al.* 2007; Liang & Zhang 2007). In addition, an increased number of flooding events might be related to the reduced evaporation by the land surface and reduced transpiration by vegetation cover in cold periods. Thus, run-off during intensive rainfall events is enhanced. This may lead to enhanced flooding.

Our results regarding the in-phase relationship between Yangtze flood occurrence and temperature (the relationship is out-of-phase for entire China) are probably due to the unique climate patterns in the Yangtze River region. Several previous studies report that variability in precipitation in the Yangtze River region is out-of-phase with the northern parts of China (Zhu & Wang 2002; Wang & Zhou 2005; Zhai *et al.* 2005; Qian *et al.* 2007). Increasing rainfall amounts and intensity in the lower reaches of the Yangtze River valley were found to be associated with warmer winters in Tibet (Wang & Zhou 2005), and the frequency of precipitation extremes along the lower Yangtze River has been increased due to increased EASM activity during the past decades (Wang & Zhou 2005; Qian *et al.* 2007). However, the relationship between frequency of droughts in the Yangtze River region and temperature is consistent with that for the entire China, indicating that flood–temperature links might be more specific for different geographical regions of China.

In summary, we propose the following linkage for the locust population and climate variations in China: during AD 950s–1950s Chinese climate alternated between cold and warm periods with a periodicity of approximately 160–170 years. During cold periods, summer rainfall over entire China was reduced due to reduced land–ocean moisture transport. The precipitation decrease in cold periods leads to increased incidence of droughts in China. At the same time, both vegetation cover and evaporation were reduced under the dry and cold climatic conditions that lead to enhanced surface run-off during intensive rainfall events and to the enhanced flooding. In addition, enhanced typhoon activity may also have contributed to increased flood frequency in southern China in cold periods. The climatic response in the Yangtze Delta region differs partly from that observed for China as a whole, in that the number of droughts, but not that of floods, is enhanced during the cold periods. The Oriental migratory locust has a wide distribution in China, including the Yangtze Delta and regions both south and north of the Yangtze (Chen 1999). Locust populations thrive in cold periods owing to favourable breeding conditions being generated by frequent droughts in the entire China as well as by frequent floods in the northern parts of their distribution range. This study thus shows how locust

plagues are consistently associated with large-scale climate changes in China at a specific frequency or period. This study gives an example on how wavelet analysis can help to reveal inter-causal links among three or more factors through mapping coherency between pairwise factors at frequency-time space. Future studies should be directed to investigations on localized locust-climate interactions, considering the different flood–temperature relationship in the Yangtze Delta region from that of entire China.

Altogether, our results suggest that global warming might not only imply reduced locust plague (but see discussion in Stige *et al.* 2007), but also reduced risk of droughts and floods for entire China. However, for the Yangtze Delta region, we expect a reduced risk of droughts but an increasing risk of floods, as may also be inferred from the observed increase in rainfall intensity (Zhai *et al.* 2005) and the increasing number of summer rainstorms (Su *et al.* 2006) in the area, probably due to stronger EASM and ISM in warm periods (Wang & Zhou 2005; Qian *et al.* 2007). Our results challenge the popular view that global warming necessarily accelerates natural and biological disasters such as drought/flood events and outbreaks of pest insects (IPCC 2007). However, as already noted by Stige *et al.* (2007), it is far from certain that the effects on droughts and floods driven by anthropogenically forced warming are the same as the effects of warming caused by natural climatic cycles, necessitating more efforts to clarify the implications of global warming on the complex interactions between climate variations, landscape changes and the dynamics of biological populations.

REFERENCES

An, Z., Kukla, G., Porter, S. & Xiao, J. L. 1991 Magnetic susceptibility evidence of monsoon variation on the Loess Plateau of central China during last 130 000 years. *Quatern. Res.* **36**, 29–36. (doi:10.1016/0033-5894(91)90015-W)

Benton, T. G., Plaistow, S. J. & Coulson, T. N. 2006 Complex population dynamics and complex causation: devils, details and demography. *Proc. R. Soc. London* **273**, 1173–1181. (doi:10.1098/rspb.2006.3495)

Blanford, H. F. 1884 On the connexion of the Himalaya snow fall and seasons of drought in India. *Proc. R. Soc. B* **37**, 3–22. (doi:10.1098/rspl.1884.0003)

Cazelles, B. & Hales, S. 2006 Infectious diseases, climate influences and nonstationary. *PLoS Med.* **3**, 1212–1213. (doi:10.1371/journal.pmed.0030328)

Cazelles, B., Chavez, M., McMichael, A. J. & Hales, S. 2005 Nonstationary influence of El Niño on the synchronous dengue epidemics in Thailand. *PLoS Med.* **2**, 313–318. (doi:10.1371/journal.pmed.0020106)

Cazelles, B., Chavez, M., Berteaux, D., Ménard, F., Vik, J. O., Jenouvrier, S. & Stenseth, N. C. 2008 Wavelet analysis of ecological time series. *Oecologia* **156**, 287–304. (doi:10.1007/s00442-008-0993-2)

Chen, G. 1939 *China successive natural and manmade disasters table*. Guangzhou, China: Jinan University Book Series.

Chen, J. 1936 Outbreaks of locusts recorded in Chinese literatures. *Bull. Zhejiang Entomol. Bureau* **5**, 188–241.

Chen, Y. 1999 *The locust and grasshopper pests of China*. Beijing, China: China Forestry Publishing House.

Dickson, R. R. 1984 Eurasian snow cover and India monsoon rainfall-an extension of the Hahn-Shukla results. *J. Climate Appl. Meteor.* **23**, 171–173. (doi:10.1175/1520-0450(1984)023<0171:ESCVIM>2.0.CO;2)

Grinsted, A., Moore, J. C. & Jevrejeva, S. 2004 Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlin. Process. Geophys.* **11**, 561–566.

Hahn, D. G. & Shukla, J. 1976 An apparent relationship between Eurasia snow cover and India monsoon rainfall. *J. Atmos. Sci.* **33**, 2461–2462. (doi:10.1175/1520-0469(1976)033<2461:AARBES>2.0.CO;2)

Hare, S. R. & Mantua, N. J. 2000 Empirical evidence for North Pacific regime shifts in 1997 and 1989. *Prog. Oceanogr.* **47**, 103–145. (doi:10.1016/S0079-6611(00)00033-1)

Hastings, A. 2001 Transient dynamics and persistence of ecological systems. *Ecol. Lett.* **4**, 215–220. (doi:10.1046/j.1461-0248.2001.00220.x)

IPCC 2007 Fourth assessment report on climate change: synthesis report. See http://www.ipcc.ch/ipccreports/ar4-syr.htm

Jiang, T., Zhang, Q., Blender, R. & Fraedrich, K. 2005 Yangtze delta floods and droughts of the last millennium: abrupt changes and long term memory. *Theor. Appl. Climatol.* **82**, 131–141. (doi:10.1007/s00704-005-0125-4)

Klvana, I., Berteaux, D. & Cazelles, B. 2004 Porcupine feeding scars and climatic data show ecosystem effects of the solar cycle. *Am. Nat.* **164**, 283–297. (doi:10.1086/423431)

Kong, Z., Du, N., Xu, Q. & Tong, G. 1992 Paleoclimatic fluctuations reflected in flora of Holocene Megathermal in the northern part of China. In *Climate and environment in megathermal period of Holocene in China* (ed. Y. Shi), pp. 48–65. Beijing, China: Ocean Press.

Kumar, K. K., Rajagopalan, B. & Cane, M. A. 1999 On the weakening relationship between the Indian monsoon and ENSO. *Science* **284**, 2156–2159. (doi:10.1126/science.284.5423.2156)

Leung, Y. K., Wu, M. C. & Yeung, K. K. 2007 Recent decline in typhoon activity in the South China Sea. In *Int. Conf. on Climate Change, Hong Kong, China*, May, 2007, pp. 29–31.

Liang, Y. & Zhang, D. 2007 Landing typhoon in China during the last millennium and its relationship with ENSO. *Adv. Climate Change Res.* **3**, 120–121. (in Chinese)

Liu, H., Sun, Z., Wang, J. & Min, J. 2004 A modeling study of effect of anomalous snow cover over the Tibetan Plateau upon the South Asia summer monsoon. *Adv. Atmos. Sci.* **21**, 864–975.

Liu, K. B., Shen, C. & Louie, K. S. 2001 A 1000-year history of typhoon landfalls in Guangdong, Southern China, reconstructed from Chinese historical documentary records. *Ann. Assoc. Am. Geograph.* **91**, 453–464. (doi:10.1111/0004-5608.00253)

Liu, Y., An, Z., Ma, H., Cai, Q. & Liu, Z. 2006 Precipitation variation in the northeastern Tibetan Plateau recorded by the tree rings since 850 AD and its relevance to the Northern Hemisphere temperature. *Sci. China D* **4**, 408–420. (doi:10.1007/s11430-006-0408-3)

Ma, S. 1958 The population dynamics of the oriental migratory locust (*Locusta migratoria manilensis* Meyen) in China. *Acta Entomol. Sin.* **8**, 1–40. (in Chinese)

Ma, S., Ting, Y. & Li, D. 1965 Study on long-term prediction of locust population fluctuations. *Acta Entomol. Sin.* **14**, 319–338. (in Chinese)

Qian, W., Lin, X., Zhu, Y., Xu, Y. & Fu, J. 2007 Climatic regime shift and decadal anomalous events in China. *Clim. Change* **84**, 167–189. (doi:10.1007/s10584-006-9234-z)

Ranta, E., Lundberg, P. & Kaitala, V. 2006 *Ecology of populations*. Cambridge, MA: Cambridge University Press.

Rouyer, T., Fromentin, J. M., Stenseth, N. C. & Cazelles, B. 2008 Analysing multiple time series and extending significance testing in wavelet. *Mar. Ecol. Progr. Ser.* **359**, 11–23. (doi:10.3354/meps07330)

Shen, C., Wang, W. C., Gong, W. & Hao, Z. 2006 A pacific decadal oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China. *Geophys. Res. Lett.* **33**, L03702. (doi:10.1029/2005GL024804)

Shumway, R. H. & Stoffer, D. S. 2000 *Time series analysis and its applications*. New York, NY: Springer.

Stenseth, N. C. & Chan, K. S. 1998 Non-linear sheep in a noisy world. *Nature* **394**, 620–621. (doi:10.1038/29177)

Stige, L. C., Chan, K. S., Zhang, Z., Frank, D. & Stenseth, N. C. 2007 Thousand-year-long Chinese time series reveals climate forcing of decadal locust dynamics. *Proc. Natl Acad. Sci. USA* **104**, 16 188–16 193. (doi:10.1073/pnas.0706813104)

Su, B. D., Jiang, T. & Jin, W. B. 2006 Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China. *Theror. Appl. Climatol.* **83**, 139–151. (doi:10.1007/s00704-005-0139-y)

Tsao, C. 1950 Historical distributions of locust plagues in China. *Chin. J. Agric. Res.* **1**, 57–66.

Turchin, P. 2003 *Complex population dynamics: a theoretical/empirical synthesis (MPB-35)*. Princeton, NJ: Princeton University Press.

Ueda, H., Iwai, A., Kuwako, K. & Hori, M. E. 2006 Impact of anthropogenic forcing on the Asian summer monsoon as simulated by eight GCMs. *Geophys. Res. Lett.* **33**, L06703. (doi:10.1029/2005GL025336)

Wang, Y. & Zhou, L. 2005 Observed trends in extreme precipitation events in China during 1961–2001 and the associated changes in large scale circulation. *Geophys. Res. Lett.* **32**, L09707. (doi: 10.1029/2005GL022574)

Wang, S., Zhao, Z. & Chen, Z. 1981 Reconstruction of the summer rainfall regime for the last 500 years in China. *GeoJournal* **5**, 117–122. (doi:10.1007/BF02582044)

Webster, P. J., Magana, V. O., Palmer, T. N., Shukla, J. & Tomas, R. A. 1998 Monsoons: processes, predictability and prospects for prediction. *J. Geophys. Res.* **103**, 14 451–14 510. (doi:10.1029/97JC02719)

Yang, B., Bräuning, A., Johnson, K. R. & Yafeng, S. 2002 Temperature variation in China during the last two millennia. *Geophys. Res. Lett.* **29**, 1324. (doi:10.1029/2001GL014485)

Yao, T., Qin, D., Tian, L., Jiao, K. & Yang, Z. 2000 Variation in temperature and precipitation in the past 2000 a on the Xizang (Tibet) Plateau—Guliya ice core record. *Sci. China D* **26**, 348–353.

Ye, H. & Bao, Z. 2005 Eurasian snow conditions and summer monsoon rainfall over south and southeast Asia: assessment and comparison. *Adv. Atmos. Sci.* **6**, 100–111.

Zhai, P., Zhang, X., Wan, H. & Pan, X. 2005 Trends in total precipitation and frequency of daily precipitation extremes over China. *J. Climate* **18**, 1096–1108. (doi:10.1175/JCLI-3318.1)

Zhang, Q., Chen, J. & Becker, S. 2007 Flood/drought change of last millennium in the Yangtze Delta and its possible connections with Tibetan climate changes. *Global Plan* **57**, 213–221. (doi:10.1016/j.gloplacha.2006.11.010)

Zhu, J. & Wang, S. 2002 80 yr oscillation of summer rainfall over North China and East Asian Summer Monsoon. *Geophys. Res. Lett.* **29**, 1672. (doi:10.1029/2001GL013997)