On the interpretation of Chinese loess as a paleoclimate indicator

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Abstract

The records of wind-blown dust (i.e., loess) in China and elsewhere are some of the most important terrestrial records of past climate changes, stretching back over the last ten million years. In the paleoclimate literature, intervals of increased dust generation have been almost always interpreted as being associated with more intense or prolonged wintertime conditions. Here it is shown show that, in accordance with modern observations, dust outbreaks in Asia are predominantly springtime phenomena. During spring, frequent cyclogenesis in the lee of the Mongolian Altai, and the passage of strong cold fronts produce the intense windstorms that loft and entrain dust into the air. The meteorology governing such outbreaks is likely to be robust in past climates. Contrary to the common paleoclimate presumption, it is actually the breakdown of the Siberian High that permits the dust-producing windstorms to occur. The importance of cold fonts in generating such windstorms suggests that cooling of high-latitude climate during the Miocene, or during glacial intervals, might play a significant role in the signal recorded in the loess deposits.

1 Introduction

Dust outbreaks in Asia are among the most dramatic of meteorological phenomena in the northern midlatitudes. Vast swaths of the continent are blanketed every year by thick clouds of wind-blown dust generated in the desert regions of Asia (Figure 1), that accumulate on land as loess. The reduction in visibility, the respiratory effects, and the severe windstorms that accompany the dust outbreaks represent significant deleterious hazards: one hundred fatalities were attributed to a severe dust storm in May, 1993 (e.g., Liu and Diamond, 2005). Dust is lofted high into the troposphere and transported across the Pacific by the prevailing winds; plumes from big outbreaks are sometimes still visible when they reach North America (e.g., Husar et al., 2001). The radiative effects of loess on climate are also thought to be significant (e.g., Claquin et al., 2003), but the magnitude of such effects is highly uncertain (e.g, IPCC, 2001). Over geologic time, loess gradually accumulates in stratified layers downwind of the source regions, most notably in the Loess Plateau located just northeast of the Tibetan Plateau. These deposits, some of which are hundreds of meters thick, constitute some of the most important continuous terrestrial climate records on Earth, stretching back over the last 8 million years (e.g., An, 2000; Porter, 2001) and possibly as far back as 22 million years (Guo et al., 2002). Dust sedimentation rate, grain size, and magnetic susceptibility are all interpreted in terms of the climatic factors controlling them. For example, these loess records have been argued as reflecting the progressive desertification of Asia during the Miocene (e.g., Guo et al., 2002), changes in atmospheric circulation and seasonality associated with the tectonic evolution of the Tibetan Plateau (e.g., Prell and Kutzbach, 1987; An et al., 2001), an increase in climate variability during the Pleistocene glacial cycles (e.g., An, 2000; Sun and An, 2005), and also Heinrich events - massive discharges of icebergs in the North Atlantic that have been associated with global changes in climate (e.g., Porter and An, 1995; Hemming, 2004). In the paleoclimate literature dust flux has been interpreted almost exclusively as a proxy for wintertime circulation. It is common to find statements like: “It is widely accepted that the Chinese loess was transported *mainly by winter-monsoon winds* driven by the Siberian-Mongolian high pressure system” (Ding et al., 2005, emphasis added). In contrast, the modern literature describes a strikingly different picture: “The simulated seasonal cycle is characterized by a maximum in late spring and a *minimum* in late autumn and *winter*...fully agrees with the seasonal cycle established from synoptic observation of dust storms” (Laurent et al., 2005, emphasis added). The purpose of the present study is to evaluate this apparent contradiction. Part of the issue lies in terminology: if the annual cycle in Asia is characterized in terms of a winter monsoon and a summer monsoon, as is commonly done in the Chinese literature, the picture of climate is quite different from when it is described in terms of the four seasons of winter, spring, summer, and fall. As is demonstrated in this paper, the other issue is that there are some robust aspects of the atmospheric circulation that are responsible for the observed springtime maximum in modern dust outbreaks. These aspects are likely to hold in past climates too, and so I show that, all else being equal, enhanced loess generation probably more properly reflects enhanced/prolonged spring conditions rather than winter, in contradiction to the usual paleoclimate interpretation.

2 Asian dust outbreaks are springtime phenomena

In the modern climate, dust outbreaks in Asia are almost exclusively springtime phenomena. Figure 2 shows dust outbreak frequency, by month, for surface stations across eastern Asia, compiled by Kurosaki and Mikami (2003) from weather station reports. The dominant peak in March, April and May is conspicuous. Zhou and Zhang (2003) report that 82.5% of severe dust outbreaks occur in these three months. Figure 2 also demonstrates that there is a clear association between these dust outbreaks and the occurrence of strong winds, defined here as a surface wind speed exceeding 6.5 ms^{-1} averaged over a three hour period. This speed is the commonly-assumed threshold for dust lofting in many numerical models (e.g., Kalma et al., 1988; Tegen and Fung, 1994), although some studies suggest a range of thresholds depending on locations and environmental factors (Kurosaki and Mikami, 2004; Ishizuka et al., 2005; Laurent et al., 2005).

As noted in the introduction, paleoclimate studies frequently presume that because average surface winds in East Asia are strongest during winter, dust production, transport, and consequent deposition should be regarded as a proxy for wintertime circulation. While it is true that the climatological mean surface winds maximize in winter, Figure 2 demonstrates that it is the wind gusts that matter for dust generation, and that these wind gusts peak in spring.

Sun et al. (2003) measure dust deposition and its minearologic and magnetic properties in an impressive array of collectors deployed across the Loess Plateau. They find a springtime peak in deposition, but to the south it is a relatively weak peak, in apparent contradiction to Figure 2. A possible interpretation is that some significant portion of the dust deposition in the southern region comes from locally reworked loess, possibly disturbed by human activities (Sun et al., 2003). This suggestion is supported by observations that dust generation in the desert regions (i.e., Figure 2; Xuan et al., 2000; Kurosaki and Mikami, 2003) and dust transport in the Pacific (e.g., Lunt and Valdes, 2002; Mahowald et al., 2006) are dominated by strong springtime peaks.

2.1 Cold air surges

The springtime peak in Asian dust outbreaks is well known from the modern observational record, and the meteorological causes have been studied in detail (e.g., Middleton, 1991; Littman, 1991;

Parungo et al., 1994; Husar et al., 2001; Uno et al., 2001; Zhou and Zhang., 2003; Liu et al., 2003; Kurosaki and Mikami, 2003, 2004; Qian, 2004; Laurent et al., 2005; Aoki et al., 2005; Ding et al., 2005). The peak wind gusts responsible for the outbreaks are associated with the passage of strong, and largely dry, cold fronts. Several factors associated with cold fronts lead to these windstorms. The intense temperature gradients across the front produce strong vertical gradients in the wind because of tendency towards thermal wind balance (e.g., Wallace and Hobbs, 2005), drawing strong winds close to the surface. Secondly, the strong vertical wind shear also enhances shear instability and mixing. Thirdly, the advancing cold dense air tends to plow under the receding warm air, lifting it and producing near surface convection. It is the combination of the close proximity of high momentum air to the surface and enhanced turbulent mixing that leads to strong surface wind gusts during frontal passages (e.g., Wallace and Hobbs, 2005; Bluestein, 1993, Pauley et al., 1996).

Figure 3 shows station data from Qitai in Xinjiang province China, near the Mongolian border (44.01 °N, 89.56 °E) for April 2001, during which several major dust outbreaks occurred. All outbreaks were marked by sharp drops in visibility (Figure 3a) as well as weather reports of dust in the air. In the case of the first event, the frontal passage is clearly denoted by the steep drop in the daily-mean temperature of 10°C over the three days (Figure 3b). This cold front was also accompanied by high winds, with maximum sustained (two minute average) wind speeds exceeding 10 m s^{-1} on the 5th and the 7th of April (Figure 3c). Precipitation of 4 mm was recorded over this period. Nearby stations also reported exceptionally strong winds: at Karamay (45.60 °N, 84.85 °E) gusts topped 34 m s^{-1}, and at Shisanjianfang (43.2 °N, 91.71 °E) gusts exceeding 40 m s^{-1} were recorded. This basic pattern is repeated for the other events, although with some variations. In the outbreak on the April 16th, the maximum sustained wind speeds again topped 10 m s^{-1}, although the temperature drop was not as sharp. On the 20th peak sustained winds were only 7.5 m s^{-1}, not much above the background level for the month and possibly suggesting a non-local source for the dust. However, on the 27th and the 28th, maximum sustained winds again exceeded 10 m s^{-1}. Precipitation totaled 10 mm between the 26th and 29th.

The relationships in Figure 3 do not demonstrate *per force* that the dust originated close to Qitai, or that transport, wind direction, soil moisture, vegetation, limited rain-out, or mesoscale interactions with local topography did not play a role in altering the concentration of dust and affecting the visibility. These factors, and probably others, cause variations in the relationships between falling temperatures, wind gusts, and local visibility. Nonetheless this and other station data during periods of major dust storms (e.g., Zhou and Zhang, 2003) support the basic climatological connections between springtime gustiness and dust outbreaks seen in Figure 2.

The recurrent role of cold air masses in dust outbreaks in eastern Asia can be seen from near-surface air temperatures. Figure 4 shows six maps of 850 mb ($\sim$1 km above sea level) daily-mean temperatures from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP-NCAR) reanalysis data sets (Kalnay et al., 1996), selected from days when Zhou and Zhang (2003) report major Asian dust outbreaks over the last 50 years. As is clear by comparison with climatological mean, the dust-generating cold fronts delimit the leading edge of large-scale cold air surges from Siberia. Although details differ from storm-to-storm, this basic picture is repeated for all of the major dust storms reported by Zhou and Zhang (2003).

The southeastward surges of cold air can be seen by following the synoptic development during the buildup to dust outbreaks. Figure 5 shows the 850 mb temperature, and also the 500 mb geopotential heights (essentially streamlines of the atmospheric flow at approximately 5.5 km altitude) for the 5 days leading up to the two major dust outbreaks in April, 2001 seen in Figure 3. In both cases the growth of a wave in the mid-tropospheric circulation produces strongly northerly flow over several days. This cold air is also advected by the general westerly circulation, and hence the cold air originates in northwestern or central Siberia. This basic evolution of the circulation, which is repeated for all of the large dust storms reported by Zhou and Zhang (2003), is the canonical picture for these Asian dust storms in the modern climate: in springtime cold air builds over Siberia during quiescent periods; during synoptic development of midlatitude storms this cold air is drawn southward. Strong gusts at the leading front of this cold surge lofts dust into the atmosphere where it is transported by the prevailing winds.

Given the complex regional orography, it is not surprising that mountain airflow dynamics also appear to play an important role in the details of any given windstorm. Aoki et al. (2004) use a high-resolution numerical model to study one dust storm in the low-lying Tarim Basin. During the passage of a cold front, the cold, dense air plunges through a gap in the topography at the eastern end of the basin. Thus, despite the large-scale flow being primarily westerly, the winds that raise the dust in the basin are actually easterly at the time of the windstorm.

2.2 The causes of the springtime predominance

In order to identify possible causes of changes in loess records, it is important to understand why there is a preponderance of dust outbreaks in springtime and not in other seasons. The foregoing analyses have shown that there are two major prerequisites for dust-generating windstorms: the growth of synoptic-scale disturbances in the atmospheric circulation and strong meridional temperature gradients. Together these combine to generate strong cold fronts which are the source of the windstorms.

Figure 6, adapted from Chen et al. (1991), shows the frequency of cyclogenesis (i.e., the development of synoptic cylones) over Asia, as a function of season. Similar results are also seen in other diagnostics (e.g., Hoskins and Hodges, 2002; and analyses available at *http://www.nerc-essc.ac.uk/∼kih/AMIP2/era_results_new.html*). Focusing first over the continent, a striking observation is the almost complete absence of wintertime cyclogenesis in central Asia, compared to the other three seasons. The frequency of cyclogenesis in spring is over three times as great as in winter. Summer and fall cyclogenesis also exceeds that in winter by at least a factor of two.

The cause of this dearth of wintertime storms is the dominant influence of the Siberian high pressure system (Figure 7a), which reflects strong land cooling and accompanying net descent of air over Asia. This results in a very stable air mass that damps vertical motions and inhibits interactions between the surface and the middle and upper troposphere. These interactions are important for the development of synoptic cyclones (e.g., Eady, 1949; Holton, 2005). A compounding factor is that the upper tropospheric subtropical jet, a focus for the propagation of upper level waves seen in Figure 5, is displaced south of the Tibetan Plateau in winter (e.g., Peixoto and Oort, 1992; Hoskins and Hodges, 2002).

It needs to be be emphasized therefore, that contrary to the common assertion in the paleoclimate literature, it is not the case that dust storms are driven by the winds associated with the Siberian High. In fact, exactly the opposite is true, it is actually the *breakdown* of the Siberian High that permits the occurrence of dust storms. Counter to the usual paleoclimate inference, enhanced or prolonged wintertime conditions actually act to *suppress* dust storms, all else being equal. Studies of the relationship between modern interannual variability and atmospheric circulation also bear out this relationship. Ding et al. (2005) find that dust outbreak frequency in Asia has a significant negative correlation with the strength of the Siberian High in spring. Other studies (e.g., Qian et al., 2004; Zhou et al., 2004; Kurosaki and Mikami, 2004) can also be interpreted as supporting this relationship.

In comparison to winter, climatological conditions are quite different in the other three seasons. the Siberian High is weak in spring and fall and absent in summer (Figure 7), and so the atmosphere is less stable to vertical displacement during those seasons than in winter. Also the upper-level jet stream is south of the plateau in winter whereas during spring, summer, and fall, it is north of the plateau (not shown). This has two consequences for atmospheric dynamics during spring, summer, and fall: firstly, the reduction in vertical stability of the atmosphere means that upper-level waves propagating on the jet stream can more easily interact with the surface to produce cyclone development; secondly, the northward location of the jet stream is also conducive to lee cyclogenesis - the atmospheric flow over and past the topography stretches vertical columns of air, and imparts a curvature to the circulation that tends to favor cyclonic development (e.g., Han et al., 1995; Davis, 1996; Hoskins and Hodges, 2002).

Off the east coast of Asia, the contrasting thermal inertia between continent and ocean produces strong wintertime temperature gradients, and the resulting baroclinicity does produce frequent coastal cyclogenesis in winter. However, despite these temperature gradients maximizing in winter, nearly twice as many storms are generated in spring as in winter (Figure 6). It is an interesting speculation therefore that the springtime peak in Asian lee cyclogenesis may play a role in the relative minimum of storminess in the Pacific in midwinter (e.g., Nakamura, 1992; Chang et al., 2002).

The other prerequisite for dust storms are strong meridional temperature gradients. In winter the whole continent is cold and the band of strong temperature gradients lies to the south of the desert regions (Figure 7). In spring a reservoir of cold air still exists in the north, but the sun has begun to warm the land in the lower midlatitudes. This leads to the large climatological temperature gradients necessary for generating intense cold fronts. By summer however, even the high latitudes have warmed up, and the meridional temperature gradients are consequently weakened. Fall temperatures looks quite a lot like spring although there are some subtle, but apparently important differences. In fall the location of the coldest air is displaced eastward compared to spring, and eastward of the major dust generating regions (Figure 7b,d). A significant reason for this is that the annual cycle in air temperature in northwestern Siberia (the source region of the cold air surges in Figure 5) is influenced by the sea ice extent in the Barents Sea. The sea ice feels the thermal inertia of the ocean mixed layer, and it reaches its maximum extent in spring, and its minimum extent in fall. Consequently the seasonal cycles in snow cover and cold temperatures in Siberia are skewed towards spring (Figure 7).

There appear to be several contributing reasons why the frequency of dust storms in fall is so much less than in spring (Figure 2). The difference in climatological temperatures (Figure 7b,d) already mentioned is one reason; a second is the approximately 50% less-frequent occurrence of cyclogenesis in fall, shown in Figure 6. This latter observation is consistent with the fact that the Siberian High is significantly stronger in fall than it is in spring (Figure 7). Other factors during the fall are that the monsoonal precipitation is skewed towards late summer (Araguas-Araguas et al., 1998) producing soil moisture (e.g., Mintz and Serafini, 1992) that inhibits dust lofting, and also vegetation that, relatedly, also persists into fall (e.g., Yu et al., 2004). Vegetation plays an important role in anchoring dust on the ground (e.g., Tegen and Fung, 1994; Mahowald et al., 1999). It is hard to estimate the relative importance of these different factors without analyzing a detailed model of dust lofting, but together they are sufficient to suppress fall dust storms. Laurent et al. (2005) attempt to look at the various factors and tentatively conclude that the frequency of wind gusts is the dominant control in the modern climate.

3 Dust storms in climate models

In seeking to reconcile variations in paleo-proxy records with the climate changes that gave rise to them, global climate models are the only tools capable of a self-consistent accounting of all the contributing factors. A necessary (but not sufficient) cause for confidence in the modeled climate changes is that the model has an adequate representation of the weather events that give rise to the proxy record. I have described the meteorological conditions for the windstorms that generate dust outbreaks: strong cold fronts and lee cyclogenesis. In both cases, the relatively coarse resolution of climate models is a serious issue. Global climate models do not represent the scale of cold fronts ($\sim$10 km resolution would be necessary compared to the 100s of kms that are typical in climate models), and so they do not properly resolve the dynamics giving rise to the wind gusts. Secondly, the model resolution may not be adequate to capture the process of lee cyclogenesis. Of course these two issues center only on the model's ability to represent the lofting of the dust into the air, and are arguably only the minimum requisites for the successful simulation of dust outbreaks by climate models. The transport, deposition, and possible re-entrainment of the dust are also important factors in the climate signal left in the loess record, and are discussed further in Section 4.

I examine one state-of-the-art climate model, the CCSM3 (Collins et al., 2006), for which daily model output was available. Model simulations for both modern and last glacial maximum climates have been performed, and have already been used to simulate the dust cycle (Mahowald et al., 2006). I evaluate the modeled 850 mb temperature over Asia, both for the mean and the high frequency variability, as a function of season. The model output is compared to NCEP-NCAR reanalysis. The purpose is to address the model's ability to reproduce the cold air surges from Siberia. In terms of getting the dust outbreaks right, this perhaps sets the lowest bar for the model since, as already noted, wind gusts occurring during the passage of cold fronts are not captured because of the coarse model resolution and are not, in any case, available from daily mean model output.

Figure 8 shows that the CCSM modern simulation does a good job reproducing the seasonal cycle in mean temperature in the reanalysis. The biggest discrepancy is over Tibet, presumably due to the interpolation of the model output down to the 850 mb pressure level over high topography. The daily model output was high-pass filtered using a sixth-order high-pass Butterworth filter to emphasize variability on 1-5 day timescales. Figure 9 plots the standard deviation of this high-frequency variability for NCEP-NCAR reanalysis and for the CCSM modern simulation. The CCSM model is clearly deficient in this aspect of the modern simulation. The temperature variability is much stronger than in the reanalysis, by about a factor of two, on average. It is also clear that there are some major discrepancies in the seasonal cycle. Figure 10 compares temperature variability from station observations, filtered in the same way as the model output, for station observations around (45 °N, 90 °E). All of the station data show a springtime peak in temperature variability. The NCEP-NCAR reanalysis reproduces the magnitude of the temperature variability in this region, but has a secondary fall peak that is larger than that at the surface stations, except possibly Baytik Shan (45.37 °N, 90.53 °E). Figure 10 also clearly shows the temperature variability in the CCSM modern simulation is too large, and peaks in late summer instead of spring. The last glacial maximum CCSM simulation has temperature variability whose overall magnitude is similar to that in the modern simulation, but has an increase in winter variance and a reduction in summer variance. However, given the model's failure to reproduce the observed magnitude and phasing of the seasonal cycle, the changes suggested for the last glacial maximum should probably be treated skeptically.

A similar set of analyses for the 850 mb winds was also made (not shown). The mean winds were in good agreement with the reanalysis but the high-frequency variability was again too large, and with a different seasonal cycle. All these calculations suggest that this particular model has difficulty in simulating the meterology of Asian dust storms. Excessive high-frequency variability appears to be a general characteristic in midlatitudes in the CCSM3 (Li, 2007), and so is not directly related to its relatively coarse resolution of T42 (about 3^o by 3^o). These results are for just one climate model and it would clearly be useful to analyze the whole suite of climate models available, with a particular focus on higher-resolution models. However, in relation to paleoclimate dust studies, these results emphasize the challenge in modeling even one component of the weather responsible for dust outbreaks in the modern climate. Inferences from the loess record about the cause of past climate changes can be made only cautiously.

4 Summary and discussion

In the modern climate, dust outbreaks in Asia arise because of a particular set of circumstances that prevail in springtime. Frequent cyclogenesis events in the lee of the Mongolian Altai combine with strong meridional temperature gradients to produce cold air surges from Siberia. These surges interact with the complex regional orography to produce intense windstorms at the leading edge of this air mass. It is during these windstorms that dust is lofted and entrained into the atmosphere.

The windstorms are conditioned on two factors: strong temperature gradients and lee cyclogenesis. In winter, lee cyclogenesis is suppressed by both the strength of the Siberian High, and the displacement of the subtropical jet stream to south of the Tibetan plateau. In summer, strong temperature gradients do not exist because the whole continent has warmed. In fall, the relative absence of dust appears to be due to subtle differences from spring (a slightly stronger Siberian High, slightly warmer temperatures) reducing the occurrence of windstorms, although soil moisture and vegetation that anchors dust to the ground remain possible contributing influences.

This paper has focused on the meteorological factors involved in the generation of dust outbreaks in eastern Asia. This is a minimum, but by no means complete, part of the climate signal reflected in the loess deposits. The loess deposits are also influenced by the processes governing the strength and extent of dust source regions, and the transport, deposition and possible re-entrainment of the loess. It is to be expected that these factors vary as a function of mean climate state. Dust modeling studies differ about the importance of changes in dust-source area during glacial climates: Mahowald et al. (1999) conclude that the records of dustiness can only be explained by significant changes in dust-source area; using a different model Werner et al. (2001) conclude that changes in circulation and precipitation alone could be sufficient. I have also not tried to address the causes of variations in magnetic susceptibility, which are argued to reflect changes in soil chemistry, and interpreted as an indicator of the intensity of the eastern Asian summer monsoon and sedimentation rate. (e.g., An et al., 1991; Liu and Ding, 1999; Porter, 2001).

Contrary to the usual paleoclimate interpretation, it is actually the breakdown of the Siberian High in spring that permits and promotes the windstorms that produce dust. This relationship is also borne out in observations of interannual variability of dust outbreaks, which are negatively correlated with interannual variability in the Siberian High (Ding et al., 2005). All else being equal, the modern record of dust outbreaks strongly suggests that enhanced dust flux ought to be interpreted as prolonged or more intense springtime conditions rather than prolonged or more intense wintertime conditions.

It is interesting to speculate what past changes in climate might be consistent with the enhancement of dust flux over the Loess Plateau. The modern record suggests that the presence of cold air at high latitudes, and in particular over western Siberia, is important. In glacial climates the presence of permanent ice sheets there would have provided a year-round reservoir of cold air as a source for the cold air surges, which together with lee cyclogensis in spring, summer, and fall (Figure 6) might permit dust outbreaks extending over a greater fraction of the year. It might also be possible that with colder summers, a reduction in rainfall and vegetation cover allows for dust outbreaks to occur in the fall. Over the longer term geological record, the gradual cooling of global climate during the Miocene coincides with the well-established aridification of central Asia and the onset of loess deposition. It has been suggested here that the sea ice maximum in spring sets the seasonal cycle of the temperature over western Siberia from which the cold surges originate. Preliminary analyses for the present climate do suggest that springs with enhanced temperature variance in central Asia are associated with increased sea-ice in the Barents Sea (Roe et al., 2004). Perhaps it is also possible that onset of winter sea-ice during the Miocene played a role in the onset of dust generation, transport, and deposition.

The above ideas are unsubstantiated speculations, and it is clear that the meteorology giving rise to dust is complicated and sensitive to small changes in any one of a number of atmospheric variables, a conclusion supported by the high degree of interannual variability of dust outbreaks in the modern climate (e.g, Parungo, 1994; Ding et al., 2005). In addition to the climate sensitivities, paleo-records are also subject to uncertainties about dust source strength and area, transport pathways, and the mechanisms of deposition and re-entrainment. All of these extra factors add uncertainty to climate changes inferred from loess records. For example, it has been estimated that recent anthropogenic desiccation of Owens Lake in California east of the Sierra Nevada, with an active emitting area of just 90 km^2, created the largest single dust source in the United States, with annual dust production of between 900,000 and 8,000,000 tons (Gill and Gillette, 1991). This illustrates a critical sensitivity of emissions to transient changes in dust sources that may themselves be a function of climate. The multiple uncertainties about controls on dust production and transport are warnings flags about the confidence with which the cause of past changes in dust flux can be confidently known. From the paleo-record, it may be possible only to make some broad generalizations about dust as a function of mean climate state. Unique interpretations of the actual climate mechanisms responsible may not be attainable.

Climate models offer potentially useful tools to study the relative importance of different mechanisms influencing the loess record. A prerequisite for their use is that they reflect the meteorology of dust outbreaks (in addition to the transport and deposition of dust), or at least correctly capture the large-scale controls. For dust outbreaks the dynamics of cold front gusts and downslope windstorms are important but occur at scales too small for climate models to capture. The one climate model examined in this study also failed to get the large-scale controls right. High-frequency variance in low-level winds and temperatures was a factor of two too large, and the phasing of the seasonal cycle was wrong. These are tough targets for GCMs to meet even in the current climate, but without demonstrated skill for the present there can be little confidence in their output under the dramatically different climate of, say, the last glacial maximum.

The paleo-loess record can be regarded as an exemplar of a general issue in the interpretation of paleoclimate records, particularly when the proxy reflects rare weather events. It highlights the importance of looking at individual case studies and interannual variability in modern observations in order to understand the meteorological and climatological controls on that weather event. It is only by careful analysis of modern observations that there is some hope of establishing the proper target for climate models, and that a level of confidence can be established as to how effectively the climate history entangled within the paleo-proxy record can be teased out. Paleoclimate studies are often motivated under the mantra that 'the past is the key to the future'. However most important for understanding what paleo-proxy records actually reflect, and in the spirit of Hutton's original approach, it is equally true that 'the present is the key to the past'.

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5 Figures

Figure 1. Desert and desertified areas in eastern Asia. Taken from Laurent et al. (2005).

Figure 2. Taken from Kurosaki and Mikami (2003). Monthly dust outbreak frequency (bars) and strong wind frequency (cricles) from Jan. 1993 to Jun. 2002 (white) and the same from Jan. 2000 to Jun. 2002 (black). The frequency of dust outbreaks is defined as the percentage of the number of dust outbreaks reported to the total number of observations within a given period at each observatory and/or given region. Similarly, the frequency of strong winds (hereafter, strong wind frequency) is defined as the percentage of the number of strong winds to the total number of observations.

Figure 3. Selected daily surface station data from Qitai in Xinjiang province, China (44.01N 89.56E), during the month of April, 2001. (a) Steep drops in visibility indicate periods of dust outbreaks. Asterisks denote days on which dust was reported (WMO codes 07, 08, and 09); (b) Daily-average surface temperature shows that the dust outbreaks occurred during times of cooling temperatures (i.e., during the passage of a cold front); and (c) maximum sustained (two minute average) wind speed (m s^{-1}). The strong sustained winds and wind gusts are responsible for lofting and transporting the dust.

Figure 4. 850 mb (i.e., $\sim$1 km elevation) temperatures from NCEP-NCAR reanalysis on days of major dust outbreaks, selected from those reported by Zhou and Zhang (2003) for the last fifty

years. The top panel shows the March-April-May mean climatology. All events show strong incursions of cold air over central Asia during major dust storms. Where the 850 mb surface lies beneath the surface elevation, the field has been interpolated down into the the topography via standard algorithms (e.g., Kalnay et al., 1996). Since the vertical structure of the fields changes quite slowly the patterns would look very similar at other levels. The green line shows the 3 km elevation contour from the NCEP-NCAR reanalysis grid.

Figure 5. Case studies of two dust outbreaks in April, 2001. Figures show 500 mb ($\sim$5.5 km elevation) geopotential heights (contour interval 100 m) and 850 mb ($sim 1$ km elevation) temperatures from NCEP-NCAR reanalysis over the 5 days leading up to the main dust storm events recored at Qitai (see Figure 3), whose location is indicated by the pink dot. Note both events show development of wave-like feature in the circulation at mid-levels in the toposphere, drawing cold air from western Siberia down across central Asia over the course of several days.

Figure 6. Number of cyclogenetic events ($\times 10^{-2}$) per 2.5^{o} quadrangle per month for (a) DJF, (b) MAM, (c) JJA, and (d) SON for the period 1958-87. Modified from Chen et al. (1991). Note the relative dearth of storms in winter, the slight springtime maximum, and the presence of storms throughout the summer and fall. Contour interval is 3.

Figure 7. Climatological 850 mb temperatures and mean sea level pressure (contour interval 4 mb) from NCEP-NCAR reanalyses, by season. See Figure 4 for more details. In winter the Siberian High is strong and the region of strong temperature gradients is displaced south of the dust source regions. In summer the entire continent has warmed up. Note also that the strength of the Siberian

High in fall is significantly greater than in spring. Temperatures in northwest Siberia are also a little cooler in spring compared to fall.

Figure 8. 850 mb temperatures, by season, from the CCSM climate model. Apart from a problem interpolating down to 850 mb over the plateau, a comparison with Figure 7, shows the model is in good general agreement with the reanalysis.

Figure 9. left panels, high frequency variability in 850 mb temperatures in the NCEP-NCAR reanalyses, by season. The reanalysis output was filtered with a sixth order high-pass Butterworth filter to emphasize variability on 1-5 day timescales. The figures show the standard deviation of this variability; right panels, the same, but for the CCSM model output for the modern climate. The CCSM model does a poor job of representing the seasonal cycle - it overestimates the variance by about a factor of two, and gets the seasonal cycle wrong.

Figure 10. Comparison between seasonal cycles in daily temperature variability in the NCEP-NCAR reanalysis, the CCSM model simulations and station observations near 45N, 90E. Analysis method as for Figure 9. Most stations (thin lines) show a springtime peak in temperature variability. The reanalysis (thick, solid line) does a fair job with the amplitude of the seasonal cycle although there is a larger secondary peak in fall than for most stations. The CCSM modern (thick, dashed line) and last glacial maximum (thick, dash-dotted line) simulations show variance that is much higher than observed. The CCSM modern simulation does not have the same seasonal cycle as the observations. The last glacial maximum simulation has a large drop in variance in summer and a large increase in winter, compared to the modern simulation. (Qitai, 44.01N 89.56E; Karamay, 45.50N 84.85E; Shisanjianfang 43.21N 91.73E; and Baytik Shan 45.36N, 90.53E)

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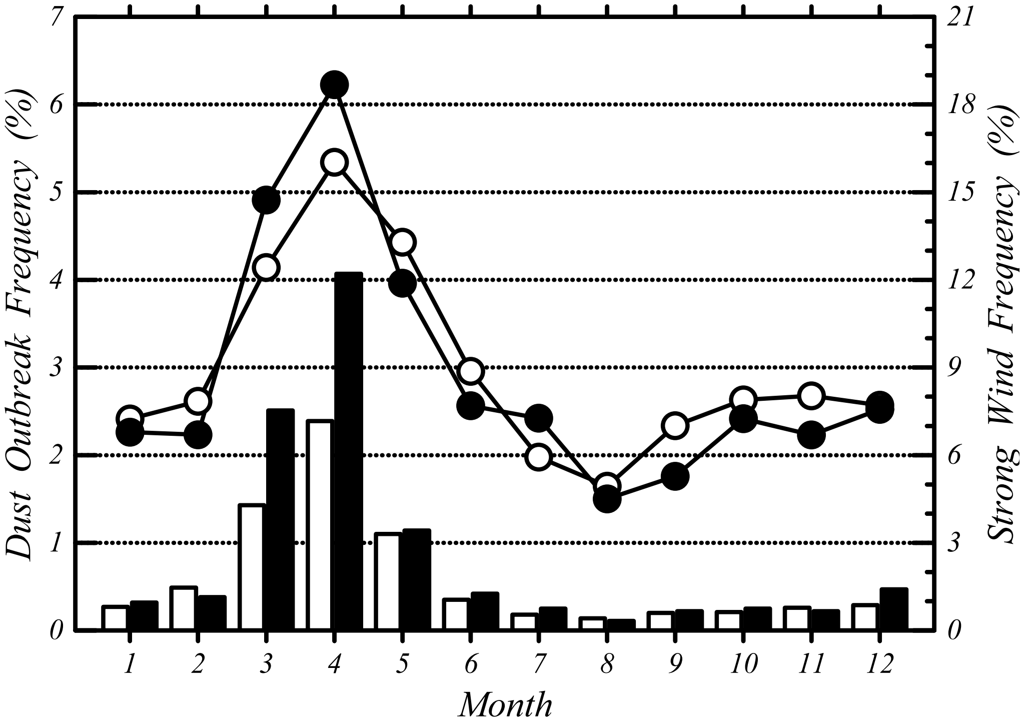

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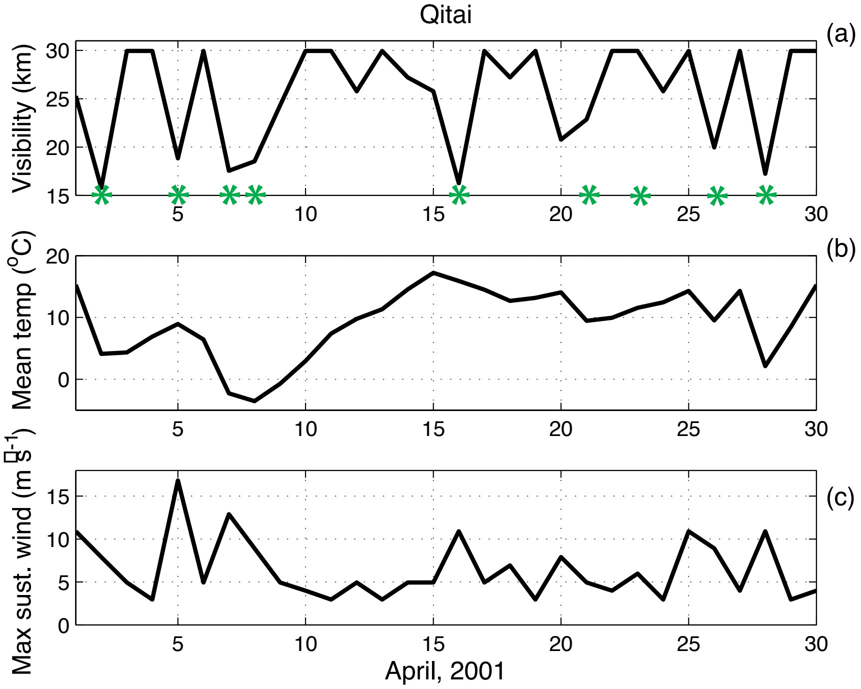

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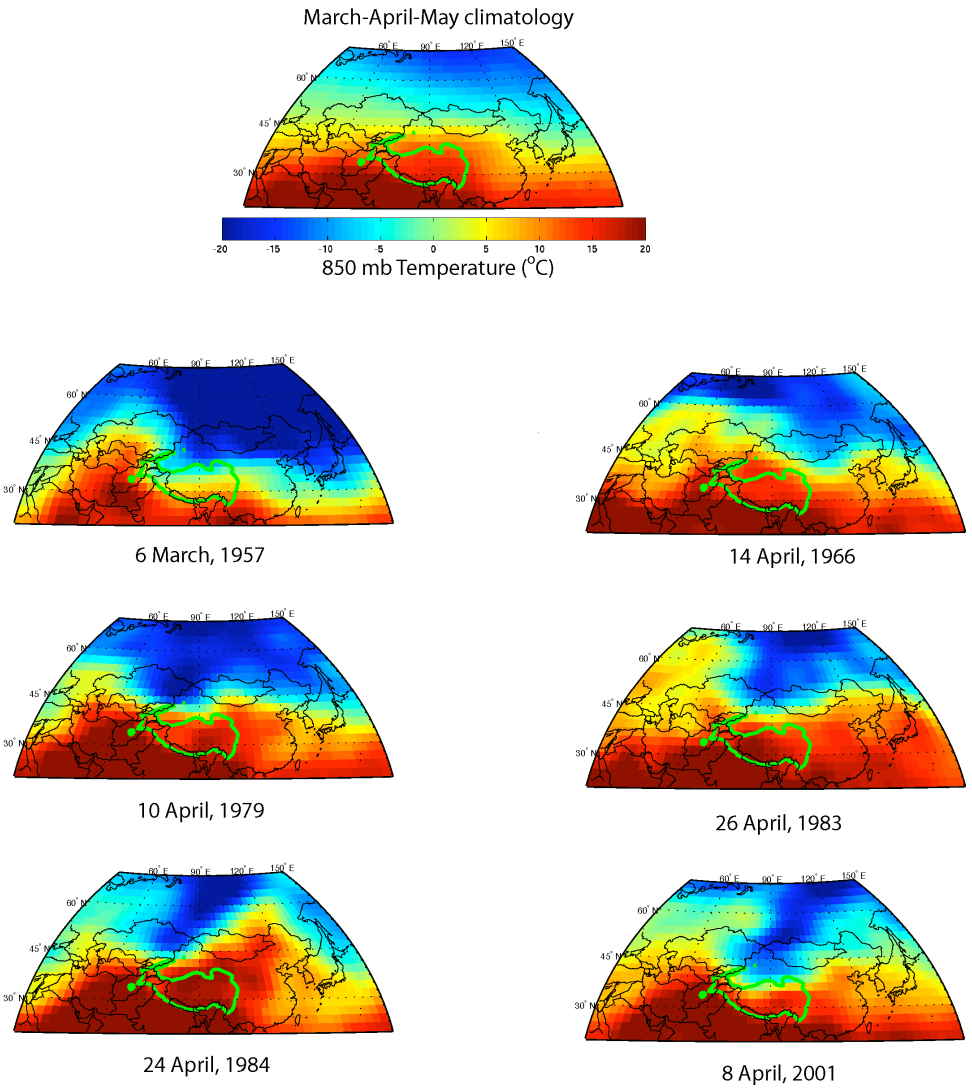

6 March, 1957

14 April, 1966

10 April, 1979

26 April, 1983

24 April, 1984

8 April, 2001

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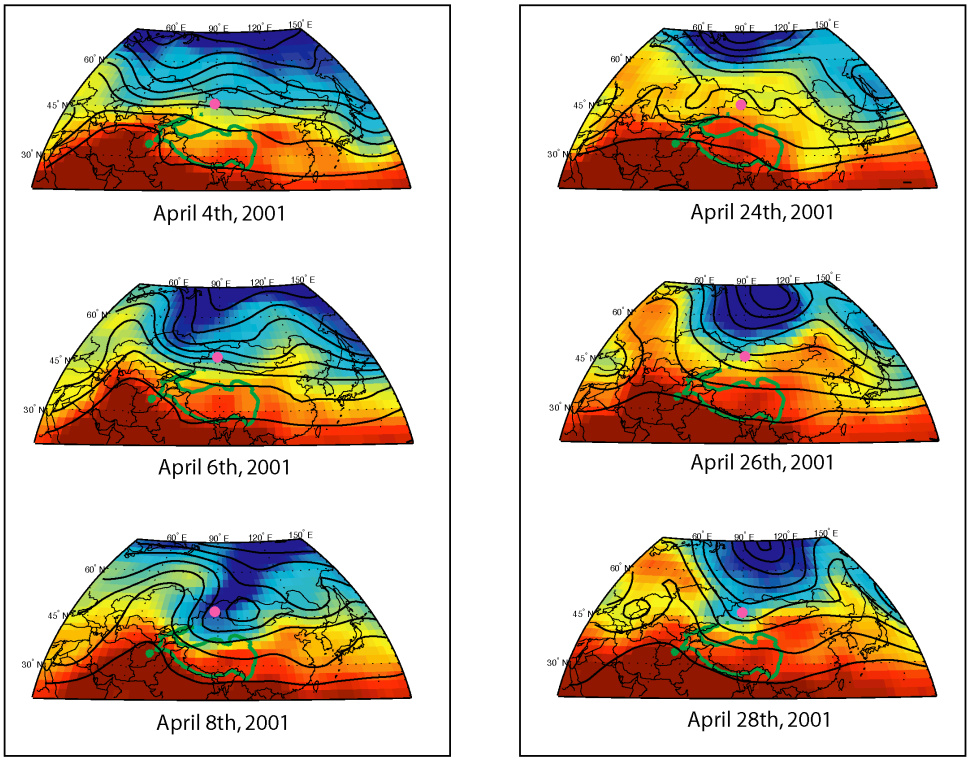
April 4th, 2001

April 6th, 2001

April 8th, 2001

April 24th, 2001

April 26th, 2001

April 28th, 2001

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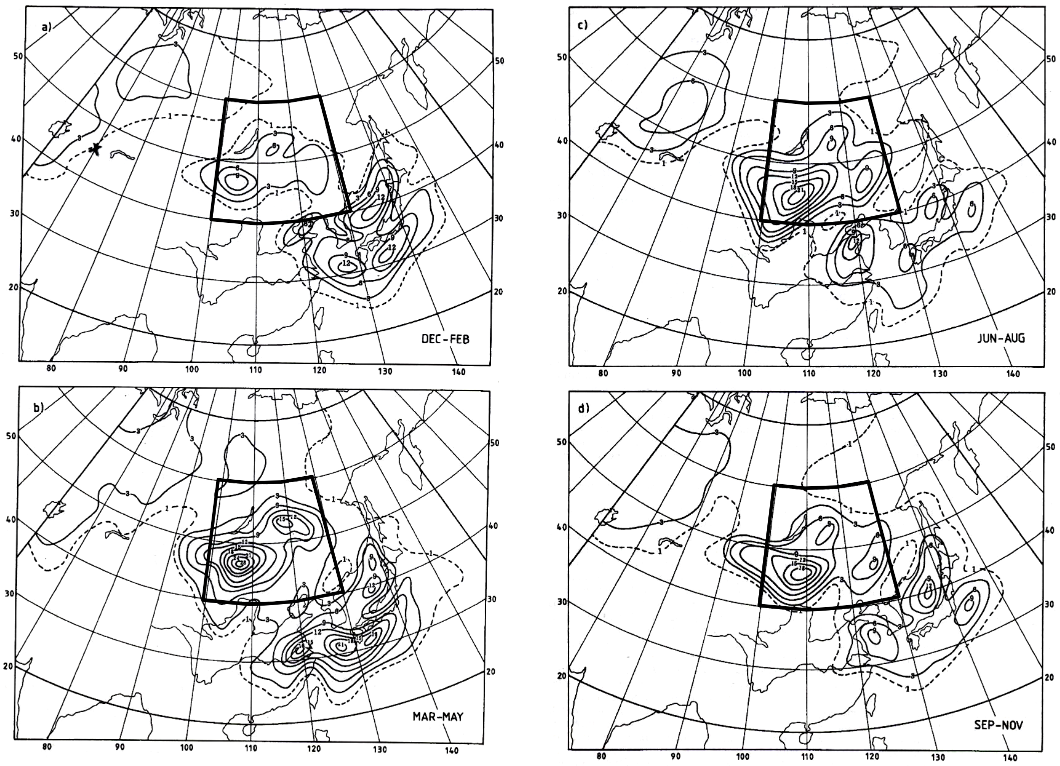

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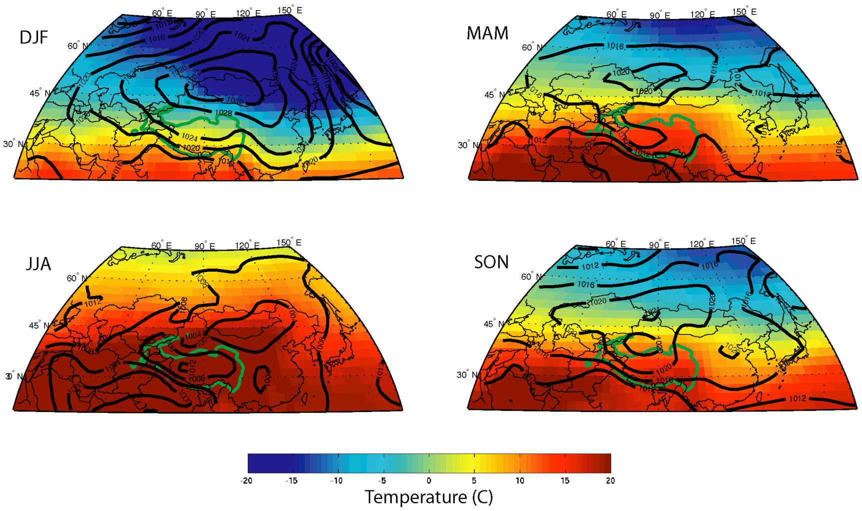

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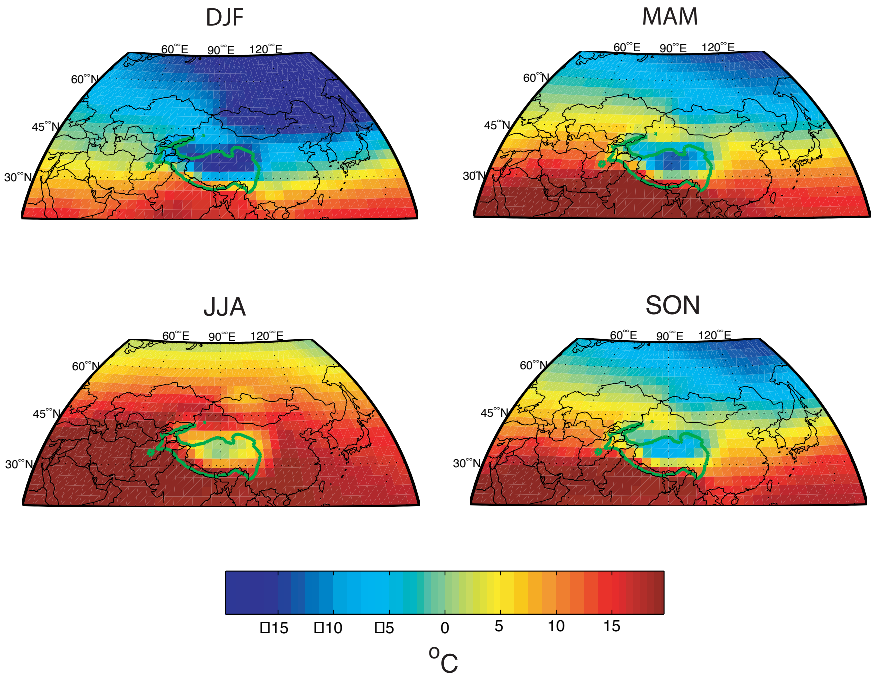

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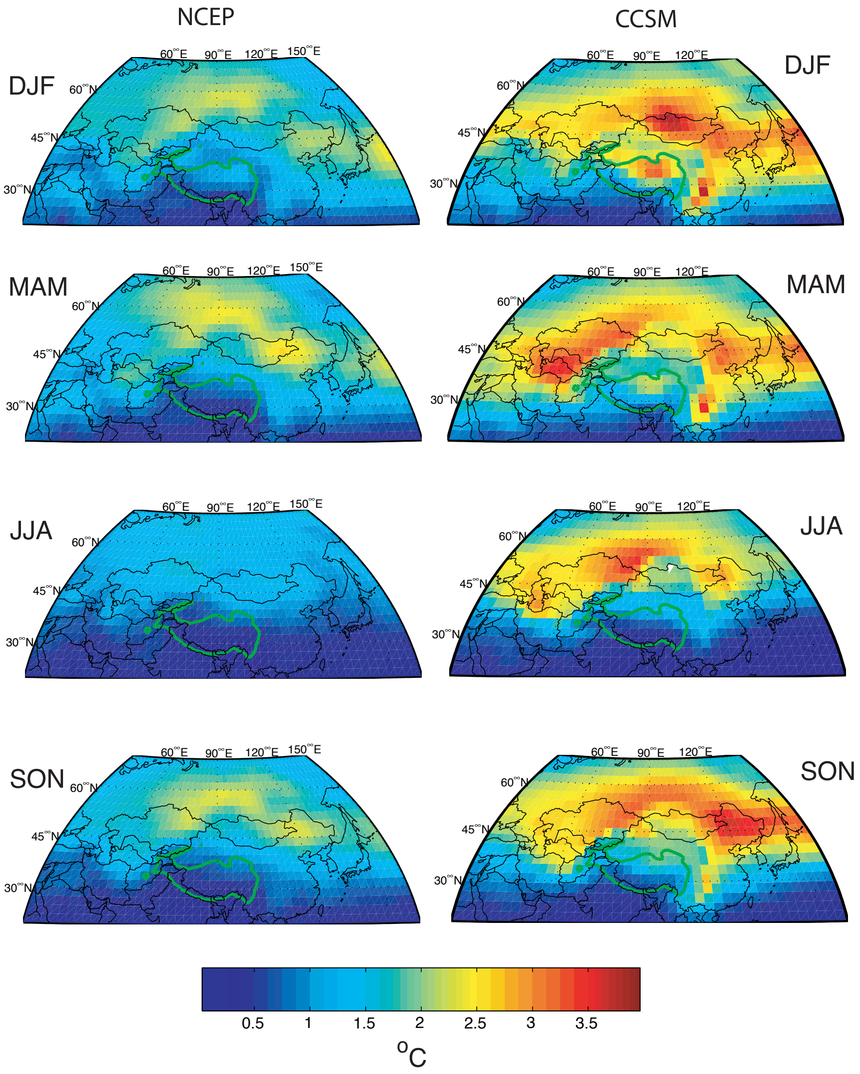

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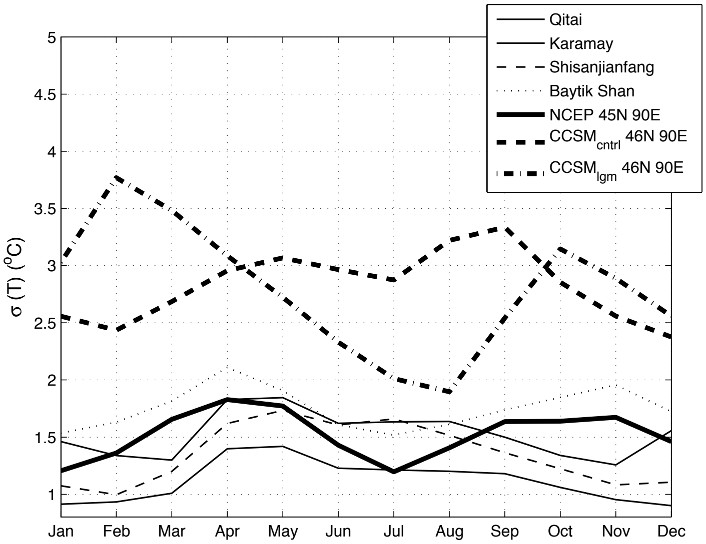

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