NOTES AND CORRESPONDENCE

A Southward Migration of Centennial-Scale Variations of Drought/Flood in Eastern China and the Western United States

QI HU AND SONG FENG

Climate and Bio-Atmospheric Sciences Group, School of Natural Resource Sciences, University of Nebraska at Lincoln, Lincoln, Nebraska

13 March 2000 and 10 August 2000

ABSTRACT

Several studies of the established warm season climate records for eastern China (1470–1997) showed alternating dry and wet periods at centennial scales. The spatial patterns show that when a dry condition or drought was observed in southern China, a wet or flood situation was found in the northern part of eastern China and vice versa. These patterns suggest a meridional variation of the centennial-scale wet/dry anomalies.

This study analyzed the same data and showed that the dry and wet anomalies initially appeared in the northern part of eastern China and then migrated southward to affect the low latitudes. An extension of this analysis to the United States revealed a similar southward migration of dry/wet anomalies that first developed in the high latitudes in the western part of the country. The average speed of the migrations in both areas is about 3.0° of latitude per 10 years.

The results suggest that mechanisms in mid- and high latitudes may play critical roles in the development of drought in high- as well as subtropical-latitude regions. The findings also indicate key areas to monitor for prediction of extended periods of frequent droughts or floods in ''downstream'' regions in the migration of the centennial-scale anomalies.

1. Introduction

The index data of warm season (May–September) rainfall in eastern China were developed from historical documentary sources and instrumental records for the time period 1470–1997 (Wang and Zhao 1981; Yao 1982; Ronberg and Wang 1987). Many studies have examined these data to understand historical climate conditions and climate evolution in China (e.g., Hameed et al. 1983; Clegg and Wigley 1984; Zhang and Crowley 1989). These studies revealed multidecadal to centennial-scale climate variations in eastern China. They also showed that the largest fraction of the variation energy in decadal to centennial scales is concentrated in variations with periods of about 85 and 130 years (Hameed et al. 1983; Clegg and Wigley 1984). An empirical orthogonal function (EOF) analysis of the spatial structure of these centennial-scale variations further disclosed a pattern showing that the northern section of the region had below (above) average rainfall when the southern part of the region was wet (dry) (Wang and Zhao 1981).

This spatial structure of the centennial-scale variations of wet and dry conditions in eastern China prompts us to speculate that the variations may have resulted from propagation of such variations in the area after they initially developed in either the southern or northern part of eastern China. This paper reports results from an examination of this hypothesis using previously published data.

2. Data and analysis

The climate data used in this analysis contained five-scale dryness/wetness intensity values from 120 stations in a historical network in eastern China for the period 1470–1997 (Wang and Zhao 1981; Peking University et al. 1981). The data at each station take a value of 1, 2, 3, 4, or 5, which represents very wet, wet, normal, dry, and very dry, respectively, for the period May–September in each of the 528 years. These data were developed using rainfall amounts from ancient Chinese documents. When observations became available in the late nineteenth century, measured rainfall in the months of May–September was used in calculating the intensity index values. Details of the validation method and the procedure for converting the observed rainfall into consistent dryness/wetness intensity values were docu-

Corresponding author address: Qi Hu, School of Natural Resource Sciences, Institute of Agriculture and Natural Resources, P.O. Box 830728, University of Nebraska at Lincoln, Lincoln, NE 68583-0728.
E-mail: qhu2@unl.edu

mented (Peking University et al. 1981; Zhang and Crowley 1989). Statistical properties, for example, consistency and persistency, of this data series have been carefully examined and established (Yao 1982; Ronberg and Wang 1987).

In this study, we used the dryness/wetness data from 65 of the 120 stations in the network (see Fig. 2 for distribution of the stations). These 65 stations cover eastern China and have few reported missing data. The remainder of the 120 stations is sparsely scattered in northeastern and western China.

Data from each of the stations were used to calculate the parameter value H (Zhang and Crowley 1989), defined as

$$H = \frac{2F}{F + D}, \tag{1}$$

where F is the number of the index values of 1 and 2 in a 10-yr period starting from the year 1470, and D is the number of index values of 4 and 5 in the same 10-yr period. A larger value of H corresponds to a higher frequency of floods, thus, a wet condition in a 10-yr period; a smaller value of H indicates a lower frequency of flood occurrence, hence a drier condition in the 10-yr period.

After obtaining the stations' H series, we grouped the stations into different bins, each of which covers a 2.5° latitude band starting from 40.0°N at the northern boundary moving southward to the southern boundary of the domain, and calculated the average H ($\overline{H}$) in each bin. This grouping method is justified by the latitudinal quasi-uniformity in the distribution of the dryness/wetness variations shown by the EOF analysis of the data (Wang and Zhao 1981).

The mean of $\overline{H}$ in each bin was removed from the 528-yr series, and $\overline{H}$ values were further divided by the standard deviation of the $\overline{H}$ series. This normalized $\overline{H}$ series for each bin was then padded at both ends using the autoregressive moving average (ARMA) model to extend the time series in order to minimize the edge effect on analysis results. From the prepared $\overline{H}$ series, the centennial-scale variations of droughts in the region were obtained after an application of the binomial band filter with cutoff frequencies at 1/50 to 1/190 cycle per year. The spatial migration of variations in this filtered time series was identified by the phase lag of the variations between adjacent latitudinal bins.

This analysis method was also applied to the gridded Palmer Drought Severity Index (PDSI) data covering the contiguous United States for the period 1700–1979 (Cook et al. 1997). A similar H was defined in which the PDSI greater than 1 were used for counting F and those smaller than -1 for counting D in (1). A similar analysis procedure was applied to this H series to get $\overline{H}$ for the United States. Because of the relatively short PDSI data series (279 yr), we applied a binomial filter to remove only the variations of periods shorter than 50 years after padding the $\overline{H}$ series using the ARMA model.

We understood that this PDSI data series was short for the analysis. The purpose of this extension was to examine whether similar spatial variation features identified in eastern China exist in the western United States, whose climate conditions are under similar influences from the equatorial and northern Pacific basin (Wallace and Gutzler 1981; Nitta and Hu 1996; Overland et al. 1999).

3. Results and discussion

Figure 1a shows the variation in $\overline{H}$ for eastern China in a time–latitude frame and features a southward migration of the extended dry and wet periods over 528 years. In the process, an anomaly of dryness (light shaded area) or wetness (dark shaded area) started in northern China and then migrated southward to affect the low-latitude regions. For instance, a dry condition developed in northern China in the late fifteenth century and early sixteenth century then spread to southern China. While migrating southward, the dry condition in northern China weakened and was later replaced by another wet anomaly. Soon after the wet condition developed and was established in northern China, it, too, migrated southward. The wet anomaly swept through central and southern China when another new dry center was developing in northern China.

There also were irregularities in the southward migration of the anomalies. For example, in the pair of dry and wet anomalies from 1470 to 1580, a separate center of anomalies of the same kind also appeared around 26°N with a tendency of moving northward. Another irregular event occurred in 1740. A wet center started around 37°N and moved to the higher latitudes. Although these irregularities exist, 9 out of 10 major events developed initially in northern China as summarized in Table 1. These dry and wet conditions recurred alternately in northern China and migrated to central and southern China in the following decades and centuries.

Our analysis confirmed that the temporal variation of the time series plotted in Fig. 1a consists of the 85- and 130-yr variations, which were identified in early studies (Wang and Zhao 1981; Hameed et al. 1983; Clegg and Wigley 1984) as the significant centennial-scale valuations. Figure 1a indicates further that the latter of the two variations dominated before the eighteenth century, and the former variation became prominent after a transition period in the eighteenth century. Both variations migrated southward. The average migration speed of the nine major southward migrating events is about 3.0° of latitude per 10 years, with the events in recent centuries moving a little faster than those prior to the eighteenth century.

We repeated the same analyses described previously using reassembled subsets of $\overline{H}$ series. This statistical test showed the same southward migration of centennial variations of dryness/wetness in eastern China. These

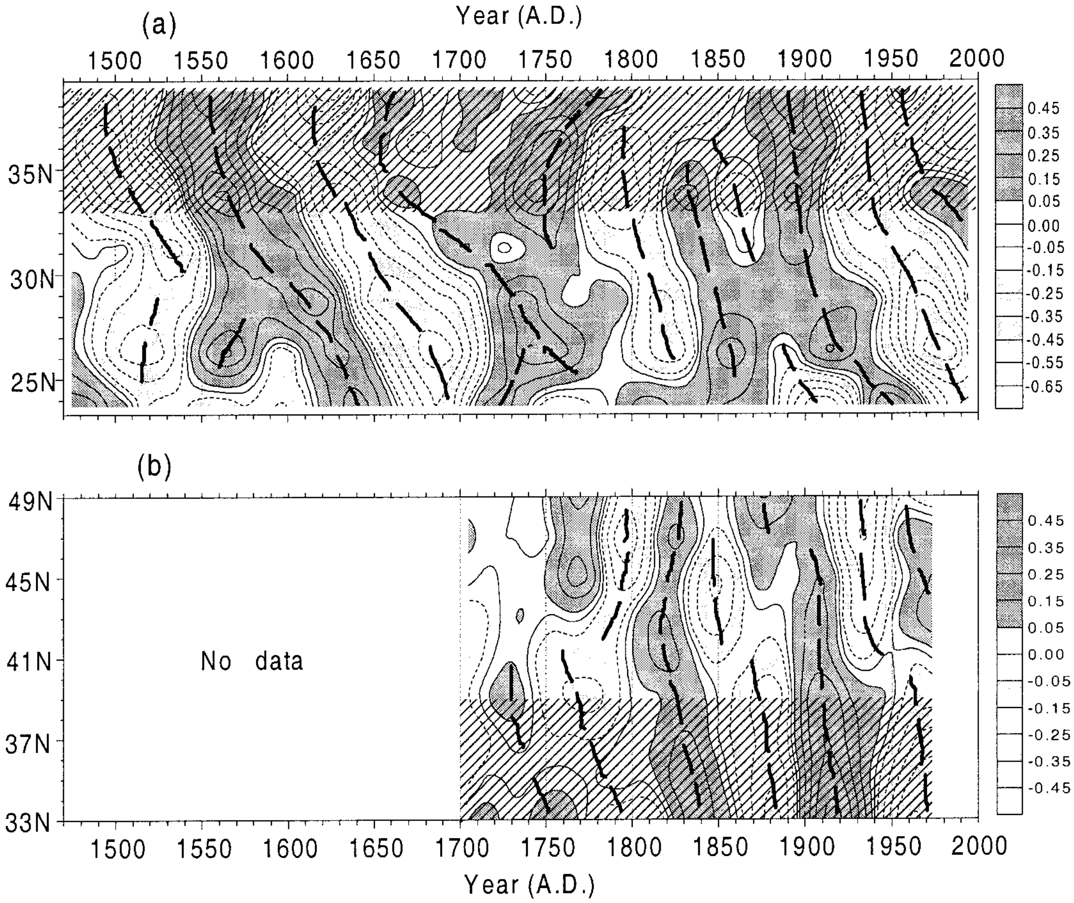

FIG. 1. (a) Time–latitude section of variations of dryness/wetness in eastern China. Dark shaded areas indicate wet, light shaded is for dry, and white is for neutral (normal) conditions. (b) Same as (a) but was derived from the PDSI data for the western United States. The stippled areas are latitudinal regions shared by these two study areas.

reassembled $\overline{H}$ series were different subsets of the original $\overline{H}$ series. They were developed by randomly removing stations in a 2° longitudinal bin between 108° and 124°E and then recalculating H and then $\overline{H}$ in the same latitudinal bins. Plots of these subsets of $\overline{H}$ showed a meridional structure similar to the one shown in Fig. 1a.

These test results confirmed the presence of the southward migration of the dry/wet anomalies in eastern China. Furthermore, a variance analysis showed that the variation associated with the centennial-scale variations migrating southward explained 35%–85% of the total variance of the H time series in each station (Fig. 2). This variance ratio was obtained by comparing the variance of variations in the band of 50–190 years and the variance of the original H time series. This result indicates the persistence and assures the significance of the centennial-scale variations and their southward migration in the region's wetness/dryness variations.

The distribution of the wet/dry anomalies in recent few decades (Fig. 1a) showed a dryness developing in northern China and a center of wetness migrating to the Yangzi River basin in southern China. This development may explain the frequent severe summer droughts in northern China, where the Yellow River has suffered flow interruptions in the early summer months for the past 30 years and damaging summer floods in south-

TABLE 1. Summary of the migration of centennial dry/wet anomalies in eastern China. Lightface rows in the table are dry events and boldface rows are wet events. (Because of the limitation in data coverage, the time and latitude are limited to the region studied.)

	Cases	Beginning time (decade)/ lat (°N)	Ending time (decade)/ lat (°N)
Southward moving	1	1490s/38	1530s/31
	2	**1550s/38**	**1640s/24**
	3	1620s/38	1680s/25
	4	1790s/37	1820s/25
	5	**1820s/34**	**1860s/25**
	6	1850s/34	1900s/24
	7	**1890s/38**	**1950s/24**
	8	1920s/38	1990s/24
	9	**1950s/38**	**1990s/31**
Northward moving	1	1510s/26	1530s/30
	2	**1740s/31**	**1780s/37**

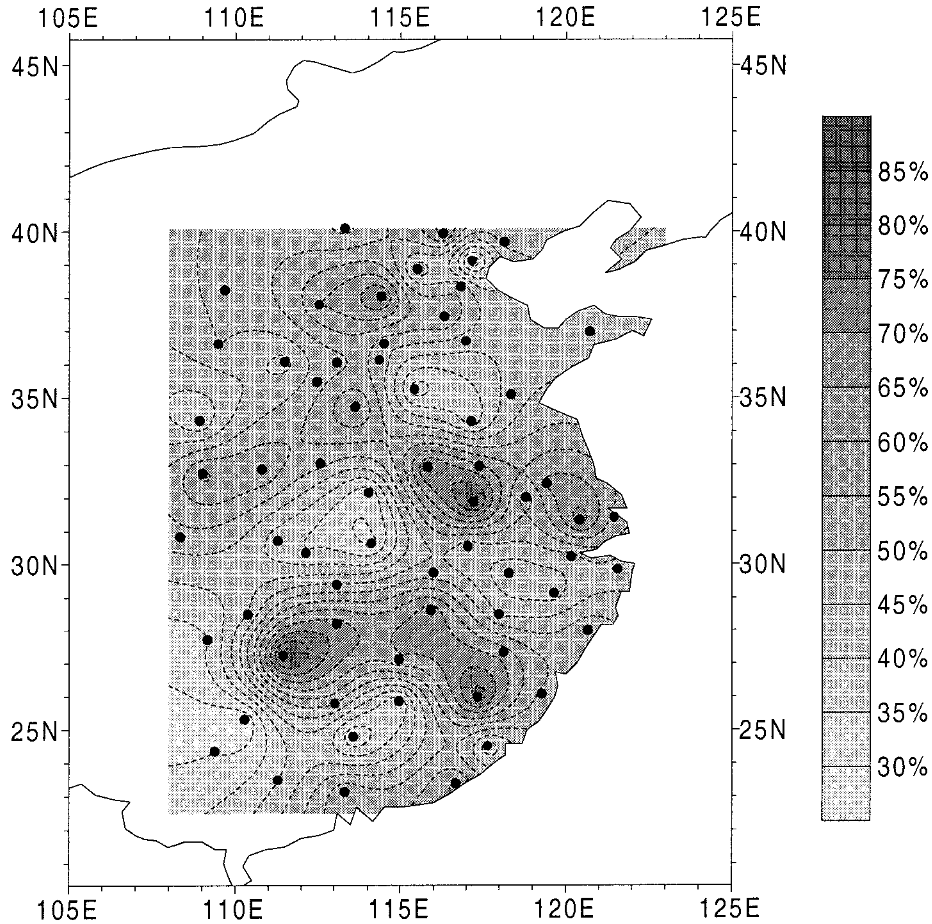

FIG. 2. Percentage of variance in the total variance explained by centennial-scale variations shown in Fig. 1a.

central and southern China in the same decades (Nitta and Hu 1996; Huang and Wang 1996).

We extended the same analysis and testing procedure described previously to the United States using the PDSI data developed from tree-ring chronology by Cook et al. (1997). [The tree-ring chronology data are different from the wet/dry index derived from the Chinese precipitation records. The latter is purely based on rainfall while the former includes effects of temperature anomalies (Hu and Willson 2000). Therefore, the *H* derived from the PDSI will be limited to dryness and wetness in the perception of the PDSI.] The data cover the 279-yr period from 1700 to 1978. We found a similar southward migration of centennial-scale dry/wet conditions in the United States west of the longitude 107.5°W. We found no propagations related to centennial-scale variations of dry/wet conditions in the central and eastern United States. This result was consistent with the difference in the dryness/wetness variations between the western United States and the central and eastern United States, indicated by our EOF analyses of the PDSI data. The EOF analysis results showed that the leading EOF of the PDSI has two variation centers, one in the western United States and the other in the eastern United States separated near the meridian 107.5°W.

The southward migration of dry/wet anomalies in the western United States is illustrated in Fig. 1b. Similar to the result shown in Fig. 1a, a dry condition first developed in the northern part of the western United States and then migrated southward to low latitudes. A wet anomaly replaced the dry anomaly in the northern region after the dry anomaly moved to the low-latitude areas. Table 2 summarizes the events in the variations. Except for a couple of minor irregular cases moving northward, the majority of the events appeared in the high-latitude region and migrated to the south. The average migration speed of these events is close to 3.0° of latitude per 10 years, similar to that in Fig. 1a. Analyses using subsets of this dataset confirmed the persistency of the southward migration.

The latitudinal coverages of the study in eastern China and in the western United States are different because of the different latitudinal span of the two countries and the availability of the data. Nevertheless, there are 6° overlapping latitudes in the two regions (stippled areas in Figs. 1a and 1b). In these shared latitudinal belts,

TABLE 2. Summary of the migration of centennial dry/wet anomalies in the western United States. Lightface rows in the table are dry events and boldface rows are wet events.

	Cases	Beginning time (decade)/ lat (°N)	Ending time (decade)/ lat (°N)
Southward moving	**1**	**1720s/40**	**1750s/33**
	2	1770s/39	1790s/33
	3	**1820s/42**	1840s/33
	4	1840s/48	1880s/33
	5	**1880s/49**	**1920s/33**
	6	1930s/49	1960s/33
	7	**1960s/48**	**1970s/42**
Northward moving	1	1770s/39	1790s/49
	2	**1820s/42**	**1830s/49**

there are similar features of the centennial-scale variations in wetness/dryness and their migrations.

The migration results in the western United States suggest a nearly out-of-phase distribution of the dry/wet anomalies in the northern and southern sections. The influence from this variation may explain the climate records that show that the southwestern United States had a relatively wet period in the first half of the twentieth century (Meko et al. 1995; D'Arrigo and Jacoby 1991; Haston and Michaelsen 1997), while the northwestern United States was in frequent droughts during the same time. From the 1950s to the 1980s, the northwestern United States became relatively rainy while the southwest suffered frequent, severe droughts (Graumlich 1987).

4. Conclusions

Using published 528-yr records of dryness/wetness intensity in eastern China, we found that the previously identified centennial-scale (85 and 130 yr) variations of the dry/wet conditions (droughts/floods) are not in synchronicity between northern and southern China. Instead, the anomaly of dryness/wetness often developed in the northern part of eastern China and then migrated southward at about 3.0° of latitude per 10 years to affect the low-latitude regions. This result was confirmed by statistical tests using different subsets of the same data, which suggest the robustness of the southward migration. A similar southward migration was also found in a shorter data series of PDSI for the western United States.

A dry condition and frequent severe droughts have prevailed in northern China for about 30 years. Interruption of the Yellow River's flow in early summer months was recorded almost every year in the period (Yao et al. 1999). In the meantime, floods reoccurred in summer seasons in southern China (Nitta and Hu 1996).

Several recent studies have investigated possible causes of this persistent anomalous climate pattern in eastern China. Xue's (1996) modeling experiments suggested that land surface changes resulting particularly from overgrazing and desertification in Mongolia and Inner Mongolia in northern China in recent decades could be a cause of the dryness in northern China. A modeling study by Huang and Wang (1996) suggested that the anomalous climate pattern in eastern China was caused by midlatitude dryness that resulted from increasing amounts of CO_2 in the atmosphere (Manabe et al. 1981; Wetherald and Manabe 1995). Our study indicates that the natural centennial-scale variations of dry/wet anomalies and their associated southward migration could be another explanation of the observed persistent anomalous climate pattern in eastern China.

The initial appearance of dry or wet anomalies in the mid- and high-latitude regions in eastern China and the western United States and the subsequent southward migration of these anomalies to the subtropical regions suggest that the persistent dry/wet anomalies in low latitudes originate in the high-latitude regions. From the perspective of centennial-scale variations, there are indications that subtropical low-latitude droughts/floods may have appeared first in the higher latitudes. We eventually may be able to predict development of similar anomalies in mid- and even low-latitude regions by monitoring the dry/wet anomaly development in the high-latitude regions in these areas.

Acknowledgments. We thank Professor M. Tang for engaging in helpful discussions with us and Drs. D. Wedin, R. Diffendal, D. Wilhite, and M. Rohrke for their comments that led to improvements of this manuscript. The review and comments of Dr. Francis Zwiers and two anonymous reviewers are appreciated. This work was supported by the USGS Global Change Program through Cooperative Agreement 1445-CA09-95-0069 with the University of Nebraska at Lincoln, and by USDA Cooperative Research Project NEB-40-008.

REFERENCES

Clegg, S. L., and T. M. L. Wigley, 1984: Periodicities in precipitation in north-east China, 1470–1979. *Geophys. Res. Lett.,* **11,** 1219–1222.

Cook, E. R., D. M. Meko, and C. W. Stockton, 1997: A new assessment of possible solar and lunar forcing of the bidecadal drought rhythm in the western United States. *J. Climate,* **10,** 1343–1356.

D'Arrigo, R. D., and G. C. Jacoby, 1991: A 1000-year record of winter precipitation from northwestern New Mexico, USA: A reconstruction from tree-rings and its relationship to El Niño and the Southern Oscillation. *Holocene,* **1,** 95–101.

Graumlich, L. J., 1987: Precipitation variation in the Pacific Northwest (1675–1975) as reconstructed from tree-rings. *Ann. Amer. Assoc. Geogr.,* **77,** 19–29.

Hameed, S., W. M. Yeh, M. T. Li, R. D. Cess, and W. C. Wang, 1983: An analysis of periodicities in the 1470 to 1974 Beijing precipitation record. *Geophys. Res. Lett.,* **10,** 436–439.

Haston, L., and J. Michaelsen, 1997: Spatial and temporal variability of southern California precipitation over the last 400 years and relationships to atmospheric circulation patterns. *J. Climate,* **10,** 1836–1852.

Hu, Q., and G. D. Willson, 2000: Effects of temperature anomalies on the Palmer Drought Severity Index. *Int. J. Climatol.,* in press.
Huang, R. H., and H. J. Wang, 1996: Observational facts and simulation of the climate and environmental changes in eastern China due to global warming. *Global Environmental Security,* Y. Suzuki, Ed., Springer-Verlag, 112–134.
Manabe, S., R. Wetherald, and R. J. Stouffer, 1981: Summer dryness due to an increase of atmospheric carbon dioxide concentration. *Climatic Change,* **3,** 347–386.
Meko, D. M., C. W. Stockton, and W. R. Boggess, 1995: The tree-ring record of severe sustained drought. *Water Resour. Bull.,* **31,** 789–801.
Nitta, T., and Z. Hu, 1996: Summer climate variability in China and its association with 500 hPa height and tropical convection. *J. Meteor. Soc. Japan,* **74,** 425–445.
Overland, J. E., J. M. Adams, and N. A. Bonf, 1999: Decadal variability of the Aleutian low and its relation to high-latitude circulation. *J. Climate,* **12,** 1542–1548.
Peking University, Central Meteorological Institute, Nanking University, 1981: *The Drought and Flood Charts of China from 1470 to 1979.* Atlas Press, 332 pp.
Ronberg, B., and W. C. Wang, 1987: Climate patterns derived from Chinese proxy precipitation records: An evaluation of the station networks and statistical techniques. *J. Climatol.,* **7,** 391–416.
Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in geopotential field during Northern Hemisphere winter. *Mon. Wea. Rev.,* **109,** 784–812.
Wang, S. W., and Z. C. Zhao, 1981: Droughts and floods in China, 1470–1979. *Climate and History,* T. M. L. Wigley, M. J. Ingrasham, and G. Farmer, Eds., Cambridge University Press, 171–288.
Wetherald, R. T., and S. Manabe, 1995: The mechanism of summer dryness induced by greenhouse warming. *J. Climate,* **8,** 3096–3108.
Xue, Y. K., 1996: The impact of desertification in the Mongolian and the Inner Mongolian grassland on the regional climate. *J. Climate,* **9,** 2173–2189.
Yao, C. S., 1982: A statistical approach to historical records of flood drought. *J. Appl. Meteor.,* **21,** 588–594.
Yao, W., Y. Zhao, L. Tang, and S. Li, 1999: Preliminary study on no-flow disaster in the lower reaches of Yellow River. *Adv. Water Sci.,* **10,** 160–184.
Zhang, J., and T. J. Crowley, 1989: Historical climate records in China and reconstruction of past climates. *J. Climate,* **2,** 833–849.