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An Improved Method to Derive Surface Albedo from Narrowband AVHRR Satellite Data: Narrowband to Broadband Conversion

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CHANGES IN DRYNESS/WETNESS IN CHINA DURING THE LAST 529 YEARS

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ABSTRACT

Historical written records of weather conditions that affect agriculture and living conditions in China can serve as a proxy for instrumental observations of the relative wetness and dryness, or precipitation amounts, for periods of time dating back to at least AD 1470. The dryness/wetness index (DW) data at 100 selected sites and at a subset of 25 sites with entirely continuous data indicate that during the growing season the number of sites with dryness increased rapidly in the 20th century, in contrast to a gradual increase and levelling off of wetness since the 18th century. Dry conditions existed mostly in northeastern China in the 16th and 17th centuries. In the 20th century, dryness prevailed in most areas in China, and the chance of occurrence at each site increased. Wet conditions have expanded from east coastal areas to inland since the 19th century. As a result of increased dryness and wetness, the number of sites experiencing normal precipitation conditions has dropped dramatically. The number of sites with extreme dryness/wetness has also increased during the 20th century, and the spatial distribution of the sites with a large chance of extreme dryness/wetness has also changed. The frequent occurrences in dryness/wetness as well as in extremes in the 20th century seem indicative of an abnormality in climate on a large scale. Spectral analyses of the DW data has revealed that cycles in dryness/wetness and their extremes have existed with periods on relatively short time scales as well as on the long time scales. The possible existence of a century-scale cycle suggests that caution should be used in relating variations in rainfall conditions to global warming. Copyright © 2000 Royal Meteorological Society.

KEY WORDS: historical data; dryness/wetness; extreme events; climate change; China

1. INTRODUCTION

Changes in global climate caused by increased CO_2 concentrations have been simulated by numerous model experiments. The results show that changes in both the mean climate and the nature of extreme events may occur (e.g. Houghton *et al*., 1990; Fowler and Hennessy, 1995). Extreme events have received increasing attention because changes in the variability and frequency of the extreme events could have a great impact on socioeconomic activities (e.g. Bernard, 1993; Mearns *et al*., 1997).

Recent droughts and floods in various regions of the world might be representative of the extreme events that appear to be occurring with greater frequency. The question arises whether the increases in the extent of dryness and wetness and their extremes is a false impression generated by the improved observations and communications. The possibility that the world is now undergoing a period of significant climatic shift has stimulated the study of the climate and weather of the past (e.g. Karl *et al*., 1995). A report by the Department of Environment in the UK (Department of Environment, 1996) indicated that climate change might already be occurring because of the number of years with unusually warm conditions during the past decade. However, reliable instrumental observations of meteorological phenomena are available for only a small fraction of the Earth's climate, and inferences from the observations can hardly be conclusive in describing low-frequency climate variations. In the USA, precipitation and temperature records are mostly available only since the late 19th century. Using these data, Karl *et al*. (1996) quantified observed changes in climate within the contiguous USA by development and analysis of a Climate Extremes Index, which is an aggregate set of conventional indicators of climates. Karl *et al*. found that the climate of the USA has become more extreme in recent decades but

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that, without information on longer time-scale variations, the magnitude and persistence of the changes are not large enough to conclude that the climate has systematically changed to a more extreme state. To extend the knowledge of climate into the past, climatologists have used various proxy data, such as observations of pollen, tree-ring, and isotopes in sediments and ice cores. For example, Lough and Fritts (1985) used North American tree-ring data available since AD 1600 to examine the past Southern Oscillation Index (SOI). A variety of proxy data can be used to study climate change.

China has a long documented history and occupies a large area. Climate data in China are highly correlated with the data from other Northern Hemisphere land areas (Bradley *et al*., 1984; Lough *et al*., 1984; Wang *et al*., 1984). Climatic phenomena in China such as floods, droughts, and the Asian monsoon are strongly influenced by interactions between the atmosphere and the tropical oceans, and they are closely linked with the global climate system (Lough *et al*., 1984; Wang and Li, 1990; Fu, 1993; Cole, 1994; Yan, 1994; Song, 1998; Fu *et al*., 1999). For example, Fu *et al*. (1999) found that greater aridity in subtropical land areas in the 1920s is related to a rapid increase of global mean surface temperature during this period, through a lessening of atmospheric baroclinicity. Thus, it is possible that long-term historical records in China could provide valuable indications on climatic fluctuations over a large portion of the Northern Hemisphere. Previous studies on climate change in China have either used precipitation records available in the recent century to study the relationship with other observed variables, such as sea-surface temperature, or have used long-term proxy data to infer the long-term climate variations. Extreme variations in climate and the associated distribution patterns have not been studied in detail. The objective of this study is to examine possible climate change in terms of temporal and spatial variations of dryness/wetness and their extremes by using the longest and spatially largest data sets available.

2. DATA

Droughts and floods are associated with blocking atmospheric circulations that tend to occur in the summer. In many kinds of Chinese historical writings, climate descriptions related to agricultural production are of great value for studying climate fluctuations (see e.g. Wang and Zhao, 1981; Shi and Zhu, 1996; Smit and Cai, 1996). The generation of annals for local geographical and governmental units expanded greatly in the 15th century and usually included descriptions of weather conditions relevant to agriculture and living conditions. Using materials from more than 2200 local annals and many other historical writings, climatologists in China have compiled an atlas, *Yearly Charts of Dryness/Wetness in China for the Last 500-Year Period* (State Meteorological Science, 1981). In the atlas, the territory of China was divided into 120 regions, and the dryness/wetness index (DW) for each year at each region was classified into five categories to represent overall climate records from spring to autumn (Table I). Definition of the indices considered severity as well as the temporal and spatial scale of the dryness/wetness. Extremely wet conditions (DW = 1) were associated with substantial flooding, and extremely dry conditions (DW = 5) were associated with severe drought, both of which were probably often accompanied by agricultural disasters and mass movements of people from one region to another. Less extreme conditions but still significant departures from ideal agricultural conditions were represented by moderately wet (DW = 2) and moderately dry (DW = 4) conditions. Normal precipitation conditions (DW = 3)

Table I. Classification of dryness/wetness from historical data at each site

Index	Description
1	Extremely wet, long-lasting/intense precipitation over large areas
2	Wet, single season moderate lasting precipitation locally
3	Normal, good harvest, no record of flood or drought
4	Dry, single season moderate drought locally
5	Extremely dry, long-lasting severe drought over large areas

were presumably ideal for existing agricultural practices. In all cases, only one designation per year was given, resulting in a general description of the dominance of wet or dry conditions occurring over the whole growing season, but with emphasis on the summer season when different dryness/wetness occurred at early or late growing season.

The number of sites recording observations each year varied considerably, gradually rising from 44 sites near the end of the 15th century to about 100 sites in 1950. If no records of dryness/wetness for a site were found in the documentation for less than 3 years, the DW of the site was interpolated based on the DW of the neighbouring sites with consideration of distance to the site. No indices were assigned or interpolated if records were not available for more than 3 years. For the years after 1951, when the use of rain gauges became widespread, the indices were estimated from precipitation measurements made between May and September, and DWs according to the criteria listed in Table II. For the instrumental observations made between 1951 and 1990, Yan (1994) obtained a very high correlation coefficient between the reconstructed DW series and the corresponding rainfall observations. This high correlation implies that the historical DW series adequately represents the variation of growing season rainfall. Since the publication of the atlas (State Meteorological Science, 1981), the DW data for 1470–1979 have been used effectively to study climate (e.g. Wang and Zhao, 1981).

For this study, 100 sites were selected for use, none of which were the sites that had missing records of more than three consecutive years. Twenty-five of the 100 sites that had no missing data were selected as a special subset. Figure 1 shows the geographic distribution of the sites. Most of the 100 sites are located in eastern China, around the Yellow River and the lower reaches of the Yangtze River, where most of the agricultural lands and population in China were located. This study uses both the original atlas data from AD 1470 to 1979 (State Meteorological Science, 1981) and the rain gauge records that have been continuously classified into DW at the end of September in each year since 1979 by the State Meteorological Administration Center in China. Thus, DW data for 529 years (AD 1470–1998) are analysed. The focus of the study is on examining the temporal and spatial variations of dryness/wetness and their extremes over the last five centuries as well as detecting possible periodicities, especially long ones. Data from the 25 sites are examined to evaluate the potential deficiencies caused by the data being missing at times for up to 3 years for the 100 sites.

3. DATA ANALYSIS AND RESULTS

The spatial distribution of the selected 100 sites as well as the 25 sites is fairly homogeneous in eastern China (Figure 1). Analyses are conducted here to detect trends in DWs in eastern China during 529 years and to examine spatial variations of conditions from century to century.

Table II. Classification of dryness/wetness from rain gauge data

Index	Standard
1	$R_i > (R + 1.17\sigma)$
2	$(R + 0.33\sigma) < R_i \leq (R + 1.17\sigma)$
3	$(R - 0.33\sigma) < R_i \leq (R + 0.33\sigma)$
4	$(R - 1.17\sigma) < R_i \leq (R - 0.33\sigma)$
5	$R_i \leq (R - 1.17\sigma)$

R_i, the total precipitation from May to September for each year i at the site; R, the climate average of the total precipitation from May to September during 1951–1979 at the site; σ, the standard deviation of the total precipitation from May to September during 1951–1979 at the site.

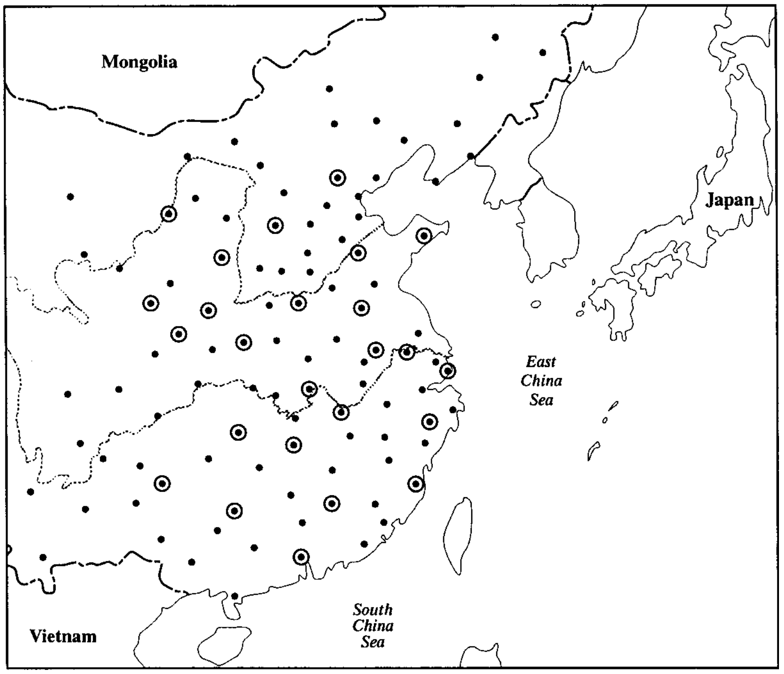

Figure 1. Geographic distribution of the selected 100 sites, of which 25 sites have the complete records (circled dot) and 75 sites have some limited missing records (dot)

3.1. Trends

To display the long-term trends of DW data from AD 1470 to 1998 for the 100 sites as well as the 25 sites, a moving average was performed on the number of sites that experienced (i) normal precipitation conditions (DW = 3), (ii) 'dryness' (dry and extremely dry conditions, DW > 3), or (iii) 'wetness' (wet and extremely wet conditions, DW < 3) in each year (Figure 2). Fifty-one years was selected as the averaging time period, because shorter averaging times resulted in excessive fluctuation, and longer averaging times tended to obscure potential trends. The results for both the 100 sites and the 25 sites showed similar long-term fluctuations and trends in the following aspects. First, the number of sites that experienced normal conditions decreased dramatically after the late 19th century, in comparison to a smaller drop in

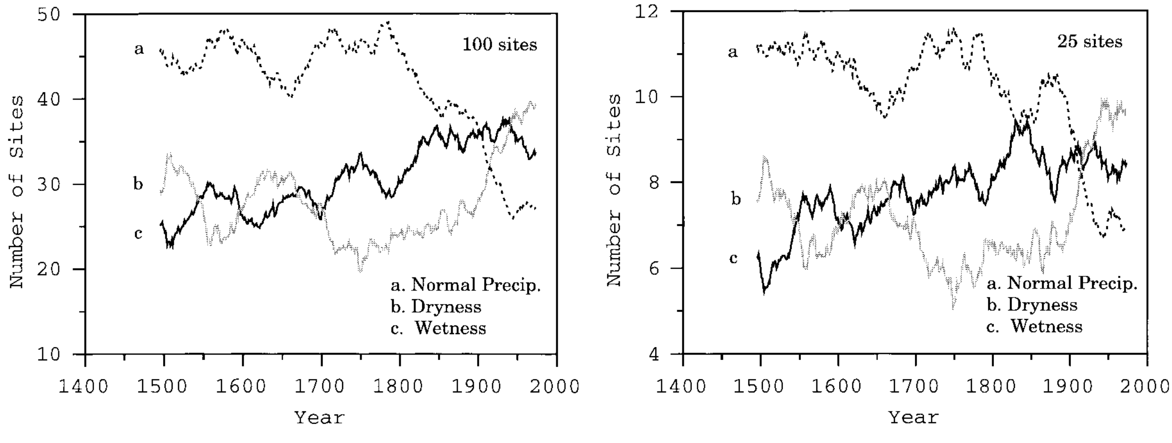

Figure 2. Fifty-one year moving averages of the number of sites that have experienced normal precipitation conditions (DW = 3), dryness (DW > 3), or wetness (DW < 3) since AD 1470, with results from the 100 sites (left), and results from the 25 sites with complete records (right)

the mid-17th century. Second, the numbers of sites that experienced wetness are comparable to the numbers of sites that experienced dryness during the 16th and 17th centuries. In the 18th and 19th centuries, however, more sites experienced wetness, and fewer sites experienced dryness. Finally, the gradual increasing trend of wetness halted after the mid-19th century, but the level of wetness remained fairly high thereafter. The number of sites that experienced dryness has been increasing quickly since the early 20th century for the set of 100 stations but less so for the 25 sites. Otherwise, little difference is detected in the trends of dryness/wetness of the 100-site data versus the 25-site data. Regression statistics in both data sets revealed significant positive slopes in trends of dryness and wetness conditions, and negative slopes in normal conditions. To further examine the similarity in trends for the two data sets, the numbers of sites with dryness/wetness were averaged over 25-year intervals, so that every value represented the average for a quarter of a century. The correlation coefficients between the two resulting time series were large: 0.94, 0.97 and 0.89 for normal, dryness, and wetness, respectively.

Figure 3 shows the temporal trends for extreme dryness (DW = 5) and extreme wetness (DW = 1). The 100-site and the 25-site time series have quite similar trends. Extreme conditions occurred at more sites in the early 16th and mid-17th centuries than during the 18th and 19th centuries. Starting in the early 20th century the number of sites that experienced extreme conditions increased significantly. The numbers of extreme-condition years averaged over discrete 25-year intervals were found to have very similar trends for the 100 sites versus the 25 sites. The correlation coefficients between the two interval-averaged time series were large: 0.91 and 0.89 for extremely dry and extremely wet conditions, respectively. Despite the high correlation, the relative magnitudes of the changes shows some differences in the 20th century; the number of extreme years for the 100-site time series increased slightly more than did the series for the 25 sites. Two reasons can be suggested to explain this difference. First is the effects of possible missing records coinciding with extreme events at some of the 100 sites, along with the difficulty of inferring extreme events by interpolation or extrapolation them from surrounding sites, especially in the earlier centuries. Because the definition of extreme dryness/wetness is for long-lasting events occurring over large areas (see Table I), however, extreme events are unlikely to be overlooked. Second is the possibility of an expansion or a shift in the spatial pattern of extreme dryness/wetness in the 20th century. Despite the relatively wide spatial scatter of the 25 sites that have the complete records, none of them is in the upper and middle reaches of the Yangtze River, and none in northeastern China (Figure 1). If more extreme events occurred in these areas in the 20th century, the increasing trends of the extreme events would not be fully reflected in the 25-site time series. To investigate this possibility, the temporal variations of spatial patterns in dryness/wetness and extreme dryness/wetness are examined next.

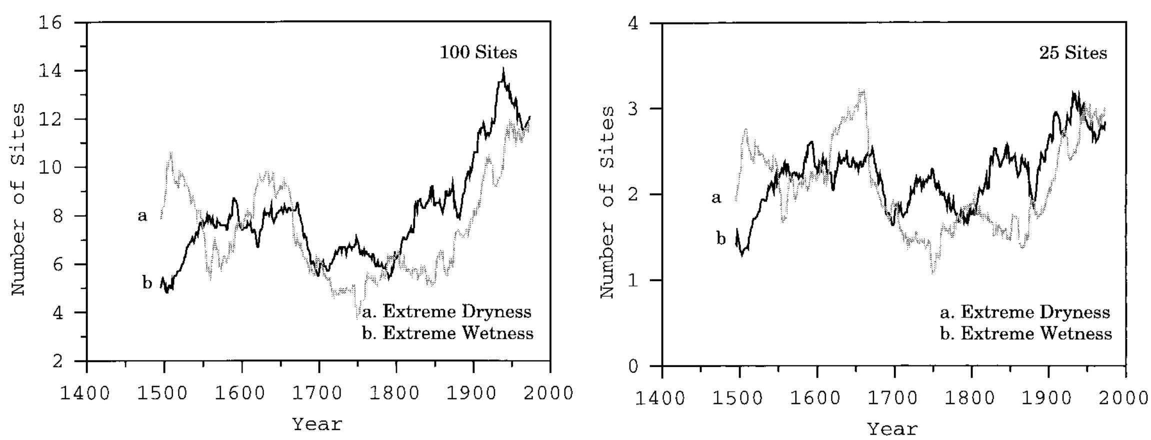

Figure 3. Fifty-one year moving averages of the number of sites that have experienced extreme dryness (DW = 5) or extreme wetness (DW = 1) since AD 1470, with results from the 100 sites (left), and results from the 25 sites with complete records (right)

3.2. Spatial patterns

Figures 4 and 5 show geographical distributions, all derived from the 100-site data set, of dryness/wetness and their extremes in each century. To construct these graphs, a simple contouring was applied based on the 'chance' of occurrence at each site, where the 'chance' is defined here as the percentage of years in each century with the appropriate value of DW.

Figure 4(A) indicates that dryness during the 20th century was considerably larger than in the previous four centuries, when dryness was mostly concentrated in the northern China and the distribution patterns varied little. The increase in the 20th century appears mostly as a spatial expansion of dryness in the northeast and southeast China, where large areas with a chance greater than 40% occurred. Figure 4(B) indicates that chance of wetness greater than 30% was along the east coastal areas before the 19th century and expanded to the west since then. A gradual expansion in 40% chance of wetness occurred before the 20th century in eastern China, especially along the middle reach of the Yangtze River. For the 20th century, the spatial patterns of areas with greater than 40% chance of wetness had shifted westward and northeastward, larger chances of wetness appeared in the northeastern China and along the upper and middle reaches of the Yangtze River.

Temporal variations in the geographical distributions of extreme dryness/wetness are illustrated in Figure 5. In the 16th and 17th centuries, a fairly frequent occurrence of extremely dry conditions existed in the northeastern China and along the lower reach of the Yellow River. But in the 18th and 19th centuries, evidence of extremely dry conditions was very limited. In the 20th century, the areas with greater than 10% chance of extremely dry conditions had expanded in northeastern China, along the Yellow River, and near the southern coast of China. Also, extremely dry conditions with a chance greater than 20% occurred in the northeast China and the middle reach of the Yellow River. The temporal changes in the patterns shown in Figure 5(A) suggest that the increase in extreme dryness shown in Figure 3 for the 100-site DW series for the 20th century can be explained mostly by an expansion of areas that experienced extreme dryness, not by a pattern shift. Furthermore, an increase in overall extreme dryness starting in the early 20th century is supported by the observed abrupt weakening in the South Asian summer monsoon and a rapid warming in the Northern Hemisphere (Fu, 1993).

In Figure 5(B), extremely wet conditions appear to have occurred sporadically and in fairly small areas from the 16th century to the 19th century. In the 20th century, the spatial distribution of extreme wetness was quite different from the previous four centuries in the way that extreme wetness with a chance greater than 10% occurred mostly in the northeastern China and along the Yangtze River. The highest frequency of chance greater than 20% for extreme wetness occurred to the north of the upper and middle reaches of the Yangtze River. The temporal changes in the patterns shown in Figure 5(B) suggest that the increase in extreme wetness for the 20th century seen in Figure 3 for the 100-site DW series can be explained mostly by an area expansion of the extreme wetness, but also partially by a change in pattern. For example, areas with a greater chance of extreme wetness appeared in the lower reach of the Yellow River in the 17th to 19th centuries than in the 20th century.

With the information available in Figures 4 and 5 on the temporal changes in spatial patterns of extreme conditions, the question that arises from Figure 3 can be better addressed on the larger increase in the number of sites that experienced extreme dryness/wetness in the 20th century with the 100-site data than with the 25-site data. That is, this difference can be explained mostly by a real increase in the number of the sites that experienced extreme dryness/wetness, especially the increases that occurred in areas not covered by the 25 sites (e.g. in northeastern China). One can not help but to think, however, that the general increases in extremes might have been caused at least in part by the transition of DW converted from using proxy records to using rain gauge data. According to Table II, the extreme wetness at each site is based only on the long-term average and standard deviation of site-specific precipitation data. Thus, some highly localized extreme wetness might have been recorded. On the other hand, the depiction of an increased extreme dryness in the 20th century is less susceptible to errors associated with the conversion from proxy to instrumental data, because drought is generally a large-scale phenomenon.

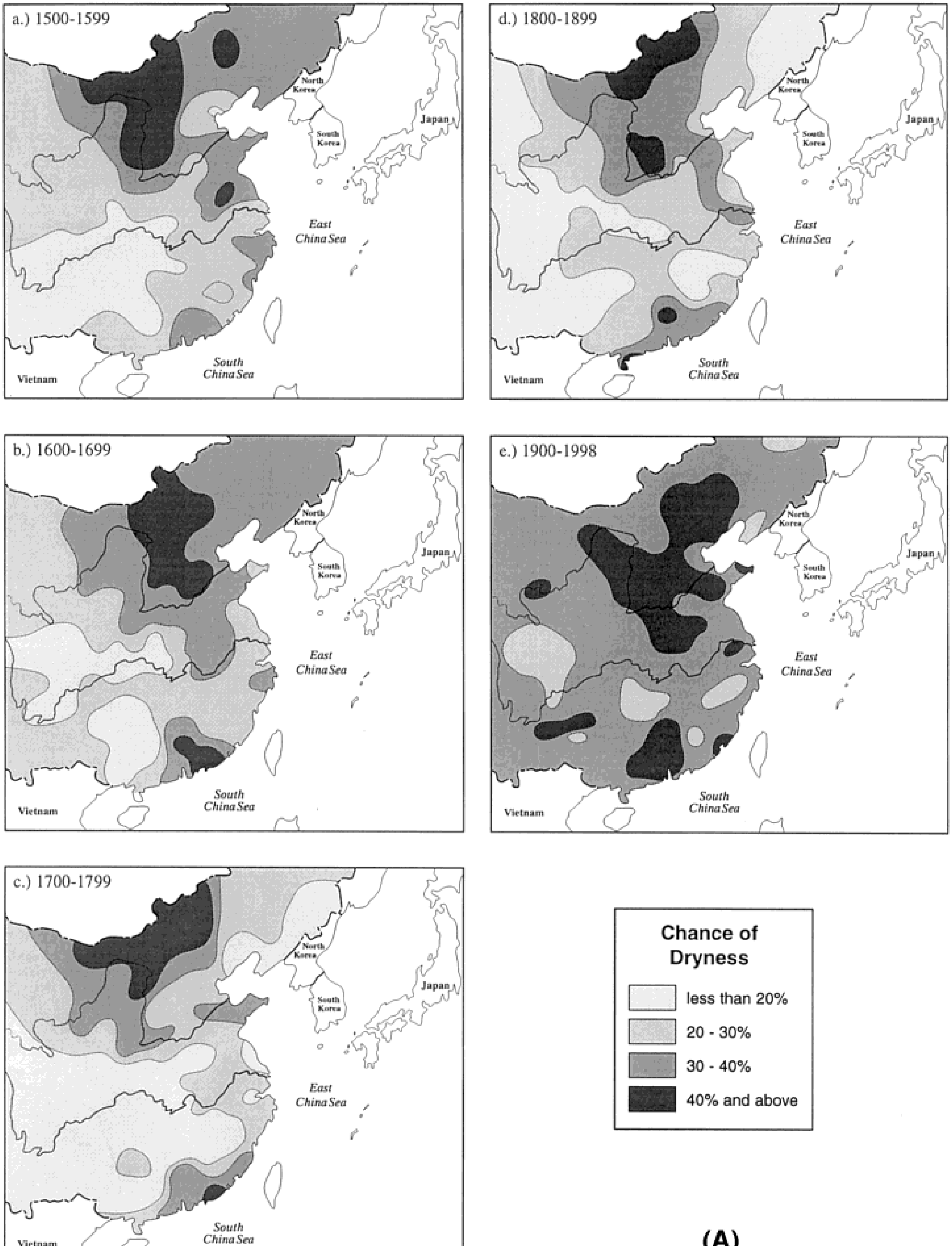

Figure 4. (A) The chance of dryness occurring in China, by century from AD 1500 to the present.

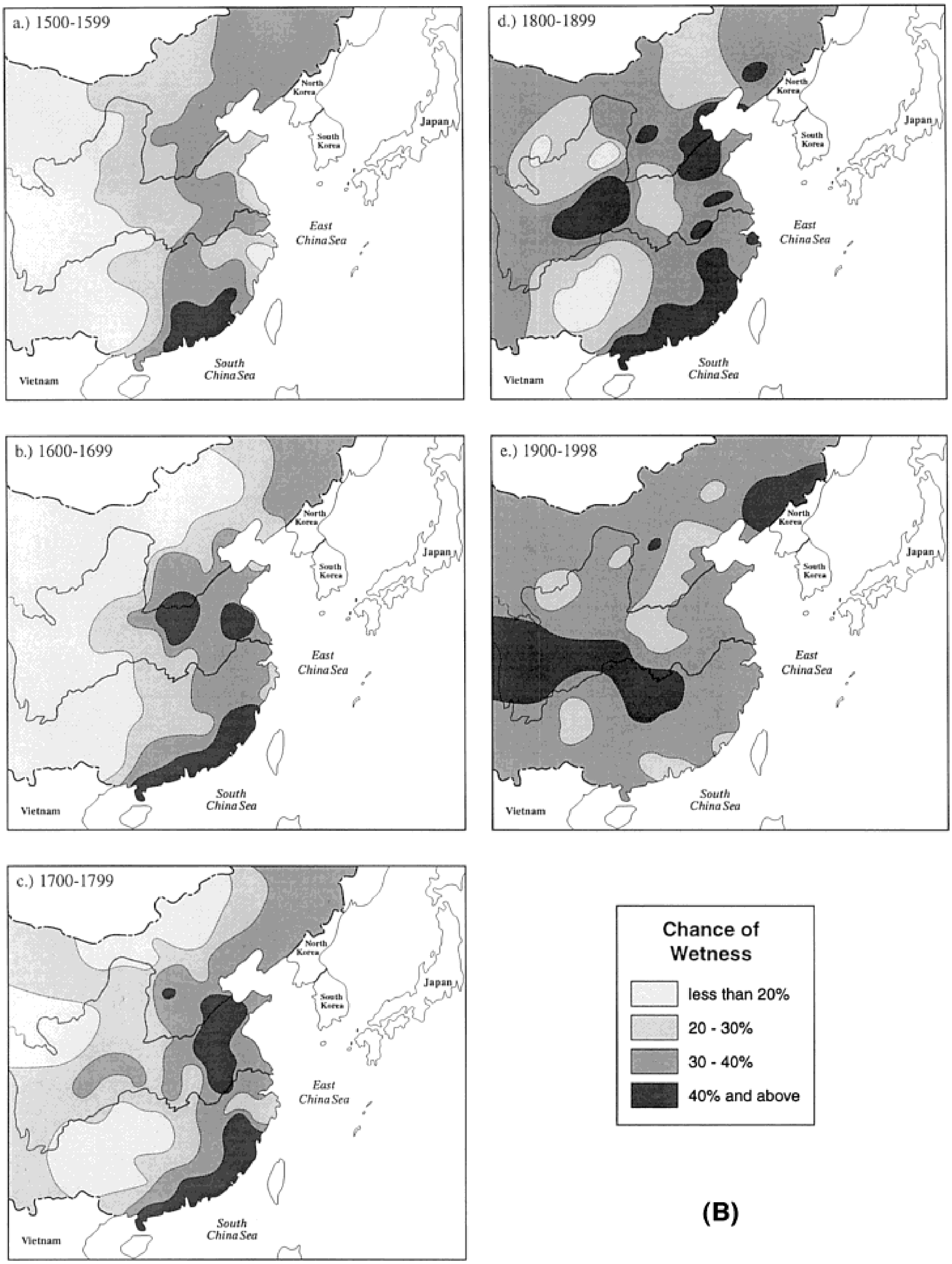

Figure 4. (B) The chance of wetness occurring in China, by century from AD 1500 to the present

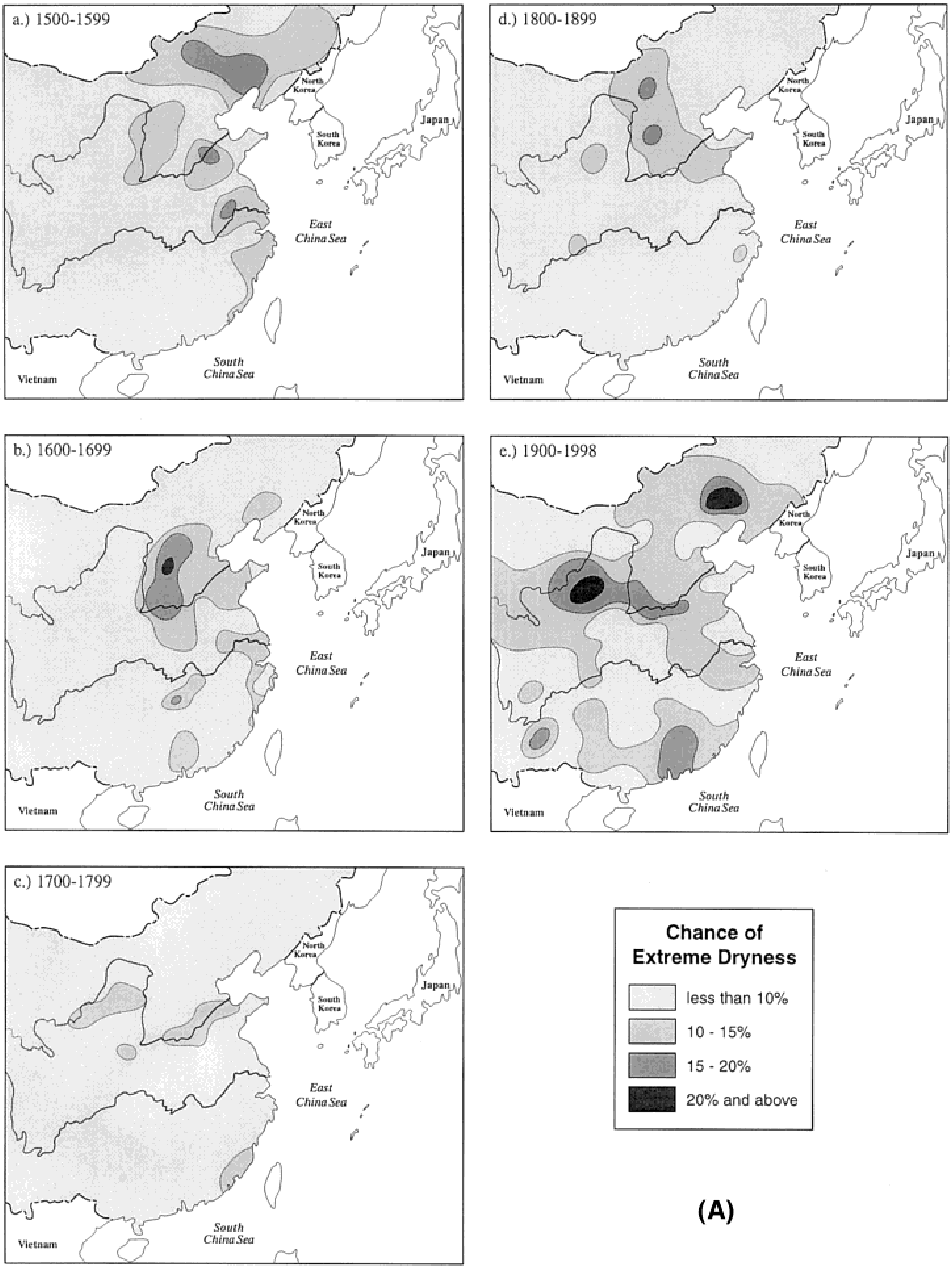

Figure 5. (A) The chance of extreme dryness occurring in China, by century from AD 1500 to the present.

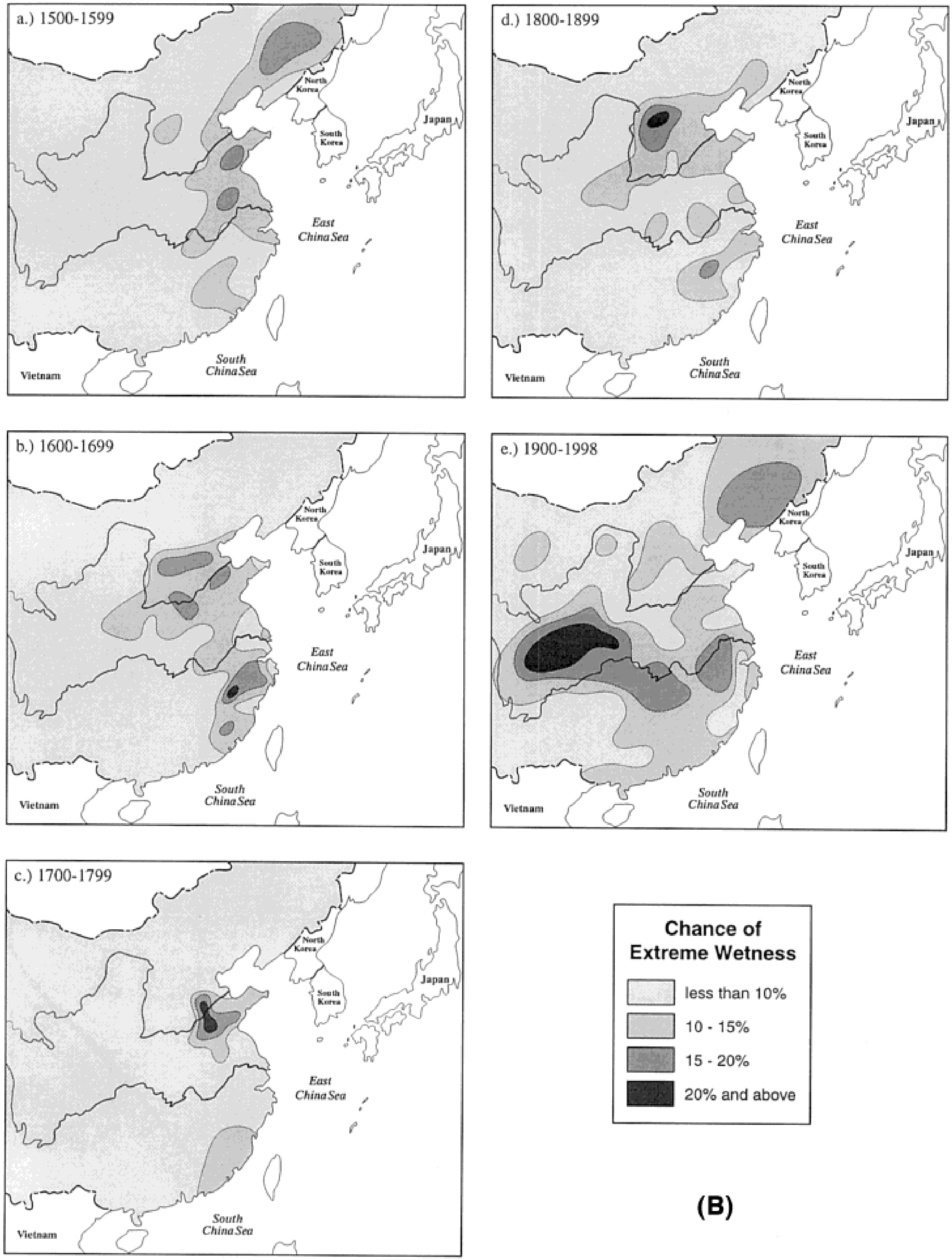

Figure 5. (B) The chance of extreme wetness occurring in China, by century from AD 1500 to the present

3.3. Periodicity of DW

The power spectrum of a data series can help one evaluate the time scales on which important variations in the data are occurring. The power spectrum analysis results shown in Figure 6, in which the squared amplitude of Fourier coefficients are plotted as a function of the frequency (or wave number), reveal several peaks significant at a confidence level of at least 95%. The maximum peaks correspond to time periods of 22 years in dryness (Figure 6(a)), 44 years in wetness (Figure 6(b)), 26.4 years in extreme dryness (Figure 6(c)), and 44 years in extreme wetness (Figure 6(d)). The significant cycles near 22 years in the occurrence of dryness and extreme dryness might relate to solar activity (Wang *et al.*, 1984). There is also considerable evidence to suggest that oceanic processes might be a good candidate for causes of decade-scale climate fluctuations (e.g. Manabe and Stouffer, 1997).

A peak at the relatively long cycle of 88 years appears in the occurrence of wetness in Figure 6(b). Because periodicity in spectral analysis is found as the ratio of the number of observations in a time series to wave number, and because only integer wave numbers can be found for periodicities, some of the periodicities in the data might not have been detected, especially the larger periodicities, For example, if a data record length is 528 years, the periodicities in spectrum analysis can be found with great precision only at years 528, 264, 176, 132, etc. Therefore, the 88-year cycle, which corresponds to wave number 6, shown in Figure 6(b) might be best interpreted as a cycle roughly on the century scale. Such long cycles can be found with less uncertainty when several centuries of data are available. For example, a 94-year

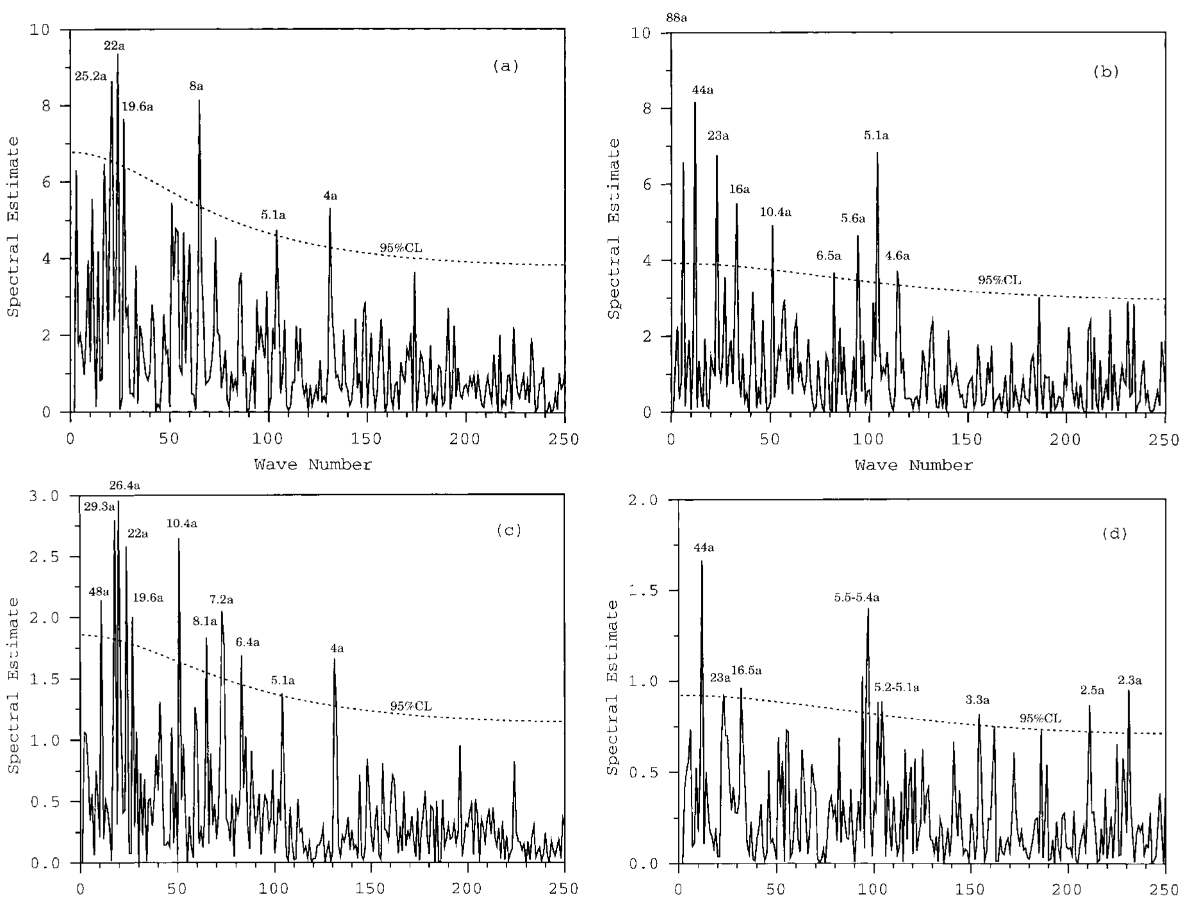

Figure 6. Power spectrum of the number of locations that experienced (a) dryness, (b) wetness, (c) extreme dryness, and (d) extreme wetness during AD 1470–1998. Periodicities that are above a 95% confidence level are labelled in the figure according to the year

cycle as well as smaller cycles of 27 and 41–50 years have been found for the ancient Chang-an region located in central China, where over 1604 years of DW records are available (Li and Quan, 1984).

4. DISCUSSION AND CONCLUSION

A 529-year DW data set based on Chinese historical writings and precipitation records during the growing season at 100 sites were used to examine the long-term trends of climate and the spatial patterns of dryness and wetness. Dryness occurred fairly frequently in the early 16th century and 17th centuries, and was distributed mostly in northeastern China. Dryness occurred less frequently during the 18th and 19th centuries. In the early 20th century, the occurrence of dryness increased rapidly, from less than 30 sites per year to nearly 40 sites per year, and the number of sites influenced by dryness remained high through the rest of the 20th century. Correspondingly, the high chance of dryness covered much more area in the 20th century than in the previous centuries. A gradual increase in wetness occurred in the 18th and 19th centuries, and it has not changed much since then. The areas with a high chance of wetness expanded, and higher-chance areas gradually shifted from the east coastal areas of China to inland, along the Yangtze river and northeast China after the 18th century. In contrast, normal precipitation has been experienced by fewer sites after the 18th century. The 20th century has seen an increase in both extreme dryness and wetness. The contention that the departures of dryness/wetness from climatological averages increased dramatically in the 20th century is supported by the analysis of 100 sites in China.

One difficulty with the data from sites for which short-term missing records were replaced by interpolation is that the frequency of unusual dryness or wetness might have been underestimated. That is, without direct observation at a particular location, the task is difficult to identify a departure from normal conditions that is greater than the departures at surrounding sites where observations are made. The departures are probably more difficult to infer when as they become stronger. Because the definition of extreme dryness and extreme wetness is for long-lasting events occurring over large area, however, they are unlikely to be ignored by various records if they did occurr. Furthermore, the comparison of the data sets between the 100 sites and the 25 sites (with no missing records) in dryness and wetness has shown strong similarities and consistent trends.

Part of the rapidly increasing trends in extreme dryness/wetness in the 20th century might be an artifact of differences in deriving DWs from the proxy data versus from rain gauge records, which were used as the sole source of precipitation information for the years since 1951. The DWs from instrumental records were determined for individual sites and did not depend on records from surrounding sites, which were considered in deriving DWs from the proxy data. This procedure may result in more extremes, such as some localized flooding, affecting the DWs based on instrumental records. But this is less likely to have an influence on extreme dryness, because drought is usually a large-scale climate phenomenon.

A dramatic increase in air temperature in the Northern Hemisphere has been detected in the early 20th century by various studies, and the association between the rapid increase of arid areas in China during the same period has been identified. The present study shows that the trend in dryness in China continued to increase during the last several decades. Further evidence of this increased dryness is that the number of days with no discharge from the Yellow River has been increasing every year (Brown and Halweil, 1998). The present study also shows that the increased wetness established in the 19th century has not declined. Such findings suggest that the interannual and spatial variability in dryness/wetness and their extremes are now large in China. Yan (1994) found that the interannual variability of wetness/dryness in China is increased during warm periods. Simulations of precipitation in a doubled-CO_2 atmosphere by global climate models suggest some increase in summer precipitation in northeast China (e.g. Thompson and Pillared, 1995). The results from the present study also see an increase in wetness and extreme wetness in northeast China. In all of these considerations, the existence of very long cycles in natural climate variability suggests that caution is needed in attributing recent changes in rainfall conditions to global warming.

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