A spatial analysis of pan evaporation trends in China, 1955–2000

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[1] Pan evaporation, an indicator of potential evaporation, has decreased during the last several decades in many parts of the world. This trend is contrary to the expectation that global warming will be accompanied by an increase in terrestrial evaporation, known as the pan evaporation paradox. In this paper we present an analysis of changes in the spatial patterns of pan evaporation in China based on data from 85 weather stations from 1955 to 2000. We found that pan evaporation decreased in China from 1955 to 2000. The decrease was statistically significant in all of China's eight climatic regions except northeast China. We also found that the decrease in solar irradiance was most likely the driving force for the reduced pan evaporation in China. However, unlike in other areas of the world, in China the decrease in solar irradiance was not always accompanied by an increase in cloud cover and precipitation. Therefore we speculate that aerosols may play a critical role in the decrease of solar irradiance in China. By subdividing China into eight climatic regions, we found that the rate of decrease in pan evaporation was highest in the northwest and lowest in the southwest. Although changes in solar irradiance are the main cause of decreasing pan evaporation, water conditions influence the sensitivity of pan evaporation to the change in solar irradiance in comparing the eight climatic regions. Thus the spatial trends of pan evaporation differ from those of solar irradiance among these regions. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 1818 Hydrology: Evapotranspiration; 1878 Hydrology: Water/energy interactions; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); *KEYWORDS:* pan evaporation, trends, China

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1. Introduction

[2] During the past half century, pan evaporation, measured by pan evaporimeters and commonly taken to represent potential evaporation, has decreased over the United States and former Soviet Union [*Peterson et al.*, 1995] and India [*Chattopadhyay and Hulme*, 1997]. The decline in pan evaporation is at odds with the expectation that global warming caused by increasing emissions of greenhouse gasses would increase potential evaporation. There are two interpretations of the possible cause of the observed decline in pan evaporation. One explanation is that the decrease in pan evaporation is consistent with widespread decreases in solar irradiance received on the Earth's surface resulting from increasing cloud coverage and aerosol concentrations. In this view, the decline in solar irradiance is seen as the main cause of the decline in pan evaporation, as it is for the decrease in diurnal temperature range [*Peterson et al.*, 1995; *Cohen et al.*, 2002; *Roderick and Farquhar*, 2002]. It is also taken as a sign of decreasing terrestrial evaporation [*Peterson et al.*, 1995].

[3] Another interpretation holds that there is a complementary relationship between actual evaporation and pan evaporation. From that perspective, the decrease of pan evaporation is seen as a sign of increasing terrestrial evaporation: increased terrestrial evaporation will increase moist air over the evaporation pan, thus reducing evaporation from the pan [*Brutsaert and Parlange*, 1998; *Lawrimore and Peterson*, 2000; *Golubev et al.*, 2001]. At present these competing explanations remain controversial. Additional data and analysis will be necessary to explain the mechanisms behind the widely observed decline in pan evaporation and its implications for understanding the influence of climate change on the global hydro-cycle.

[4] The purpose of this paper is to present a new analysis of the trends of pan evaporation over the past half century in China, on a regional basis and for the country as a whole. We compare pan evaporation measurements with other climate parameters such as mean, minimum, and maximum temperature; solar irradiance; water vapor pressure; cloud cover; relative humidity; and precipitation. In our analysis we explore the possible causes

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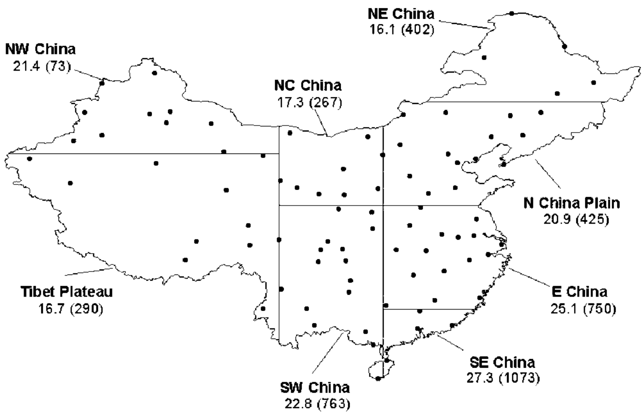

Figure 1. Eight climatic regions in China and the spatial distribution of the 85 weather stations used in this study with the warm season (May–September) air temperature (°C) and precipitation (mm, in parentheses) for each climatic region.

of changing pan evaporation rates, considering these alternative explanations.

2. Data and Analysis Procedures

2.1. Data

[5] Data for this study were provided by the China Meteorological Administration from 85 stations across China for the period of 1951–2000. The stations are well distributed across China including the Tibetan plateau. Measurements include pan evaporation, daily precipitation, mean temperature, maximum temperature, minimum temperature, water vapor pressure, cloud cover, relative humidity, and solar irradiance. The water vapor pressure was calculated based the measured relative humidity and the estimated saturation vapor pressure which was determined by air temperature. Temperature and relative humidity were measured four times a day (at 0200, 0800, 1400, and 2000 h), and the daily mean water vapor pressure was obtained by averaging the four vapor pressure measurements. Daily mean water vapor pressure and relative humidity were processed and included in the historical data sets of the Climate Data Center (CDC) under the China Meteorological Administration.

[6] We took several steps to ensure the quality and consistency of the data used in this study. We found that in the earliest years of this data set (1951–1954), measurements for some stations are inconsistent or missing for more than 20 consecutive days, so this period was excluded. Measurements for the period of 1955–2000 were made using the same standards and instrumentation at all stations, ensuring the homogeneity of data quality. Cases of missing data were found as late as 1960; for the period of 1955–1960, 15 stations reported missing data for some number of days between May and September, accounting for less than 0.1% of all measurements. No station reported missing data for more than 8 consecutive days, nor for more than 45 total days in the study period. Where data were missing for fewer than 3 consecutive days, we used a direct interpolation method to estimate the missing observations. For 3 or more consecutive days with missing data, we estimated the missing values using the stepwise regression method with all other stations with valid values for those dates. The regression results were good for all measurements and stations with missing observations, with R^2 values >0.95 for most regression equations; the minimum R^2 value was 0.82.

2.2. Analysis Procedures

[7] We began our analysis by calculating for each station the seasonal (May to September) means of daily mean temperature, maximum temperature, minimum temperature, water vapor pressure (e_a), cloud cover, relative humidity (Rh), vapor pressure deficit (VPD), and solar irradiance (R) as well as seasonal total precipitation and pan evaporation during the warm season months (May–September). We calculated VPD based on the daily mean water vapor pressure and relative humidity reported in the CDC's data sets as VPD = e_a (100 − Rh)/Rh. We then computed regional averages for each parameter and each of China's eight climatic regions. The eight regions are defined by latitude and longitude but coincide roughly with China's socioeconomic macroregions [*Qi et al.*, 2004]. Regional values for each parameter were calculated as the unweighted arithmetic average of these values for all stations in each region. The results for China as a whole were derived from these averaging the values for these eight climate regions, weighted by the land area of each region. Figure 1 shows the locations of weather stations and the average warm season temperature and precipitation, 1955–2000, for the eight climatic regions. We computed the trend of each parameter with linear regressions for each of the regions and for the country as a whole. The time series of pan evaporation was compared with other parameters to estimate the relative influence of climate parameters on pan evaporation.

3. Results and Discussion

3.1. Changes of Pan Evaporation

[8] For China as a whole, pan evaporation decreased over the past half century (Figure 2). The decline is statistically significant (at the 99% level). The downward trend of pan

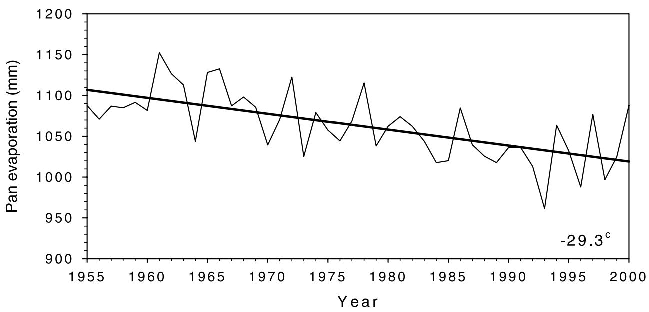

Figure 2. Temporal dynamics of warm season (May–September) pan evaporation (mm) for China as a whole, 1955–2000. The thick line represents the pan evaporation trend with the rate (mm decade^{-1}) shown in the lower right corner of the chart. Superscripts in this and subsequent figures indicate significance: a, significant at the 90% confidence level; b, significant at the 95% confidence level; c, significant at the 99% confidence level.

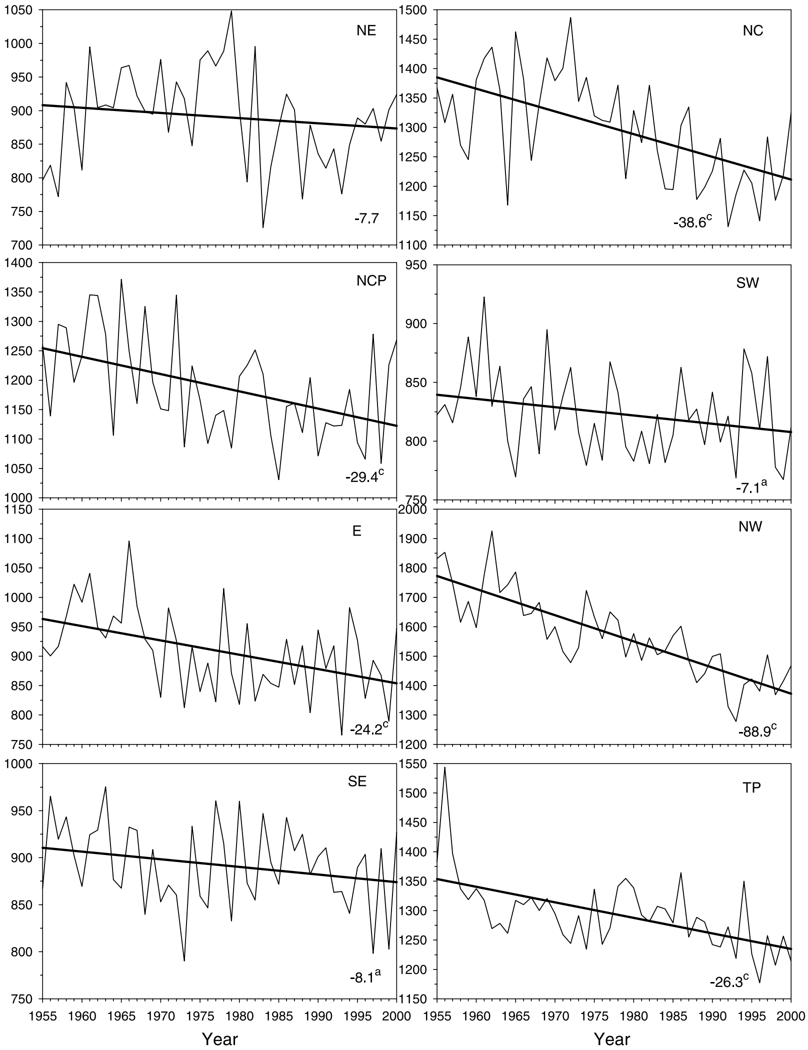

Figure 3. Temporal dynamics of pan evaporation (mm) for the eight climatic regions of China, 1955–2000. The thick lines represent the pan evaporation trends with the rate of the trends (mm decade^{-1}) shown in the lower right corner of each chart. Superscripts indicate significance levels (as in Figure 2).

evaporation in China was −29.3 mm/decade, similar to the findings reported in several other countries [*Peterson et al.*, 1995; *Chattopadhyay and Hulme*, 1997]. To see whether there are spatial differences in the change of pan evaporation within China, we examined the pan evaporation trends of China's eight climatic regions (Figure 3). Pan evaporation declined the most in the northwest, with successively smaller rates of decline moving south and east. The lowest rate of decline was in the southwest, with the decreases statistically significant in all regions except northeast China. The spatial pattern of change in pan evaporation rates was contrary to the pattern of average warm season precipitation, which was the lowest in the northwest and increased from the northwest to the southeast. The range of decrease of pan evaporation appeared to be greatly influenced by atmospheric humidity, with the downward trend attenuated in humid areas. But humidity was obviously not the only factor that influenced the change in pan evaporation: southwest and east China had similar precipitation levels but substantially different pan evaporation trends.

3.2. Possible Contributing Factors

[9] Average temperatures in China's warm season months (May through September) have increased by 0.11°C decade^{-1} across the period of 1955–2000. This increase was observed in all eight climatic regions and was statistically significant in all but the northwest and east China (Figure 4). The increase in mean temperatures is expected to make near-surface air less saturated and, as such, increase the rate of terrestrial evaporation and potential evaporation. But as we have seen, pan evaporation showed a trend of decline over most of China and in other regions in the last 50 years or so. The contrast between expectation and observation is called the pan evaporation paradox and calls for a theoretical explanation [*Roderick and Farquhar*, 2002].

[10] We compared time series total pan evaporation values with time series of various climatic parameters,

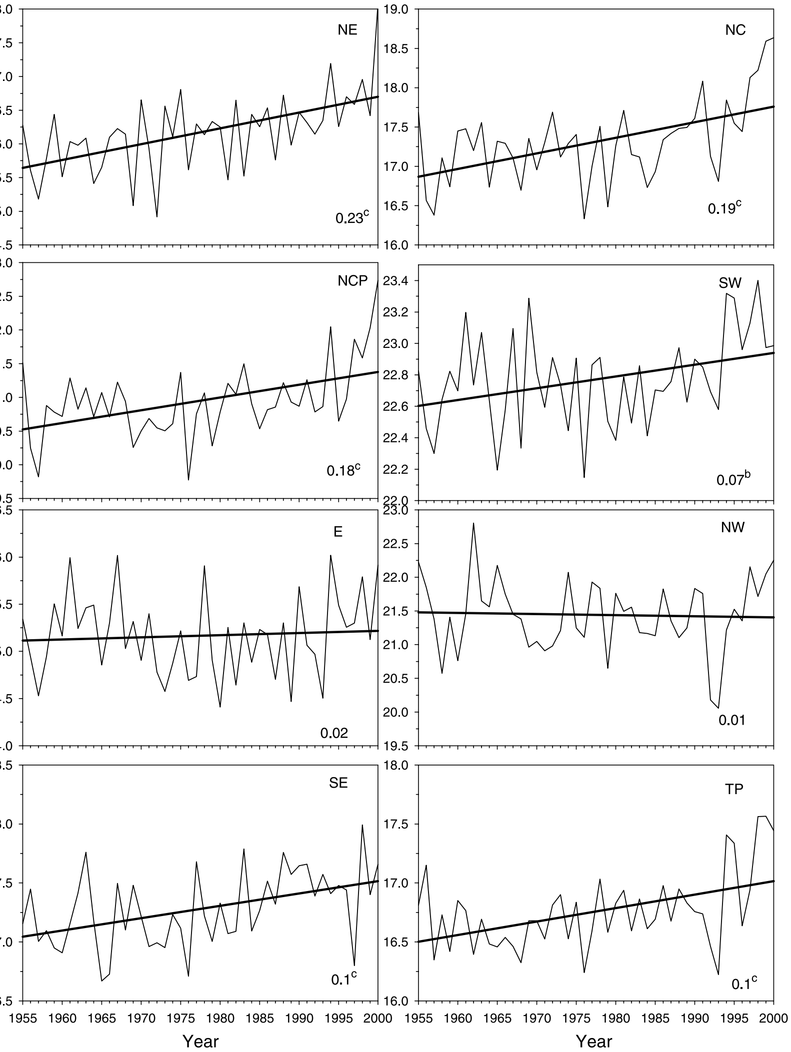

Figure 4. Temporal dynamics of warm season (May–September) air temperature (°C) for 8 climatic regions of China, 1955–2000. The thick lines represent the air temperature trends with the rate of the trend (°C decade^{-1}) shown in the lower right corner of each chart. Superscripts indicate significance levels (as in Figure 2).

including mean temperature, maximum temperature, minimum temperature, diurnal temperature range (DTR), cloud cover, total precipitation, and VPD. Pan evaporation was most highly correlated with DTR, with an r^2 of 0.8. DTR also declined over this period, and the high correlation suggests that the declines in DTR and pan evaporation may share a common cause. Decreased pan evaporation accompanied by decreasing DTR has also been reported elsewhere in the world [*Peterson et al.*, 1995] but is not universal; a report from India found decreased pan evaporation accompanied by increasing DTR [*Chattopadhyay and Hulme*, 1997]. *Dai et al.* [1999] show that the DTR is strongly affected by clouds through their effects on surface solar radiation [*Easterling et al.*, 1997] and, to lesser extent, by soil moisture and precipitation through evaporation. Our result also suggests that DTR may integrate the effects of these factors and thus have a stronger correlation with pan evaporation than any of these individual factors. Our multiple regression analysis indicates that DTR is equivalent to the combination of solar irradiation, VPD, and precipitation in explaining the variance of pan evaporation for China as a whole (Table 1).

[11] Aside from DTR, pan evaporation is most highly correlated with solar irradiance, VPD, and precipitation, with r^2 values of 0.64, 0.49 and 0.3, respectively. These three variables together explained 78% (r^2 = 0.78) of the variance in pan evaporation from 1955 to 2000 at national level using a multiple linear regression model. By regions, these three variables explained from 55% of the variance in pan evaporation in southeast China to 90% in east China using multiple linear regression models (Table 1). Adding air temperature to the multiple regression models did not improve the model performance at the national level, though air temperature significantly improved the models in the northeast, the northwest, and the Tibetan Plateau of China (Table 1). Pan evaporation in China correlates poorly with the change in cloud cover (r^2 = 0.08). While in many other parts of the world cloud cover has increased in recent decades, China's cloud cover has shown a decreasing trend since 1955 [*Kaiser*, 2000]. Above all, given the trend of

Table 1. Coefficient of Determination (r^2) Between Pan Evaporation and Other Climate Variables (May–September), 1955–2000, in China Using Multiple Linear Regression Models[a]

Regions	Independent Variables	
	VPD, P, R	VPD, P, R, T
Nationwide	0.78	0.79
Northeast China (NE)	0.58	0.66
North China Plain (NCP)	0.76	0.77
East China (E)	0.90	0.90
Southeast China (SE)	0.55	0.56
North Central China (NC)	0.61	0.62
Southwest China (SW)	0.80	0.80
Northwest China (NW)	0.87	0.91
Tibetan Plateau (TP)	0.62	0.74

[a]VPD, vapor pressure deficit; P, precipitation; R, solar irradiance; T, air temperature.

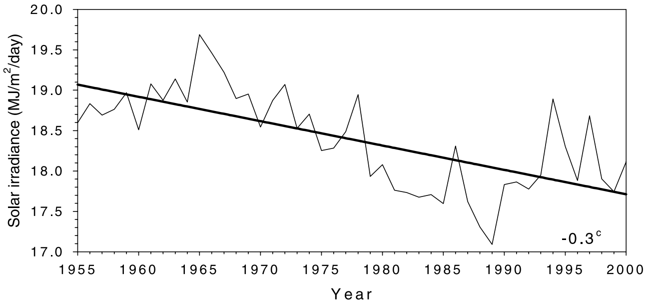

Figure 6. Temporal dynamics of warm season (May–September) solar irradiance (MJ m^{-2} day^{-1}) for China as a whole, 1955–2000. The thick line represents the solar irradiance trend with the rate of the trend (MJ m^{-2} day^{-1} $decade^{-1}$) shown in the lower right corner of the chart. Superscripts indicate significance levels (as in Figure 2).

declining cloud cover in China as well as cloud cover's negative effect on pan evaporation, we would expect pan evaporation to increase if cloud cover were the main cause of the change in pan evaporation rates. Therefore we conclude that cloud cover change does not have great effect on the observed trend of pan evaporation in China.

[12] We found that pan evaporation was highly correlated with DTR, solar irradiance, VPD, and precipitation in China. These findings are consistent with previous reports. The correlation with solar irradiance and VPD was positive; with precipitation it was negative. Of these, VPD and precipitation saw no significant change for China as a whole over the past several decades, while solar irradiance significantly decreased (Figures 5, 6, and 7). This suggests that the decrease of pan evaporation was mainly caused by the decrease in solar irradiance. It seems that proposed complementary relationship between pan evaporation and terrestrial evaporation cannot explain the decline in pan evaporation seen in China as a whole. To the contrary, our analysis of China as a whole supports the previous report that the decline in pan evaporation results from a decrease in solar irradiance [*Roderick and Farquhar*, 2002]. However, we should note that cloud cover in China showed a decline in the last several decades, meaning that decreasing solar irradiance in China cannot have been caused by changes in cloud cover as has been observed in other areas. (Aerosols may well be responsible, but we presently lack the data to confirm this hypothesis.)

[13] To further test the hypothesized complementary relationship between pan evaporation and actual evaporation, we investigated the relationships of VPD and precipitation with pan evaporation on a regional basis. Pan evaporation has significantly decreased in most climatic regions of China except the northeast region. The decrease is significant from the arid northwest to the humid southeast. VPD, however, showed a statistically significant increase in the southeast, north central China, and the North China Plain (Figure 8). The trend of increasing VPD would be expected to have a positive effect on pan evaporation change, so we conclude that changes in VPD cannot explain the widely observed decreases in pan evaporation. Precipitation increased in the northwest, east China, and the Tibetan Plateau; it decreased in the other five climatic regions (Figure 9). Again, these trends do not support the view of an inverse relationship between pan evaporation and precipitation. In that view, increased precipitation would be accompanied by increased terrestrial evaporation, which in turn would lead to decreased pan evaporation [*Lawrimore and Peterson*, 2000]. In summary, the trends of VPD and precipitation could not

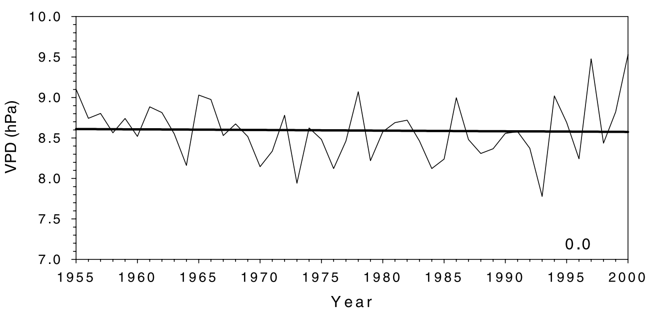

Figure 5. Temporal dynamics of warm season (May–September) water vapor pressure deficit (VPD, hPa or 100 Pa) for China as a whole, 1955–2000. The thick line represents the VPD trend with the rate of the trend (hPa $decade^{-1}$) shown in the lower right corner of the chart.

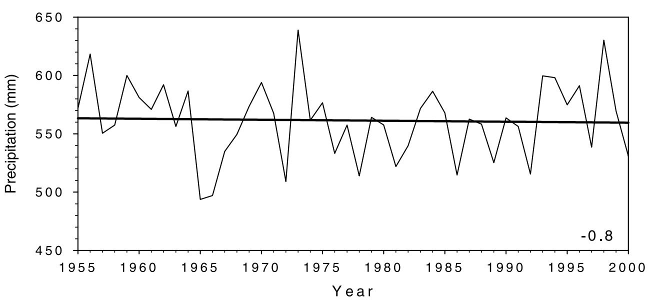

Figure 7. Temporal dynamics of warm season (May–September) precipitation (mm) for China as a whole, 1955–2000. The thick line represents the precipitation trend with the rate of the trend (mm $decade^{-1}$) shown in the lower right corner of the chart.

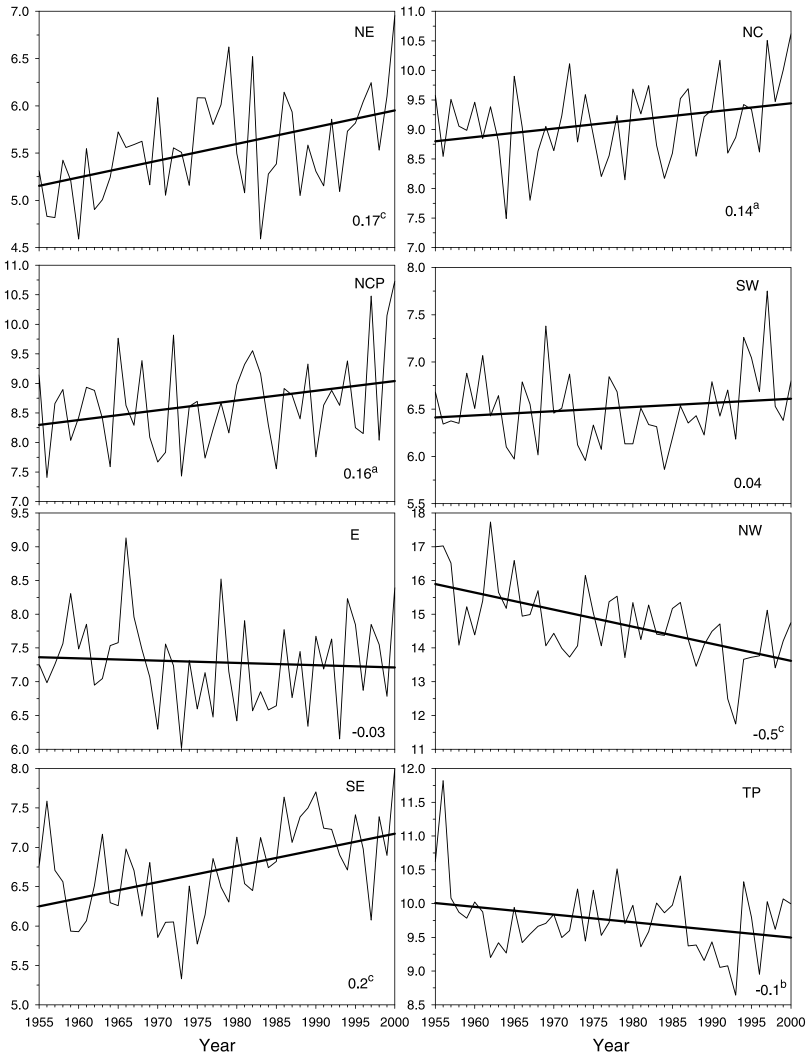

Figure 8. Temporal dynamics of warm season (May–September) water vapor pressure deficit (VPD, hPa or 100 Pa) for China's eight climatic regions, 1955–2000. The thick lines represent the VPD trend with the rate of the trend (hPa decade^{-1}) shown in the lower right corner of each chart. Superscripts indicate significance levels (as in Figure 2).

be the main cause of the decrease in pan evaporation across China.

[14] Of the eight climatic regions of China, solar irradiance declined significantly in seven regions, all except the northeast (Figure 10). Similarly, pan evaporation declined significantly in the same seven climatic regions (as shown in Figure 3). Among those seven regions where pan evaporation declined significantly, we see that the rate of decline is highest in the northwest and progressively less as we move from northwest to southeast. Solar irradiance declines significantly in the same climate regions, but the spatial pattern is reversed with the highest decrease in the southeast. This difference in spatial patterns indicates that there must be other factors besides solar irradiance that influence the decline in pan evaporation.

[15] The trends of VPD and precipitation exhibit spatial patterns that differ from the trends of both pan evaporation and solar irradiance. Warm season precipitation increases as we move from northwest to southeast. Since pan evaporation is strongly negatively correlated with precipitation, and the spatial pattern of precipitation runs contrary to the spatial pattern of change in pan evaporation, it appears that water conditions regulate the sensitivity of pan evaporation to solar irradiance.

[16] We can illustrate this relationship by comparing the trends in two climatic regions, north central China and the North China Plain. Temperature and VPD showed similar trends in these two climate regions. Solar irradiance declined faster in the North China Plain, while pan evaporation declined faster in north central China. Higher precipitation and lower VPD in the North China Plain made pan evaporation less sensitive to the change in solar irradiance, compared with north central China. The difference in the sensitivity of pan evaporation to the change in solar irradiance resulted in a faster decline in north central China than in the North China Plain. Thus we see that water conditions influence pan evaporation trends, resulting in a spatial pattern that differs from that observed for solar irradiance.

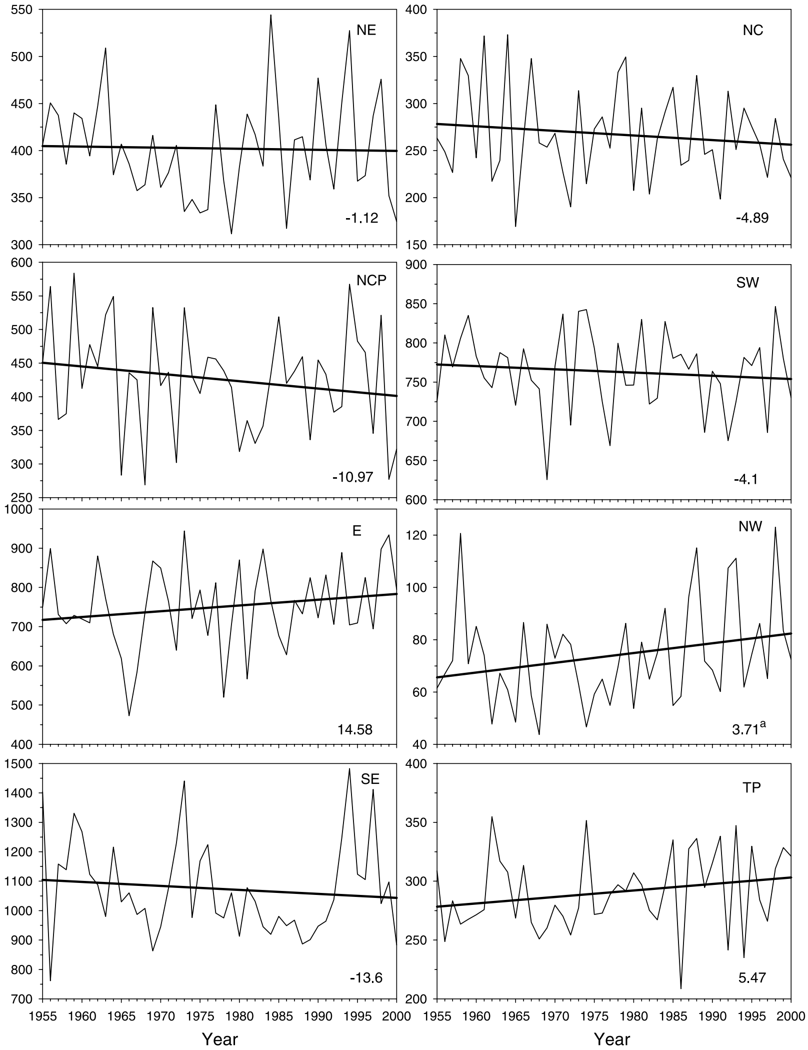

Figure 9. Temporal dynamics of warm season (May–September) precipitation (mm) for China's eight climatic regions, 1955–2000. The thick lines represent the precipitation trend with the rate of the trend (mm decade^{-1}) shown in the lower right corner of each chart. Superscripts indicate significance levels (as in Figure 2).

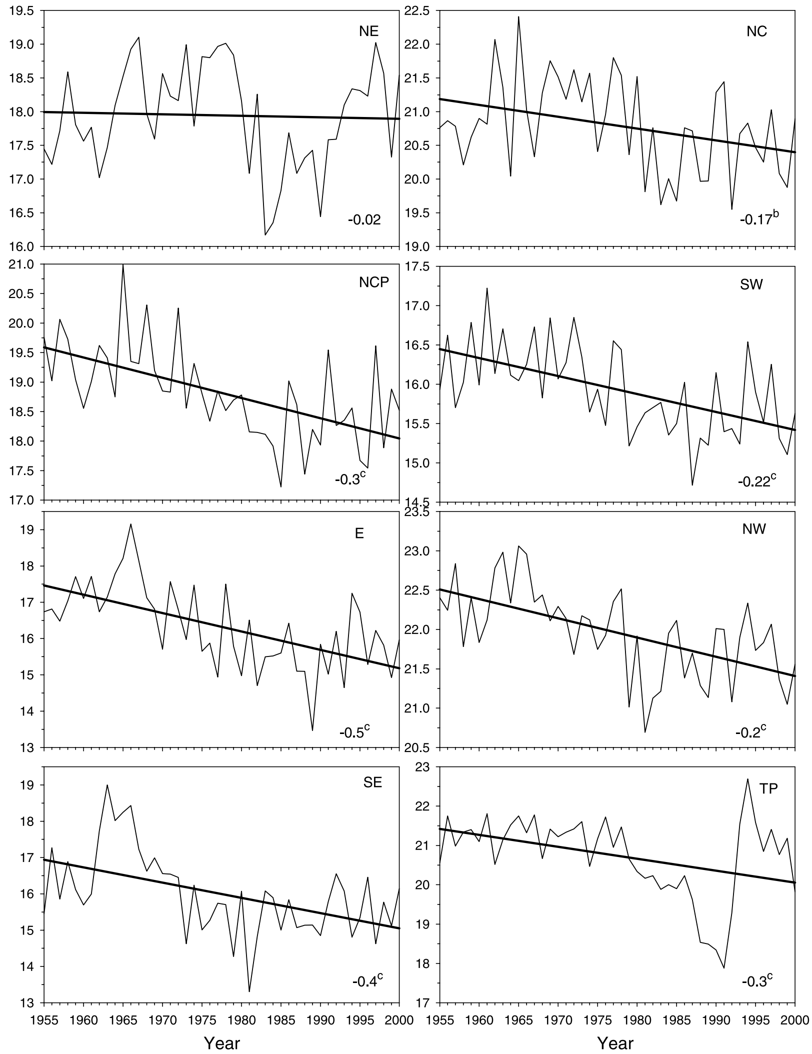

Figure 10. Temporal dynamics of warm season (May–September) solar irradiance (MJ m^{-2} day^{-1}) for China's eight climatic regions, 1955–2000. The thick lines represent the solar irradiance trend with the rate of the trend (MJ m^{-2} day^{-1} $decade^{-1}$) shown in the lower right corner of each chart. Superscripts indicate significance levels (as in Figure 2).

This relationship is consistent with the faster decrease in pan evaporation in arid regions.

4. Conclusions

[17] Our analysis supports the interpretation that the widespread decline of pan evaporation is mainly caused by decreasing solar irradiance. China's situation differs from that reported in analyses of other areas. Previous analyses of other parts of the world, such as North America, have associated declines in solar irradiance with increasing cloud cover and precipitation. There, declines in pan evaporation have accompanied these increases in precipitation. But as we noted earlier, cloud cover in China as a whole decreased over the past several decades (along with solar irradiance), while precipitation and VPD showed no significant change. Pan evaporation in the climatic regions of China has decreased whether precipitation and VPD have increased or decreased.

[18] Nonetheless, the spatial pattern of change in pan evaporation differs from that of solar irradiance in China over the period of 1955–2000. The steepest declines in pan evaporation are found in the northwest, while the steepest declines in solar irradiance appear in the southeast. We find that differing in water conditions account for the inconsistencies between the spatial patterns of change of pan evaporation and solar irradiance. It seems that although solar irradiance plays the main role in decreasing pan evaporation, other parameters influence or mediate its effect. Future work on the pan evaporation paradox should consider this finding that water conditions influence the sensitivity of pan evaporation to changes in solar irradiance.

[19] **Acknowledgments.** The authors thank Ye Qi and the Climate Data Center, China Meteorological Administration, for providing the historical climate data for this study, and two anonymous reviewers for helpful comments. Rutgers University and the New Jersey Agricultural Experiment Station provided funds and facilities for data analysis.

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