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Interannual characteristics of the surface hydrological variables over the arid and semi-arid areas of northern China

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Abstract

The characteristics of the surface humid index (SHI) were analyzed based on 160 station data in China from 1951 to 1998. The surface humid index is defined as $SHI=(P)/(P_e)$, where P_e is potential evaporation suggested by Thornthwaite's method. The difference between the evolutionary features of the SHI in typical arid regions of north China (Huabei and the northwest) was compared. The results show that the SHI is decreasing (drying trend) in the Huabei region of north China but is increasing in some areas of northwest China (wetting trend). Under regional warming, the drought in the center of north China mainly resulted from the decrease in precipitation and is partly due to the increase in evaporation. A dry period of about 40 years was revealed from the historical data over the area. Increasing evaporation caused by increasing temperature probably intensified the drought in that area, but is not the main reason for the drought. It is the less precipitation that mainly results in the present drought in north China. In addition, the SHI variations in different seasons were also analyzed; the result indicates the notable difference of SHI variation between seasons. Finally, the geographical distribution of annual SHI variation over China was given.

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Keywords: surface hydrological variables; climate variation; surface humid index (SHI); drought

1. Introduction

As a serious environmental problem, drought is closely related to the climate variation and other surface hydrological processes. In the past, many studies discussed drought only through analyzing the climate variable such as precipitation. However, drought is not only a climate issue, but is also a factor affected by other environmental processes, such as

* Corresponding author. Fax: +86-10-62045230. *E-mail address:* mazg@tea.ac.cn (Z. Ma). evaporation, runoff and surface air temperature, which determines that it should be studied from a multidisciplinary view. How to express the total character of drought is the key to correctly understand the cause of drought.

In this paper, the surface humid index (SHI), a parameter suggested by Hulme et al. (1992), was employed to analyze the state of dry and wet in the surface over the arid region of north China. This parameter can reasonably reflect the dry/wet state of land surface in that it considers two major surface hydrological processes—precipitation and potential

evaporation—simultaneously (Manabe, 1981). Meanwhile, other processes affecting the dry and wet state of surface were also discussed here, and the probable relationship between drought and regional warming was investigated.

In the arid and semi-arid regions of north China, the climate variation have been studied by many researchers (Wei and Cao, 1998; Yan, 1995, 1999). These works analyzed in detail the temporal and spatial variation of precipitation but did not depict the overall characteristics of drought. For example, the decrease in precipitation does not mean that drought ensues as a result of the uncertainty of evaporation. Also, the increase of precipitation cannot represent wetting land surface. Recently, some studies (Hulme et al., 1992; Fu, 1994; Thomas, 2000) emphasized the expression of the drought characteristics on the view of a multidisciplinary study. In these papers, the evaporation, the dry/wet state in the global scale, and the drought index were investigated. Nevertheless, the dry/wet state in the land surface of the arid area of north China and their differences between seasons and regions are not clear. These studies did not analyze the dry/wet trend and their relation with global warming. Manabe's results (Manabe, 1981; Wetherald and Manabe, 1999) indicated that the soil moisture in mid-latitude in summer would decrease under global warming. In that case, the situation in the arid and semi-arid region of north China is an important scientific and social problem because of its influence on water resource management and utilization. Therefore, temporal and spatial variation, as well as the differences between two typical drought regions, will be investigated in this paper.

In this paper, the trend and regional difference of interannual variation were investigated, showing the test of significance of the trend in the regions and the geographical distribution of SHI. The long-term variation of surface hydrological budget in the two typical areas has been investigated.

2. Data and method

The data are from the Chinese Meteorological Administration from 1951 to 1998. There are 160 observational stations in China with monthly precipitation and surface temperature. Some long serial data were taken from the Carbon Dioxide Information Analysis Center (CDIAC) numeric data package NDP012 and NDP039, updated and enlarged version of the original NDP data package by Tao et al. (1991), and added the recent years data of monthly precipitation and surface temperature from Chinese Climate Center. The same data were used throughout this paper.

According to Hulme et al.'s (1992) suggestion, the surface humid index (SHI) can be written as follows:

$$SHI = \frac{P}{P_{e}}$$
(1)

where P is the observational monthly precipitation, and $P_{\rm e}$ is the monthly potential evapotranspiration. Using modified Thornthwaite's scheme (Ma, 1999), potential evapotranspiration was calculated only from the monthly mean surface temperature. In formula (1), it is easy to see that the SHI includes two important factors affecting the water budget of land surfaceprecipitation and potential evaporation. So it is a rational parameter to be used for analyzing wet/dry state (WDS) in the land surface, but in winter of north China, because the surface temperature is always under 0 °C, $P_e \equiv 0$, SHI $\rightarrow \infty$. Therefore, the SHI is not suitable to indicate the WDS in that season. In winter, the precipitation can be used for representing the WDS. The difference between precipitation and evaporation (P - E, where P is the observationalmonthly precipitation and E is the monthly evaporation) was used to explore the historical characteristics. Evaporation (E) was calculated using Gao's scheme (Yang and Song, 1999).

The Mann–Kendall method (simply named M–K method; Snyers, 1990; Fu and Wang, 1992) was used for testing the significance of the trend of the WDS.

Two typical regions are the Huabei region (named as HR as follows) and the northwest region of north China (NR), respectively. HR is from 35°N to 42°N and is to the east of 110°E. Because of complicated geography and various climate conditions, we split the northwest region into two subregions, one is the No. 1 region (named as NR 1) extended to north of 35°N and to the west of 95°E, the other is the No. 2 region (named as NR 2) covering from 95°E to 105°E and to the north of 35°N. There are 24 observational stations



Fig. 1. Distribution of the stations in the three subregions.

in HR, 13 stations in NR 1 and 6 stations in NR 2. The extent of every region was plotted in Fig. 1.

3. The interannual variation of two typical drought regions and their difference

In order to conveniently analyze the general regional characteristics of the WDS and to compare the difference between two regions, the area mean in a subregion was calculated. Some results depict the whole evidence as follows.

3.1. Interannual variation of SHI during the flood season

In north China, precipitation mostly occurs in the flood season (from May to October), so the WDS in the period can represent the annual WDS. Therefore, from the WDS of the flood season, we can see the annual WDS. The data of monthly precipitation and monthly mean temperature are from the Chinese Meteorological Administration from 1951 to 1998.

Fig. 2 is the interannual variation of the area mean SHI in the flood season in the different subregions, which was calculated by the M–K method. It is a 10-year running mean. Fig. 2 shows that there is a dominant trend of decrease of SHI in HR since the

1950s spaced by a weak increase within 1970s. So it can be concluded that there has been a drying trend (decreasing SHI) in HR since the 1950s. The drying trend reached the significance of 95% in the region. In contrast, the increasing trend of surface temperature (T) existed in the period, and the trend also reached the significance of 95%. Meanwhile, we can find that the trend of SHI is opposite to that of the T in the region. The analysis also indicates the decreasing trend of precipitation after the middle of 1970s, which is consistent with the present decreasing WDS in HR. Probably, the increasing T and decreasing P are the main reasons that cause the drying trend, and introduce a warm and dry situation.

From Fig. 2, there is a little increasing trend of SHI in NR 1 in the flood season after 1980s, but the trend cannot reach the significance. In NR 2, a decreasing SHI exists after the 1980s. Concerning the variation of the temperature, a decrease of T in NR 1 and an opposite trend in NR 2 can be found after the 1980s.

According to the analyses above, some conclusions can be drawn. In HR and NR 2, the increasing temperature intensifies the present drying trend of the land surface because of decreased precipitation, then the drying land surface will further increase *T*. This fact agrees with the modeling results under global warming (Manabe, 1981).



Fig. 2. Regional mean variation and their test of SHI and air temperature (H=10-year running mean; T= annual mean temperature. The upper figure is original, and the lower is the test of trend of SHI by the Mann–Kendall method).

3.2. Interannual variation in different seasons

Although SHI in the flood season basically represents the characteristics of the WDS in the whole year, it cannot depict the interannual variation in various seasons and their differences between seasons. In this section, these will be explored.

Fig. 3 shows the anomaly of the 9-year running area mean in the three subregions. The facts as follows can be obtained.

The *T* (monthly mean temperature) in north China is generally under 0 °C in winter, and the potential evapotranspiration cannot occur, so the potential evapotranspiration is zero. Under this condition, the precipitation basically represents the WDS. From the precipitation pattern in the winter, we can find that there is an increasing trend of precipitation in the two subregions of the northwest part of China, and is of a notable period variation in NR 1 from 1951 to 1998. In contrast, a remarkable increasing temperature has occurred in the two subregions. There is no obvious trend of precipitation variation, but a period of oscillation of about 15 years exists in HR. The notable increasing trends of temperature can be detected in the three subregions in winter.

In spring, there is a humid phase (increasing WDS) in the three subregions, especially in NR 1 where a dramatic increase of the SHI has occurred after the 1980s. Comparing the variation of precipitation and temperature, we can see that the humid trend resulted from a decreasing temperature and an increasing precipitation in NR 1. However, in NR 2 and HR, the humid phase is only related to the increasing precipitation because the increasing potential evapotranspiration that results from increasing temperature is not enough to offset the increasing precipitation. Therefore, as a representative parameter of WDS, the SHI has been increased. This means a cold and humid state in NR 1, but a warm and humid state in HR and in NR 2. From Fig. 3, we can also find that there are phase differences in the relation between precipitation and temperature during different periods in the three subregions. In NR 1, the trend of precipitation had been agreeable with that of temperature from the middle 1950s to the early 1970s. But after the 1970s, the phase between them is obviously reversed. These phase differences between different periods also exist in other subregions. There are two positive anomaly periods of the SHI (humid period) in HRone is in the middle of the 1950s: the other has started since the early 1970s. The latter was weaker than the former. In NR 1 and NR 2, the latest humid period is stronger than others.

In summer, the warming and drying trend existed before the middle 1980s, and then a remarkable cold and humid stage in NR 1, as a result of the increasing precipitation and decreasing temperature, occurs. In NR 2, the distinguished humid period had occurred after the 1970s, and the humid state had weakened during the middle 1980s, then it has been intensified once again. In this period, the temperature varied from the notable decreasing temperature to increasing tem-



Fig. 3. Anomalies of surface humid index in the three subregions.

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perature trend. In other words, the state of climate had varied from cold and humid (CH) to warm and humid (WH). In HR, the SHI has successively decreased since 1950s, relate little change had occurred from the middle 1960s to the middle 1970s. Then, the SHI has sharply decreased, and a sustained drying trend of the SHI has been formed in HR of summer. Meanwhile, we found that although there was a little increasing precipitation, the SHI has decreased along with the successively increased temperature in that area. Therefore, the surface hydrological variables (such as SHI) are greatly affected by surface climate variables like precipitation and surface temperature.

In fall, there has been a rapid increase of SHI in NR 1 after the 1970s. The temperature and precipitation have rapidly increased in the same period. This indicated that though increasing temperature can decrease the moisture of land surface, the SHI in the area has increased mainly due to rich precipitation. In NR 2, the SHI has sustained small values for a long period after the 1980s, and reached its historical minimum. The decrease of precipitation and increase of temperature may be the main reason. However, the cold and humid (CH) state was an obvious characteristic of this area before the 1980s because of increasing precipitation and decreasing temperature. In HR, the negative anomaly of the SHI since the middle 1960s changed into positive anomaly; in other words, the present WDS is humid. The temperature variation gives the remarkable increasing trend, which results in a warm and humid surface state in HR at present.

Based on the analyses above, some conclusions can be reached. In NR 2, the drought (negative anomaly of the SHI) of land surface has occurred in fall, but in HR, it has occurred in summer. These facts were distinguished because of the decrease of precipitation and the increase of surface temperature in the region. In other words, the decrease of precipitation resulted in the forming of the drought, the regional warming further intensifies the surface drought, and then the drying land surface has positively affected the atmosphere. The complicated interaction between the surface hydrological processes and atmosphere in the arid and semi-arid area of north China needs to be investigated deeply in the future. In HR, the drought of land surface mainly occurred in summer because of the decrease of precipitation and the increase of surface temperature. It should be indicated that the anomaly of the SHI in fall changed from a negative to a positive value after the middle 1980s, which means changing the drought state into the wet state in HR. Manabe (1981) showed that the soil moisture in middle latitude would decrease under $2 \times CO_2$ because of the decrease in precipitation and increase in surface air temperature in the zone. Therefore, we see that the drought in HR and in the east part of northwest China is oppositely correlated with the regional warming. In that case, whether the regional warming in the subregions resulted from under $2 \times CO_2$ condition needs further discussion.

4. The test of the seasonal SHI trend in the three subregions

The results above show notable trends of the SHI in different seasons and different subregions. However, the credibility of the results needs to be tested. In this section, the trends of different seasons in the three subregions were tested by the M–K method (Mann– Kendall method).

Fig. 4 gives the test curves of the SHI and the temperature in various seasons in the three subregions. As shown in Fig. 4, there is a notable increase in the temperature trend in all three subregions in winter, and they could pass the significance of 95%. However, there is the increasing trend in precipitation in NR 2. Although there is the positive anomaly of the SHI in HR during spring, this wet trend did not pass the significance of 95% (the absolute value is more than 2), and the increasing temperature passed the significance of 95%. Meanwhile, both the wet and the warm trends of temperature during spring passed the significance of 95% in NR 1 and NR 2. In summer, the drying trend of land surface in HR can pass the test of significance, and there was no obvious trend of temperature variation. The WDS in NR 2 successively maintained a cold and wet surface state. In NR 2, the decreasing trend of temperature passed the significance of 95%, but the wet trend of the WDS did not. In fall, the warming and drying trends of WDS in HR and NR 2 passed the significance of 95%. The warm and wet states are the main characteristics of NR 1.



Fig. 4. Annual trends of SHI in the three subregions in different seasons by the M-K method (solid line=SHI; dotted line=temperature).

5. The geographical variation of SHI

The geographical variation of the SHI will help us to understand the spatial variation of the interaction between the surface hydrological processes and the atmosphere. In this section, the geographical variation of the SHI was given in Fig. 5 by the M-K method. In order to highlight the interannual variation trend in the arid and semiarid areas of north China and the difference between them, and that in the humid area of south China, the geographical variation in south of China have also been analyzed, and the original data was processed by a 9-year running mean. From Fig. 5, some evidences show the large geographical differences and the seasonal differences of the SHI; the SHI is decreasing in most areas in the east of 100°E and in the north of 35°N. This means a drying trend of land surface in these areas.

All drought trends passed the significance of 95% (the absolute value of the number of the contour in the pattern exceeds 2). An interesting fact is that there is an opposite variation trend in the two sides of $100^{\circ}E$ in the north part of $35^{\circ}N$ —the drought in the east and the wet state in the west. Further, the geographical variation in the flood season was investigated in Fig. 5. The

remarkable drought of land surface appeared in the east part of northwest and northeast, and in HR, the wet trend in the central and western part of northwest.

Meanwhile, the seasonal difference of geographical variation has been analyzed. As mentioned above, precipitation in winter basically depicts the WDS. Because many analyses of the characteristics of the precipitation in the season in China have been performed, we will not give a result for winter. Fig. 6 shows the trends of WDS in three seasons by the M-K method. The results indicate that a smaller extent of the drought in spring than in other seasons in north China. Its position is more northward, and an obvious drought trend appeared in most areas of the northern part of the northeast part of China and in the east of HR. The annual geographical variation of the SHI is roughly consistent with that in the flood season. The notable drought trends of land surface occurred in HR, in the east part of northwest, in the south part of northeast and in the north part of Xingjiang. Generally speaking, there are wet trends of land surface in the central northwest and the north part of northeast China in the summer. In fall, except for the wet trends of land surface in the west part (NR 1) and the plateau region, there are drought trends in the rest regions of north China. The



Fig. 5. Annual trend of SHI in China from 1951 to 1998 (solid line=drying; dashed line=wetting).



Fig. 6. Annual trend of SHI in different seasons in China from 1951 to 1998 (the order is the same as in Fig. 5).

wet and dry phases in different stations							
Beijing		Huhehaote		Xian		Wulumuqi	
Dry Phase (<300 mm)	Wet phase $(\geq 300 \text{ mm})$	Dry Phase (<150 mm)	Wet phase $(\geq 150 \text{ mm})$	Dry Phase (<150 mm)	Wet phase $(\geq 150 \text{ mm})$	Dry Phase (<40 mm)	Wet phase $(\geq 40 \text{ mm})$
1845–1885 1897–1949 1964–present	1886–1896 1950–1963	1919–1954 1964–present	1955-1963	1927–1945 1968–1978 1988–present	1946–1967 1979–1987	1912–1937 1963–1978	1938–1962 1979–present

 Table 1

 Wet and dry phases in different stations

center of the drought was located in the Weihe valley and the lower reaches the Yellow River valley.

6. Long-term variation of surface hydrological budget in two typical areas

In the analysis, the differences between the observational precipitation and evaporation calculated by Gao's method can be used for representing the WDS: $\nabla w = P - E$, where *P* is observational monthly precipitation and *E* evaporation. The characteristics of the WDS were discussed through analyzing ∇w variation. The data is from the long-term instrumental databases in China (Tao et al., 1991). Because there are no enough stations in the arid area, several stations were added to represent the three subregions (see Table 1).



Fig. 7. Annual variation of $\nabla w(=P-E)$ in Beijing and Wuloumuqi.

Fig. 7 shows the ∇w variation of the 9-year running mean in the Beijing station and Wulumuqi. From Fig. 7, there is a periodic variation of dry and wet in the Beijing station, the representative of HR. But the duration of dry phase and wet phase is different. In general, the duration of dry phase is about 40 years, which is longer than the duration of wet phase by about 29 years. Also, we can find that there are three dry periods and two wet periods for 150 years; the present state of HR is in the latest dry phase since the middle 1960s. This characteristic can be found in other observational sites of HR. But in the Xian station and in Wulumuqi, the representatives of NR 1 and NR 2, respectively, the duration of dry phase and wet phase is about 20 years. Comparing with HR, the duration is shorter and the frequency is higher. It is noted that the present state of WDS in NR 1 is located in the wet phase, which is opposite with the phase in NR 2. The above facts can be found in Table 1. From the analyses of historical data above, there are remarkable periodic and regional variations in the arid and semi-arid areas.

What have caused the present drought in north China? Some ideas suggested that the drought is mainly due to increasing human activities such as increasing emission of CO₂ and sulphur (Manabe, 1981; Wetherald and Manabe, 1999). However, from the analyses, the state of WDS in most parts of north China were located in the natural dry phase; the main reason for this should be the decreasing precipitation in the area. Nevertheless, the increasing temperature intensified the drought. The relationship between precipitation, temperature and evaporation, drawn from the temperature and precipitation in Beijing, was given in Fig. 8. The results show less precipitation but higher evaporation, caused by high surface air temperature in the last 30 years. Also, we found that the present evaporation reaches its highest level since 1840, and the precipitation is still in the low phase. Recently, the small increase in precipitation is about 100 mm in Beijing, while evaporation has increased about 55 mm; the difference between them is 45 mm. Generally specking, the P-E in the wet phase should exceed 400 mm. The difference between recent precipitation and evaporation is the one-fourth of that value, so little increase of precipitation is not enough to make the land surface wet. Meanwhile, from the left pattern of Fig. 8, a positive correlation between the surface air temperature and evaporation has clearly existed since the middle 1960s, which is a good evidence that increas-



Fig. 8. Annual variation of evaporation, temperature and precipitation in Beijing.

ing temperature intensifies the drought. However, since evaporation is controlled by many variables such as net surface radiation and soil moisture, etc., these will be discussed in another paper.

7. Summary

The above results indicate that the SHI is a reasonable parameter to depict the wet and/or dry state on the land surface based on its solid physical basis considering two fundamental component of the hydrological budget in the land surface. Some conclusions were given as follows:

- In the three subregions, there is the notable interannual variation of the SHI and the evident regional differences. Opposite phases of interannual SHI variation exist between HR and NR 1 and NR 2. There was a wet trend of land surface in NR 1 in the past 20 years, but there were dramatic dry trends of land surface in NR 2 and HR.
- There is a large difference of interannual SHI variation trend between seasons. In HR, the drought trend occurred mainly in summer; in NR 2, it occurred mainly in fall. There has been the wet trend of land surface in NR 1 in spring and fall. The phases related to the surface temperature trend are opposite between two seasons—cold and wet in spring; warm and wet in fall. The cold and wet trend of land surface is the interannual character in NR 2 in spring and summer.
- The drought trends of land surface occurred in most parts of north China Except in NR 1. These facts can be validated by the interannual trends of flood season. The intensity of the drought of land surface varies in the three subregions.
- Analyses of the long-term data show that there are droughts in HR and NR 2 at present that are due to the decreasing precipitation rather than increasing temperature, and that there is a wet phase in NR 1 due to increasing precipitation.

The influence of the global warming on the region WDS is an important problem for future study on the interaction between the surface hydrological processes and climate variation. The above analyses show a notable positive correlation between the surface air temperature and evaporation. Because evaporation is controlled by several processes, the relationship between evaporation and other factors needs further study in order to understand the influence of regional warming on surface hydrological processes.

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