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Interdecadal change of atmospheric stationary waves and North China drought*

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The inderdecadal change of atmospheric stationary waves (ATW) has been investigated for the two periods 1956–77 and 1978–99. The trough of ATW in the middle and low layer of the troposphere over the Asian continent has experienced a significant weakening during the past two decades, which exerts a great influence on the North China climate. The ATW in 200 hPa has also exhibited some changes since 1977, as a stationary ridge appeared over the northwestern China while a stationary trough appeared above North China. This leads to an increasing of the upward motion above northwestern China and a decreasing above North China. A west–east section of the stationary waves at 40°N shows that the ATW above North China tilted westward for the period 1956–77, but was almost upright during 1978–99. The composite analysis confirms that the climate mean ATW pattern after 1977 is similar to the dry pattern for North China, while the rainy pattern is similar to that before 1977. In consequence, the North China drought is partly due to the interdecadal change of the ATW over boreal Asia in the recent two decades.

Keywords: atmospheric stationary wave, North China drought, interdecadal change, dry and rainy climate pattern

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1. Introduction

The North China drought, with its severity and persistence, has attracted more and more attention and concern. It is commonly suggested that, instead of being an isolated event, the drought comes from the general background of global warming[1−4] and involves many physical causes. For instance, the East Asian summer monsoon has remained in its weak phase since the 1980s;[5,6] the subtropical high in the northwestern Pacific has appeared more frequently at a further southwest position than its climate location;[7] the South Asian high more often stayed at its eastern phase;[8] the aero-troughs and ridges on mid-latitude westerly became weak.[9] There are several possible physical factors that may result in the anomalies in the monsoon and circulation, such as variation of the sea ice in high latitudes,[10] change of the surface vegetation,[11,12] land use,[13] the atmospheric black-aerosol,[14] the interdecadal ENSO events,[15,16] the weakening of the thermal convection over western Pacific warm pool,[17] anomalous heating of Tibetan plateau,[18] variation of the Indian ocean SST, the weakening of South Asian summer monsoon,[19] and so on. A recent study indicated that the eastern China rainfall in rainy season and the East Asian summer monsoon are even connected with the variation of the circulation and the sea ice in the southern hemisphere.[20]

The North China drought has already involved the theory of climate formation as it has lasted for so long.[21] In fact, study has revealed that the most significant interdecadal increment of the pressure in the northern hemisphere appears in northwestern China and Mongolia,[7] which entails the wind anomaly in middle or high latitude, and the biggest departures of 850 hPa north wind are seen in the East Asian monsoon zone. These interdecadal changes, which are closely related to the North China drought according to correlation analysis,[9] are all reflecting the anomaly of the climate stationary wave, or the aero-

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troughs and ridges on boreal westerly. The zonal difference of climate is determined, in some degree, by the atmospheric stationary waves (ATW) associated with the non-homogeneous heating on the surface and land–sea distribution. It may be more convenient and reasonable to study the ATW in order to understand the mechanism and the background of the climate anomaly in North China. How have the climate stationary waves changed in the recent 20 years under the background of global warming? How the change influence a certain regional climate, for example the East Asian climate, is one of the important scientific problems that need to be studied in detail.

In the following, firstly we elaborate on the change of the ATW pattern and its climate implication, using NCEP reanalysis of geopotential heights on mandatory pressure levels. Then a composite method is employed to find the characteristic quasi-ATW patterns corresponding to more or less precipitation in North China. A comparison between the patterns and the ATWs for the two periods 1958–77 and 1978–99 will be performed so as to understand the relationship between North China drought and the interdecadal change of ATW. Considering the notable decreasing of North China rainfall in July and August our investigation will focus on the interdecadal change of ATW for midsummer.

2. Stationary wave and its climate implication

The ATW refers to the distribution of climate mean aero-troughs and ridges, or pressure departures from its zonal mean. For instance there are 3 waves on the westerly in middle latitudes with 3 aero-troughs and ridges in the northern hemisphere wintertime, and 4 waves in summertime. Climate ATW is defined as

$$\bar{h}^*(\lambda,\varphi) = \overline{h}(\lambda,\varphi) - [\bar{h}](\varphi), \tag{1}$$

where the first term in the right-hand side is a climate mean geopotential high field, and the second one is the zonal mean of the climate field. The square brackets "[ ]" represent a zonal mean operator, the star "*" refers to stationary eddies or the departure field from its zonal mean, and the bar "–" means climate mean. The period for the climate mean should generally be greater than 30 years, as is well known.

The quasi-stationary wave of atmosphere usually refers to a planetary wave that moves very slowly or stays almost at a fixed phase, for example the planetary Rossby wave, 2-dimensional spherical Rossby wave and so on.

Since the period of averaging operation for the interdecadal time scale is shorter than 30 years due to the limits of the data used, the mean waves for such a period should be referred to as a quasi-stationary wave. However, for avoidance of aliasing we still call the quasi-stationary waves on interdecadal time scale hereafter the ATW. In order to display the interdecadal change of the ATW, setting the length of a time series as $2M$, the ATW for the two periods ($2M$) are respectively defined as

$$(\bar{h}_1^{t_1})^*(\lambda,\varphi) = \overline{h}_1^{t_1}(\lambda,\varphi) - [\bar{h}](\varphi), \tag{2}$$

$$(\bar{h}_2^{t_2})^*(\lambda,\varphi) = \overline{h}_2^{t_2}(\lambda,\varphi) - [\bar{h}](\varphi), \tag{3}$$

where the average period is $t_1 = t_2 = M$, and $\bar{h}$ for computing reference $[\bar{h}](\varphi)$ is still the climate mean over the domain $[1,\ 2M]$. Comparing (2) and (3) one can read the interdecadal change of the ATW directly. It is evident that the interdecadal change of the ATWs includes the global warming tendency. In this case the difference of $(\bar{h}_1^{t_1})^*(\lambda,\varphi)$ and $(\bar{h}_2^{t_2})^*(\lambda,\varphi)$ can be expressed in another form:

$$(\bar{h}_2^{t_2})^*(\lambda,\varphi) - (\bar{h}_1^{t_1})^*(\lambda,\varphi) = \overline{h}_2^{t_2}(\lambda,\varphi) - \overline{h}_1^{t_1}(\lambda,\varphi). \tag{4}$$

Equation (4) shows that the interdecadal change of the ATWs is exactly the same as the interdecadal change of the geopotential high fields for the two periods. However, Eqs.(2) and (3) may be a more convenient form for studying the relationship between ATW and rainfall anomaly by use of synoptic analysis, because one can directly read their amplitude and phase changes from their difference fields, which are easily combined with the dynamic and synoptic principles.

The ATW has great impact on regional weather and climate. First, ATW is the climate background of the quasi-stationary waves, which are the most important factors that influence the interannual variability of a regional climate. Secondly, the quasi-stationary waves are the circulation background for synoptic systems or transient eddies, which means that the geographic locations of active transient eddies are associated with the ATW.[22] For instance two maximum centres of the transient eddy variances are located at the east side of the major aero-troughs in East Asia and North America, respectively. In addition, atmospheric teleconnection patterns are also influenced by the ATW,[23,24] which determines the basic zonal flow that is a key condition for the propagation of low-frequency oscillations in atmosphere. Besides, the

ATW phase is an important factor that influences the effect of the interference between the transient eddies and itself.

In general the interannual variability of a regional climate is mainly influenced by quasi-stationary waves, teleconnection patterns, or transient eddy activities,[25] but a long-term persistent climate anomaly, for instance the North China drought, is probably connected with the change of climate background or ATW. It may be helpful to understand the mechanism of regional climate anomaly if ATW change is investigated.

3. Stationary waves in 500 hPa

The reference $[\bar{h}](\varphi)$ in Eqs.(2) and (3) should be a zonal mean on a latitude circle according to the classical definition of ATW, since there are about 3–4 stationary waves along a latitude-ring in middle latitudes for northern hemisphere, and a regional weather and climate is more directly correlated to the ATW across the surrounding region. Hence we focus our attention to the ATW over Eurasia. Under this consideration the reference $[\bar{h}](\varphi)$ in Eqs.(2), (3) can be computed only on the section 10°E–180°E, rather than a complete latitude ring. Setting P1 representing 1956–77, and P2 representing 1978–99, we calculate the ATWs of the 500 hPa geopotential height fields for the two periods, respectively. The July and August ATWs are what we are mainly concerned with in the rest of the paper.

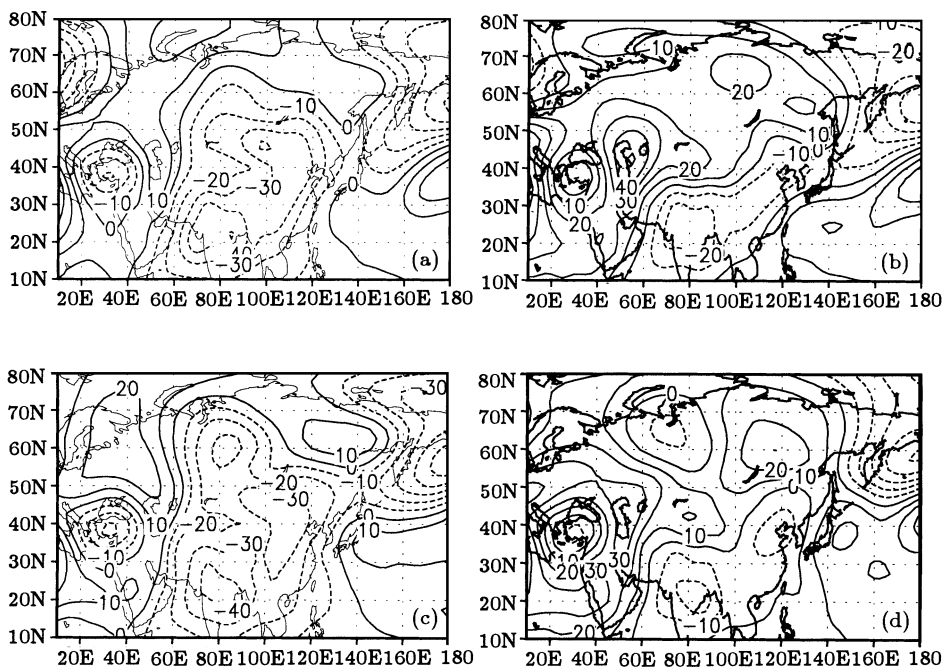


Fig.1. 500 hPa stationary waves on 10°E–180°E for P1(1956–1977) and P2(1978–99), (unit: gpm). (a) July for P1; (b) July for P2; (c) August for P1; (d) August for P2.

The 500 hPa ATW calculated for P2 (Fig.1(b), (d)) seems not to be favourite for North China rainfall during midsummer. For P1 a huge ATW trough in the middle and high latitudes occupies the Asian continent, and an ATW ridge is situated over northeastern China and eastern Siberia (Fig.1(a), (c)). Under this circumstance the boreal cold flow from northwestern China or northwestern Asia can easily invade into North China which can possibly affect the China rainfall during midsummer. For P2 the pressure over northwestern China and Mongolia increases with the development of an ATW ridge, and the original huge trough becomes a very narrow one lying from the Korean peninsula to South Asia. The new ATW ridge over the Asian continent plays a large-scale block that baffles the northwest cold flow to North China. On the other hand, the subtropical high stretches westward (Fig.1(b), (d)) and obstructs the summer monsoon from further advancement northward. As a consequence, there is more rainfall in the south of China and less rainfall in North China after 1977. The pressure increase over northwestern China has another effect, i.e. the additional pressure gradient made by the pressure increment in the north of China produces an

additional north wind anomaly that overlies the East Asian summer monsoon with a negative effect. Therefore, the interdecadal ATW anomaly is not only one of the causes for North China drought but also a factor that depresses the East Asian summer monsoon in the east of China during 1978–99.

4. Composite analysis

According to the categorization of the China Climate Centre the mainland of China is divided into 15 divisions, each of which includes a number of representative observatories. North China, one of the divisions, has 17 observatories that are located at such cities as Chengde, Beijing, Tianjing, Shijiazhuang, Dezhou, Xingtai, Anyang, Yantai, Qingdao, Weifang, Jinan, Linyi, Heze, Zhengzhou, Changzhi, Taiyuan and Linfen. The meteorological records for 1956–2000 are used in our study because most of the observatories were built after 1955. The rainfall records of the 17 observatories make up the monthly rainfall sequence of North China. We select 7 rainfall samples that are bigger than others in the monthly sequence, and another group of 7 samples that are less than others for the same sequence for July and August, respectively. The two groups of years are listed in Table 1.

Table 1. 7 rainy years and 7 dry years during 1956–2000.

Rainy	July	1957	1960	1964	1970	1973	1977	1996
years	August	1956	1963	1964	1974	1976	1995	1996
Dry	July	1968	1980	1986	1987	1992	1997	1999
years	August	1957	1968	1979	1980	1983	1989	1991

Based on Table 1 we can find two characteristic patterns, i.e. a rainy pattern and a dry pattern, composed by the 7-year geopotential height fields corresponding to the more or less rainfall records in Table 1, respectively. The rainy pattern is similar to the climate mean fields for P1 (Fig.2(a)), and the dry one is similar to that for P2 (Fig.2(b)). From Table 1, one can find that most of the rainy years are in the period before 1977, and, by contrast, most of the dry years appears in the second twenty years (P2).

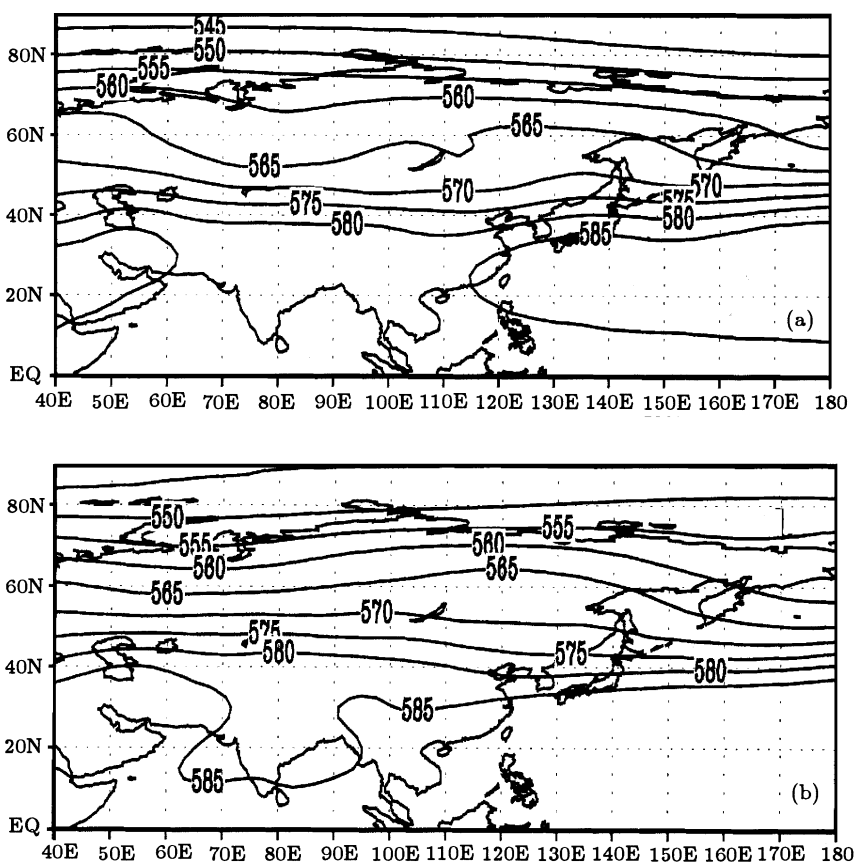


Fig.2. Composite 500 hPa geopotential fields by 7 rainy years and 7 dry years in Table 1, (a) rainy pattern; (b) dry pattern.

In the rainy pattern the subtropical high moves to a further north position than its climate, and the boreal westerly wanders to further south latitudes over the Asian continent; huge aero-trough situates at Balchaš Lake, and another small one is around Bajkal Lake. In this case more disturbances and more intensive monsoon can join together over North China with more rainfall during the midsummer. As for the dry pattern, the westerly locates at higher latitudes than its climate position, and the subtropical high stretches southwestward, and a weak aero-ridge appears over northwestern China throughout Balchaš Lake. Under this pattern North China would be generally controlled by the northwest flow that produces a dry climate.

5. Stationary waves in 200 hPa

The 200 hPa ATW also changed in July during 1978–99. There was an ATW ridge (Fig.3(a)) above North China for P1, while it was replaced by an aero-trough for P2 (Fig.3(b))). Owing to synoptic principle the 200 hPa aero-ridge corresponds likely to a divergence flow with an upward motion, whereas an aero-trough corresponds to a convergence flow with downward motion. Consequently, it favours the development of small and mesoscale systems or transient eddies in middle or high latitudes under a 200 hPa aero-ridge, while these systems would be restrained under an 200 hPa aero-trough. In the recent 22 years the south Asian ATW high in 200 hPa has become strong and stretched eastward coupling with a westward extension of the subtropical high in the northwestern Pacific in the middle and low troposphere (Fig.2(b)), which is, as well known, favourable to the rainfall in south China, but not for North China rainfall. In addition the 200 hPa ATW high over northeastern China becomes weak during 1978–99 (Fig.3 (b)), which is also not favourable to North China rainfall because the positive departures of 200 hPa geopotential height over northeastern China is favourable to North China rainfall according to a composite analysis in the next section.

Additionally, the interdecadal difference field of 200 hPa geopotential height in July shows a west–east large-scale pattern, of which the positive part is over northwestern China and surroundings, and the negative part is over North China and about. This pattern of interdecadal change clearly coincides with the climate pattern, i.e. the dry climate in North China and wet climate in northwestern China in the recent 20 years (Fig.3(c)). It seems that the interdecadal difference pattern in 200 hPa may be regarded as a climate indicator that is well correlated to the zonal climate pattern for northern China.

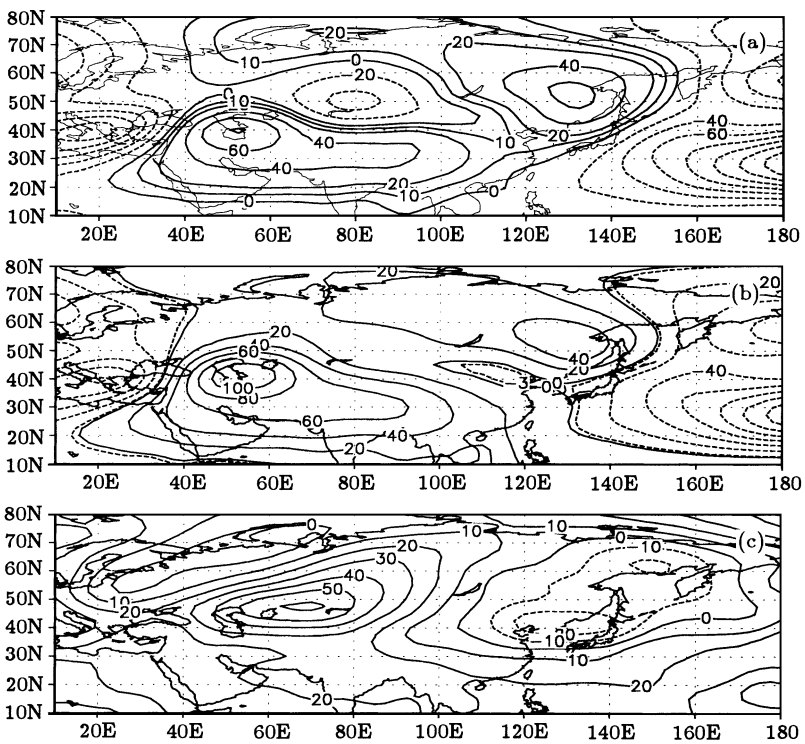


Fig.3. Eurasian atmospheric stationary waves in 200 hPa. (a) July for 1956–76 mean; (b) July for 1978–98 mean; (c) Interdecadal difference (unit: gpm).

In July the composite patterns of the quasi-stationary waves in 200 hPa based on Table 1 confirm the results analysed with the synoptic principle in the former section. The rainy pattern (Fig.4 (a)) is similar to the climate mean height field (Fig.3(a)) for 1956–77, while the dry pattern (Fig.4(b)) is similar to that (Fig.3 (b)) for 1978–99. Moreover, the difference field between the patterns (Fig.4(c)), i.e. the difference between dry pattern and rainy pattern, is similar to the interdecadal change of the 200 hPa height field for the recent 22 years (Fig.3(c)). In Fig.4(b) one can find a stationary trough stretching westward into the area above North China, which is very similar to the case in Fig.3(b). In consequence when the ridge over North China and the northeastern China throughout the Japanese Sea becomes strong with a South Asian high at its western phase in 200 hPa, it is likely to be a rainy climate in North China, and vice versa. It is easily realized that the interdecadal change of general circulation in 1977 seemed like a converter that converts a rainy climate into a dry climate for North China.

In August, the ATW structure and interdecadal difference of 200 hPa geopotential height field are similar to that of July's. As their composite results are also analogous, it is unnecessary to discuss them again.

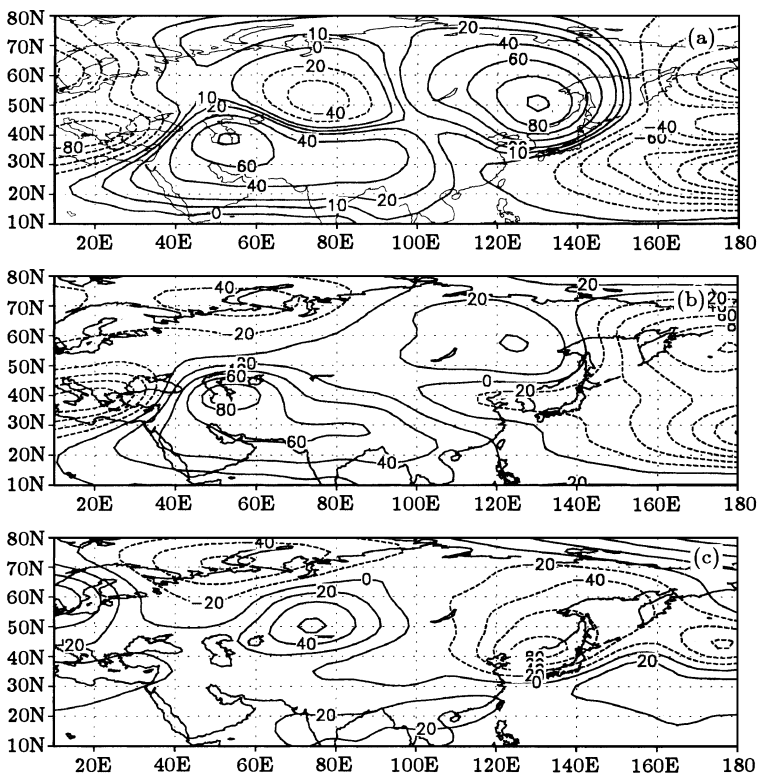


Fig.4. Composite 200 hPa quasi-stationary patterns and their difference. (a) Rainy pattern; (b) dry pattern; (c) dry pattern minus rainy pattern (unit: gpm).

6. Vertical change of stationary waves

The vertical structure of July–August stationary waves has changed in middle latitudes if we notice the zonal section of the ATW at 40°N (Fig.5). Before 1977 there was a huge ATW trough in middle and low troposphere between the domain 65°E–155°E in July and August, in which the bottom of the ATW trough locates in 98°E–118°E across the northwestern China and North China (Fig.5(a)). After 1977 the huge trough was considerably weakened and shifted a large step eastward. The phase curve with the value 0 at about 60°E before 1977 moved onto the east side of 100°E after 1977 (Fig.5(b)). The ATW phase above North China (110°E–120°E) tilted westward with altitude and there is an ATW ridge in the upper troposphere and an ATW trough in low troposphere before 1977, which is favourable to the release of the available potential energy of atmosphere,[23] while there is

almost no vertical declining of the ATW phase above North China in the period 1978–99. If considering the interference of different scale motions, the phase decline westward with altitude has a positive effect on the growth of synoptic system or small and mesoscale systems, because such an ATW structure with a ridge in up-layer and a trough in low layer coincides with the vertical structure of these systems which have a divergence flow on their tops and a convergence flow at the bottoms. After 1977 there is a ATW trough above North China from 700 hPa throughout 200 hPa, and there is almost no phase difference with height. This structure is evidently not favourable to the development of rainfall systems over North China. The vertical ATW structure at 35°N is also similar to that at 40°N. Therefore, the interdecadal change of the ATW structure is one of the important causes for the North China drought since the 1980s.

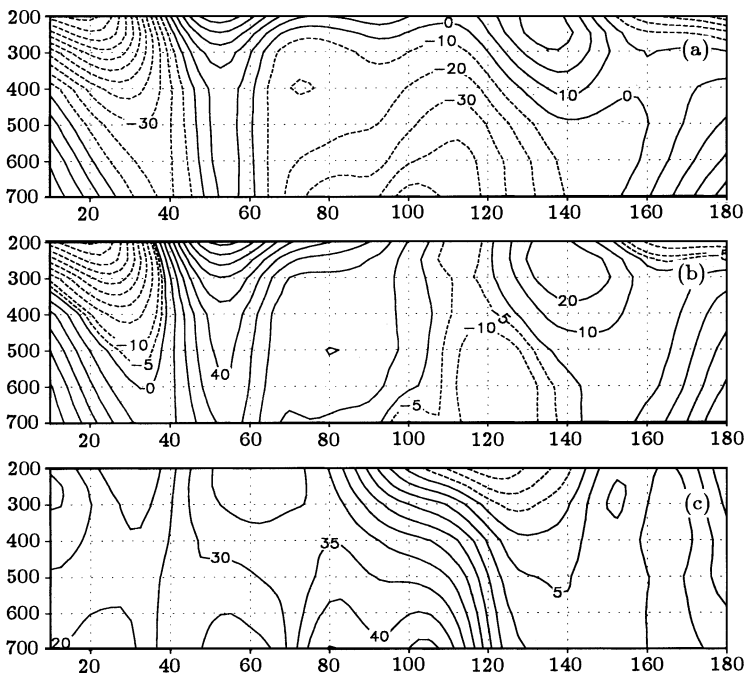


Fig.5. Section at 40°N for July–August mean stationary waves. (a) 1956–77; (b) 1978–99; (c) difference field between (b) and (a) (unit: gpm).

The July and August mean ATW has a tropical structure on the section at 25°N over East Asia (Fig.6). There is an ATW trough in the low-layer and a ridge in up-layer over the land, but there is an inverse vertical structure over the East Sea out of the eastern coast of China. Such type of ATW structure may be forced by the East Asian summer monsoon.[23] The low-layer trough at this latitude weakened too (Fig.6(b)), as has happened in higher latitudes in the recent 22 years, but the up-layer ridge becomes strong due to the extension eastward of the South Asian high in upper troposphere. The composite effect is positive to the rainfall in the south of China during the 1980s and 1990s.

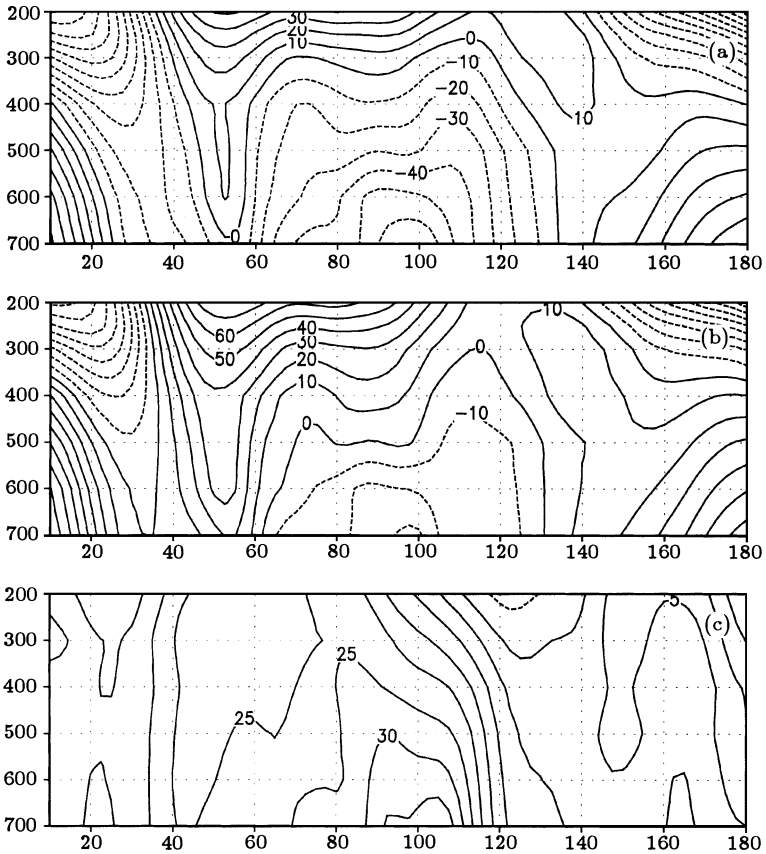


Fig.6. Section at 35°N for July–August mean stationary waves. (a) 1956–77; (b)1978–99; (c) difference field between (b) and (a) (unit: gpm).

7. Conclusions

The above results manifest that the midsummer ATW over Eurasia has been significantly changed during the past two decades. There was a huge ATW trough over the Asian continent in 500 hPa during 1958–77, but a narrow weak one situated from the Korean peninsula throughout the India subcontinent from 1978 onward. Thus a northwest flow dominated over North China, which further reduced the rainfall there since then. In 200 hPa there is a zonal pattern of the interdecadal change of geopotential height for July and August, of which the positive part is over northwestern China, and the negative part is over North China. Such a pattern implies a positive effect on the northwestern China rainfall and a negative effect on North China rainfall in midsummer. Besides, the vertical structure of ATW at middle latitudes has also been changed. Its huge trough across the Asian continent in the middle and low troposphere before 1977 becomes very weak and shifts eastward in the recent 22 years, while the 200 hPa ATW ridge over North China in 1956–77 is replaced by a trough after 1977. The tilt westward of the ATW phase above North China before 1977 becomes almost upright for 1978–99. The composite analysis about North China rainfall confirms that the ATW pattern for 1956–77 corresponds to the composite rainy pattern, whereas the pattern for 1978–99 is similar to the dry pattern composed. In all, the interdecadal change of the ATW structure over Eurasia produced a negative impact on North China rainfall, and is probably one of the important causes for North China drought since 1977.

Finally, the reason that accounts for the change of the ATW structure over Eurasia is still a scientific problem. A numerical investigation with and without mountain[23] shows that the ATW forced by the mountains has a relatively small scale and an equivalent barotropic structure, and its amplitude increases with altitude and reaches its maximum at the tropopaus nearby. Nevertheless, the ATW produced by the diabatic heating on the surface has no such increasing tendency toward the tropopaus, with a spatial scale larger than that forced by the mountains. As the maximum interdecadal change of the ATW we calculated has a large scale in low troposphere over the Asian continent, hence the ATW change mentioned above

is probably caused by the distribution changes of the diabatic heating on the surface, resulting from desertification, land-use, surface vegetation change and so on. However, this needs to be studied further with a high-resolution regional climate model.

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