A decomposition study of moisture transport divergence for inter-decadal change in East Asia summer rainfall during 1958–2001*

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(Received 18 January 2012; revised manuscript received 30 May 2012)

In this paper, we report on the results of an investigation into inter-decadal changes in moisture transport and divergence in East Asia for the two periods 1980–2001 and 1958–1979. The aim is to explore the mechanism of summer rainfall change in the region after abrupt changes. The relevant changes are calculated using ERA-40 daily reanalysis datasets. The results show that both stationary and transient eddy moisture transports to the Chinese mainland have declined since the abrupt change in atmospheric general circulation in the late 1970s, leading to more rainfall in South China and less in the North. The anomalous rainfall pattern coincides well with anomalous large-scale moisture divergence in the troposphere, of which stationary-wave or monsoon transport is dominant, in comparison with the contribution of the transient eddies. Furthermore, their divergences are found to be in opposite phases. In addition, meridional divergence is more important than its zonal counterpart, with an opposite phase in East Asia. Abnormal zonal moisture convergences appear in northwestern and northeastern parts of China, and are related to the excess rainfalls in these regions.

An increase in transient eddy activity is one of the major mechanisms for excess rainfall in northern Xinjiang. Consequently, the anomalous rainfall pattern in East Asia results from a decline of the East Asian monsoon after the abrupt change, while the rainfall increase in northwestern China involves anomalies of both stationary waves and transient eddies on boreal westerly over the mid- and high latitudes.

Keywords: inter-decadal climate change, moisture transport, transient eddy, East Asian monsoon

PACS: 92.30.Bc, 92.60.Ry **DOI:** 10.1088/1674-1056/21/11/119201

1. Introduction

Global atmospheric circulation experienced a planetary scale abrupt change in the late 1970s under global warming.[1−5] Meanwhile, regional climate presented various changes, such as the weakening of the East Asian summer monsoon (EASM),[6] resulting in serious floods in South China and severe drought in the North.[7−10] The acidification that has taken place in northern China has led to a persistent shortage of water resources,[11] degradation of ecosystems and noticeable desertification problems in North and Northwest China.[12] Frequent floods in South China have placed huge pressures on local infrastructure and hydro-facilities. All told, these changes have brought about great losses to the Chinese economy,[13] and it is therefore very necessary to study the mechanisms of inter-decadal climate change for reducing the potential hazards in the near future.

Long-term drought and severe floods in East Asia must be related to atmospheric general circulation or monsoon anomalies.[14,15] The EASM's circulation pattern is very complicated,[16] in which a dominant role is played by the western Pacific subtropical high (WPSH), which determines, to a great extent, the position of the summer monsoon rainfall belt in East Asia.[17] Observation analysis has indicated that the WPSH has shifted to a farther south and west location after the abrupt change, and the accompanying shift of the associated rainfall belt has led to frequent floods in the south of China, especially in the Yangtze River basin.[18] Correspondingly, the northern hemi-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 40775048 and 41075058) and the Special Scientific Research Fund of Public Welfare Profession of China (Grant No. GYHY201106016).

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spheric westerly has also shifted southward with the WPSH, strengthening the lower-layer northerly winds and restraining the northward advance of the EASM, which has been one of the key physical causes for long-term drought in North China since the 1980s. As is well known, decadal-scale variation of the WPSH is related to phase change of the Pacific decadal oscillation (PDO), which presents as a seesaw pattern of sea surface temperature anomalies (SSTAs) over the tropical and northern Pacific.[19,20]

One of the most important functions of the EASM is water vapour transport to the middle and high latitudes in East Asia. Indeed, one kind of EASM index was even defined by column-integrated water vapour transportation.[21] Oscillation of the EASM can greatly affect both moisture transport and rainfall over East Asia. Simmonds *et al.*[22] compared moisture flux and divergence in wet and dry years respectively in East Asia during the period 1980–1996 using ECMWF daily gridded analysis datasets, and found that there was much stronger northward moisture transport with convergence from the southern boundary of the Chinese mainland in wet years compared with dry years over East Asia. Furthermore, an investigation into the relationship between summer rainfall and monsoon using NCEP/NCAR reanalysis data and observation records from 448 stations in China led to the conclusion that the inter-decadal increase in precipitation is related to strengthened moisture transport.[23,24] Meanwhile, the drought in North China has been significantly correlated with a decline in water vapour transport across the southern boundary of the Chinese mainland with the help of ERA-40 reanalysis data.[25]

North China is a region where the westerly and northward summer monsoons meet. Thus, summer rainfall is directly affected by the interaction between these two factors. The strength of the summer monsoon is significantly correlated to large-scale SSTAs over the tropical ocean,[26] but it is also influenced by atmospheric stationary waves or transient eddies in boreal westerly winds. One of the noticeable features of monsoonal rainfall is its persistence and large proportion of convective rainfall.[27] The monsoon would be interrupted as soon as it is hit by strong cold air flow from the north. Hence, frequent cold air activities would reduce the summer monsoon rainfall in East China. So, it is necessary to break down the moisture transport into two parts, i.e., the mean and transient components,[28] for exploring their respective influences on summer rainfall. In the mid and high latitudes, monthly wind moisture transport represents stationary wave or monsoon transport, while transient eddy moisture transport refers mainly to the transport of moving synoptic-scale perturbations. In another similar study, zonal mean moisture transport is partitioned into three parts: transport by zonal mean meridional circulation, planetary waves and synoptic-scale waves. The planetary waves are found to play a key role in transporting water vapour from the tropics to the subtropics, while synoptic-scale transport is found to be more important in the mid and high latitudes than in the lower latitudes.[29] In fact, the planetary wave transport is almost equal to stationary moisture transport, while synoptic-scale transport is the same as that by transient eddies. A similar result was also reported in a decomposition investigation using NCEP/NACR reanalysis data.[30] Opposite phases were found between the divergences of stationary and transient eddy moisture transport, implying that the stationary and transient modes are in discrepancy in terms of their moisture divergence.[31]

In this paper, inter-decadal changes in moisture transport and divergence are calculated using ERA-40 reanalysis data, with the aim being to explore the mechanism by which the anomalous rainfall pattern (i.e. the decadal-scale seesaw pattern of more rainfall in South China and severe drought in North China) has appeared in East Asia since the abrupt change in the late 1970s. Decomposition is a key method to assess the influences of transient eddies and monsoon on the summer rainfall.

The rest of the paper is organized as follows. In Section 2, the data and methods used in the study are introduced, and in Section 3, we describe the variations in summer rainfall over North China and the Yangtze River basin. The decomposition results of moisture transport and divergence are described in Sections 4 and 5, respectively. In Section 6, a further decomposition analysis of the divergences in zonal and meridional directions is presented. Transient eddies and their inter-decadal changes are discussed in Section 7, and finally some concluding remarks are given in Section 8.

2. Data and methods

The calculations presented in this paper are conducted using ERA-40 daily reanalysis data,[32] with a resolution of $2.5^\circ \times 2.5^\circ$ (latitude×longitude), and

including specific humidity and two wind components (u, v) at nine isobaric levels (1000, 925, 850, 775, 700, 600, 500, 400, 300), geopotential height at 200 hPa, precipitable water and surface pressure. The precipitable water is represented by the amount of water in a vertical column of air per unit area. Monthly precipitation data from the Global Precipitation Climatology Centre (GPCC) gridded products[33] with a horizontal resolution of $0.5^\circ \times 0.5^\circ$ are used to calculate the inter-decadal change in rainfall, and the observed precipitation data from 160 stations in China are supplied by the Beijing Climate Center (BCC).

In this paper, inter-decadal change refers to the difference between two time-mean variables over the two periods 1980–2001 and 1958–1979. Meanwhile, the inter-decadal change percentage is defined as the change over the period 1958–1979 for measuring the changes in precipitation, precipitable water, and transient eddy variance. The transient eddy variances are only computed at 200 hPa, and its definition is as follows:[34]

$$\mathrm{TE} = \frac{1}{L}\sum_{i=1}^{L}(\overline{h_i - \bar{h}})^2, \tag{1}$$

where h_i refers to the daily geopotential height (in units of gpm), $\bar{h}$ is the monthly-averaged height, and L is the day number in a month. Total water vapour or moisture transport (MT) refers to vertically integrated column moisture flux from the surface to 300 hPa (in units of $\mathrm{kg{\cdot}m^{-1}{\cdot}s^{-1}}$). The MT is explicitly defined as the term on the left-hand side of Eq. (2)

$$\frac{1}{g}\int_{P_{300}}^{P_\mathrm{s}} \bar{\boldsymbol{V}} q \mathrm{d}p = \frac{1}{g}\int_{P_{300}}^{P_\mathrm{s}} \bar{\boldsymbol{V}}\bar{q}\mathrm{d}p + \frac{1}{g}\int_{P_{300}}^{P_\mathrm{s}} \overline{\boldsymbol{V}'q'}\mathrm{d}p, \tag{2}$$

where q is the air specific humidity, u and v are the two horizontal wind components, p is the air pressure, P_s is the surface air pressure, g is the acceleration due to gravity, and $\boldsymbol{V}$ is the velocity. The over-bar denotes the monthly mean, and the prime represents the daily deviation from the monthly mean. The two terms on the right-hand side of Eq. (2) represent the monthly MT (denoted as MMT, hereafter) and transient eddy MT (represented with TMT, hereafter), respectively.[23] In fact, the MMT consists of stationary wave MT (SMT) and zonal mean circulation MT. The latter can be ignored in mid and high latitudes due to its relatively small contribution to the total MT. Hence, MMT can approximately represent SMT and therefore monsoon MT in the East Asian monsoon zone. The MT divergence can be calculated as follows:

$$D_q = \frac{\partial Q_\lambda}{a\cos\varphi\partial\lambda} + \frac{\partial Q_\varphi}{a\partial\varphi}, \tag{3}$$

where a is the Earth's radius; λ and φ denote longitude and latitude, respectively (in units of radian); and Q_λ and Q_φ in Eq. (2) denote the zonal and meridional components of the MT or MMT, or SMT or TMT, respectively. For convenience, we hereafter call the first and the second terms on the right-hand side of Eq. (3) zonal and meridional MT divergences, respectively. Considering the sensitivity in calculating abnormal rainfall percentages, a number of grids are fitted with a default value if their climate precipitation amounts are all below 1.0 mm.

3. Rainfall evolution

There are various timescales involved in rainfall evolution. For instance, the overall trend, which seems to be related to either global warming or multi-decadal change in climate; inter-annual variation, which is significantly correlated with ENSO cycles; inter-decadal variation, which is related to the abrupt inter-decadal change in northern hemispheric circulation of atmosphere in the late 1970s.

Inter-decadal climate change has caused a severe drought in North China and excess rainfall in the south, especially in the Yangtze River basin since the abrupt change. There are 17 recording stations located in North China, and 14 of these belong to the middle and lower reaches of the Yangtze River basin in this study. The evolution of summer rainfall in North China and the river basin can be characterized by precipitation sequences averaged over this group of stations. Figure 1 shows that the precipitation in North China is above the normal before the mid-1970s and then decreases from the 1980s onward, while the precipitation in the middle and lower reaches of the Yangtze River basin is above the normal in the 1950s and below the normal in the 1960s and 1970s, before jumping to a new level after the abrupt change. The inter-decadal change in the East Asian precipitation pattern is seemingly of a 60-year period, which may have resulted from the phase change of the PDO or

Atlantic multi-decadal oscillation (AMO).[35,36]

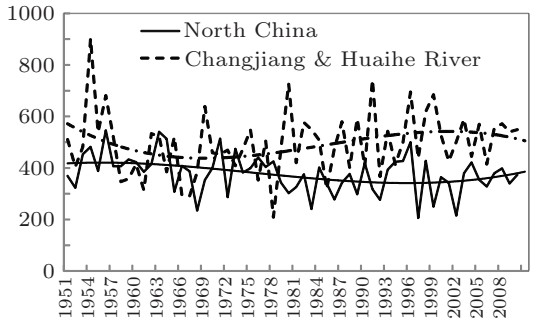


Fig. 1. Evolutions of summer precipitation in North China (solid line) and the Yangtze River basin (dashed line) during 1951–2010 (in units of mm).

4. Moisture transport

Changes in precipitation must be correlated with changes in MT and background precipitable water. Our calculations show that the drought in North China corresponds to a decrease in precipitable water and northward MT, while the flood in the Yangtze River basin corresponds to anomalous eastward MT and a slight increase in precipitable water after the abrupt change (Fig. 1). The significant changes in MT and precipitable water also appear in the tropical Indian Ocean and West Pacific after the abrupt change. For instance, although northward MT across the equator over the western Indian Ocean is intensified, this is in contrast to the scenario of the eastern equatorial Indian Ocean. Meanwhile, the large water vapour transport belt related to the southwest monsoon over the Indian Ocean shifts southward after the abrupt change and converges to the western and eastern parts of the northern tropical Indian Ocean, giving rise to more precipitable water over the near-equator region of the ocean. On the other hand, northward MT across the equator between 100°–140°E increases and converges to the Philippines with the westward abnormal MT from the western Pacific, leading to an increase in precipitable water in the tropical western Pacific. These changes cause the inter-tropical convergence zone (ITCZ) over the western Pacific or the monsoon convergence zone over the northern Indian Ocean, to shift southward from the late 1970s onward. This may be one of the key mechanisms that lead to a further-south WPSH and a weaker East Asian monsoon after the abrupt change.

Decomposition shows that the inter-decadal change in MMT (Fig. 2(b)) is very similar to that of MT (Fig. 2(a)), implying that MMT contributes mostly to MT anomalies over East Asia, South Asia, and Southeast Asia. In addition, there are southward TMT anomalies over East Asia (Fig. 2(c)), which is a resistant force against the northward MT as summer monsoon advances.

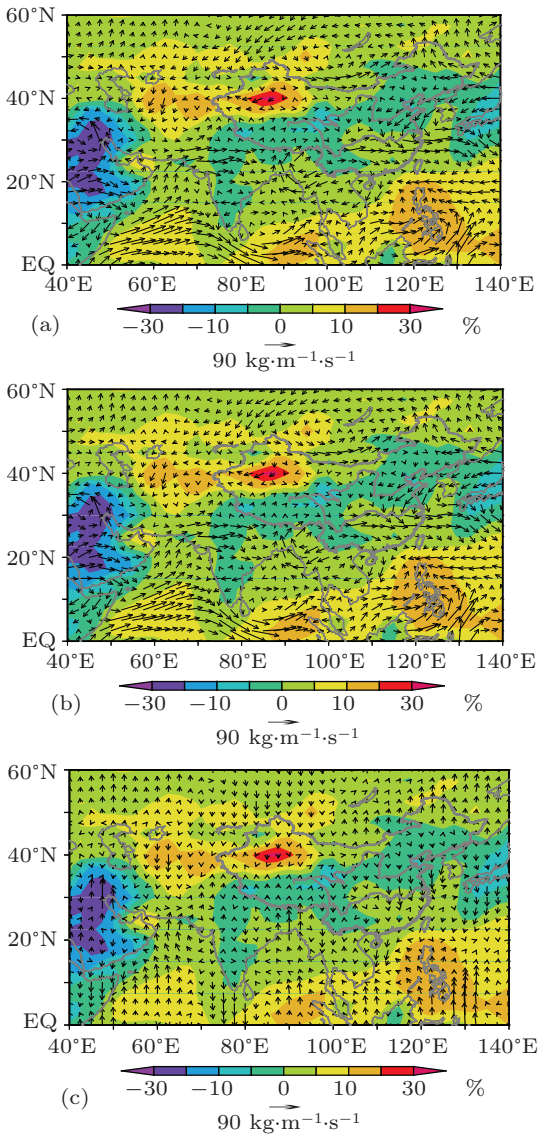


Fig. 2. (colour online) Inter-decadal changes in the column-integrated moisture transport vector (unit: $\mathrm{kg{\cdot}m^{-1}{\cdot}s^{-1}}$) in the troposphere and the precipitable water percentage for the two periods 1980–2001 and 1958–1979: (a) MT, (b) MMT, (c) TMT.

5. Decomposition of moisture divergence

The anomalous rainfall pattern after the abrupt change can be clearly seen in the GPCC precipitation data (Fig. 3). There is a rainy zone along the Yangtze River basin and a rainy area over northwestern China in summertime, while two dry climate zones appear in

northern and southern China, respectively, of which one extends from the eastern part of Northwest China to North China, and then the northern part of Northeast China, while the other is situated along the southern coast of the Chinese mainland. A surprise result is that the anomalous rainfall pattern over East Asia coincides well with the pattern of large-scale MT divergence anomalies.[37] However, there exists a number of small-scale factors that also exert influences on the rainfall in East Asia, for instance, local thermal convections and small topography forcing.

Figure 3 shows that the areas of excess rainfall correspond to negative MT divergence anomalies or MT convergence centres, such as those over the Yangtze river basin and northeastern China, whereas areas of less rainfall correspond to positive MT divergence anomalies or anomalous MT divergence centres in North China and the eastern part of Northwest China. Decomposition of MT divergence shows that the pattern of MMT divergence anomalies (Fig. 3(b)) resembles the MT divergence anomalies in East Asia (Fig. 3(a)), which means that MMT divergence anomalies form a dominant component of MT divergence anomalies in East Asia and implies that the anomalous rainfall pattern results mainly from large-scale MT anomalies related to the abnormal East Asian summer monsoon. The TMT divergence anomalies are usually smaller than MMT divergence anomalies in magnitude, and their patterns (Fig. 3(c)) are almost in opposite phase compared with MMT divergence anomalies, except for the coastal zone around the Bohai Sea and the eastern part of Northwest China. This implies that the inter-decadal change in TMT is almost negative in terms of its influence on the change in large-scale MT or MMT divergence. As a result, the regional characteristics of the anomalous rainfall pattern could be interpreted by different mechanisms. Consequently, the inter-decadal increases in precipitation along the Yangtze River basin and over northeastern China result mainly from anomalous MMT or monsoon MT convergences, while their divergences each are a major force against the dry climate along the southern coast, in North China and in the eastern part of Northwest China. Conversely, the excess summer rainfall in the northern Xinjiang province is seemingly caused by the increase in local TMT convergence, in contrast to southern Xinjiang (the Tarim basin) and the west Gansu province where the increased rainfall is, to a greater extent, involved in intensified MMT or SMT convergence after the abrupt change.

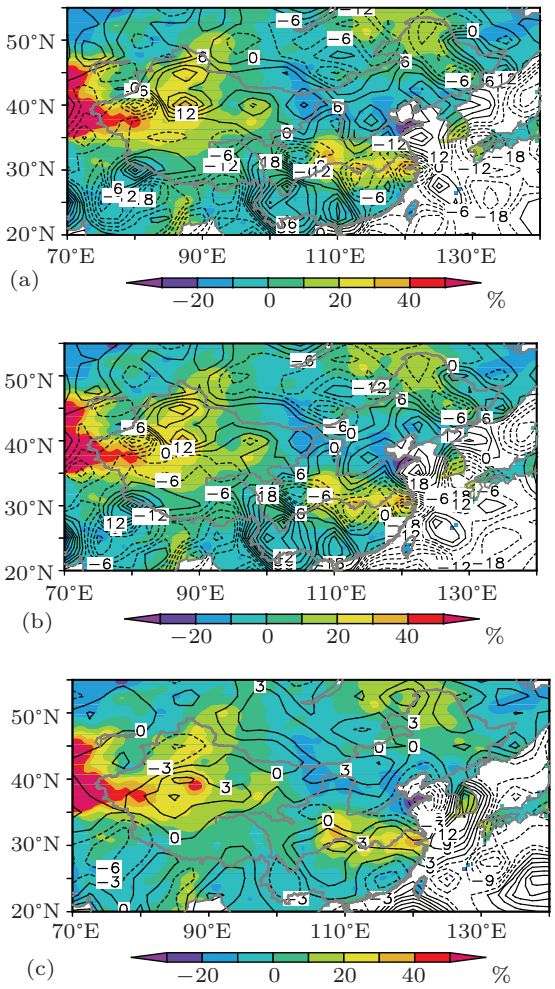


Fig. 3. (colour online) Inter-decadal changes in column-integrated moisture transport divergence anomalies (unit: 10^{-6} kg·s^{-1}) in the troposphere and precipitation percentage for the two periods 1980–2001 and 1958–1979: (a) MT, (b) MMT, (c) TMT.

6. A further decomposition

The MT divergence anomalies or their decompositions consist of zonal and meridional components as shown in Eq. (3). Our calculations show that their phases are opposite to each other (Figs. 4(a) and 4(b)), as with wind divergence. Comparing the results reveals that the meridional MT divergence anomaly field (Fig. 4(a)) resembles that of MT divergence anomalies (Fig. 3(a)), implying that the meridional components of MT divergence anomalies determine the major characteristics of MT divergence anomalies, except in Northeastern China where the contributions to negative MT divergence anomalies are made by zonal MT divergence anomalies (Fig. 4(b)). Moreover, the meridional component field (Fig. 4(c)) resembles that of MMT divergence anomalies (Fig. 3(b)), or that of

MT divergence anomalies. Thus, it is the meridional MMT or monsoon anomalies that lead to the anomalous rainfall pattern in East Asia after the abrupt change. Zonal MT divergence anomalies lead to water vapour divergence over most of East Asia, except for two excess rainfall centres over the Yangtze River basin (Fig. 4(d)), implying that zonal MT divergence anomalies create constrained effects on rainfall in the basin, but are favourable for rainfall over the rest of East China.

The TMT divergence anomaly decomposition shows that in northern parts of China, their two components are also in opposite phases to each other, and, in the south, are almost in the same phase (Figs. 4(e) and 4(f)). The inter-decadal changes in meridional TMT divergence anomalies favour precipitation in northern Xinjiang, the Huaihe River basin and in North China (Fig. 4(e)), while its zonal components favour rainfall in western Xinjiang, Northeast and North China, and along the southern coast. The contributions to anomalous TMT divergence over the Yangtze River basin in Fig. 3(b) are mainly made by zonal TMT divergence anomalies. The characteristics of the two TMT divergence anomaly components are greatly affected by the traces of transient eddies resulting from our weather forecasting practices as is well known. However, the characteristics of the two MMT divergence anomaly components are largely affected by quasi-stationary wave anomalies of boreal westerly, and by summer monsoon conditions in mid and lower latitudes.

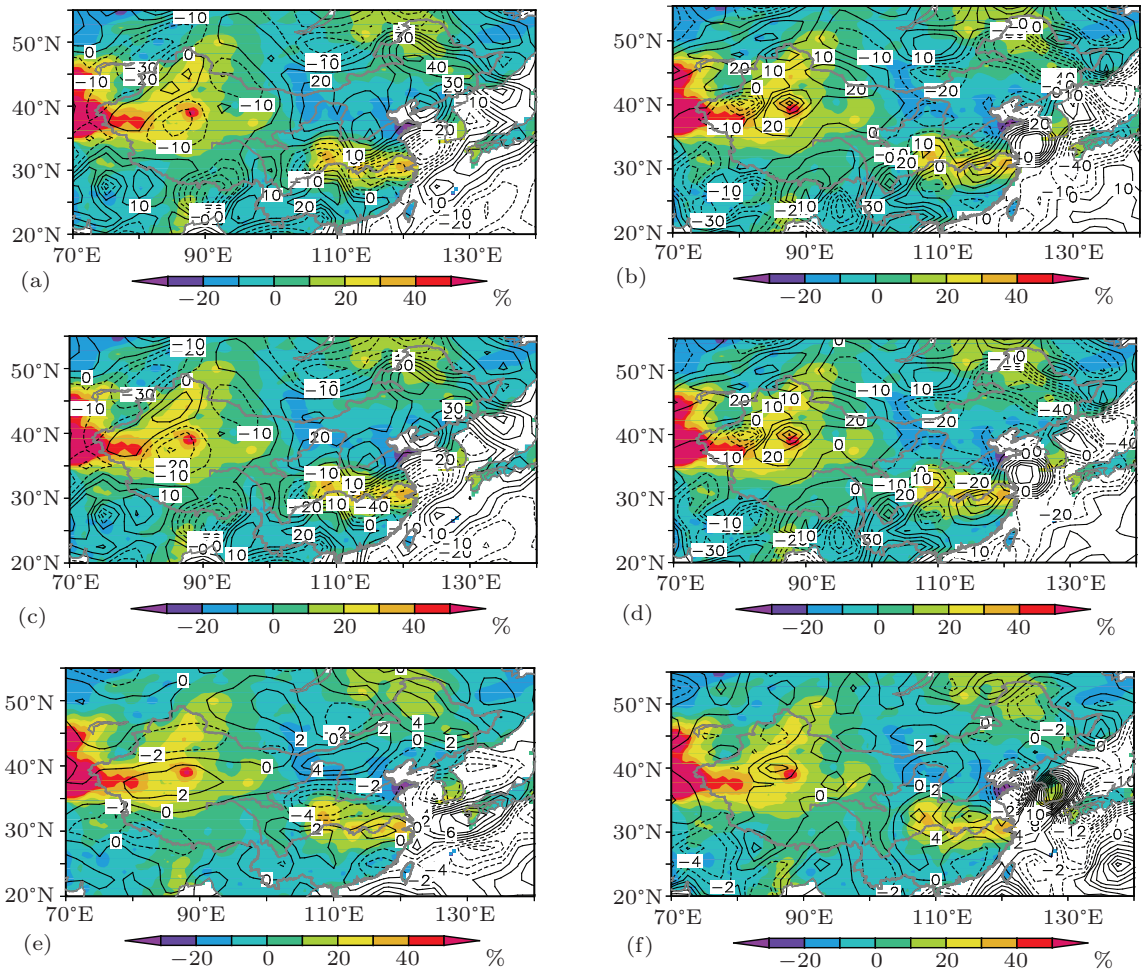


Fig. 4. (colour online) Meridional and zonal changes of column-integrated moisture transport divergence in the troposphere and precipitation percentage for the two periods 1980–2001 and 1958–1979: (a, c, e) meridional components of MT, MMT and TMT divergence anomalies, respectively (unit: 10^{-6} kg·s^{-1}); (b, d, f) zonal components of their counterparts.

7. Transient eddies

Transient eddy activity also shows an inter-decadal change from the late 1970s on. It can be described by the variance of one of the atmospheric variables, and the changes can be measured by the change in variance percentage for the periods 1980–2001 and 1958–1979. The results show that the eddy activity becomes weak over most of Eastern China, except the western Tibetan Plateau and Tarim basin in western China and eastern China (Fig. 5). The increased rainfall belt over the Yangtze River basin corresponds to a decrease in transient eddy activity and is situated near the weak centre of the transient eddy intensification in its north direction, while the severe drought regions in North China are almost just below the centre. This result confirms again that, as shown in Figs. 5 and 2(c), enhanced eddy activity plays a negative role in the MMT convergence region, and therefore monsoon rainfall over East Asia. This implies that persistent monsoon rainfall needs a weak cold flow in order to maintain a weak thermal contrast across the rainfall belt in Changjiang and the Huaihe river basin. Nevertheless, intensified activity of transient eddies represents an increasing number of synoptic processes appearing, which is favourable for rainfall in non-monsoon-controlled regions, for instance the inland dry zone in northwest China. So, the severe drought in North China is partly a result of enhanced transient eddy activity. In addition, the contribution to the increase in transient eddy moisture convergence in northern Xinjiang in Fig. 3 is made partly by more transient eddy activity, in addition to an increase in water vapour content from 1980s onward.

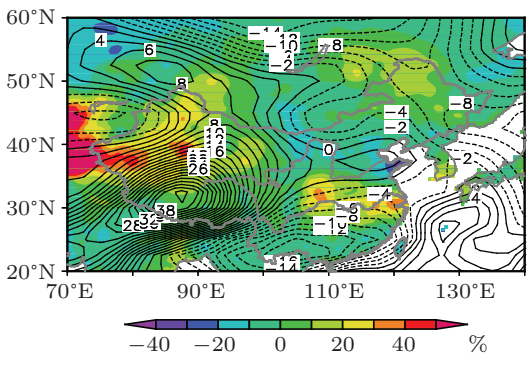


Fig. 5. (colour online) Inter-decadal percentage changes in summer rainfall and transient eddy activity at 200 hPa for the periods 1980–2001 and 1958–1979.

8. Concluding remarks

This study enables us to conclude that the inter-decadal change in East Asian summer rainfall since the late 1970s is strongly related to the changes in moisture transport, moisture divergence, and precipitable water in the troposphere over East Asia. After the abrupt change, more rainfall concentrates over the Yangtze River basin and South China, corresponding to an increase in westward moisture transport, large-scale moisture convergence and precipitable water in the troposphere. Meanwhile, North China and eastern parts of Northwest China each have experienced a very dry climate from 1980 onward, corresponding to a decline in northward moisture transport, moisture convergence and precipitable water. Decomposition shows that the contributions of the change in East Asian moisture divergence are made mainly by MMT or monsoon water vapour transport, of which the meridional component of the MMT is dominant. However, zonal MMT anomalies are more important for the moisture convergence or rainfall in northeastern China and southern Xinjiang. On the other hand, the anomalous TMT convergence is a major contributor to the excess rainfall in northern Xinjiang due to increases in air water vapour content and transient eddy activities, while the transient eddy plays a negative role in water vapour convergence in East China. The special features of the abnormal TMT divergences may be related to changes in thermal dynamic structure of the atmosphere and stationary wave distributed in the boreal westerly with global warming. The physical mechanism of the inter-decadal changes in moisture transport and the eddy activity needs a further investigation in the future.

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