Three dimensional structure of atmospheric water vapor transportation and its relationship with the summer flood/drought situations over Huaihe River Basin

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Abstract. Using the observational and JRA-25 reanalysis datasets, three dimensional structure of water vapor transportation and its relationships with the summer flood/drought situations are investigated in summer time over the Huaihe River Basin (HRB) in eastern China. Results show that there exist major net water vapor input from the western and southern boundaries and net water vapor output in the eastern and northern ones. The water vapor transported from the Bay of Bengal and the South China Sea regions are critical to the precipitation in the HRB region. A typical flood has close relationships with positive anomaly of the transported water vapor from the Bay of Bengal. For a typical drought year, water vapor transported from the Bay of Bengal, as well as the South China Sea, are greatly reduced. And the contribution of the South China Sea is relatively large. Water vapor transported by the tropical westerly also plays a key role in the summer precipitation of the HRB area. Results suggested that the region of the southeast of the Tibet Plateau plays a key role as "transfer post".

1. Introduction

Hydrological cycle in the atmosphere-terrestrial coupling system is a crucial component in climate system. It includes precipitation, evaporation, water vapor transpiration, stream flow, and changes in precipitable water in atmosphere, ground water, soil moisture, snow, lake and other water body. It plays an important role in climate system as it is the media that transpiration the nutriment and energy among the components of climate system [1]. Especially the case of atmospheric water vapor, it's not only a water body that condenses the rainfall but also a greenhouse gas with the release of latent heat to influence the atmospheric circulation patterns. Study on the hydrological cycle, the atmospheric water vapor transport has drawn more and more attention as its importance to drought and flood and sensitivity to anthropogenic effects [2-4].

Many studies of atmospheric branch of water cycle have focused on basin scale to global scale [5-12]. In summer, the East Asian is the strongest water vapor convergence area, the source and the transport of atmospheric water vapor and its character over China associate with East Asian monsoon has also been discussed [13-21]. It has been revealed that there are three key moisture channel has relationship with summer rainfall in eastern China, exactly, the Bay of Bengal (BOB) and the South China Sea (SCS), the tropical Northwest Pacific (WNP), and the westerly in middle latitude. Due to the different research object, region, and period for concern and discussion, which channel plays a

relative important role is still open debated.

The HRB is located in the central and eastern China, and its precipitation is dominated by monsoon in summer. Many studies have shown that the flood /drought occurs frequently bringing a high risk to this area and has a great impact on livelihood. Previous studies in the HRB usually concern the relationship of water vapor and rainfall in mesoscale [22-25], in addition, take the Yangtze river basin and the HRB as a whole object to be investigated. However, many results have shown that these two area have their own character, which should be considered separately [26-28]. And as the shortage of high resolution data, the atmospheric branch of water cycle in HRB is less concerned in the angel of climate and lack of described in detail. Recent atmospheric reanalysis data sets from the Japan Meteorology Administration (JMA), with a resolution of $1.25° \times 1.25°$, have provided a comprehensive opportunity to study three dimensional structures of atmospheric water vapor transportation and its relationship with the summer flood/drought situations over the HRB [29].

The outline of this paper is as follows: section 2 introduces the data and methodology and section 3 describes anomalies of the moisture transport and budget and its impact on summer rainfall in HRB in inter-annual scale. Concluding remarks are given in section 4.

2. Data and methodology

2.1. Data
This study employs the isobaric data set from JRA25, with a horizontal resolution of 1.25º×1.25º and 23 vertical layers per 6 hours a day from 1980 to 2005, which is obtained from the Japan Meteorological Agency (JMA). Studies have shown it has a certain capability to characterize the global water cycle features besides the East Asia's [30].

2.2. Methodology
Considering the existence of large terrain, which may produce false information when calculating the total water vapor transport by water vapor and wind field below the surface which include in the datasets during the vertical integration. In order to eliminate the impact of the terrain, the upper integral limit is taken to 100 hPa, the lower limit is taken as Surface pressure (Ps) and a total of 12 vertical layers. The whole atmospheric water content (Q), the zonal moisture transport (Q_u) and meridional moisture transport (Q_v) are calculated as follows:

$$Q(x,y,t) = -\frac{1}{g}\int_{P_S}^{P_T} q(x,y,p,t)dp \tag{1}$$

$$Q_u(x,y,t) = -\frac{1}{g}\int_{P_S}^{P_T} q(x,y,p,t)u(x,y,p,t)dp \tag{2}$$

$$Q_v(x,y,t) = -\frac{1}{g}\int_{P_S}^{P_T} q(x,y,p,t)v(x,y,p,t)dp \tag{3}$$

Where P_S is the surface pressure, P_T is the upper integral limit, u is zonal wind, v is meridional wind, and g is the gravity acceleration.

According to Digital Elevation Model (DEM), delimiting the boundaries of the HRB, it is generalized as a rectangle area (112.5~121.25 ºE, 31.25~36.25 ºN) and shown in figure 1. Based on it, 27 representative stations over the HRB are selected from the 833 stations daily precipitation dataset, which is downloaded from the National Meteorological Information Center, to characterize the average rainfall in the HRB. The specific location of each station is shown in figure 1 labeling as black point.
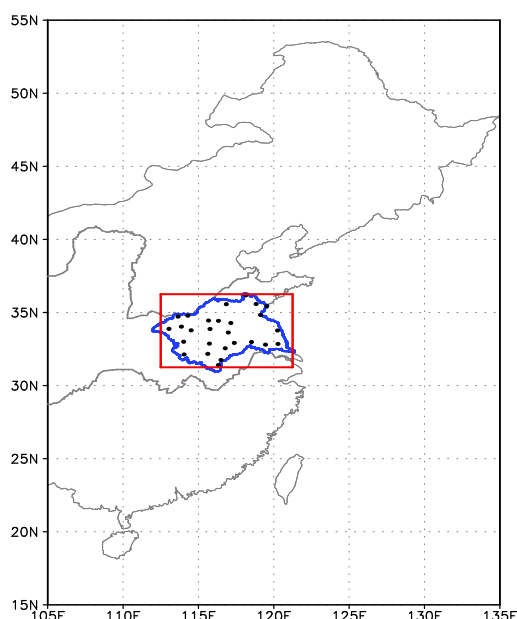
Figure 1. Distribution of stations over the HRB (black dots), the curve represents the scope of the HRB, and the rectangular boxes represents the ideal range of the HRB (112.5~121.25ºE, 31.25~36.25ºN).

2.3. Flood/Drought year definition

Variation of summer precipitation over the HRB shows in figure 2, and a typical flood/drought year is defined as the average value plus/minus the standard deviation. Exactly, when $R \geq \bar{R} + \sigma$, it means a typical flood year, when $R \leq \bar{R} + \sigma$, it means a typical drought year. Where R represents summer rainfall, $\bar{R}$ represents the average summer rainfall for many years and σ is the variance of summer rainfall for many years. After a judgment, take 1982, 1991, 2000, 2003, 2005 as typical flood years and 1985, 1988, 1992, 1997, 1999 as typical drought years over the HRB.
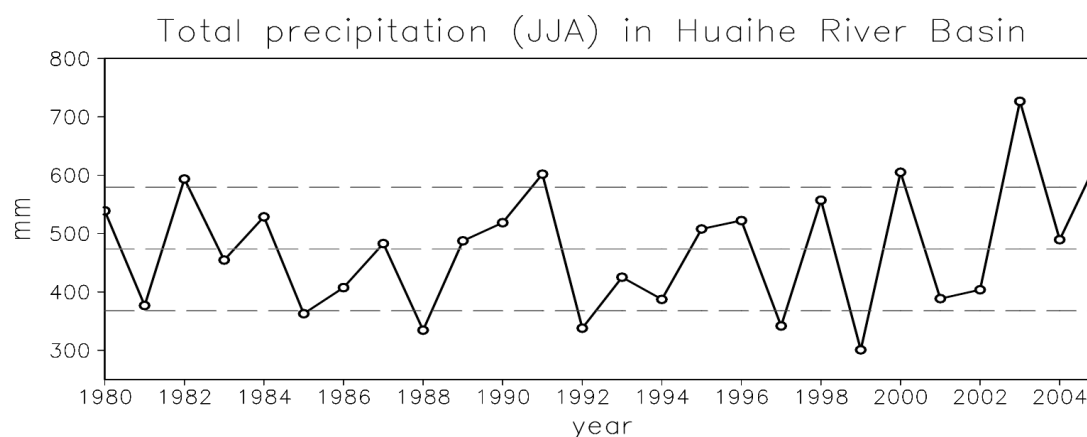

Figure 2. Variation of summer precipitation over the HRB, where the middle dotted line is an average and the other two are the average plus/minus the standard deviation (units: mm).

3. Results

3.1. Horizontal water vapor transportation characteristics

Horizontal water vapor transport anomaly in a typical flood year is showed in figure 3(a). It has demonstrated there is an anomaly gyre in the East China Sea, a north water vapor channel and a south one convergent near 30° N. And these two channels together with a strong southwest water vapor channel from the Bay of Bengal form a strong convergence belt. In the meanwhile, the subtropical

synoptic system in the south of 30°N is enhancing. There are three water vapor flow which causes the unusual convergence over the HRB. The first one is from the Bay of Bengal characterized by southwest water vapor transport anomaly, which transports to the northeast near 30° N and joins mid-latitude westerly water vapor transport anomaly, thus made the water vapor convergent over the HRB. The second one is from the South China Sea with southerly water vapor transport anomaly. The third one is the northerly water vapor transport anomaly. Because the northern boundary is not the main water vapor source in summer precipitation in the HRB, which are mainly affected by abnormal changes of the western and southern boundaries. When the precipitation is more in the HRB, the northern boundary reflects a removal effect and it means water vapor transported to the north is decreased. Therefore, water vapor which comes from the Bay of Bengal and South China Sea are the critical source to the summer positive precipitation in the HRB.
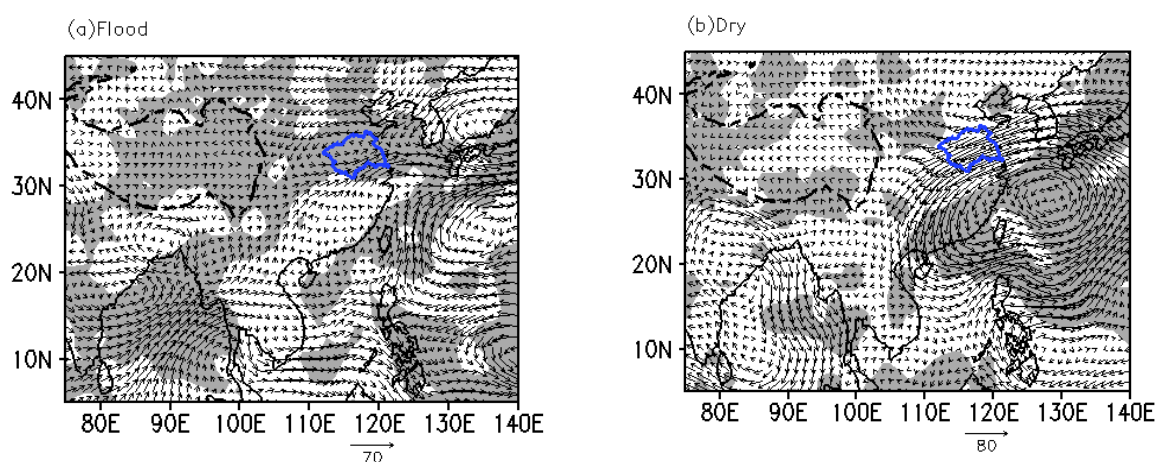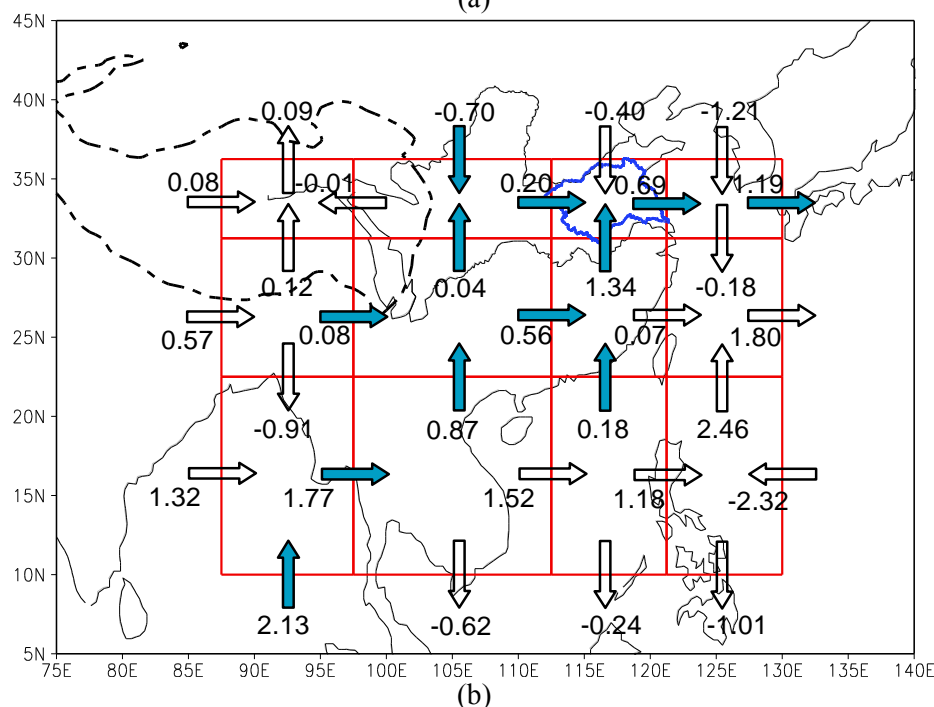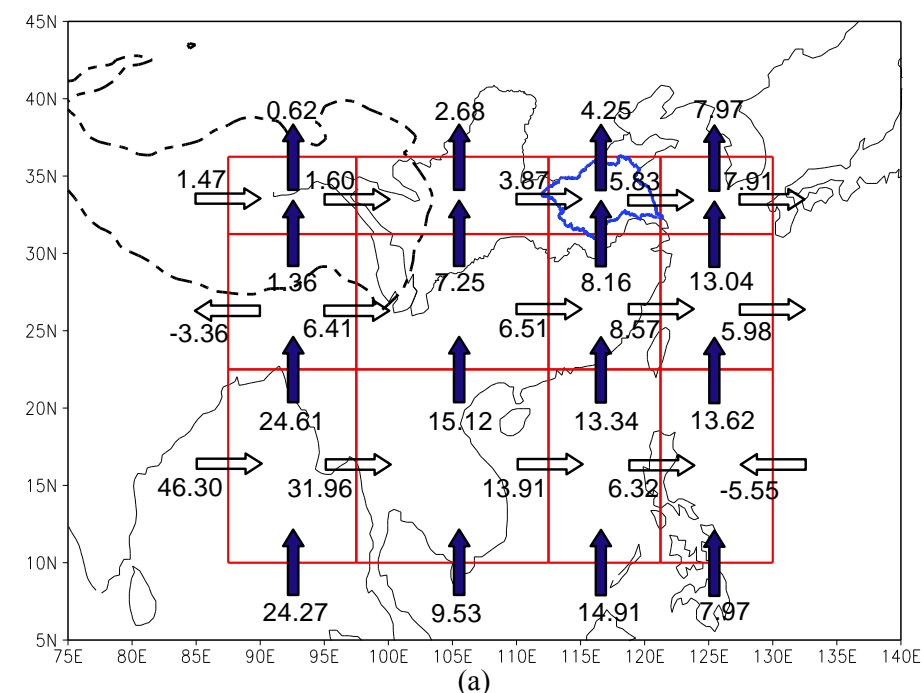

Figure 3. The mean vertically integrated water vapor flux anomalies (Units: $kgm^{-1}s^{-1}$) over the HRB in typical floods years (a) and drought years (b), and the shaded part represents negative water vapor flux divergence, the real thick curve shows the scope of the HRB and the dash curves indicates 3000 m terrain height

The above analysis shows that water vapor transported from the Bay of Bengal and South China Sea play a key role in the droughts and floods over the HRB. Cyclonic(anti-cyclonic) anomalous in the east sea surface of the mainland has provided a large circulation background for the water vapor transport and the integrated water vapor transport is closely related with the circulation pattern, which also reflects that the North Pacific subtropical high has impact on precipitation to some extent over the HRB. When the subtropical high is strong (weak), it corresponds to more (less) precipitation in the HRB, which is in substantial agreement with the conclusion of Gao [26].

To further consider the role and contribution of different water vapor channels and key areas to abnormal summer precipitation in the HRB, use sub-region technology to take a quantitative analysis on the water vapor transport key area of Asian summer monsoon and analyse water vapor budget in each boundaries of different sub-regions. To facilitate discussion, we assume the east (north) transport is positive. Positive value indicates a net water vapor input in the western and southern boundaries, vice versa. And positive value indicates a net water vapor output in the eastern and northern boundaries, vice versa.

The climatic characteristics of Asian monsoon water vapor budget in summer are shown in figure 4(a). The water vapor is mainly transported from west(south) to east(north) which exhibits net inputs(outputs) in the western(eastern) and southern(northern) boundaries. There are two exceptions, firstly, when the warm and wet air origin from the Bay of Bengal moves northward, which encounters the large plateau terrain, thus can cause a westward flow with a net water vapor output in the western boundary. The other one is associated with the Western Pacific subtropical high which can cause

easterly winds prevailed in its south, thus results in net water vapor input in the eastern boundary. In the low latitude regions, in addition to the Western Pacific, the other regions are mainly net water vapor input in the western boundaries. But in the middle latitude regions, there are mostly net inputs in the southern boundary. Under the climatic average condition, the southern and western boundaries are net water vapor input and the magnitude of southern boundary is larger than the western one. The eastern and northern boundaries are net water vapor output and the magnitude of the eastern one is larger than the northern one. Overall, the HRB is a net water vapor convergence zone.
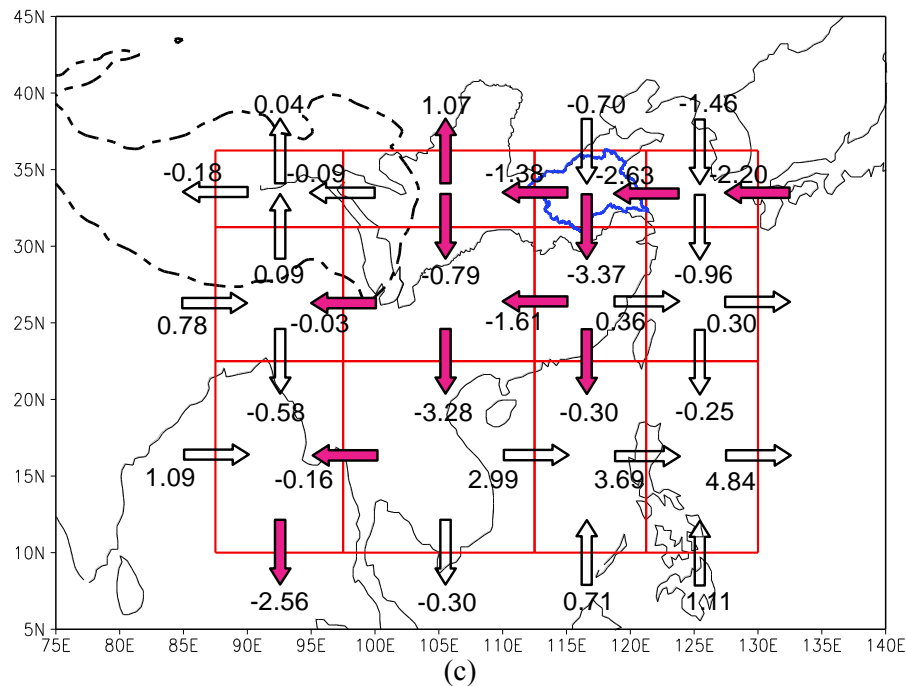

(a)

(b)

Figure 4. Water vapor budget in each boundary of the sub-region of Asian summer monsoon area (unit: 10^7 kgs^{-1}) for climate average (a), anomaly composition of typical flood years (b) and dry years (c).

Figures 4(b) and 4(c) are synthesis results of the water vapor transport anomaly in sub-region in typical flood/drought years. It can be concluded the zonal budget is negative and the meridional budget is positive in flood years with a total budget of 3.20×10^7 kg/s, which is more than 26 years value on average. Compared with the normal year, the net output increases in the eastern boundary while the net output decreases in the northern one, and it increases in the western and southern boundaries. The zonal water vapor channel contributes little to the whole basin's water vapor budget. Water vapor convergence which dues to the southern meridional transport is the most important water vapor sources to the whole basin. In drought years, the total budget is 0.53×10^7 kg/s, less than that 26 years on average, which is caused by the significant water vapor reduction (41%) from the net input of southern boundary, followed by the western boundary (36%), a net reduction of output was mainly due to decrease of the water vapor source.

Take the HRB as the center region and track the anomaly of water vapor channel outward, the opposite transport direction are marked by solid arrows between figures 4(b) and 4(c). There are two water vapor transport anomaly in the Bay of Bengal and South China Sea, which has relationship with the rainfall anomaly in the HRB, as the conclusion has mentioned before. When it is flood in the HRB, the meridional water vapor converges in the HRB, the zonal water vapor transport anomaly by the westerly wind is apt to northward and the meridional water vapor transport anomaly diverges in the South China Sea, and vice versa. Contrast figures 4(b) and 4(c), the anomaly water vapor transport in the four boundaries of each sub-region is opposite in the southeast borders of the Tibet Plateau in different years in the HRB, and the variation of water vapor transport in the southeast of Tibet Plateau is a key factor for summer precipitation in the HRB. The northward water vapor transport and mid-latitude subtropical westerly water vapor transport converge and transport to the HRB, similarly, the eastward water vapor flow and northward water vapor transport from the South China Sea also covers and transport to the HRB. The variation of water vapor output in the eastern boundary is greater than that in the northern one in a typical flood/drought year.

3.2. Vertical water vapor transportation characteristics

To further understand the vertical structure of water vapor transport anomaly which had impact on the summer precipitation anomaly in the HRB, make the longitude-altitude and latitude-height vertical cross section in typical synthetic flood/drought year in the HRB, as shown in figures 5 and 6.
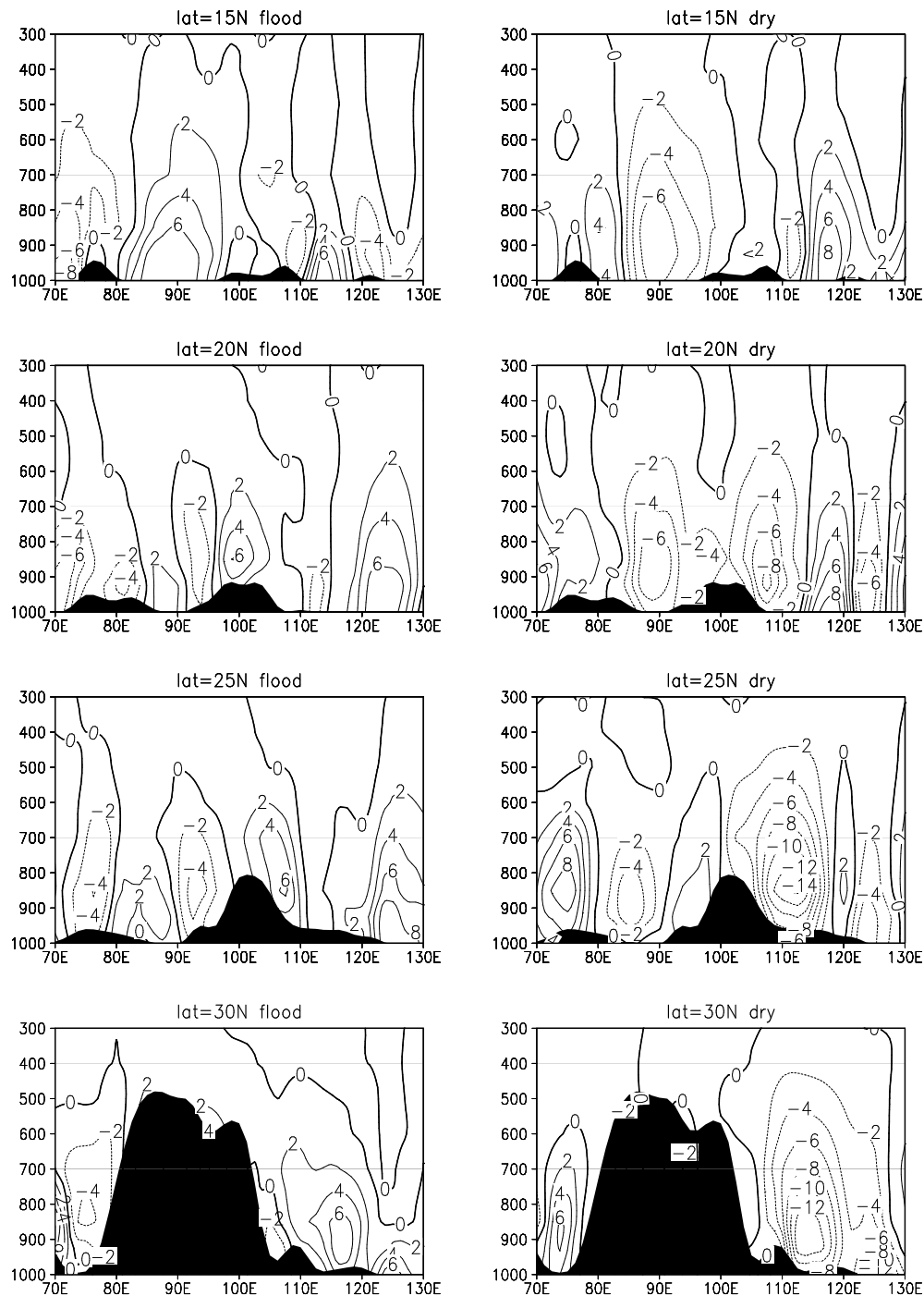

Figure 5. Synthesis longitude-height cross section of the meridional water vapor transport anomaly in flood/drought situations in the HRB (Unit: $10^{-3}\,\mathrm{ms^{-1}}$, the terrain are shaded, synthesis flood (drought) year in the HRB are shown in the left (right) column, the latitude where the cross section through is marked in the figure).
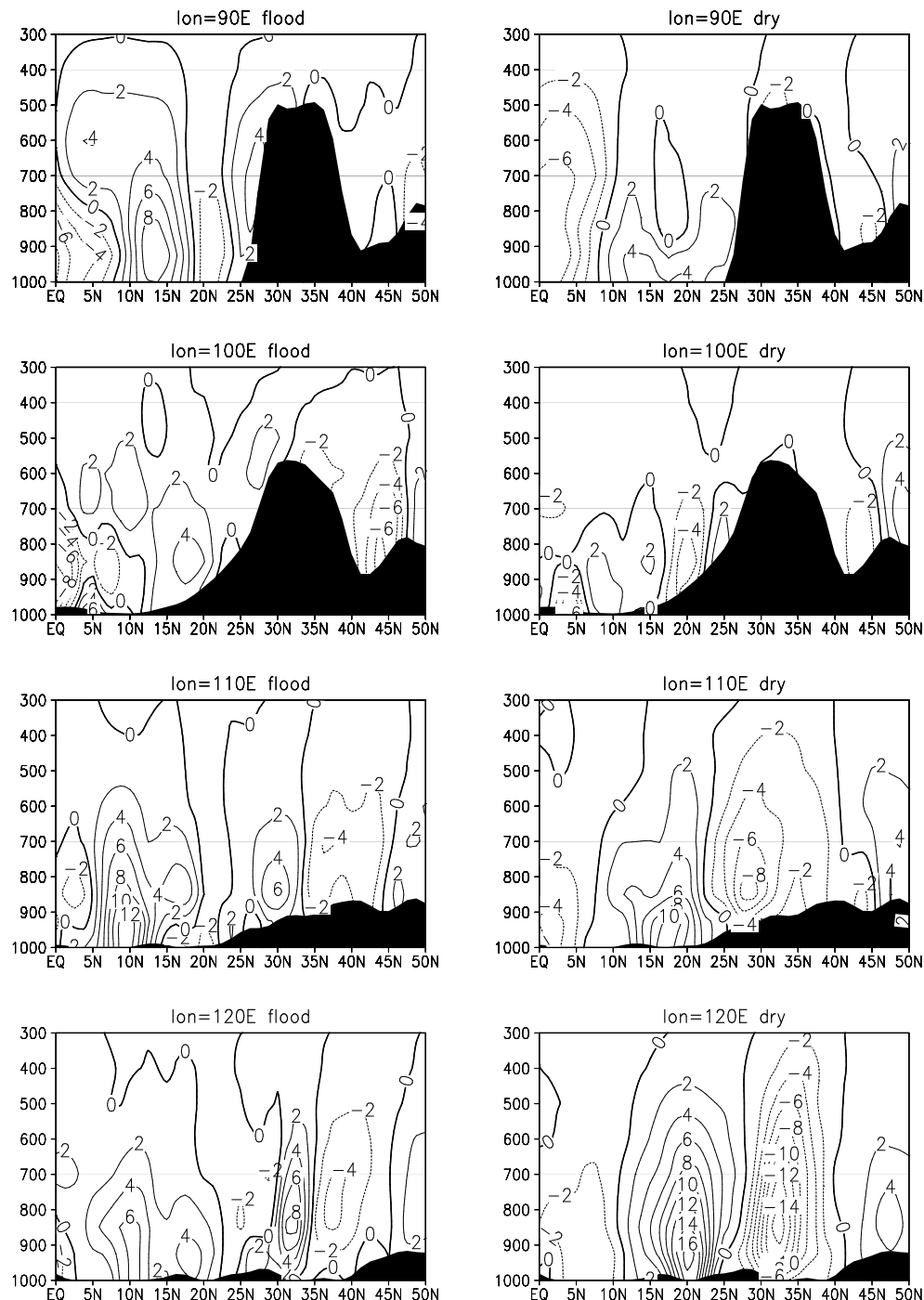
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Figure 6. Same as figure 5, but for the latitude-height cross section.

The result has shown that vertical distribution of meridional water vapor transport flux anomalies has anti-phase characteristics. In typical flood years, it has shown a positive water vapor transport anomalies in the eastern Bay of Bengal and South China Sea, and the former is more significant than the latter. In typical drought years, it has shown a negative water vapor anomalies in the Bay of Bengal and the west of the South China Sea, and the latter is slightly significant than the former. Thus, the water vapor transported from the Bay of Bengal and South China Sea are both critical to the

precipitation in the HRB. For a typical flood year, it is mainly caused by the abnormal positive water vapor transported from the Bay of Bengal. For a typical drought year, water vapor transported from the Bay of Bengal and the South China Sea are greatly reduced and the contribution of the South China Sea is relatively large.

The latitude-height cross section of the summertime zonal water vapor transport anomaly in typical flood/drought years in the HRB is shown in figure 6. In typical flood years, the positive zonal water vapor transport anomaly over the HRB can track back to the positive water vapor transport anomaly in the southeast of the Tibet Plateau which is relatively local and the meridional range is relatively narrow. In typical drought years, the negative zonal water vapor transport anomaly over the HRB can track back to the negative water vapor transport anomaly by the westerly over the Tibetan Plateau and it is relatively wide in meridional. The zonal water vapor transported from the southeast of the Tibet Plateau is one of the vital factors to the summer precipitation in the HRB.

Take correlation analysis between the summer precipitation in the HRB and meridional (zonal) water vapor transport in the corresponding period and they are high correlated both with the meridional and zonal water vapor transport (figure 7). It has pointed out that the water vapor transported from southeast of the Tibetan Plateau has a major impact on the water vapor budget of its surrounding area, Yangtze River, and the eastern area of the northwest region. To the HRB, it affects the abnormal precipitation and works as a "transfer post".
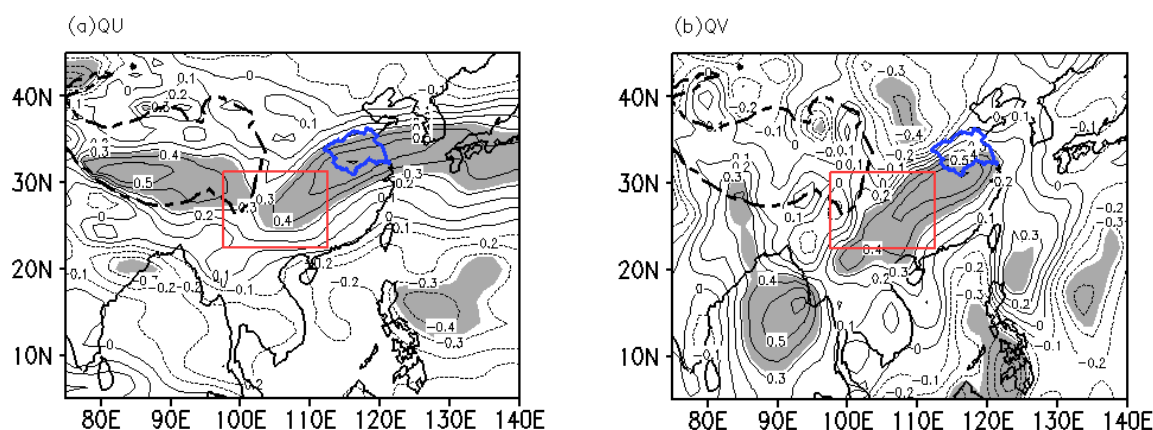

Figure 7. Correlation coefficient of the summer precipitation in the HRB with the same period zonal water vapor transport (a) and meridional water vapor transport (b), shaded area in a 90% confidence level.

4. Conclusions and discussions

Using the station observation precipitation data and JRA-25 high resolution reanalysis data, a comprehensive analysis is carried on the characteristics of atmospheric water cycle in the HRB, the water vapor transport structure is analyzed in typical flood/drought years in the HRB. The main conclusions are the following:

- In typical flood/drought years in the HRB, the entire atmospheric water content anomaly appears a reverse phase distribution pattern. The main source of water vapor which results in the summer precipitation are the Bay of Bengal, the South China Sea, the westerly belt and the tropical western Pacific.
- The water vapor transported from the Bay of Bengal and the South China Sea regions are critical to the precipitation in the HRB region. A typical flood year is mainly due to positive abnormal of the transported water vapor from the Bay of Bengal. For a typical drought year, water vapor transported from the Bay of Bengal and the South China Sea are greatly reduced, thus the contribution of the South China Sea is relatively large. Water vapor transported by the tropical westerly also plays a key role in the precipitation of the HRB. Therefore, when the

zonal westerly anomaly is northward, it can make more water vapor along the southeastern edge of the plateau to convergent and accumulate, when the zonal westerly anomaly is southward, the situation is on the contrary.

- The southeast of the Tibet Plateau is a key area for summer precipitation anomaly in the HRB, plays as a "transfer post".

In our current study, as data limited, 26 years data is used to investigate the characteristics of water vapor transpiration and precipitable water variability over HRB. It has pointed out the summer precipitation over HRB has inter-decadal variability and contains a distinct abrupt change in the mid-1970s [26]. However, our result only applies to the period after mid-1970s, and more data would be need to make a comprehensive investigation about the change of the atmospheric branch of water cycle over HRB in a longer time scale for further research.

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