Chapter 6

General Summary and Discussion

This chapter summarizes the key findings of this thesis, provides some discussion of my current understanding of climate research, and gives some ideas for research in the near future.
6.1 Introduction

This thesis aims for a better understanding of the water cycle in the atmospheric branch, which has the potential to extend the warning time of extreme hydrological events such as flood and drought (Lavers et al., 2014). Driven by this basic notion, four studies have been conducted during my PhD study.

6.2 A preliminary case study

Via preliminary meteorological research (Chapter 2), knowledge of atmospheric science and meteorology was used to build a big picture of the factors associated with heavy rainfall in China. We analysed in detail the mechanisms that led to heavy rainfall in Beijing. Meanwhile, transport processes, including vertical profiles, mean humidity variations, and relative importance of the water vapour transport paths, were further quantified by back-trajectory analyses and cluster analyses.

Specifically, an upper-level jet coinciding with the diffluent zone at 200 hPa was found steering the formation and the movement direction of the low-level vortex. At 500 hPa, three typical circulation patterns (i.e. the southwesterly jet residing at 500 hPa; high pressure in the east and low pressure in the west; trough in the north and vortex in the south), which are found being favourable for heavy rainfall in previous studies (e.g. Miller, 1972; Crisp, 1979; Tao, 1980; Zhu et al., 1981; Sun et al., 2013), were identified in the “7.21” event. Dry air at 700 hPa and moist air at 850 hPa defines a region of convective instability (Ahrens, 2009). At 850 hPa, a strong southerly current of moist air could be found to the south of the threat area (Figure 2.6). This warm moist air current intensified the convective instability and transported significant amount of moisture from the south.

The source regions of the large volume of water necessary to sustain the intense rainfall are diagnosed using a Lagrangian back-trajectory analyses (Stohl and James, 2004, 2005). Approximately 77% of the moisture was transported from the Bay of Bengal (BoB). For the first time, transport processes, including vertical profiles, mean humidity variations, and the relative importance of the rain-paths, were quantified by back-trajectory analyses and cluster analyses.
6.3. Where does the atmospheric water vapour come from and how does it get transported to the target region?

The results highlight the importance of the southwestern path in transporting moisture to northern China, which accounts for 88.4% of the moisture from the BoB, and 68% of the total "7.21" event. The trajectory results for the last 4 days agree with Sun et al. (2013). However, they calculated the backward trajectory for only 4 days. Consequently, moisture they found with different source regions in shorter backward simulation times actually came from the same source region (BoB) in longer simulation periods.

6.3 Where does the atmospheric water vapour come from and how does it get transported to the target region?

After this preliminary meteorological research, a 4-year climate study has been conducted to form a general picture of the source-sink relationship to the water vapour over the eastern China. The analysis suggested that the North Indian Ocean and regions governed by the WNPSH are the main moisture source regions in summer, highlighting the importance of the summer monsoon. Similar results were obtained both in traditional moisture source studies (e.g. Ding, 1994; Staff Members of the Academia Sinica, 1957; Hsu, 1958) and in recent trajectory studies (e.g. Sun and Wang, 2015; Wei et al., 2012; Drumond et al., 2011). The East China Sea, South China Sea and the western North Pacific are the main moisture source regions in winter. These results are in good quantitative agreement with previous trajectory studies (Sun and Wang, 2014, 2015) even though their target regions are smaller. Local evaporation over the central, eastern, and northern parts of China plays an important role as moisture sources during the whole year, consistent with the quasi-isentropic back-trajectory study by Dirmeyer et al. (2009).

A "circulation constraint method" has been proposed in Chapter 3 to detect where and how the moisture over the eastern China comes from. The quantitative importance of different source regions and the fate of moisture from each source region could thus be calculated for the first time in a more objective manner. In winter, the largest inflow is through the dry westerlies, however these do not form net precipitation. Winter precipitation is driven by the much smaller
contribution of the tropical oceans. In summer, the monsoons are the most important moisture sources, providing 67% of the moisture with 42% of the inflow air masses. In general, maritime air masses contain more water vapour than continental air masses, and are more prone to form net precipitation over the eastern China. According to this research, however, higher specific humidity does not necessarily mean higher precipitation efficiency. Obviously, topography and local meteorological processes also play a role in forming precipitation (Trenberth, 2011).

### 6.4 What controls the amount of water vapour in the atmosphere?

Chapter 2 and 3 detected where the water vapour comes from and how it is transported to the region of interest. Living experiences tell us that regions can have quite different humidity conditions despite the fact that the distances to the source regions may be similar. Obviously, besides water vapour supply, other factors can play an important role in influencing the amount of water vapour as well. Chapter 4 is dedicated to an objective and comprehensive understanding of the water vapour amount in the atmosphere and seeking a better understanding of the regional climate.

By using stepwise model selection, the statistical relationships between seven primary climatic variables and CWV over eastern China have been detected. The statistical relationships between $U, T_{850}, T_2, SST, E$ and CWV show strong regional and seasonal dependence. Generally, in westerlies controlled regions, zonal winds show a removing effect. In monsoon regions, zonal winds show a moistening effect in May and a weak effect in July to August. In contrast, evaporation mainly shows a moistening effect on CWV over monsoon-free regions and indicates a removing effect (of precipitation) over monsoon regions.

For most part of eastern China, the meridional winds are positively related to CWV. This is consistent with the current understanding of the EASM (Ding, 1994). The statistical relationship between OLR and CWV is quite stable, always negative, in eastern China. Surprisingly, we found the low-level air temperature
(neither $T_2$ nor $T_{850}$) not necessarily positively related to the vapour content. Even evaporation can show a negative relationship with CWV, under the overall effect of land surface heating, convective precipitation, land surface moistening, and larger evaporation.

By using the PMVD method, the relevant importance of each climatic variable was estimated. Various climatic processes (including the zonal and meridional winds, evaporation, and convective activities indicated by OLR) can be the key factors controlling the CWV. While recognizing the importance of the Clausius-Clapeyron relation to the water holding capacity of the atmosphere, this study calls for a more objective and comprehensive understanding of the causes of water vapour variability. Since the atmosphere is normally undersaturated, the water-holding capacity of the atmosphere is not necessarily the dominant factor. Instead, the removing effect from the westerlies, the drying out effect indicated either by OLR or by $E$, and the moistening effect from $E$ can show primary influence on the vapour content at various locations in different months.

### 6.5 Which type of climate signals favour large seasonal rainfall over northern China?

After an overall understanding of water vapour, the source, path, and amount, we may want to know when water vapour tends to condense into precipitation. After all, precipitation is the direct natural water supply and therefore directly related to various water related issues such as flood and drought. Chapter 5 is therefore dedicated to a comprehensive understanding of signals driving wet summers in northern China. Importantly, a fundamental question has been raised and discussed: to what extent can we believe the result of composite analysis?

Composite analyses suggested that the cyclonic anomaly over Mongolia at 500- and 850-hPa is closely associated with wet summers in northern China, not only for the rainfall formation processes, but also for the water supply. Interestingly, we found the most profound signals come from the Southern Hemisphere, not only for the high confidence level, but also for the large magnitude of the
composite anomalies, and for the large size of the key regions we defined in Section 5.4.

To what extent can we believe the result of composite analysis achieved in Section 5.3? In order to evaluate the reliability of composite analysis, a simple and straightforward notion was used. Similar to Boschat et al. (2016), the phrase ‘reversibility’ was used: when the signals driving wet summer in northern China have been extracted appropriately, in turn, wet summers should be predicted based on these signals. While Boschat et al. (2016) suggested that the message contained in the structure of composites may be quite misleading, we showed that the composite analysis is highly reliable when it has been formed appropriately. Based on the signals from composite analysis, 10 of 13 wet summers can be predicted. Cross-validation further shows that, based on the signals from composite analysis, previously unseen wet summers can be predicted as well, with the mean absolute percentage error (MAPE) lower than 6%.

6.6 Strengths, limitations, and ideas for future research

6.6.1 Strengths of the present thesis

The present thesis has both methodological and practical strengths. In terms of methodology, chapter 3 provides a "circulation constraint method", which can group numerous trajectories into reasonable clusters. Chapter 5 provides a fundamental methodology to evaluate the reliability of composite analysis. In terms of practical application, considering the widely conflicting composite results shown in previous studies in various disciplines, I suggest that any linkages extracted from the composite analysis should be tested either by the reliability analysis proposed here or by other appropriate procedures proposed in the future, according to the notion of reversibility proposed by Boschat et al. (2016).

The advantages of the circulation constraint method lie in the following aspects. First, it adds constraints from the general circulation features. Since the positions of the seasonal cluster mean paths of air masses from the source regions to eastern China are relatively stable, the definition of the moisture source region based on the circulation feature is thus stable as well. Second, while the former
approaches only depict the limits of the "uptake sectors" (Sodemann et al., 2008; Sun and Wang, 2014, 2015), our "circulation constraint method" further gives the major flow paths and the variation of the moisture content on the paths. Third, based on results from this novel method, further researches such as the quantitative importance of different source regions, the fate of water vapour from each source region could be conducted for the first time in an objective manner.

The advantages of the novel reliability analysis lie in the following aspects. First, as the name implies, it can evaluate the reliability of composite analysis, which is missed in most of the previous studies. Second, instead of using several boxes to extract signals subjectively, here we extract signals based on key regions objectively. The definition of key region is of great importance. On one hand, it guarantees only the right signals above particular confidence levels are extracted. Therefore the unrelated background noises will not be involved in our analysis. On the other hand, it enable us to extract signals globally. Therefore valuable information will not be missed. Third, since the composite values largely rely on the selection of the base period, \( \alpha A \) divides the magnitude of composite anomalies into ten degrees and thus the scenario similarity does not rely solely on any particular composite values. In this way, signals extracted based on various threshold values (\( \alpha \)) can be compared and analyzed as discussed in Section 5.4.2.

### 6.6.2 Limitations and ideas for future research

While the present thesis contributes some new notions and methodologies, I have to acknowledge that, frequently, I also encountered bottlenecks. While a lot of them have been solved and applied to the composing of the present thesis, almost half of them have not yet been solved. Here I list two of these unsolved problems, in order to document my current understanding of climate research.

First of all, signals from the Southern Hemisphere are closely related to the climate in the Northern Hemisphere. The reasons documented in the main text are as follows: “not only for the high confidence level, but also for the large magnitude of the composite anomalies, and for the large size of the key regions we defined in Section
5.4” . However, the most important reason is that, according to my computation result at this stage, wet summers documented in chapter 5 can be predicted very well based on signals from the Southern Hemisphere. The accuracy of the reversibility is much better than signals from the Northern Hemisphere.

A large number of studies exist that detect statistical relations of the climate between the Southern and Northern Hemisphere (e.g. He et al., 2017; Li et al., 2012c; Nan and Li, 2003; Wu et al., 2009) and several physical explanations have indeed been proposed (e.g. Tomas and Webster, 1994; Sun et al., 2009; Wu et al., 2015; Liu-Y et al., 2015). However, they neither proved the reliability of signals detected by statistical methods nor provided any systematic physical or mathematical derivation for the proposed physical mechanisms. Therefore, while I believe relations of the climate between the Southern and Northern Hemisphere do exist, no existing theory has yet shown convincing explanation from a physical perspective. Unfortunately, this thesis cannot provide such a physical theory either.

Second, in section 2.3, three typical circulation patterns at 500 hPa, which are found being favourable for heavy rainfall in previous studies, have been identified in the “7.21” event as well. However, at the moment when I am writing this chapter, I can neither say that all of the empirical patterns are a 100% correct nor that all of them are truly responsible for the occurrence of this specific heavy rainfall. After all, such a statement should be supported by solid physical explanations, or at least, by significance test based on sufficient number of events. The value of the study at 500 hPa for “7.21” event lies however, in its detailed description of the related processes. It can be considered a bench mark case study, that together with sufficient number of other related case studies, can contribute to further research in the future. In addition, coupling the severe-storm forecasting procedures with the trajectory model, especially with the horizontal moisture transport, has the potential to largely extend the warning time in the future (Lavers et al., 2014).
In the composing of this thesis, I found a 4-step research procedure can be very useful for climate research: first, detect associations/signals by statistical method; second, evaluate the reliability of the statistical result; third, find the real signals and remove the noises and fourth, reveal the physical mechanisms behind the detected signals.