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Aspects of interannual climate variability

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Aspects of interannual climate variability

by

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A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

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CHAPTER 1  General Introduction

Introduction

Interannual variability of atmospheric circulations and hydro-climate condition have received enormous attention from the meteorological community past decades, due to not only scientific interest, but also economic and social impact on our daily life. A synthetic analysis on the year-to-year change was initiated by the pioneering work performed by Walker (Walker and Bliss 1932, 1937) and has been conducted by many previous studies (e.g., Bjerkness 1969; Wallace and Gutzler 1981; Horel and Wallace 1981; Chen and Weng 1998, and others). However, less attention has been devoted to the interannual variability during the northern summer season. The importance of summer climate can be easily recognized by intense rainfall activity during the northern summer season, which is vital in many fronts human life. Drought and flood in summer occasionally result in severe damage. For example, 23 billion dollars and 48 deaths were reported in 1993 Midwest flood, and 56 billion dollars and 7,500 deaths in 1988 drought (NCDC, NOAA). Therefore, the mechanisms to cause the summer interannual variability of atmospheric circulation and hydro-climate condition must be understood. Two different aspects of the interannual climate variability during the northern summer season are studied. One is the interannual variability of the boreal-forest rainbelts, and the other is the interannual variation of the North American monsoon rainfall. Also, the summer climatological features of the boreal-forest rainbelts are discussed.
Boreal forest and associated rainbelts in high latitudes

The Arctic Ocean basin and subarctic boreal forest/tundra regions play a crucial role in regulating the global climate system. One example is fresh water cycle which regulates the thermohaline circulation in the global ocean and eventually the weather and climate of the entire earth (Aagaard et al. 1985; Chen et al. 1994). The boreal forest also plays an important role in the global carbon cycle. The boreal forests over two northern land-masses (Eurasia and North America) comprise nearly one-third of the global wood-lands, while the tropical rain forests contain another half (Montaigne 2002). Both forests work as two lungs for the earth filtering/storing the carbon dioxide and other greenhouse gases out of the atmosphere. Recently, a potentially important role played by Arctic components in the balance and maintenance of the global climate system have been recognized (e.g., Randall et al. 1998). However, subarctic boreal forest/tundra regions have received less attention. Thus, a research on the summer climatological feature and interannual climate variability are presented in Chapters 2 and 3, respectively.

In view of the importance of the boreal forests to the global climate and the ecosystem, enough water supply by summer rainfall to these forests during growing seasons is an important issue in the high-latitude climate system. Therefore, the most fundamental research aspect is how the rainfall along the boreal forest (hereafter the ‘boreal-forest rainbelts’) can be generated and maintained following Chen (1985). This will also provide us a clue on the interannual variation of the boreal-forest rainbelts. The north-south thermal gradient between the Arctic Ocean and snow-free land-masses during the northern summer season maintains a baroclinic zone along the Arctic seaboard, particularly over Northern Eurasia and Alaska. Dzerdzeevskii (1946) and Kurashima (1968) suggested that this baroclinic zone is a key factor to the development of the Eurasian summer frontal zone. This suggestion was further explored by Serreze et al.’s (2001) ex-
tensive analysis on the Arctic frontal activity with NCEP/NCAR reanalysis (Kalnay et al. 1996). They found that during summer maxima in frontal frequency and cyclogenesis appear Northern Eurasia and Alaska along 60°N – 70°N. Contrasting the Arctic frontal activity and precipitation, Serreze et al. (2001) suggest that ‘the summer frontal activity over Eurasia and Alaska and associated cyclogenesis will manifest in precipitation.’ A detailed analysis of water vapor transport associated with the boreal-forest rainbelts is needed to further substantiate Serreze et al.’s suggestion concerning the linkage between the boreal-forest rainbelts and the Arctic frontal/cyclone activities.

Transient disturbances which might be responsible for hydrological maintenance of the boreal-forest rainbelts are embedded in the summertime stationary waves in high latitudes. The lower level North Atlantic anticyclone actually extends eastward across the European continent to reach central Eurasia, west of Lake Baikal (White 1982). In contrast, the northward extension of the East Asian monsoon thermal low covers Manchuria of China and Stanovoy Khrebet of Russia, covering from south of Lakes Baljash and Baikal to Tartar Strait. These two distinct summer circulation regimes in the northern hemisphere were identified by White (1982): a tropical/subtropical monsoon regime and a high-latitude equivalent-barotropic regime. The Arctic frontal/cyclone zone and the rainbelts in Northern Europe extend eastward along the Arctic seaboard, while those in Eastern Siberia shift southward (Serreze et al. 2001). How does this change in the high-latitude circulation regimes between two parts of the Eurasian continent have dynamical linkage to the latitudinal displacement of the high-latitude frontal and cyclone zone and the boreal-forest rainbelts? The North American continent also undergoes a circulation regime change. The Pacific-coastal trough is located along the Canadian Rockies and the Alaskan Range, while the Icelandic low and the North Atlantic anticyclone form the confluent flow over the Eastern Canada. The former could contribute the formation of synoptic and meso scale cyclones through the interaction of topography and surface inflow from the North Pacific Ocean (Lynch et al. 2002). How
can these dynamically different environments affect the boreal-forest rainbelts in Alaska and the rest part of northern Canada?

Based upon a review on previous studies, two hypotheses are proposed to explain the aforementioned research aspects.

1. The boreal-forest rainbelts over two northern land-masses (Eurasia and North America) are maintained by the convergence of water vapor transport by transient disturbances (which form 'minor storm tracks').

2. The large-scale dynamic structures: (i) eastward extension of the North Atlantic anticyclone toward Northern Europe and northward intrusion of the East Asian monsoon low toward Eastern Siberia in the Eurasian continent, and (ii) confluent flow over northeastern Canada, and the Pacific-coastal trough over Alaska in the North American continent, grant localized characteristics on the maintenance mechanism of the boreal-forest rainbelts at different locations.

Interannual variation of the boreal-forest rainbelts

As discussed earlier, the boreal forest over two northern land-masses play an important role in regulating the global climate system. One example is that the boreal forest functions as a terrestrial carbon sink which sequester some portion of the global carbon from fossil fuels. Under the Kyoto Protocol of the United Nations framework and convention on climate change, industrialized nations can use certain forest biomass sinks to meet their greenhouse gas emission reduction commitments. Although significant and largescale changes in vegetation cover occurred transiently over centurial and millennial time scale, there is evidence of structural vegetation changes in response to climate variation of much shorter-interannual and decadal time scales (Lucht et al. 2002; Myneni et al. 2001). Thus, an effort is made in Chapter 2 to reveal the interannual variability of
the boreal-forest rainbelts during the northern summer season, with a focus on depiction of the interannual variation and proposing a possible mechanism.

It was reported recently by Rogers et al. (2001) that the hydrological cycle (represented as moisture flux convergence or $P - E$) north of $70^\circ N$ exhibit a coherent interannual variation in concert with North Atlantic Oscillation (NAO; van Loon and Rogers 1978) and Arctic Oscillation (AO; Thompson and Wallace 1998, 2000, and Thompson et al. 2000). Since the boreal forest is a boundary of the Arctic Ocean, it is conceivable that the NAO may have impact on the interannual variation of the boreal-forest rainbelts around the North Atlantic Ocean (e.g., Hurrel 1995). In Eastern Siberia, the interannual variation of the East Asian monsoon system can extend its influence toward high latitudes (e.g., Chen and Weng 1998a,b; Lau et al. 2000). The Nitta-like teleconnection short-wave train (Nitta 1987; Lau and Weng 2002) may exert some impact on the Alaskan rainbelts. As discussed in the summer climatological features, the transient disturbances, equivalently the convergence of transient water vapor flux, may play an important role in the interannual variation of the boreal-forest rainbelts.

A brief discussion on previous studies on the interannual climate variabilities and the summer climatological aspect of the boreal-forest rainbelts leads us the following hypothesis.

1. The interannual variation of the boreal-forest rainbelts is largely affected by that of transient disturbances.

2. Two prominent interannual variation modes (the NAO and the teleconnecting patterns associated with the interannual variation of the East Asian summer monsoon) may force the boreal-forest rainbelts to oscillate with different phases at different locations.
Interannual variation North American monsoon rainfall

The term 'monsoon' is traced to an Arabic root meaning 'season', representing seasonal reversal in both the atmospheric circulation and enormous rainfall amount. The importance of the monsoon climate is easily recognized by its large contribution to the annual rainfall amount. About half of annual rainfall is concentrated during monsoon season (e.g., Douglas et al. 1993). Its impact easily propagates into the agroecosystem and economic activity. In other words, a failed or excessive monsoon rainfall result in economic and social disasters. Most of Mexico and southwestern part of the United States belong to the monsoon climate regime (hereafter 'the North American monsoon') and undergo dramatic year-to-year variation of monsoon rainfall which exceeds its climatological mean value at some locations (Higgins et al. 1999; Stensrud et al. 1994). A classical view on the summer monsoon circulation is well reflected by the monsoon circulation theory (e.g., Wallace and Hobbs 1977, their Fig. 9.8; Holton 1992, hig Fig. 11.9), particularly the spatially in-phase relationship between the monsoon high/low and divergent circulation. In contrast, a spatially quadrature phase-shift is eminent from recent analysis (Schubert et al. 1993). Chen (2003) revised the classic monsoon circulation model and explained that the east-west divergent circulation driven by a large scale east-west differential heating/cooling which may not be 'warm land' and 'cold ocean' is responsible for the maintenance of the monsoon thermal low at lower troposphere and the monsoon anticyclone at the upper troposphere through the 'Sverdrup' vorticity balance. It was further shown that the revised monsoon circulation model can be applicable to the North American monsoon (Chen 2003).

Monsoon climate variabilities over the North/South American form an important principal research area (G3) of the CLIVAR (Climate Variability and Predictability, WCRP 1998) programme. Various mechanism responsible for the maintenance of the North American monsoon circulation (e.g., Barlow et al. 1998) and its interannual
variation (e.g., Higgins et al. 1998, 1999; Carleton and Carpenter 1990; Castro et al. 2002). Our current study employs the revised maintenance mechanism (Chen 2003) as a touchstone for the investigation on the interannual variability of the North American monsoon. In other words, the North American thermal low and the Mexican high are maintained by the east-west divergent circulation connecting the western tropical Atlantic and the eastern tropical Pacific. The maintenance is illustrated by the east-west divergent circulation through the interaction between the rotational and divergent flow satisfying the Sverdrup balance. Furthermore, this east-west divergent circulation is driven by an east-west differential heating between the two basins: the warm air rising over the tropical Atlantic and the cold air sinking over the eastern tropical Pacific (Chen 2003). The following hypothesis are proposed.

1. The interannual seesaw of the east-west divergent circulation across the North American monsoon region is one of the key mechanisms to determine seasonal departures of monsoon circulation and rainfall, which can be induced by the thermal contrast between tropical eastern Pacific and tropical Atlantic Oceans.

Thesis Organization

The current study contains three papers in accordance with the following three chapters. The first paper (Chapter 2) presents the climatological features of the boreal-forest rainbelts during northern summer season (June-August). Following an introduction to the boreal-forest rainbelts and a brief description of observational data and methodology, the analysis on the hydrological maintenance of the rainbelts is discussed in terms of transient water vapor flux. The dynamical maintenance by the transient disturbances and their interaction with the summertime stationary waves at high latitudes are presented in the following sections. First study depicts the hydrological and dynamical processes which are responsible for the boreal-forest rainbelts and discuss the relation-
ship between the transient disturbances and the summertime stationary waves in high latitudes.

The second paper (Chapter 3) deals with the interannual variation of the boreal-forest rainbelts. After reviewing previous studies and hypotheses are proposed based upon our previous study in Chapter 2 on the summer climatological aspects of the boreal-forest rainbelts, the structure and signature of the interannual variability of rainbelts are presented. A possible mechanism which cause the interannual variation of the boreal-forest rainbelts is suggested, considering the following two aspects. One is the role of transient disturbances in the interannual variation, and the other is the possible dynamical linkage between transient disturbances and the summertime stationary waves. Second paper focuses on the understanding of the the interannual variation of the boreal-forest rainbelts and the role played by the transient disturbances.

The third paper (Chapter 4) discussed the interannual variation of the North American monsoon rainfall. A hypothesis is made based on the brief review of revised maintenance mechanism of the monsoon circulation. After the identification of wet/dry summers of the North American monsoon, the interannual seesaw oscillation of the east-west divergent circulation across the monsoon regions is investigated, which plays a crucial role in the maintenance of the monsoon circulation. Minor portions of wet/dry summers of the North American monsoon cannot be explained by the aforementioned mechanism. A possible explanation is suggested in the last section. A general conclusion is given in Chapter 5 to summarize and emphasis the present study.

Acknowledgments

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CHAPTER 2  Maintenance of the boreal-forest rainbelts
during northern summer

A paper submitted to the *Journal of Climate*

Jin-Ho Yoon and Tsing-Chang (Mike) Chen

Abstract

Boreal forests which exist along 60°N in the Eurasian and the North American continents should be grown and maintained by warm seasonal rainfall. As revealed from satellite observations and various precipitation sources, zonally elongated rainbelts appear along these forests. Previous studies suggested that the strong baroclinic zones formed by large north-south thermal gradients across the Arctic seaboard generate and develop the frontal/cyclone activity (minor storm tracks), which in turn produce summer rainfall along boreal forests. It was observed by this study that baroclinic zones associated with strong Arctic westerlies coincide with minor storm tracks and boreal-forest rainbelts only in Eastern Canada. In contrast, this coincidence does not occur in Northern Europe, East Siberia, and the Alaska-Pacific coast, because boreal-forest rainbelts in these regions are located further south of strong Arctic westerlies and ahead of high-latitude troughs over Central Eurasia, the Bering Sea, the Labrador Sea, and the Norwegian Sea. Therefore, instead of baroclinicity along strong Arctic westerlies, favorable environments for the formation of minor storm tracks are developed by positive vorticity advections ahead of these high-latitude troughs. The water vapor budget
analyses performed with NCEP and GEOS-1 reanalyses show that the boreal-forest rainbelts are essentially maintained by the convergence of water vapor flux associated with transient disturbances at high latitudes.

1. Introduction

The most interesting features of summer climate in the Arctic/subarctic regions are frontal zones and rainbelts south of the Arctic coastal line in Northern Eurasia and North America. The frontal activity and rainfall of these two northern land-masses, which are closely related to each other, peak in the summer season (Serreze et al. 2001). Geographically, the summer frontal activity and rainfall lie along boreal forests (Krebs and Barry 1970), comprising one third of the global woodland (Montaigne 2002), and playing a vital role in regulating the global climate by filtering/storing carbon dioxide and other greenhouse gases (e.g., Bonan et al. 1995; Lutch et al. 2002; Myneni et al. 2001). Summer rainfall at high latitudes provides water resource to the boreal forest ecosystem and supplies freshwater to the thermohaline circulation in the Atlantic Ocean through north-bound river discharge (Chen et al. 1994), which may affect the global climate (e.g., Aagaard and Carmack 1989; Aagaard et al. 1985; Bjornsson et al. 1995; Delworth et al. 1993; Zhang et al. 1993).

The boreal forests over the two northern land-masses can be clearly identified by Normalized Difference Vegetation Index (NDVI) (marked by thick lines in Figure 2.2a). The belt-shaped rainfall zones along $60^\circ N$ are depicted by several precipitation data sources [e.g., CMAP (Xie and Arkin 1997), GHCN (Easterling et al. 1996), and ensemble of three reanalyses (Gibson et al. 1997; Kalnay et al. 1996; Schubert et al. 1993) shown in Figures 2.2b-d]. Because the tundra ecosystem can exist even on the permafrost grounds (Krebs and Barry 1970), the boreal forests represented by high values of NDVI can extend somewhat poleward in comparison with high-latitude rainbelts. Regardless
of this minor discrepancy, summer rainbelts coincide well with the subarctic zones of high NDVI values, indicators of the boreal forests. In other words, boreal forests and summer rainbelts at high latitudes exhibit a similar longitudinal distribution pattern. Therefore, these subarctic rainbelts will be referred hereafter as "boreal-forest rainbelts". Because the boreal forests need water during growing season, how these boreal-forest rainbelts are maintained at high latitudes during northern summer becomes the major concern of the present study.

Figure 2.1 Boreal forests (green color) in North America (left) and Eurasia (right), after Montaigne (2002).

In spite of the existence of two major storm tracks over the North Pacific and the North Atlantic Oceans, intensive frontal activity areas (the Arctic frontal zone named
by Reed and Kunkel 1960) exist over high-latitude land-masses during summer season. The frontal/storm activity associated with the Arctic frontal zones (referred to as minor storm track hereafter, to distinguish from the two oceanic storm tracks) was suggested to be a mechanism responsible for summer rainfall at high latitudes (Serreze et al. 2001). The formation of minor storm tracks and boreal-forest rainbelts can be also contributed by synoptic scale cyclones. It was suggested by previous studies (e.g., Dzerdzevskii 1945; Kurashima 1968; Serreze et al. 2001) that the thermal contrast between the snow-free land surface and the cold Arctic Ocean maintains high-speed westerlies through the thermal wind relationship along the Arctic seaboard. These strong Arctic westerlies develop minor storm tracks through synoptic cyclogenesis by baroclinic instability (Charney 1947). Search for the maintenance mechanism(s) of the boreal-forest rainbelts leads to the following questions: (1) What are the horizontal distribution and possible maintenance mechanism(s) of the subarctic transient disturbances? (2) If the subarctic transient activity is strong along the boreal-forest rainbelts, can the summer rainbelts be produced by this transient activity?

Examining the maintenance of the global water vapor distribution, Chen (1985) split water vapor flux into different components: stationary and transient in time, and rotational and divergent in space. It was observed that large water vapor content over three tropical continents was maintained by the stationary divergent component, including contributions from both the local Hadley and the planetary east-west circulations. In contrast, the transient divergent component is an important agent supplying water vapor to two oceanic storm tracks. If the storm activity along subarctic minor storm tracks is responsible for maintaining the boreal-forest rainbelts, it is likely that transient water vapor flux is more crucial than the stationary one. In order to test this argument, the water vapor budget is analyzed in the present study.

The three-dimensional structure and dynamical function of summertime stationary waves in the tropics and midlatitudes were examined by White (1982) and Chen (2003),
Figure 2.2  Long-term summer mean of (a) NDVI, (b) precipitation from University of Delaware and GHCN v2, (c) precipitation of CMAP, and (d) precipitation from three reanalyses.
but those in high latitudes have not been explored. In order to investigate the main­
tenance mechanism of boreal-forest rainbelts, several dynamical aspects of the high-
latitude summer climate features (including the structure of summertime stationary
and the maintenance mechanism of subarctic minor storm tracks) were analyzed. This
study is arranged in the following manner. Data and the analysis method used in this
study are presented in Section 2. Description of the boreal-forest rainbelts and transient
activities are given in Section 3. Some possible mechanisms responsible for the formation
of minor storm tracks in the high latitudes are discussed in Section 4. Maintenance of
the boreal-forest rainbelts is illustrated in Section 5, and concluding remarks will be in
Section 6.

2. Data and Analysis methods

Data used in this study includes: precipitation, vegetation index, reanalyses, and
cyclone tracks. Precipitation used to portray boreal-forest rainbelts was derived from
four different sources: 1) the Global Historical Climate Network version 2 (GHCN,
Easterling et al. 1996), 2) the grid analysis of station precipitation data (Willmott et
al. 1994, obtained from the Climate Diagnostic Center, NOAA), 3) Climate Prediction
Center (CPC) Merged Analysis of Precipitation (CMAP) (Xie and Arkin 1997), and 4)
ensemble of three reanalyses including NCEP/NCAR reanalysis (Kalnay et al. 1996),
European Center for Medium-Range Forecast (ECMWF) reanalysis (Gibson et al. 1997),
and the Goddard Earth Observing System assimilation data (GEOS1) (Schubert et al.
1993). The first two datasets provide only precipitation over land, while the last two
cover the entire globe.

Regardless of reanalyses biases in high latitudes [e.g., spectral distortion at high
latitudes and excessive rainfall in the NCEP/NCAR moisture fields (Serreze and Hurst
2000)], the NCEP/NCAR (Kalnay et al. 1996) and GEOS-1 reanalyses (Schubert et al.
1993) may well represent some important features of high-latitude summer climate, such as thermal frontal activity and circulation structures by the NCEP/NCAR reanalysis at high-latitude land-masses (Serreze et al. 2001). Therefore, meteorological variables (e.g., wind field, temperature, water vapor flux, etc.) of these two reanalyses were used for the water vapor budget analysis and other diagnoses. While a depiction of boreal forests presented by Montaigne (2002) is shown in Figure 2.1, the NDVI of the NOAA/NASA Pathfinder AVHRR Land Program supplied by the Distributed Active Archive Center (Code 902.9) at the Goddard Space Flight Center (Justice et al. 1985) was applied to attain a more accurate portrayal of these forests (Figure 2.2a).

Cyclone occurrence frequency was determined by a incorporation of objective and subjective approaches: (i) The objective algorithm designed by Dr. Mark Serreze of the University of Colorado (Serreze 1995; Serreze et al. 1997) was used to identify cyclone locations with the 6-hourly Northern Hemisphere (NH) sea-level pressure data from the NCEP/NCAR reanalysis for the period from 1979 to 2002. This algorithm employs a series of search patterns, e.g., testing whether central sea-level pressure is lower than surrounded grid-points by at least 1 hPa to identify center locations of cyclones. (ii) After their locations were detected by this objective algorithm, we need to determine whether these identified cyclones are migrating. Therefore, locations of these cyclones were subjectively checked with daily 850-mb streamline charts superimposed with rainfall generated by NCEP/NCAR reanalysis. Disturbances with a center of sea level pressure not smaller than its surrounding grid by 1 hPa and with a translation speed smaller than 5° day⁻¹ were excluded. The cyclone occurrence frequency \( \bar{N} \) is the accumulation of migrating cyclones with a closed low center and rainfall within each 5° × 5° box over summer season.

Horizontal derivatives (e.g., divergence and vorticity) computed at high latitudes on the equal latitude-longitude grid system are usually contaminated by false values generated by the Pole Problem, due to decreasing zonal spacing between grid points.
toward the pole. To avoid this computational predicament in this grid system, the octagonal grid system used by the National Meteorological Center (former NCEP) for its operational forecast model (Shuman and Hovermale 1968) was adopted. This grid system provides an almost equal-distance and regular square mesh near the pole to avoid the Pole problem. The computational procedure consists of two steps. First, wind vectors on the 2.5° x 2.5° latitude-longitude grid system north of 60°N were projected on the octagonal grid system by a 16-point Bessel interpolation. Second, the computed horizontal derivatives on the latter grid system were then projected back to the former grid system by the same interpolation scheme, and merged with data south of 45°N computed on the former grid system for further analysis with Burrows (1974) approach.

The hydrological maintenance of the boreal-forest rainbelts is illustrated in terms of the atmospheric water vapor budget:

\[ \frac{\partial W}{\partial t} + \nabla \cdot \vec{Q} = E - P, \tag{2.1} \]

where \( W, \vec{Q}, E, \) and \( P \) are precipitable water, vertically-integrated water vapor flux, evaporation, and precipitation, respectively. The water vapor budget [Eq.(2.1)] is simplified based on the following reasons. The long-term summer (June-August) mean budget analysis was performed so that the storage term \( \frac{\partial W}{\partial t} \) was negligible. Following Chen (1985), the water vapor flux \( \vec{Q} \) was split into two components: rotational \( \vec{Q}_R \) and divergent \( \vec{Q}_D \). However, only the latter is crucial in maintaining water vapor source/sink, \( (E - P) \). Because of the lack of observations, evaporation was neglected in the diagnostic analysis. Finally, the summer-mean water vapor flux is divided into two components in time: stationary \( \vec{Q}^S \) and transient \( \vec{Q}^T \). With these considerations, the water vapor budget [Eq.(2.1)] may be approximated by the following form:

\[ P \approx -\nabla \cdot \vec{Q}^S_D - \nabla \cdot \vec{Q}^T_D. \tag{2.2} \]

It will be shown later by our analysis (contrast \( \vec{P} \) with \( \vec{Q}^S_D \) and \( \vec{Q}^T_D \)) that only the transient component plays a primary role in maintaining boreal-forest rainbelts. Therefore,
Eq.(2.2) is simplified further as:

\[ P \approx -\nabla \cdot \tilde{Q}_D, \quad (2.3) \]

Because \( \tilde{Q}_D \) can be contributed by both convergence and divergence of transient water vapor flux, these two hydrological processes may numerically cancel each other in the long-term average. Hydrologically, divergence of water vapor flux depletes water vapor supply to prevent precipitation production. In contrast, rainfall is maintained only by the convergence of water vapor flux. Thus, Eq.(2.3) is approximated by:

\[ P \approx [\text{sgn}(\cdot) \nabla \cdot \tilde{Q}_D], \quad (2.4) \]

The symbol \( \text{sgn}(\cdot) \) represents negative values of \( \tilde{Q}_D \) (i.e., convergence of transient water vapor fluxes) included in the long-term average. Transient water vapor flux \( \tilde{Q}_D \) is primarily driven by transient disturbances which may have an average life cycle of about five days (Smirnov and Moore 1999). The 2-7 day Butterworth bandpass filter (Murakami 1979) was applied to isolate contribution of synoptic disturbances to transient water vapor flux. After applying this filtering process, Eq.(2.4) is further approximated by,

\[ P \approx [\text{sgn}(\cdot) \nabla \cdot \tilde{Q}'_D], \quad (2.5) \]

where \( \tilde{Q}'_D \) is the 2-7 day filtered divergent water vapor flux.

3. Boreal-forest rainbelts and transient activity

As documented by Xie and Arkin (1997), major summer rainfall in the Northern Hemisphere occurs over summer monsoon regions (including South/East Asia, southwestern North America, and West Africa) and two oceanic storm tracks in the North Pacific and the North Atlantic Oceans (Figures 2.2b-d). However, the summer rainfall
along boreal forests in the subarctic regions has not been well examined and documented. The boreal-forest rainbelts seem to be zonally elongated along 60°N, but some regional characteristics are observed. For example, the rainbelt in East Siberia is located somewhat southward than that in Northwestern Europe, and the rainbelts along the Alaska-Pacific coast and Eastern Canada do not seem to belong to the same entity.

Previous studies (e.g., Serreze et al. 2001) suggested that the cyclone/frontal activity along the Arctic frontal zones in high latitudes may be responsible for the occurrence of summer rainfall over these regions. To test this suggestion, we should first understand how transient activity over high-latitudes land-masses is generated and maintained. Salient features of the summer transient activity depicted by the cyclone occurrence frequency ($N_f$) in Figure 2.3a may be highlighted as follows:

- Two oceanic storm tracks over the North Pacific and the North Atlantic Oceans: The North Pacific storm track is elongated from Japan to the west coast of Canada, while the North Atlantic storm track is stretched from the northeastern part of North America, across south of Greenland, to Iceland. These two oceanic storm tracks are coupled with the upper-tropospheric jet streams (Figure 2.3b). The spatial structures of these two oceanic storm tracks (Figure 2.3a) bear a close resemblance to those depicted by (850mb) in White (1982).

- Subarctic minor storm tracks in Eurasia and North America: Several distinct maxima of the transient activity appear in Northwestern Europe, Central Eurasia, Manchuria/Eastern Siberia, and Western and Eastern Canada (Figure 2.3a). A comparison between storm activities (Figure 2.3a) and rainfall (Figure 2.2) reveals a clear correspondence between these two quantities at mid- and high latitudes. The further comparison between upper-tropospheric westerlies (Figure 2.3b) and storm activities shows that the coupling of the minor storm track with strong
Figure 2.3  Long-term summer mean of (a) cyclone occurrence frequency, and (b) the zonal wind at 300mb. Contour intervals are 2.0ms$^{-1}$ with lightly (darkly) shading if the values are larger than 8(16)ms$^{-1}$ for (b).
westerlies only exists in the Eastern Canadian Arctic, as suggested by Serreze et al. (2001). In contrast, minor storm tracks in other regions are located somewhat south of strong Arctic westerlies. For example, the minor storm tracks in Central Eurasia and East Siberia appear south of the strong Arctic westerlies and north of mid-latitude jet stream. Therefore, the baroclinicity associated with strong Arctic westerlies across this longitudinal section do not seem to be related to genesis of transient disturbances along minor storm tracks.

In addition to the baroclinic instability, a possible mechanism responsible for the establishment of minor storm tracks may be inferred from the structure of large-scale circulation at high latitudes. The most conspicuous features of this circulation system shown in Figure 2.4 are the four subarctic troughs in Central Eurasia, the Bering Sea, the Labrador Sea, and the Norwegian Sea. A careful examination of the summer subarctic circulation reveals that minor storm tracks and boreal-forest rainbelts are located ahead of these troughs. How do these subarctic troughs develop preferable environments for the formation of minor storm tracks? The spatial relationship between these troughs, minor storm tracks, and strong Arctic westerlies indicates that the summer transient activity in eastern Canada is maintained by the strong north-south thermal gradient across the Arctic seaboard, while those located ahead of these upper-tropospheric troughs are closely related to strong vorticity advection. The later situation will be elucidated in Section 4.

It was already shown that minor storm tracks are located along boreal-forest rainbelts. What is the hydrological implication of this spatial alignment between boreal-forest rainbelts and minor storm tracks? The most significant divergent component of transient water vapor flux exists along major oceanic storm tracks (Chen 1985). It is likely that the boreal-forest rainbelts over Arctic Eurasia and North America is maintained by convergence of transient water vapor flux along minor storm tracks. This
Figure 2.4 The streamline of the long-term summer mean $\bar{V}_{(250mb)}$ and $\bar{V}_{(850mb)}$ with light (dark) shading if zonal wind is larger than $8(16)\text{ms}^{-1}$ in (a).
argument will be substantiated by water vapor budget analysis in Section 5.

4. Large-scale circulation over the high-latitudes

The NH summer circulation consists of the tropical/subtropical monsoon and the equivalent barotropic structure in mid latitudes (White 1982; Chen 2003). Up to the present time, the structure of the high-latitude summer circulation has not been extensively analyzed. In order to facilitate our search for the mechanism in generating and maintaining the transient activity along minor storm tracks, the three-dimensional summer circulation structure in the high latitudes should be well depicted. To serve this purpose, the 250-mb and 850-mb streamline charts and latitude-height cross-sections of zonal wind at three longitudinal locations of minor storm tracks and boreal-forest rainbelts are presented in Figures 2.4 and 2.5, respectively.

The summer circulation in high latitudes is characterized by four major troughs (marked with thick dashed lines on Figure 2.4a) at Central Eurasia, the Bering Sea, the Labrador Sea, and the Norwegian Sea, along with four ridges (denoted by thick solid lines). Strong Arctic westerlies are located north of these Arctic ridges at New-Siberian Islands, the Beaufort Sea, and the Barents Sea along 70°N (Figure 2.3b). As shown by latitude-height cross-sections of zonal wind at these three locations (Figures 2.5a-c), Arctic westerlies with maxima at 300mb are clearly separated from midlatitude maximum westerlies. In East Siberia, the lower-level cyclonic flow (indicated by an arrow in Figure 2.4b) is overlaid by an upper-level ridge. This vertical phase reversal of atmospheric circulation characterizes a monsoon system (White 1982; Chen 2003). This East Siberian monsoon low is merged with the northward extension of the East Asian summer monsoon low (indicated by the monsoon southerly flow). Over northwestern North America, a trough forms along the Alaska-Pacific coast in the lower troposphere (Figure 2.4b marked with thick dashed line). This trough may be established by the
interaction between the impinging moist maritime flow from the North Pacific and the coastal topography of Alaska (e.g., Alaskan Range and Canadian Rockies). In Eastern Canada, the merger of the cold/dry flow from the Canadian Arctic and the warm/moist flow from the North Atlantic Ocean forms a strong confluent flow (Namias and Clapp 1949). The strong north-south thermal gradient across this confluence and the upper-tropospheric westerlies over this region constitute an active frontal and stormy zone (Serreze et al. 2001).

Let us first examine maintenance of the strong Arctic westerlies. As suggested by previous studies, strong westerlies along the Arctic seaboard form an environment conducive for the genesis of transient disturbances. The existence of upper-tropospheric westerlies at high latitudes is a result of the thermal wind relationship. This argument becomes clear by comparing 300-mb zonal wind \([u(300mb)]\), Figure 2.6a, with the corresponding thermal wind \([u_T(300mb - 850mb)]\), Figure 2.6b. During the summer season, the Arctic Ocean remains at freezing temperatures and partially covered by sea ice (Gloerson et al. 1992), while the land-masses surrounding the Arctic Ocean are much warmer (Serreze et al. 2001). This thermal contrast between the cold Arctic Ocean and the warm land-masses maintains strong Arctic westerlies which in turn support the existence of a minor storm track over Eastern Canada. However, the strong Arctic westerlies are actually located farther north of minor storm tracks and the boreal-forest rainbelts at most of locations including northwestern Europe, East Siberia, and Alaska (Figures 2.5d-f). The contrast between strong Arctic westerlies and the rainfall/transient activity along these three locations of the boreal-forest rainbelts clearly indicates that the former is located at 70°N (Figures 2.5a-c), while the latter are mainly at 50°N - 50°N (Figures 2.5d-f). In view of this spatial disparity between strong Arctic westerlies and minor storm tracks (Figure 2.5), the baroclinicity across the Arctic seaboard does not seem to exert any impact on cyclogenesis over these regions.

A possible formation mechanism of minor storm tracks may be developed in terms
Figure 2.5 The latitude-height cross-section (y-z) of zonal wind at 45°E (a), 130°E (b), and 150°W (c), respectively. Contour interval is 1 ms⁻¹, with light (dark) shading if zonal wind is larger than 5(10) ms⁻¹. The latitudinal histograms and line plots of cyclone frequency and precipitation at the same longitudes in (a)-(c).
Figure 2.6  Long-term summer mean of (a) the zonal wind at 300mb, (b) thermal wind between 300mb and 850mb, and (c) stream line with zonal vorticity advection at 250mb. Contour interval is 1ms\(^{-1}\) for (a) and (b). The values in (a) and (b) are light shading if they are larger than 12ms\(^{-1}\). Three maxima of the Arctic westerlies are dotted on (b). The vorticity advection are heavily (lightly) shaded if the values are larger (smaller) than \(+1\)(\(-1\))m\(^{-2}\)s\(^{-1}\).
of the conceptual model of a developing baroclinic short wave theory in terms of the quasi-geostrophic theory (e.g., Holton 1992): a coupling between the upper-tropospheric trough and a surface cyclone. As shown by the quasi-geostrophic omega equation, two geostrophic forcings may maintain the upward motion associated with falling surface pressure: vertical differentiation of vorticity advection (increasing with height), and a local maximum of thermal advection (e.g., Carlson 1998). Because the upper-level westerlies are stronger, the vorticity advection in the upper troposphere is larger in magnitude than it is at the surface. Therefore, ahead of troughs in the upper troposphere, the vertical differentiation of vorticity advection, which enables the upper-level flow to be more cyclonic with height, induces the ascending motion. Consequently, the positive upper-tropospheric vorticity advection causes the surface pressure fall which results in the formation of a surface cyclone. It was shown in Figures 2.3-2.5 that transient activity along minor storm tracks and boreal-forest rainbelts primarily concentrate in regions ahead of the upper-tropospheric troughs at high latitudes. For instance, the transient activity and summer rainfall over Eastern Siberia appear ahead of the Central Eurasia trough. To test this mechanism, the vorticity advection by the zonal flow at 250mb $[\zeta_A(250mb) = -u \frac{\partial^2 \zeta}{\partial x^2}]$ is displayed in Figure 2.6c. Areas with positive vorticity advection (heavily stippled) located at the eastern sides of these troughs (marked as thick dashed line) cover the minor storm tracks over Northern Europe, Eastern Siberia, and Alaska.

Along with four major troughs at the upper troposphere in high latitudes, the East Siberian monsoon low and the Alaska-Pacific coastal trough also form a favorable environment for the development of minor storm tracks and boreal-forest rainbelts. It was argued by some previous studies (Kurashima 1968; Samel et al. 1999) that the northward intrusion of monsoon rainfall can reach Manchuria around 50°N. Thus, the boreal-forest rainbelt and the minor storm track over East Siberia (from south of Lake Balkash and Baikal to Tartar Strait) are formed under the influence of the East Siberian monsoon low (indicated by an arrow on Figure 2.4b). When an extratropical cyclone
originating from the North Pacific arrives at the west coast of the North American continent, this system starts decaying and possibly induces lee-side cyclogenesis east of the Rocky mountain (Carlson 1998). However, a series of numerical experiments performed by Lynch et al. (2001) with a limited area model demonstrated that interaction between the Alaskan Range and maritime inflow can form a favorable environment for the development of the frontal activity along Alaskan-Pacific coast. Although a detailed analysis of the Alaska-Pacific coastal trough is beyond scope of our current study, it is conceivable that this development of frontal activity is related to the lower-tropospheric trough along the coast.

It was suggested by previous studies that the Arctic frontal/cyclone activity is generated/maintained by the baroclinic zone along the Arctic seaboard. As revealed from our observation, this argument may be only applicable to the transient activity over Eastern Canada. Most of the minor storm tracks and boreal-forest rainbelts, which exist ahead of these troughs and further southward away from strong Arctic westerlies, are formed/maintained by the effect of positive vorticity advection ahead of the upper-tropospheric troughs at high latitudes. In addition to these upper troughs, the East Siberian monsoon low and the Alaska-Pacific coastal trough form a special environment conducive to the genesis of transient disturbances over these areas.

5. Maintenance of the boreal-forest rainbelts

Three different formation mechanisms of minor storm tracks, and frontal/cyclone activity are considered to be responsible for producing rainfall along boreal forests. Previous studies (Overland et al. 1996; Serreze et al. 1995) pointed out that the transient component contributes about 62 and moist static energy. Also, transient water vapor flux associated with synoptic-scale cyclones accounts for much of atmospheric water transport over northern parts of North America (Smirnov and Moore 1999). Therefore,
the transient water vapor flux associated with fronts/cyclones along minor storm tracks plays a vital role in maintaining the boreal-forest rainbelts. An analysis of the water vapor budget was pursued to test this argument.

As expressed by Eq.(2), rainfall can be maintained by convergence of stationary and transient water vapor fluxes. The major NH rainfall appears over the Asian and North American monsoon regions and the two major oceanic storm tracks (Figures 2.2b-d). The stationary water vapor flux ($\bar{Q}^T$) shown in Figure 2.7a indicates that these major NH summer rainfall centers are maintained by convergence of stationary water vapor flux ($-\nabla \cdot \bar{Q}^T_D$). The stationary divergent water vapor flux is driven by the summertime large-scale divergent circulation in the tropics and midlatitudes (Chen 1985). However, the contrast between $P$ and $-\nabla \cdot \bar{Q}^T_D$ does not show a clear indication that boreal-forest rainbelts at high latitudes are supported by stationary water vapor flux (Figure 2.7a).

In view of this passive role of stationary water vapor flux in maintaining boreal-forest rainbelts, transient water vapor flux is the potentially dominant hydrological process. The structure of transient disturbances at high latitudes is the same as those of midlatitudes (Reed and Kunkel 1960). Analyzing aircraft observations, Reed and Kunkel argued that clouds associated with typical baroclinic waves in the high-latitudes are mainly located ahead of a cyclone center as a typical mid-latitude storm (Chen et al. 1996). In other words, these clouds and accompanied precipitation are maintained by convergence of water vapor flux east of a cyclone center. The passage of any synoptic disturbances across a given region is accompanied by the alternation of low-level convergence and divergence. In order to concentrate our attention on the maintenance of precipitation, only convergence of transient water vapor flux associated with synoptic disturbances [as suggested by Eq.(2.5)] is considered. The contrast between convergence of transient water vapor flux ($[\text{sgn}(\nabla \cdot \bar{Q}^T_D)]$) (Figure 2.7b) and precipitation (Figures 2.4b-d) strongly supports our argument that the boreal-forest rainbelts are maintained by convergence of transient water vapor flux associated with the transient disturbances along the minor
Figure 2.7  Long-term summer mean of (a) stationary water vapor flux and its divergence and (b) transient water vapor flux and its divergence.
The weather systems in high latitudes frequently alternate between cyclonic and anticyclonic flows (Reed and Kunkel 1960). Thus, convergence and divergence of water vapor flux fluctuations in concert with passages of cyclone and anticyclone systems, respectively. Consequently, the transient component of the water vapor flux is more important than stationary component along boreal-forest rainbelts over the two northern landmasses. This argument may be further supported by observation of large evaporation amounts. Based on site observations in the middle of the Lena river over East Siberia (65.15°N, 129.37°E) during the GEWEX (Global Energy and Water Experiment) Asian Monsoon Experiment (GAME)-Siberia, Ohta et al. (2001) reported that evaporation becomes comparable or even larger than total rainfall in East Siberia. Therefore, to balance the total atmospheric water vapor content, the summer-mean water vapor flux should not exhibit strong convergence along boreal forests. The small convergence of water vapor flux and large values of evaporation imply intensified recycling along boreal forests, which is defined as a ratio between evaporation and the summation of precipitation and water vapor flux convergence \( \rho \simeq \frac{E}{P + (\nabla \cdot Q)} \) (Trenberth 1999). In other words, moisture supplied by evaporation (from land surfaces and boreal forests) forms an important source of atmospheric water vapor, which precipitate out from the atmosphere to land surfaces without being significantly transported out to other regions. Seemingly functioning as a 'catalyst', transient disturbances effectively convert atmospheric water vapor into rainfall. However, further effort with regional/global climate models with land-surface schemes are necessary to test this argument.

6. Concluding Remarks

Along boreal forests in Eurasia and North America at high latitudes, there exists belt-shaped/circumpolar summer rainfall ('boreal-forest rainbelts') strong transient activity...
('minor storm tracks'). The mechanism(s) responsible for generating and maintaining summer rainbelts at high latitudes is investigated in the present study. To reveal this mechanism, two questions are raised: (1) What is the formation mechanism of minor storm tracks over two northern land-masses during summer season? And (2) can boreal-forest rainbelts be maintained by convergence of transient water vapor flux associated with transient disturbances along minor storm tracks? Our major findings can be summarized as follows:

- It was suggested that the frontal/cyclone activity over these two northern land-masses might be developed through baroclinic instability caused by strong Arctic westerlies along the Arctic seaboard (e.g., Dzerdzeevskii 1945; Kurashima 1968; Serreze et al. 2001). A careful examination of boreal-forest rainbelts, minor storm tracks, and upper-tropospheric westerlies (Figures 2.2 and 2.3) reveals that the aforementioned argument is only applicable to those in Eastern Canada. In contrast, rainbelts and minor storm tracks in other locations (Eastern Siberia, Northwestern Europe, and Alaska-Pacific coast) are further southward of strong Arctic westerlies, and concentrate on regions east of four upper-tropospheric troughs at high latitudes. Therefore, a coupling between the upper-tropospheric trough and surface cyclones (e.g., Holton 1992) is suggested as a possible formation mechanism of minor storm tracks. Strong positive vorticity advection ahead of the upper-tropospheric troughs may constitute a favorable environment for cyclogenesis and development of minor storm tracks over these regions.

- Regardless of different formation mechanisms of minor storm tracks at high latitudes, meso- and synoptic scale storms play a crucial role in maintenance of boreal-forest rainbelts. Our water budget analysis reveals that stationary divergent water vapor flux (shown as $\tilde{Q}_D^S$ and $-\nabla \cdot \tilde{Q}_D^S$ in Figure 2.7a) does not supply water vapor to produce summer rainfall at high latitudes, and that convergence of transient
water vapor flux associated with meso- and synoptic scale disturbances along minor storm tracks (represented by \( \text{sgn}(-)\nabla^{\|}_{\kappa} \) and \( \text{sgn}(-)\nabla\cdot\mathbf{Q}_{\kappa}^{\|} \) in Figure 2.7b) supplies water vapor to form/maintain the boreal-forest rainbelts. Our argument, to some extent, is consistent with results of previous studies. In high latitudes, transient transport accounts for much of atmospheric water and energy transport (Overland et al. 1997; Serreze et al. 1995). Based on the station observation of the GAME-Siberia experiment, significant evaporation forms an important water vapor source over East Siberia (Ohta et al. 2001). It is likely that this atmospheric water vapor is effectively recycled by transient disturbances along boreal forests.

In addition to positive vorticity advection by high-latitude troughs in the upper troposphere, surface lows are observed in East Siberia and along Alaska-Pacific coast (Figure 2.4b). The former is associated with the northward extension of the East Asian monsoon, and the latter is formed by interaction with maritime inflow from the North Pacific Ocean and topography (the Alaskan Range). Although a detailed analysis on these two regional circulation structures is beyond scope of our present study, it is conceivable that the surface monsoon low over East Siberia and the surface trough along Alaska-Pacific coast can also assist to form minor storm tracks over these regions.

The boreal-forest rainbelts over the two northern land-masses are not only an interesting feature of the high-latitude summer climate, but also a potentially important component in the global climate system. For instance, any change in hydrological processes over the northern land-masses can alter freshwater outflow to the Arctic Ocean through north-bound river discharge, which may provide an important impact on the global climate through the thermohaline circulation in the global ocean (e.g., Zhang et al. 1993). Sequential studies will be devoted to investigation of the interannual variation of boreal-forest rainbelts and transient activities, which could enlighten long-term climate variability of northern high latitudes. Regardless of large improvement of data
quality and the recognition of the potential importance of the Arctic/subarctic regions to the global climate change, the basic features of the climate and circulation, such as the annual variation have not been well demonstrated (Randall et al. 1998; Wei et al. 2002). Features of the Arctic/subarctic summer climate system addressed in this study, including boreal-forest rainbelts and minor storm tracks, can be used as a validation tool for model performance.

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CHAPTER 3  Interannual variation of the boreal-forest rainbelts

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Abstract

The most interesting feature of summer climate at high latitudes is rainfall along the boreal forests. Our present study investigates interannual change of boreal-forest rainbelts. It was revealed that summer rainfall along boreal forests undergoes quasi-periodic oscillation with short-scale waves and that rainfall anomalies exhibit apparent eastward propagation. Analysis of water vapor budget with NCEP/NCAR reanalysis demonstrated that anomalous rainfall at high latitudes is maintained by anomalous convergence of transient water vapor flux. It was found that the interannual change of frontal/cyclone activity is responsible for that of transient water vapor flux, eventually generated by that of summer stationary waves at the upper troposphere through anomalous vorticity advection. In other words, anomalous positive vorticity advection ahead of the trough at the upper troposphere can constitute a favorable environment for developing baroclinic waves and summer rainfall.
1. Introduction

Understanding causing mechanism(s) and prediction of interannual variation of rainfall have been one of the major challenges to the meteorological community. A good example is the effort made by previous research to reveal the year-to-year change of rainfall at various locations caused by El Niño and the Southern Oscillation (ENSO) (e.g., Walker and Bliss 1932; Ropelewski and Halpert 1987, and others). These studies primarily focused on rainfall in the tropics and the midlatitudes. However, interannual variation of rainfall at high latitudes has received less research attention compared to that of the tropics and the midlatitudes (Rogers et al. 2001; van Loon and Rogers 1978; Walsh and Chapman 1990). Thus, an effort was made to investigate the interannual variation of rainfall at high latitudes during northern summer season in our present study.

The most outstanding feature of high-latitude summer season is rainfall along the boreal forest (hereafter ‘boreal-forest rainbelts’) over the Eurasian and North American continents (Fig. 2 in Yoon and Chen 2004). Thus, year-to-year change of boreal-forest rainbelts will be mainly investigated in our present study. During the northern summer, these subarctic rainbelts are maintained by convergence of transient water vapor flux associated with frontal/cyclone activity (Serreze et al. 2001; Yoon and Chen 2004). It was also demonstrated that the summer stationary waves at high latitudes (four major troughs at Central Eurasia, the Bering Sea, the Labrador Sea, and the Norwegian Sea) constitute preferable environments for developing transient disturbances through positive vorticity advection ahead of these troughs. Can a similar argument be applicable to the interannual variation of the boreal-forest rainbelts? In other words, more rainfall along the boreal forests might be caused by an increased frontal/cyclone activity and anomalous positive vorticity advection.

The interannual change of boreal-forest rainbelts can have a potentially profound
impact on the global climate change. For example, the long-term change of hydrological processes over the two northern land-masses might be induced by the interannual change of the boreal-forest rainbelts. Eventually, fresh water outflow from the Arctic Ocean toward the northern Atlantic Ocean could be altered, which results in a modulation of the thermohaline circulation in the global ocean and the global climate condition (e.g., Aggard and Carmack 1989; Delworth et al. 1993; Zhang et al. 1993). Major research efforts dealing with the high-latitude climate and its variability have focused on the winter season. Because the maximum transport of fresh water occurs during the warm season (Bjornsson et al. 1995), the climate variability of the warm season is as important as that of the cold season.

Importance of the interannual variability of rainfall at high latitudes to the global climate change attracts our research attention. Thus, this paper is arranged in the following manner. In Section 2, with a brief review of summer climatological aspects of boreal-forest rainbelts (Yoon and Chen 2004), research questions are raised. A detailed discussion on the interannual variability of the boreal-forest rainbelts is provided in Section 3. Some concluding remarks and a possible mechanism are presented in Section 4.

2. Research questions

The interannual variation of boreal-forest rainbelts can be easily depicted with longitude-time (x-t) diagrams (Figure 3.1) of summer rainfall anomalies averaged from 55°N to 60°N, because summer rainbelts are zonally elongated along this latitudinal circle (Fig.2 of Yoon and Chen 2004). Summer rainfall anomalies are furnished with two different datasets: the Climate Prediction Center (CPC) merged precipitation analysis (CMAP, Xie and Arkin 1997) and the Global Historical Climate Network version 2 (GHCN, Easterling et al. 1996). The latter provides only precipitation over land with rain-
Figure 3.1 The longitude-time (x-t) diagram of summer-seasonal anomalies of rainfall obtained from CMAP and GHCN. Contour interval is 0.15 mm day$^{-1}$. 
gauge observation, while the former covers both the land and the ocean with satellite estimations.

The x-t diagrams of summer rainfall anomalies exhibit a couple of remarkable characteristics: apparent eastward propagation and quasi-periodic oscillation with a shorter scale in the east-west extension. Power spectra analysis is applied in the zonal and time axis of x-t diagrams to examine the spatial-temporal characteristics (Figure 3.3)). Power spectra along zonal axis (Figure 3.2a) indicate that the dominant horizontal scale of anomalous rainfall is a relatively shorter scale (waves 3-6). There exist two frequency
regimes (Figures 3.2b-c): high-frequency mode (shorter than the 3-year period), and low-frequency mode (4- to 7-year period). What mechanism(s) is responsible for these outstanding features? Prior to the discussion on these features, we shall delineate how this anomalous rainbelts is maintained. The analysis of maintenance mechanisms(s) of anomalous rainfall along boreal forests can provide solid evidence on its reality. Thus, we shall progress our discussion in the following procedure:

- First, let us analyze how anomalous rainfall along the boreal forest is formed. It was found in our previous study (Yoon and Chen 2004) that only convergence of transient water vapor flux is important in producing summer rainfall at high latitudes, while that of stationary water vapor flux does not play any significant role in maintaining boreal-forest rainbelts. Transient water vapor flux derives its major contribution from meso- and synoptic- scale disturbances with a life cycle of about five days. Thus, the water vapor budget was simplified using the following form [Eq.(3.1)]:

\[ P \simeq [\text{sgn}(-) \nabla \cdot \bar{Q}'_D], \quad (3.1) \]

where \( \bar{Q}'_D \) represents the convergence of 2-7 days Butterworth bandpass (Murakami 1979) filtered water vapor flux and the symbol \( \text{sgn}(-) \) stands for only negative values of (i.e., convergence of transient water vapor fluxes) included in the long-term average. Based upon this modified water vapor budget in summer climatology [Eq.(3.1)], it is likely that anomalous summer rainfall along boreal forests may be maintained by the anomalous convergence of transient water flux. This can be summarized by the following form [Eq.(3.2)]:

\[ \Delta P \simeq \Delta[\text{sgn}(-) \nabla \cdot \bar{Q}'_D], \quad (3.2) \]

To test this idea, an analysis of the anomalous water vapor budget [Eq.(3.2)] is performed with the NCEP/NCAR reanalysis (Kalnay et al. 1996) in the next sec-
tion. Also, it will be demonstrated that anomalous convergence of transient water vapor flux is constituted by interannual variation of cyclone occurrence frequency ($N_f$).

- Second, how can the interannual variation of transient activity at high latitudes be generated? Cyclone activity along the boreal forest can be developed in terms of the conceptual model of a developing baroclinic short wave in terms of the quasi-geostrophic theory (e.g., Holton 1992): a coupling between the upper-tropospheric trough and a surface cyclone. As shown by the quasi-geostrophic omega equation, vertical differentiation of vorticity advection (increasing with height) maintains the upward motion associated with falling surface pressure (e.g., Carlson 1998). Because the upper-level westerlies are stronger, the vorticity advection in the upper troposphere is larger in magnitude than it is at the surface. Therefore, ahead of the troughs in the upper troposphere, the vertical differentiation of vorticity advection, which enables the upper-level flow to be more cyclonic with height, induces the ascending motion, causes the surface pressure fall, and consequently, results in the formation of a surface cyclone (Yoon and Chen 2004). Thus, a hypothesis is proposed here: Anomalous summertime stationary waves may produce anomalous transient activity at high latitudes through anomalous vorticity advection at the upper troposphere. It is likely that the shorter-scale wave regime (waves 3-6) of stationary waves have direct influence on anomalous rainfall, due to shorter-scale nature of anomalous rainfall based on the power spectra analysis.
3. Interannual variation of the boreal-forest rainbelts and transient activities

Summer rainfall is produced by convergence of both stationary and transient water vapor flux. At most of the regions in the tropics, interannual variation of warm-season rainfall is primarily caused by the convergence of the stationary water vapor flux. For example, anomalous monsoon rainfall over Indonesia and Indochina can be induced by year-to-year changes of the stationary water vapor flux (Chen and Yoon 1999). In contrast, boreal-forest rainbelts are maintained only by the convergence of transient water vapor flux [Eq.(3.1)] (Yoon and Chen 2004). Can anomalous convergence of transient water vapor flux maintain summer rainfall anomalies along boreal forests, as hypothesized in [Eq.(3.2)]? To answer this question, the x-t diagram of the summer-seasonal anomalies of convergence of transient water vapor flux ($\Delta[\text{sgn}(-)\nabla\cdot\vec{Q}_{T}]$) is constructed in Figure 3.3a. Ignoring the fine structures, anomalous rainfall and convergence of transient water vapor flux exhibit, to some extent, a similarity in the year-to-year change. Thus, it is concluded that increased (decreased) summer rainfall is primarily maintained by the anomalous convergence (divergence) of transient water vapor flux along boreal forests [Eq.(3.2)]. The importance of the transient component in the interannual change of atmospheric heat/moisture transport at high latitudes during the summer season is consistent with results shown in some previous studies (e.g., Overland et al. 1996; Serreze et al. 1995).

Our next concern is to examine whether the anomalous convergence of transient water vapor flux is constituted by frontal/cyclonic activity. The x-t diagram of anomalous cyclone occurrence frequency ($\Delta N_f$) is drawn in Figure 3.3b. Cyclone occurrence frequency is determined by an incorporation of objective and subjective approaches. The objective algorithm designed by Dr. Mark Serreze of the University of Colorado (Serreze 1995; Serreze et al. 1997) was used to identify cyclone locations with the 6-hourly
Figure 3.3 The longitude-time (x-t) diagrams of convergence of transient water vapor flux, cyclone occurrence frequency, and vorticity advection by zonal wind. Contour intervals are $2 \times 10^{-8} \text{kgm}^{-2}$, $0.2 \text{num/season}$, and $1 \times 10^{-11} \text{ms}^{-2}$, respectively.
Northern Hemisphere (NH) sea-level pressure data from the NCEP/NCAR reanalysis for the period from 1979 to 2002. After their locations were detected by this objective algorithm, the subjective screening process was applied to ensure identified cyclones were migrating. The cyclone occurrence frequency \( N_f \) is the accumulation of migrating cyclones with a closed low center and rainfall within each \( 5^\circ \times 5^\circ \) box over the summer season. Contrast between the interannual variation of convergence of the transient water vapor flux \( \Delta [\text{sgn}(\nabla \cdot \vec{Q}_D)] \) in Figure 3.3a) and transient activity \( \Delta N_f \) in Figure 3.3b) clearly indicates that the former is generated by the latter. Therefore, interannual variation of transient disturbances along the boreal forests produces anomalous convergence of transient water vapor flux and eventually summer rainfall.

It was demonstrated that positive vorticity advection ahead of major subarctic troughs at the upper troposphere constitute favorable environments for the development of transient disturbances (Yoon and Chen 2004). It was hypothesized that interannual variations of the subarctic large-scale circulation could drive that of the transient activity through anomalous vorticity advection (summarized in the following diagram).

\[
\Delta P \simeq -\Delta [\text{sgn}(\nabla \cdot \vec{Q}_D)] \quad \leftrightarrow \quad \Delta N_f \quad \leftrightarrow \quad \zeta_A
\]

To test this idea, the x-t diagram of vorticity advection at the upper troposphere \( (\Delta \zeta_A(250mb), \text{ where } [\zeta_A(250mb) \equiv -u \frac{\partial \zeta}{\partial z}] \) is constructed in Figure 3.3c. Horizontal derivatives (e.g., divergence and vorticity) computed at high latitudes on the equal latitude-longitude grid system are usually contaminated by false values generated by the 'Pole Problem', due to decreasing zonal spacing between grid points toward the pole. To avoid this computational predicament in this grid system, the octagonal grid system used by the National Meteorological Center (former NCEP) for its operational forecast model (Shuman and Hovermale 1968) was adopted. A detailed description of transforming data between the grid systems by 16-point Bessel interpolation is found.
in Yoon and Chen 2004. A contrast between interannual variation of both transient activity ($\Delta N_f$ in Figure 3.3b) and vorticity advection ($\Delta \zeta_A(250mb)$ in Figure 3.3c) suggests that the latter can produce and generate the former through interaction between upper-tropospheric vorticity advection and surface cyclogenesis (Holton 1992; Carlson 1998). Thus, it can be inferred that the interannual variation of summertime stationary waves at high latitudes is responsible for that of the boreal-forest rainbelts.

To further link the interannual variation of both boreal-forest rainbelts and summertime stationary waves at high latitudes, horizontal plots of anomalous rainfall and geopotential height at 400mb with short-waves filtered (waves 3-10) ($()^5$) are constructed for three summers (83 JJA, 86 JJA, 88 JJA). The reason the short-wave filter was applied is that x-t diagram (Figure 3.1) and power spectra analysis of rainfall anomalies (Figure 3.2) infer dominance and importance of shorter-scale waves. Apparent eastward propagation is emerged with relatively shorter-scale waves (about $20^\circ - 30^\circ$ along at $60^\circ N$, approximately 2000Km). Therefore, from east to west coasts of the Eurasian continent, there exist two or three anomalous rainfall centers, which varies/oscillates with a time lag. In the Eurasian continent, a positive anomalous rainfall and transient activity (marked with a closed circle in Figure 3.4) are located west of the Ural mountains (83 JJA), east of the Ural mountains (86 JJA), and north of Lake Baikal (88 JJA). It is also observed that rainfall and anomalous trough/ridge has a horizontal quarter-phase lag. Therefore, more (less) rainfall is ahead of the trough (ridge), which can satisfy the classic cyclone model (i.e., the Rossby wave dynamics) as shown in Chen et al. (1996). In other words, warm/moist (cold/dry) air converges ahead (rear side) of the cyclone center and forms an upward (downward) motion branch of the secondary circulation, which eventually acts as a generator of vorticity through the vortex stretching term. The quarter phase lag between anomalous rainfall and upper-tropospheric circulation ensures a hydrologic-dynamic coupling of the interannual variation of summertime short waves at high latitudes.
Figure 3.4  The summer-seasonal anomalies of short-wave filtered geopotential height at 400mb and rainfall. Contour interval is 10m.
4. Concluding Remarks

The remaining question is what causes the interannual variation of summertime short-waves at high latitudes, which will be a major subject of our future study (including apparent eastward propagation). However, it must be noted that from one location to the next, the horizontal distance is about a couple thousand kilometers, while the time intervals are more than 2-3 years. Instead of an eastward propagation, an alternative perspective of this special interannual variation of the boreal-forest rainbelts must be provided in our future work. Summer rainfall along the boreal forests (boreal-forest rainbelts) exhibits a substantial interannual variation. In our present study, the interannual variation of these rainbelts and maintenance mechanisms are investigated. Our major findings can be highlighted as follows:

- Convergence of transient water vapor flux is very crucial in maintaining summer rainfall over two northern land-masses [Eq.(3.1)]. The same argument is applicable to the interannual variation of boreal-forest rainbelts. Contrast between rainfall anomalies ($\Delta P$) and anomalous convergence of transient water vapor flux ($\Delta [\text{sgn}(-)\nabla \cdot \vec{Q}_D]$) reveals that the former can be maintained by the latter [Eq.(3.2)]. A further comparison with anomalous cyclone occurrence frequency ($\Delta N_f$) infers interannual variation of the transient water vapor flux is generated by that of the cyclone activity. In summary, the interannual variation of the boreal-forest rainbelts is generated by that of transient disturbances through the convergence of the transient water vapor flux. Power spectra of anomalous rainfall in time and zonal dimensions (Figure 3.2) disclose dominance of a shorter-scale wave in the zonal direction ($20^\circ - 30^\circ$ along the latitudinal circle along $60^\circ N$), and the quasi-periodic oscillation with a period of 5-7 years.

- Our previous study showed that cyclone activity can be generated by a positive vorticity advection, based on a classic model of interaction between the upper-
tropospheric troughs and surface cyclones (e.g., Holton 1992). It is not surprising to find that anomalous vorticity advection at the upper troposphere ($\Delta \zeta(250mb)$) exhibits a similar interannual variation of cyclone occurrence frequency ($N_I$). Thus, interannual variation of summertime stationary waves (short-wave regime) at high latitudes can exert substantial influence on that of the boreal-forest rainbelts through transient activity. A possible mechanism responsible for interannual variation of high-latitude summer circulation and boreal-forest rainbelts can be suggested by considering how anomalous the short-wave train can be formed during the summer season at high latitudes.

Boreal forests play as an important terrestrial carbon sink, which accounts for 15-30% of the annual global carbon from fossil fuels and industrial activities (Lucht et al. 2002; Montaigne 2002). Terrestrial carbon sink, equivalently forest biomass sinks, can be used as an alternative to meet greenhouse gas emission commitments under the Kyoto Protocol of the United Nations framework and convention on climate change. The summer climate at high latitudes influences forest growth through precipitation, temperature, and eventually soil moisture which will constrain plant growth. Also, changes in forest cover could feed back on the regional/global climate through modification of surface temperatures and precipitation by altering the surface albedo and influencing $CO_2$ concentration (Bonan et al. 1995). Although significant and large-scale changes in vegetation cover occurred transiently over centennial and millennial time scales, there is also evidence of structural vegetation changes in response to climate variation of a much shorter-interannual or decadal time scale (Lucth et al. 2002; Myneni et al. 2001). This carries an important message regarding this current study that the interannual change in boreal-forest rainbelts could induce those of boreal forest and even the global climate system with various altered feedback mechanisms.
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CHAPTER 4  Interannual variation of the North American monsoon rainfall

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Abstract

The interannual variation of the North American monsoon (NAM) circulation and rainfall is generated by anomalous east-west divergent circulation across the NAM region. During wet (dry) monsoons, the enhanced (suppressed) east-west circulation with upward (downward) motions over the Tropical Atlantic Ocean and downward (upward) branches over the Eastern Tropical Pacific Ocean formed by anomalous differential heating between these two basins can intensify (suppress) the monsoon thermal low, the Mexican high, and eventually convective activity/rainfall. The planetary-scale circulation (wave 1) hinders development of the NAM circulation. In contrast, it is found that this planetary-scale circulation (wave 1), to some extent, is in-phase with the interannual variation of the inter-basin scale circulation. Thus, the planetary-scale circulation expedites formation of the anomalous east-west divergent circulation across the NAM regions. Some cases are found, where the inter-basin scale circulation cannot decide the anomalous circulation patterns over the NAM regions. For these exceptional cases, the impact exerted by the anomalous North-Pacific short-wave trains across the North Pacific Ocean is suggested to be responsible for the interannual variation of the NAM
1. Introduction

The southwest United States and most of Mexico exhibit a monsoonal climate ('North American Monsoon', hereafter NAM) from July to August (Douglas et al. 1993; Higgins et al. 1997; Stensrud et al. 1995). About half of the annual rainfall concentrates during this period, which provides valuable water resources and severe weather systems that develop more frequently over these regions, causing loss of human life and economic damage. The influence of the NAM is not just confined in the regional scale, but also extends to other parts of the contiguous United States throughout of the phase relationship between the monsoon rainfall and the Great Plains weather and climate (Higgins et al. 1998). Therefore, the Pan American Climate Studies (PACS) and the Variability of American Monsoon System (VAMOS) research programs have been developed to attract more research attention on empirical, numerical, and observational studies of the NAM (NOAA 1998). Among the aforementioned research aspects, the interannual variability of monsoon rainfall becomes an interesting and an important subject, because this year-to-year change of monsoon rainfall can be used for long-term/seasonal forecasting (Higgins et al. 1998). Our present study is devoted to determine the mechanism(s) causing the interannual variation of the NAM rainfall.

Numerous efforts have been made to reveal the controlling factors of the year-to-year change of the NAM rainfall. These can be summarized into two general categories: remote and in-situ factors. The influence of the tropical Pacific Sea Surface temperatures (e.g., \(\Delta SST\) over the NOAA NINO3.4 regions) on the NAM rainfall can be an example of the former, while the impact caused by memory of snow-cover extent over the western North America may be an example of the latter (e.g., Carleton and Carpenter 1990; Castro et al. 2001; Hawkins et al. 2002; Higgins et al. 1999; Gutzler 2000). Regardless
of the many different forcing mechanisms, a close correlation was found between the intensity of the NAM circulation [e.g., summertime mid-tropospheric subtropical ridge (Carleton and Carpenter 1990)] and anomalous monsoon rainfall. Thus, we shall investigate the interannual variation of the NAM circulation and its causing mechanism, prior to further research on the corresponding variation of the NAM rainfall.

The upper-level summer flow across North America is characterized by the Mexican high, flanked by two oceanic troughs over the Pacific and the Atlantic Oceans (Krishnamurti 1971). In the lower troposphere, the continental heat low (overlaid by the Mexican high) in the southwestern United States is juxtaposed with the Pacific and the Atlantic anticyclones (White 1982). Centers of the upper-level high actually coincide with the monsoon rainfall core (Higgins et al. 1997). Thus, the most conspicuous features of the NAM circulation are the North American thermal low (continental heat low) and the Mexican high (monsoon anticyclone). These monsoon low and high of the NAM are maintained by the east-west divergent circulation (satisfying the Sverdrup vorticity balance), supported by a thermal contrast between heating over the western tropical Atlantic and cooling over the eastern tropical Pacific (Gill 1980; Chen 2003). Therefore, it is likely that any change in this east-west divergent circulation and differential heating between two oceans suggested by Giannini et al. (2002) may induce the intensification/suppression of the NAM circulation.

The NAM circulation is well depicted by the medium-wave regime (waves 2-8) in the summer climatology (Chen 2003). However, in the interannual time-scale, this medium-wave scale must be considered as the combination of two different regimes: (i) the inter-basin scale regime (wave 2) and (ii) the short wave regime (waves 3-8). The former can well capture the aforementioned continental low and high, and the zonal seesaw oscillation between the eastern tropical Pacific and the tropical Atlantic Oceans, while the latter is related to the PNA-like wave train or the short-wave train along the North Pacific rim (e.g., Higgins et al. 1997; Lau and Weng 2002; Trenberth et al. 1988).
Therefore, the interannual variation of the inter-basin scale circulation will be primarily investigated because it is a key element in the NAM circulation. On the other hand, it was found that the planetary-scale circulation (wave 1) does suppress further development of the NAM circulation in the summer climatology, due to its spatial alignment (Chen 2003). It will be also discussed how these two different scale waves (including the planetary-scale and the short-scale waves) affect the interannual variation of the inter-basin scale circulation across the NAM regions and the monsoon rainfall.

Based upon the revised monsoon circulation model (Chen 2003), the interannual variation of the NAM circulation is investigated with a focus on the inter-basin scale circulation, and a possible impact by the short-wave train and the planetary-scale wave is discussed. Thus, our present study is arranged in the following way: Research hypotheses are proposed based upon the review of the maintenance mechanism of the NAM circulation in Section 2. Wet and dry monsoons are identified in Section 3. Interannual variation of the east-west divergent circulation and its linkage to the wet and dry summers of the NAM are analyzed in Section 4. The impact exerted by the planetary-scale wave and the anomalous short-wave trains on the interannual variation of the NAM circulation and rainfall are discussed in Section 5. Concluding remarks are given in Section 6.

2. Research hypotheses

Let us first discuss the scale of the east-west divergent circulation across the NAM regions, which is responsible for maintaining the NAM high and low. It was pointed out by Chen (2003) that this east-west divergent circulation is well depicted by the medium-scale wave regimes (waves 2-8). In contrast, only wave 2 (inter-basin scale) is used in our present study (Figure 4.1). The reasons why this inter-basin scale is used instead of waves 2-8 are as follows. First, the ratio of the variance of wave 2 to
that of waves 2-8 potential function \( \frac{\text{Var}(\chi^2)}{\text{Var}(\chi^{2-8})} \) is 62% and 46% for 200mb and 850mb, respectively. Second, it was found that interannual variation of short-scale wave becomes discernible over the North American continent (e.g., Lau and Weng 2002; Castro et al. 2001). Therefore, the medium-scale wave (waves 2-8) is separated into two different regimes: inter-basin scale (wave 2), and short-wave train (waves 3-8) in our present study.

Figure 4.1 Long-term summer mean of the (a) \( \psi(200mb)_2 \), (b) \( \psi(30^\circ N)_2 \), (c) \( \psi(850mb)_2 \), (d) \( \chi(200mb)_2 \), (e) \( u_D, -\omega((30^\circ N)_2 \) and (f) \( \chi(850mb)_2 \). Contour intervals are \( 10^6 \text{m}^2\text{s}^{-1} \), \( 10^8 \text{m}^2\text{s}^{-1} \), \( 5 \times 10^5 \text{m}^2\text{s}^{-1} \), \( 5 \times 10^5 \text{m}^2\text{s}^{-1} \), \( 5 \times 10^5 \text{m}^2\text{s}^{-1} \), for (a), (b), (c), (d), and (f), respectively, with all the positive values lightly shaded. Upward (downward) motion are shaded darkly (lightly) if the \(-\omega\) is larger (smaller) than \( +10^{-4}\text{mb/s} \) \((-10^{-4}\text{mb/s}) \) in (b).
Although fine structures of the NAM circulation (e.g., low-level surge in the Gulf of California) are not very well depicted by the NCEP/NCAR reanalysis (Kalnay et al. 1996), large-scale circulation features are relatively well represented (Barlow et al. 1998). Two important features of the NAM circulation, as pointed out by Chen (2003), are found (Figure 4.1): (i) the vertical phase reversal of the monsoon circulation (thermal low at the lower troposphere and monsoon high at the upper troposphere) in Figures 4.1a-c, and (ii) a spatially quadrature relationship between divergent circulation and the rotational circulation in Figures 4.1d-e. It was shown that the east-west divergent circulation is driven by the east-west differential heating formed by the inter-basin sea surface temperature (SST) distribution over the western tropical Atlantic and the eastern tropical Pacific (Chen 2003).

A number of previous studies (Andrade and Sellers 1988; Carleton and Carpenter, 1990; Higgins et al. 1998, 1999; Yu and Wallace 2000, and others) attempted to link the interannual variation of the NAM rainfall to the SST variation over the eastern tropical Pacific, based upon a classical monsoon circulation model (Holton 1992). In other words, cooler SSTs over the eastern tropical Pacific are observed during wet monsoons, inferred from stronger north-south Hadley circulation (Higgins et al. 1997). However, the differential heating between the eastern tropical Pacific and the western tropical Atlantic oceans is more important in maintenance of the NAM circulation in a revised monsoon circulation model (Chen 2003). Giannini et al. (2000) found a zonal seesaw in the sea-level pressure between the equatorial Pacific and the tropical Atlantic oceans. Thus, an anomalous east-west divergent circulation associated with the aforementioned sea-level pressure seesaw oscillation (Giannini et al. 2000) possibly enhance/suppress the climatological divergence and eventually rotational circulation through the Sverdrup vorticity balance. It is hypothesized that any changes in the east-west divergent circulation across the NAM regions induced by the anomalous heating/cooling between the eastern tropical Pacific and the tropical Atlantic oceans may cause the interannual
variation of the North American summer monsoon circulation and rainfall.

The horizontal scale and intensity of the NAM are much smaller than the Asian counterpart (Ting and Reiter 1984). This is caused not only by the size of both continents, but also by the scale/alignment of dominant summertime stationary waves over two monsoon systems. The NAM is mainly explained by waves 2-8 components (Chen 2003), while the Asian counterpart is composed of waves 1 and 2 (Holton and Colton 1972). This ultra-long wave can suppress further development of the NAM circulation, due to its spatial alignment with the medium-scale waves (2-8) (Chen 2003). A question may be raised concerning the role played by the planetary-scale wave on the interannual variation of the east-west divergent circulation across the NAM regions. This will be discussed in a later section with a comparison of spatial alignments between the planetary-scale and the inter-basin scale waves during wet/dry monsoons.

The summer droughts and floods in the central United States are remotely linked to the tropical Pacific SST anomalies through the PNA-like wave train, as suggested by previous efforts (e.g., Mo et al. 1997; Ting and Wang 1997; Trenberth et al. 1988). On the other hand, a possible linkage between the western tropical Pacific and the North American continent was constructed through the short-wave train during the summer season (Lau and Weng 2002). It was further shown that this summer short-wave over the North Pacific rim could affect wet/dry conditions of the NAM region (Higgins et al. 1999; Castro et al. 2001), which may be induced by the North Pacific SST. Therefore, a role played by the North-Pacific short-wave train will be discussed in a later section.

3. Identification of wet/dry cases

Three different datasets are employed to identify wet and dry summers of the North American monsoon: (1) OLR (Outgoing Longwave Radiation) measured by NOAA's polar orbital satellites (obtained from the Climate Diagnostic Center, NOAA), (2) the
CPC (Climate Prediction Center) merged analysis of precipitation (CMAP, Xie and Arkin 1997), and (3) rainfall observed at a station over the United States and Mexico generated by the CPC (US-Mex, Higgins et al. 1999). OLR can represent a deep convection and be used as rainfall proxy with a threshold of \(235 W m^{-2}\) (Chen and Yen 1994; Mitchell et al. 2002). The long-term summer mean of \(\Delta OLR\), \(P(CMAP)\), and \(P(US - Mex)\) are shown in Figures 4.2a-c. Intense precipitation is concentrated on northwest Mexico and extends to the southwestern part of the United States including Arizona, New Mexico, and Colorado (e.g., Douglas et al. 1993; David and Comrie 1997; Negri et al. 1993, and others). To measure the interannual variability of monsoon rainfall, the root-mean-squares (hereafter ‘rms’) of \(\Delta P(CMAP)\), \(\Delta P(US - Mex)\), and \(\Delta[\Delta OLR]\), (where \(\Delta[]\) is departure from the long-term summer mean, represented as \([\cdot]\)) are displayed in Figures 4.2d-e. A significant interannual variability of the NAM rainfall is observed over the southwestern part of the United States and Mexico.

Histograms of area-averaged \(\Delta[\Delta OLR]\), \(\Delta P(CMAP)\), and \(\Delta P(US - Mex)\) over the analysis domain (105°W – 100°W and 15°N – 25°N, marked with solid box in Figure 4.1a), based on the rms and summer climatology values, are presented in Figure 4.3. If is larger (smaller) than 20\(W m^{-2}\), it is identified as a wet (dry) summer of the NAM [darkly (lightly) shaded in Figure 4.3]. Also, histograms of and are used for verification. The following 9 wet and 9 dry summers are identified from 27 summers during the period of 1974 to 2000:


Wet and dry summers defined above are, to some extent, close to the results shown in Higgins et al. (1999). Some differences arise from the analysis domain of both studies. The domain used in our study encompasses larger areas, including both northern Mexico
Figure 4.2 Long-term summer mean of the (a)$[\Delta OLR]$, (b) $P(CMAP)$, and (c) $P(US - Mex)$ as well as the rms of seasonal departures of the (a)-(c) in (d)-(f), respectively.
and southwestern United States to assess the impact of the inter-basin scale circulation on the interannual variation of the monsoon rainfall.

4. Interannual variation of the east-west divergent circulation across the NAM regions

Based upon our hypothesis, it is likely that during wet (dry) monsoons, the local east-west divergent circulation across the NAM regions may be enhanced (suppressed). The lower-tropospheric divergent circulation, which can be directly influenced by anomalous SSTs over the eastern Pacific and the western Atlantic oceans, can be a good representative of this local east-west circulation. To test our hypothesis, the phase-amplitude diagram of the wave-2 filtered potential function at 850mb averaged between 10°N and 20°N is constructed in Figure 4.4a. The phase (angle) represents the location of the convergence center at the lower troposphere, while the amplitude (length) indicates its intensity. Salient features are summarized as follows:

- Phases of the divergent circulation during wet and dry monsoons are clearly separated.

- It is particularly interesting to observe that the phases during wet (dry) monsoons are located, to some extent, in the same (opposite) quadrant with the summer-mean phases (marked with a thick line). Therefore, the east-west divergent circulation across the NAM regions is enhanced (suppressed) during wet (dry) seasons.

This phase-amplitude diagram strongly substantiates our hypothesis that the interannual variation of the NAM circulation and rainfall is modulated by the zonal seesaw oscillation of the east-west divergent circulation across the monsoon regions. However, two wet and two dry cases (1990, 1993, and 1996, 2000, marked with arrows in Figure 4.3) are exceptional in Figure 4.4a. In other words, during these four seasons, the
Figure 4.3 Histograms of the area-averaged (a) $\Delta [\Delta OLR]$, (b) $\Delta P(CMAP)$, (c) $\Delta P(US - Mex)$, over the NAM regions (marked in Figure 4.1).
Figure 4.4  Phase-amplitude diagrams of the potential function at 850mb wave-2 and -1 filtered averaged between 100 N and 200 N. Wet and dry monsoons are marked as dark shading and dot, while the summer climatology is marked with thick line.
anomalous east-west circulation structure does not exhibit a prominent zonal seesaw oscillation across these regions, in spite of clear wet and dry conditions over the NAM regions. Thus, other mechanisms (the short-wave train and the planetary-scale wave) may play more crucial roles in deciding wet/dry conditions over the NAM regions.

We shall examine the three-dimensional circulation structures during wet and dry monsoons, using the composite method to assert that during wet monsoons the NAM circulation is stronger. To answer this, the following questions are raised:

1. Q1: Do the NAM low and the Mexican high tend to intensify (weaken) during wet (dry) monsoon?

2. Q2: Does the anomalous east-west divergent circulation across the NAM regions $[u_D, -\omega]$ exhibit enhancement (suppression) to support the stronger (weaker) monsoon low and high during wet (dry) seasons, and also satisfy the Sverdrup vorticity balance?

3. Q3: Do anomalous differential heatings between the tropical Atlantic and the eastern tropical Pacific oceans induce the enhanced/suppressed east-west divergent circulation across the NAM regions during wet/dry monsoons?

To answer the above questions, a composite of atmospheric circulations during wet (dry) monsoons are displayed in Figures 4.5, 4.6, 4.7, and 4.8. First, increased (decreased) convective activity and precipitation over the most of Mexico and southwestern United States are apparent during wet (dry) in Figure 4.5 (Figure 4.6). Also, the out-of-phase relationship between rainfall anomalies over the NAM regions and the central United States is observed (Higgins et al. 1999). Answers to the above questions are highlighted as follows:

1. A1: The deepened thermal low (Figure 4.5c) and the filled Mexican high (Figure 4.5a) are coincident with the increased rainfall over the NAM regions. The
Figure 4.5  Same as Figure 4.2 except for the wet composite of the seasonal departures. Contour intervals are $2^5 m^2 s^{-1}$, $2^5 m^2 s^{-1}$, $1^5 m^2 s^{-1}$, $5^4 m^2 s^{-1}$, for (a), (b), (c), (d), and (f), respectively. All positives are lightly shaded, and upward (downward) motion are shaded darkly (lightly) if the $-\Delta \omega$ is larger (smaller) than $+10^{-5} mb/s (-10^{-5} mb/s)$ in (e). Anomalous rainfall and $\Delta[\Delta OLR]$ values are shaded lightly (darkly) if the values are larger (smaller) than $+0.2 (-0.2) mm day^{-1}$ and $+1(-1) W/m^2$, respectively.
Figure 4.6  Same as Figure 4.5 except for the dry composite of the seasonal departures.
vertical phase reversal of the streamfunction over these regions is clearly observed in Figure 4.5b, an important characteristic of monsoon circulation (White 1982; Chen 2003). An opposite circulation structure to the wet is clearly apparent in Figure 4.6.

- A2: The enhanced/suppressed east-west Walker circulation depicted by $\Delta [u_D, -\omega]$ maintains the atmospheric divergent circulation portrayed by $\Delta [\chi, V_D]$, which is spatially in quadrature relationship with the stronger/weaker rotational flow ($\Delta \Psi$) during wet/dry monsoons at lower and upper atmosphere in Figures 4.5 and 4.6.

To clarify the dynamical maintenance of the anomalous inter-basin scale circulation, a simplified streamfunction budget analysis is adopted (Chen 2003). It is revealed that the Sverdrup vorticity balance is applicable for the anomalous circulation of wet/dry monsoons [summarized in Eqs. (4.1) and (4.2)]:

$$ v_R \beta + \nabla \cdot (f \mathbf{V'}) \simeq 0. \quad (4.1) $$

The inverse laplacian operator is applied to Eq (4.1),

$$ \psi_{A2} + \psi_{X12} \simeq 0. \quad (4.2) $$

Anomalous rotational flows with the inter-basin scale ($\Delta \psi^2$) are maintained by the counter action between the $\beta$-effect and the stretching terms in both the upper and lower tropospheres (Figure 4.7). The anomalous upward (downward) branches of the east-west divergent circulation across the NAM regions over the tropical Atlantic (eastern tropical Pacific) generate enhanced (suppressed) vorticity stretching, which must be balanced with the $\beta$-effect.

- A3: The composite of $\Delta SST$ of wet monsoons is constructed (only wet composite shown in Figure 4.8c). The relationship between diabatic heating ($\Delta Q$) and diver-
Figure 4.7 Same as Figures 4.5 and 4.6 (a)-(b), except for the streamfunction tendencies induced by the advection and stretching terms at 200mb and 850mb. Contour interval is $10 m^2 s^{-2}$ with light shading for positive values.
Figure 4.8  Same as Figures 4.5 and 4.6d and f, except for the potential function generated by the potential function budget equation in (a) and (b). The wet composite of sea surface temperatures is in (c) with contour of 0.1°C and lightly (darkly) shaded if the values are larger (smaller) than +0.1(−0.1)°C.
gent circulation ($\Delta \chi$) is analyzed using the velocity potential ($\chi \dot{Q}$)-maintenance equation (Chen and Yen 1991; Chen 2003).

\[ \chi = \nabla^{-2} \left[ \frac{\partial}{\partial p} \left( \frac{1}{\sigma C_p} \dot{Q} \right) \right] - \nabla^{-2} \left[ \frac{\partial}{\partial p} \frac{1}{\sigma} \left( \frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T \right) \right], \quad (4.3) \]

and it can be further simplified as the following form:

\[ \chi = \chi \dot{Q} + \chi_{HA}. \quad (4.4) \]

where $\sigma$, $\vec{V}$, $T$, $C_p$, $p$, and $\dot{Q}$ are static stability, velocity vector, temperature, specific heat with constant pressure, pressure, and diabatic heating, respectively. Since thermal advection is generally much smaller than diabatic heating in the NAM (Chen 2003), Eq.(4.3) may be approximated by

\[ \chi \simeq \chi \dot{Q}, \quad (4.5) \]

which clearly explains a linkage between diabatic heating and the divergent circulation. Diabatic heating ($\dot{Q}$) was estimated by the residual method of the thermodynamic equation following Chen and Baker (1986). It is clearly revealed that during wet monsoons larger thermal contrast (warmer eastern tropical Pacific and colder western tropical Atlantic oceans) generates corresponding anomalous diabatic heating (easily indicated by anomalous diabatic heating at $200\text{mb}$ [$\Delta \dot{Q}(200\text{mb})$] in Figure 4.8a), and the enhanced east-west divergent circulation (Figures 4.8a and b). Eventually, stronger monsoon lows and highs are maintained by this enhanced divergent circulation by the ‘Sverdrup vorticity balance’ [Eq.(4.2)].

As pointed out by some previous studies (Carleton and Carpenter. 1990; Higgins et al. 1998), wet/dry monsoons are closely related to the intensity of the upper-tropospheric
monsoon anticyclone over the NAM regions. Our composite analysis clearly demonstrated that the stronger (weaker) monsoon low/high are dynamically maintained by the corresponding east-west divergent circulation, induced by anomalous heating (cooling) over the eastern tropical Pacific and cooling (heating) over the tropical Atlantic Oceans.

5. Discussion

Planetary-scale wave

During the summer season, the planetary-scale wave forms a gigantic thermal low (the Tibetan high) over East Asia, while an anticyclone (trough) covers the western hemisphere at the lower (upper) troposphere. Thus, this planetary-scale wave (wave 1) suppresses further development of the NAM (Chen 2003), driven by the east-west Walker circulation \((u_D, -\omega)\) with upward (downward) motions over the warm pool (Central America). How does this planetary-scale circulation affect the interannual variation of the NAM circulation and rainfall?

The phase-amplitude diagram of the wave-1 filtered velocity potential at 850mb averaged between 10°N and 20°N is presented in Figure 4.4b. It is observed that the phases of wet and dry summers are, to some extent, separated. Further, the phase of summer mean is somewhat closer to those of dry monsoons, while in the inter-basin scale, the summer-mean phase is in the same quadrant as the wet monsoons. In other words, the role played by this planetary-scale circulation in the interannual variation of the NAM is opposite to that in the summer climatology.

A composite circulation structure of this planetary-scale wave during wet summers is constructed in Figure 4.9. A gigantic anomalous trough and anticyclone are located along the tropical Atlantic Ocean, which may enhance the anomalous NAM low and the Mexican high, respectively. As inferred from the phase-amplitude diagram (Figure 4.4b),
the east-west Walker circulation (Figure 4.9e) connecting the warm pool over the western tropical Pacific and the tropical Atlantic oceans support formation of the inter-basin scale seesaw oscillation (Figure 4.5d). It is also remarked that this planetary-scale wave may link both the NAM and the Asian monsoon systems.

Figure 4.9 Same as Figures 4.5 and 4.6 except for the wet composite of the seasonal departures with wave-1 filter.

**Short-wave train**

Four cases (1990, 1993, and 1996, 2000) are found, which cannot be explained by the interannual variation of the zonal seesaw oscillation in the inter-basin and the planetary
scales. What mechanism is responsible for these wet/dry monsoons? A remaining and potential mechanism is the short-wave train along the North Pacific rim. Modeling and diagnostic studies suggest its existence and possible impact on the climate of the North American continent (e.g., Higgins et al. 1998; Higgins et al. 1999; Lau and Weng 2002; Chen 2003). The influence of this teleconnection pattern on the NAM was further analyzed by Castro et al. (2001). In their Fig.14, an anomalous heating and cooling distribution over the Pacific Ocean generated this teleconnecting wave pattern, which can modulate the location and intensity of the monsoon high from its climatology. In other words, especially when the east-west divergent circulation in the inter-basin and the planetary scales cannot dominate the anomalous circulation structures over these regions, this short-wave train may play a substantial role in determining the wet or dry monsoons.

One case example (1993 dry monsoon) is analyzed in Figure 4.10 with short wave (waves 3-8) filtered. Salient features of the short-wave train and its impact on the NAM circulation are as follows: (i) The NAM low is displaced eastward, attached to the North-Pacific short-wave train at the lower troposphere. The anomalous circulation supports the wet condition over the Great Plains, while it suppresses the development of the heat low and rainfall. (ii) The vertical structure of this short wave train exhibits ‘barotropic’ as shown in Chen (2002).

The most significant difference between this short-wave train and the zonal seesaw of the east-west divergent circulation can be found in the vertical structure and the dynamical maintenance mechanism. The former is vertically uniform (barotropic) so that the Rossby wave dynamics is applicable, while the latter exhibits a vertical phase reversal (monsoonal) so that the Sverdrup vorticity balance holds (Chen 2003). The impact exerted by the short-wave train on the interannual variation of the NAM rainfall is important in some years, when the zonal seesaw of the east-west divergent circulation does not generate a clear anomalous circulation structure over the monsoon regions.
Figure 4.10  The seasonal departures of 1993 summer with short wave filtered (waves 3-8). Contour intervals are $10^6 m^2 s^{-1}$, $5^5 m^2 s^{-1}$, $10^5 m^2 s^{-1}$, and $5^4 m^2 s^{-1}$ for (a), (b), (c), and (d), respectively with light shading for positive values.
Further effort is necessary to understand under what condition this short-wave train becomes more important and how it is formed/maintained.

6. Concluding Remarks

The rainfall over southwest United States and Mexico undergoes a significant inter-annual variation, which tends to be even larger than the summer climatology at some locations (Higgins et al. 1998). Many different factors affecting wet/dry monsoons have been proposed (including $\Delta$SST over the Pacific Ocean and snow coverage over the Rocky Mountains) (e.g., Higgins et al. 1997; Castro et al. 2001; Hawkins et al. 2002). Above all, a close correlation between the intensity of the Mexican high at the upper troposphere and the monsoon rainfall was observed (Carleton and Carpenter 1991; Higgins et al. 1997). Thus, any mechanism which can modulate the monsoon high and low may be responsible for the interannual variation of the NAM rainfall. The Mexican high and the North American thermal low are maintained by the east-west divergent circulation (well depicted by the medium-scale waves), with upward (downward) motion over the warm tropical Atlantic Ocean (the cool eastern tropical Pacific) (Chen 2003). It is hypothesized that any change in the local east-west divergent circulation may result in the corresponding change of the monsoon high/low and eventually rainfall.

The medium-scale wave (2-8) is further separated into two different regimes: inter-basin scale and short-wave regime, because wave 2 is responsible for more than 50% of the variance of this medium-scale wave, and some previous studies reported the importance of anomalous short-wave trains along the North Pacific rim on the weather/climate of the Central Plains and the NAM. On the other hand, the planetary-scale wave hinders further development of the NAM circulation in the summer climatology (Chen 2003). The interannual variation of the east-west circulation in the inter-basin scale is analyzed first, and also the impact exerted by the anomalous short-wave train and the planetary-
scale wave is discussed in the present study. Our major findings can be highlighted as follows:

- **The east-west divergent circulation across the NAM regions (the interannual variation of the inter-basin scale circulation):** Because more than 70% of the wet/dry cases are explained by this inter-basin scale seesaw oscillation over the two basins, it is concluded that the interannual variation of the NAM rainfall can be primarily affected by that of the inter-basin scale east-west divergent circulation over the eastern Pacific and the tropical Atlantic oceans. During wet monsoons, an anomalous upward (downward) motion over the tropical Atlantic (the eastern tropical Pacific) make the east-west divergent circulation stronger, which eventually induces the deepened thermal low and the filled Mexican high through the Sverdrup vorticity balance. Eventually, an enhanced monsoon low/high can generate more convective activity and rainfall. An opposite circulation structure is found during dry monsoons. This relationship can be summarized in the following diagram.

\[
\Delta P \iff \Delta \psi \iff \Delta [\psi_A, \psi_{\chi}] \iff \Delta [\chi, \chi_{\Delta}] \iff \Delta SST
\]

- **The impact exerted by the planetary-scale circulation (wave-1):** It was determined from the phase-amplitude diagram that the planetary-scale wave assists to form the inter-basin east-west divergent circulation during wet/dry monsoons. It is further suggested that a linkage between the interannual variation of the Asian monsoon and that of the NAM can be established through this planetary-scale circulation.

- **The North-Pacific short-wave train:** The anomalous short-wave train around the North Pacific rim likely plays a crucial role in deciding wet/dry conditions of the NAM (e.g., Chen and Weng 1998; Nitta 1987; Castro et al. 2001; Lau and Weng 2002; Higgins et al. 1999), when the aforementioned inter-basin and planetary
scale circulation cannot provide a dominating impact on the interannual variation of the NAM circulation.

Our current study performed a diagnostic analysis to substantiate our hypothesis. Further work using numerical simulations with either a global climate model or regional climate model is planned and will provide more solid evidences on our hypothesized mechanism. It has been shown that localized factors (e.g., snow extent over the southern United States or soil moisture) play an important role in regulating regional hydro-climate (e.g., Gutzler 2000). Our present study focuses rather on the large-scale circulation and remote forcing mechanisms. It is desired in our future work to investigate the role of the local factors (such as snow coverage over the Rocky Mountains) and its interaction with the proposed mechanism here to gain an integrated picture of the climate variability of the North American summer monsoon.

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CHAPTER 5  General Conclusion

Conclusions

Interannual climate variability during the northern summer season has been investigated in our current study. After Walker’s pioneering work (Walker and Bliss 1932, 1937), many previous studies have documented and discussed the structure and the dynamical/thermodynamical causes (e.g., Bjerkness 1969). However, relatively less attention have been devoted on the summer climate variability. Thus, two different aspects of the interannual climate variability during the northern summer season have been discussed. One is the interannual variation of the boreal-forest rainbelts, and the other is the interannual variation of the North American monsoon rainfall. Also, the summer climatological aspect of the boreal-forest rainbelts from a hydrological and dynamical perspectives was presented in prior to its interannual variability. Several hypotheses were proposed to demonstrate our proposed subjects and were substantiated with diagnostic analysis.

In Chapter 2 of this study, the hydrological and dynamical processes associated with the boreal-forest rainbelts are presented. The boreal forest grow by rainfall along these forests (names as the ‘boreal-forest rainbelts’). It is found that the boreal-forest rainbelts are maintained by the convergence of water vapor flux related to transient disturbances such as individual meso- and synoptic- scale storms (denoted as ‘minor storm tracks’ to distinguish major storm tracks in the North Pacific and North Atlantic Oceans). These transient disturbances are embedded in the summertime stationary waves over the Arctic
and the subarctic regions. The Arctic/subarctic summer circulation is characterized by three Arctic ridges over the Barent Sea, the New-Siberian Islands, and the Alaska-the Beaufort Sea. These ridges are coupled with the eastward extension of the North Atlantic anticyclone at the lower troposphere, the East Siberian monsoon which is the northern extent of the East Asian summer monsoon, and the narrow Alaskan Pacific-coast trough line, respectively. A clear transition of the circulation structure emerges from the barotropic stationary eddies (associated with the Barent ridge) to the East Siberian monsoon low (associated with the New-Siberian Islands ridges) over Eurasia, and from the narrow Alaska Pacific-coast trough to the confluent flow of the East-Canadian Arctic trough and the North Atlantic circulation over North America. The strong baroclinic zones with jet stream-like westerlies along the three aforementioned ridges maintain the minor storm tracks indicated by frontal activity (Serreze et al. 2001), cyclone frequency, and variance of transient variables. The coincidence of the convergence of transient water vapor flux with the transient activities and the boreal-forest rainbelts substantiate the maintenance mechanism of the rainbelts by transient disturbances. Furthermore, dynamical maintenance of the jet stream-like westerlies and the aforementioned three ridges are discussed using thermal wind relationship, simple energetics computations, and quasi-geostrophic geopotential height tendency equation.

In Chapter 3 of this study, the interannual variation of summer rainfall along the boreal-forest rainbelts is investigated. Rainfall along the boreal-forest and Arctic frontal zone plays an important role not only in the regional scale but also to the global climate system. River runoff from the rainbelts over two northern land-masses could be an important source of fresh water in the Arctic Ocean basin which induce thermohaline circulation in the global ocean (e.g., Aagaard et al. 1985; Chen et al. 1994). Based upon previous summer climatological aspect in Chapter 1, the interannual variation of the boreal-forest rainbelts are discussed. Two major issues of this subject are as follows. (1) whether a significant and recurrent interannual variability can be found in rainfall
amount, and (2) what mechanism can drive/maintain the interannual variation. These two aspect are answered in this chapter.

First, a significant interannual variability of summer rainfall is eminent along the boreal-forest rainbelts over two northern land-masses (Eurasia and North America). Two interesting features of rainfall interannual variabilities are found: (i) regionally different phases with smaller scale, and (ii) a clear eastward propagation of seasonal rainfall anomalies. Second, a key mechanism to drive the interannual variation of rainfall is possibly an year-to-year change of the convergence of transient water vapor flux accompanied by meso- and synoptic- scale storms. The longitude-time (x-t) diagrams and sequenced horizontal plots of rainfall and storm activity reveal a close relationship between rainfall and storm activity. This result concurs with the findings of our previous chapter about the summer climatological aspect of summer rainfall along boreal forest. Furthermore, the interannual variability of storm activity can be linked to that of stationary waves in high latitudes -NAO over the North Atlantic Ocean and the teleconnecting pattern associated with the interannual variation of the East Asian monsoon (e.g., Chen and Weng 1998a,b; Hurrel 1995; Lau et al. 2000; vanLoon and Rogers 1978).

In Chapter 4 of this study, the interannual variation of the North American monsoon rainfall is studied, based upon a revised maintenance mechanism of the summer monsoon circulation (Chen 2003). The most conspicuous elements of the North American monsoon circulation are the thermal low at the lower troposphere, and the Mexican high at the upper troposphere. These are maintained by the east-west divergent circulation with diabatic heating/upward motion branch over the tropical Atlantic Ocean and cooling/downward branch over the eastern tropical Pacific (Chen 2003) through the Sverdrup vorticity balance. In this paper, the interannual variation of the aforementioned east-west divergent circulation is extensively analyzed. It is found that most of wet (dry) summers of the North American monsoon are coincident with the enhanced (suppressed) east-west divergent circulation which induces intensified (weakened) the
monsoon circulation (e.g., Carleton and Carpenter 1990). However, it is found that other mechanism (short-wave train across the North Pacific rim) plays a non-negligible role for minor cases. The influence by the short-wave train which is excited by anomalous heating/cooling over the Pacific Ocean is shown with a case example.

In summary, any change in the east-west divergent circulation across the North American monsoon regions induced by the anomalous heating/cooling over the tropical Atlantic and the eastern tropical Pacific induce the changes of the North American monsoon thermal low, the Mexican high, and the monsoon rainfall. For some minor cases, the short-wave train over the North Pacific rime is suggested to be an important in deciding wet/dry monsoons.

**Suggestion for future works**

Our current study has primarily focused on diagnostic analysis of observations and reanalysis. Further analysis with the global climate model such as NCAR CCM or NASA NSIPP and the regional climate model is proposed to further substantiate our hypothesis proposed in this study. Some suggestions for future research are made along with two major directions. One is *Boreal forest and associated rainbelts in high latitudes*, and the other is *the North American summer monsoon*

**Boreal forest and associated rainbelts in high latitudes**

The Arctic Ocean basin and surrounding boreal forest/tundra regions play a crucial role in regulating the global climate system. However, a simulation of these high-latitude climate in the global or regional climate model have been hampered by scarcity of qualified observation and improper treatment on the land surface processes or other physical parameterization (Randall et al. 1998). Recently, potentially important role played by the Arctic climate components in the balance and the change of the global climate sys-
tem have been recognized. However, subarctic boreal forest and tundra regions received less attention. Thus, a detailed analysis on the subarctic regions with a focus on the summertime boreal forest and associated rainbelts using the global climate models or the regional climate model is proposed.

Several interesting features shown by diagnostic analysis in earlier chapters can be further tested with the numerical models:

- The inter-relationship between the boreal-forest rainbelts and the minor storm tracks: First of all, it has to be investigated whether the models can generate proper amount of rainfall and transient disturbances along the boreal forest. Usually, the simulated Arctic climate is usually cold and dry compared to observations (e.g., Randall et al. 1998).

- Summertime stationary waves in high latitudes: Interesting features over the Arctic/subarctic areas (such as jet stream-like westerlies and associated three ridges) has to be evaluated.

- Interannual variation of the boreal-forest rainbelts: The most interesting feature noted earlier is the clear eastward propagation of the rainbelts. To explain this peculiar phenomena, a hypothesis made. 'Combined effects of several interannual variation modes make this eastward propagation of rainfall anomalies'. To substantiated this hypothesis, several numerical simulation with different boundary conditions which cause different interannual variation modes will be of use to further support our diagnostic finding.

**Interannual variation of the North American monsoon rainfall**

Our current study found that the interannual seesaw oscillation of the east-west divergent circulation across the North American monsoon regions. Numerical experiments
with either the global climate model or the regional climate model are suggested. Modified sea surface temperature over two basins can provide us more quantitative assessment on the inter-relationship between the interannual seesaw of the east-west divergent circulation and that of the monsoon rainfall. In other words, sequential numerical experiments will be performed with different thermal contrast between two basins. It is expected from our diagnostic analysis that anomalous heating and cooling over the tropical Atlantic Ocean and the eastern tropical Pacific Ocean may generate stronger monsoon circulation and more rainfall over the North American monsoon regions. Therefore, an effort will be made with the global climate model or the regional climate model to further investigate the interannual variation of the North American monsoon rainfall.

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References


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