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Review

The Guiding Role of Rossby Wave Energy Dispersion Theory for Studying East Asian Monsoon System Dynamics

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Abstract: This paper is written to commemorate the 10th anniversary of academician Ye Duzheng (Yeh T.C.) pass away and his great contributions to the development of atmospheric dynamics. Under the inspiration and guidance of the theory of Rossby wave energy dispersion, remarkable progresses have been made in research on planetary wave dynamics and teleconnections of atmospheric circulation anomalies. This paper aims to make a brief review of the studies on the propagating characteristics of quasi-stationary planetary waves in a three-dimensional spherical atmosphere and the dynamic processes of the interannual and interdecadal variabilities of the East Asian summer and winter monsoon systems. Especially, this paper systematically reviews the progresses of the studies on the impacts of the interannual and interdecadal variabilities of the East Asia/Pacific (EAP) pattern teleconnection wave train propagating along the meridional direction over East Asia and the "Silk Road" pattern teleconnection wave train propagating along the zonal direction within the subtropical jet from West Asia to East Asia on the East Asian summer monsoon system and the summer precipitation variability in China, under the guidance of the theory of Rossby wave energy dispersion. Moreover, this paper reviews the dynamic processes of the impact of the interannual and interdecadal oscillations of the propagating waveguides of boreal quasi-stationary planetary waves on the variability of the East Asian winter monsoon system.

Keywords: Rossby waves; energy dispersion; East Asian monsoon system; dynamic processes; planetary wave train

Citation: Huang, R.; Huangfu, J.; Liu, Y.; Lu, R. The Guiding Role of Rossby Wave Energy Dispersion Theory for Studying East Asian Monsoon System Dynamics. *Atmosphere* **2023**, *14*, 962. https://doi.org/10.3390/atmos14060962

Academic Editor: Anthony R. Lupo

Received: 14 April 2023
Revised: 24 May 2023
Accepted: 28 May 2023
Published: 31 May 2023

1. Introduction

It has been 10 years since academician Duzheng Ye left us. His pass away was a great loss not only to the atmospheric science community in China but also to the international atmospheric science community. This article is written to commemorate the 10th anniversary of his pass away and to remember his great contributions to the development of atmospheric dynamics.

It is well known that the theory of Rossby wave energy dispersion [1] proposed by Duzheng Ye more than 70 years ago is one of the classical theories of atmospheric dynamics. The theory of Rossby wave energy dispersion is not only widely used in weather forecasting but also inspire the development of planetary wave dynamics, especially the study on the propagating characteristics of quasi-stationary planetary waves in two- and three-dimensional spherical atmosphere [2–11] and the teleconnection mechanism of global atmospheric circulation anomalies [12–20]. Under the guidance of the theory of Rossby wave energy dispersion proposed by academician Ye, the research on the dynamic processes of the variability of the East Asian monsoon system has been made in recent years. In particular, our research group studied the dynamic processes of the impacts of the East Asian/Pacific (EAP) and Silk Road (SR) pattern teleconnection wave trains on the variability of the East Asian summer monsoon system [16,21]. In addition, significant progress has achieved in the studies on the dynamic processes of the variability of the East Asian winter monsoon system due to the oscillations of the propagating waveguides of quasi-stationary planetary waves in the three-dimensional spherical atmosphere [22–25]. Thus, this paper presents a brief review of the recent studies on the dynamic processes of the interannual and interdecadal variabilities of the East Asian summer monsoon system and the dynamical impact of the interannual and interdecadal oscillations of the propagating waveguides of quasi-stationary planetary waves on the East Asian winter monsoon system. Besides, under the guidance of the theory of Rossby wave energy dispersion, some studies in China and abroad related to the dynamic processes of the East Asian monsoon system are simply reviewed in this paper. Many figures in this paper are the result of our recent analysis using 60-year reanalysis data and summer precipitation data in eastern China for 1961–2020.

2. The Guiding Role of the Theory of Rossby Wave Energy Dispersion in the Study on Quasi-Stationary Planetary Wave Propagation in a Three-Dimensional Spherical Atmosphere

The theory of Rossby wave energy dispersion proposed by academician Ye has not only benefited the study on the two-dimensional propagation of quasi-stationary planetary waves in the spherical atmosphere but also played a guiding role in the study on the three-dimensional propagation of quasi-stationary planetary waves in the spherical atmosphere during boreal winter.

2.1. Study on the Propagating Waveguides of Quasi-Stationary Planetary Waves in the Spherical Atmosphere during Boreal Winter

After academician Duzheng Ye proposed the theory of Rossby wave energy dispersion, many meteorologists focused on the energy dispersion of planetary waves in the vertical direction of the atmosphere. For example, several meteorologists [26,27] applied the concepts of the wave refraction index and energy, respectively, to study the vertical propagating characteristics of quasi-stationary planetary waves in the basic flow with a vertical wind shear. Later, Dickinson [5] applied the concept of waveguides to study the vertical propagating characteristics of quasi-stationary planetary waves in the ideal basic flow in boreal winter and proposed that quasi-stationary planetary waves can propagate from the troposphere to the stratosphere over high latitudes, which is called the polar waveguide. After the Dickinson's study, Matsuno [6,7] studied the vertical propagation of quasi-stationary planetary waves from the troposphere to the stratosphere in the actual basic flow in boreal winter and proposed the dynamic mechanism of the stratospheric sudden warming. He noted that the propagation of tropospheric quasi-stationary planetary waves into the stratosphere and their interaction with the stratospheric basic flow leads to the stratospheric sudden warming in boreal winter. Thus, the theory of Rossby wave energy dispersion guided the study on the propagating characteristics of quasi-stationary planetary waves in the atmosphere from the troposphere to the stratosphere, which established the theoretical basis for the study on the mechanism of tropospheric-stratospheric interactions.

Guided by the theory of Rossby wave energy dispersion and based on the studies made by Matsuno [6,7], Huang and Gambo [10,11] systematically studied the characteristics of the three-dimensional propagations of quasi-stationary planetary waves in a spherical atmosphere using the wave refraction index and the E-P flux, respectively.

Huang and Gambo [11] studied the characteristics of three-dimensional propagation of quasi-stationary planetary waves in the actual basic flow using the wave refraction index. Figure 1 shows the vertical distribution of boreal winter Q_0 and a schematic diagram of the propagating waveguides of quasi-stationary planetary waves in the three-dimensional atmosphere, where $Q_0 = Q_k + k^2/\cos^2\varphi$ (Q_k is the square of the refraction index for wavenumber k, calculated from the basic flow and related parameters; k is the wavenumber, and φ is latitude). In Figure 1, we can see that the propagations of quasi-stationary planetary waves in the three-dimensional atmosphere in boreal winter exist two waveguides. The first waveguide is called the polar waveguide [5], i.e., quasi-stationary planetary waves can propagate from the troposphere to the stratosphere at high latitudes through this waveguide. Similarly, Figure 1 shows that quasi-stationary planetary waves can also propagate from the lower troposphere at mid-latitudes to the upper troposphere at low latitudes through the second waveguide. This propagating waveguide over low latitudes is called the "low-latitude waveguide" or "alternate waveguide". As shown in Figure 1, if there is a quasi-stationary planetary wave generated by a forcing source at low or mid-latitudes, it cannot propagate directly from the troposphere to the stratosphere at mid-latitudes but can propagate quasi-horizontally from the troposphere at low or mid-latitudes to high latitudes and then to the stratosphere at high latitudes through the polar waveguide, and it can also propagate to the upper troposphere at low latitudes through the low-latitude waveguide. This schematic picture indicates that the propagations of quasi-stationary planetary waves in the three-dimensional atmosphere in boreal winter are not limited to the propagation through polar waveguide but also exist the propagation through the low-latitude waveguide.

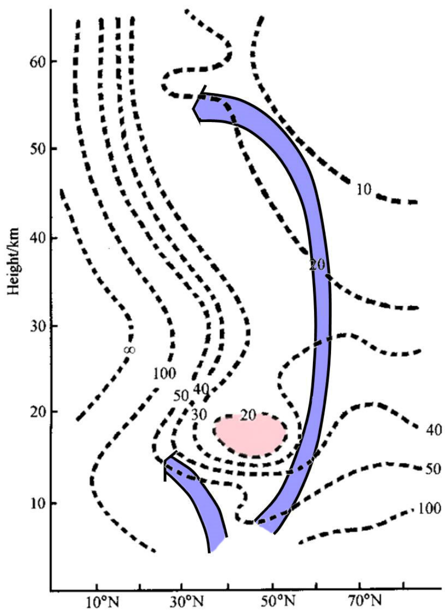

Figure 1. The vertical distribution of Q_0 (refraction index, dashed lines) and a schematic diagram of the waveguides of the three-dimensional propagations of quasi-stationary planetary waves in boreal winter (from Huang and Gambo [11]).

2.2. Waveguides of Quasi-Stationary Planetary Wave Propagation Characterized by the E-P Flux

The characteristics of three-dimensional propagations of quasi-stationary planetary waves in the atmosphere over the Northern Hemisphere can also be studied in terms of the wave energy flux. Eliassen and Palm [27] studied the vertical propagation of waves using the concept of energy flux, which was generalized by Andrews and McIntyre [28] in the 1970s, and they proposed the E-P flux under the β-plane approximation. Later, Edmon et al. [29] extended it to a sphere under the assumption that $\Delta f/f$ is small within the Rossby deformation radius.

Since the E-P flux of quasi-stationary planetary waves is parallel to the group velocity of the wave, meaning the E-P flux can represent the propagation of wave energy. Therefore, the E-P flux can be used to graphically characterize the propagations of quasi-stationary planetary waves in the three-dimensional atmosphere. Figure 2 shows the distributions of the E-P fluxes of quasi-stationary planetary waves averaged for 60 winters which were recently calculated by using the NCEP/NCAR reanalysis data from 1961 to 2020. As clearly shown in Figure 2, there are two propagating waveguides of quasi-stationary planetary waves in the three-dimensional atmosphere in boreal winter. The first waveguide is the propagation of planetary waves from the troposphere to the stratosphere at high-latitudes via the polar waveguide, while the other is the propagation of planetary waves from the mid-latitude region to the upper troposphere at low latitudes via the low-latitude waveguide. Comparing Figures 1 and 2, the propagating characteristics of quasi-stationary planetary waves in the spherical atmospherie during boreal winter (as shown in Figure 2) are consistent with the results analyzed earlier using the wave refraction index.

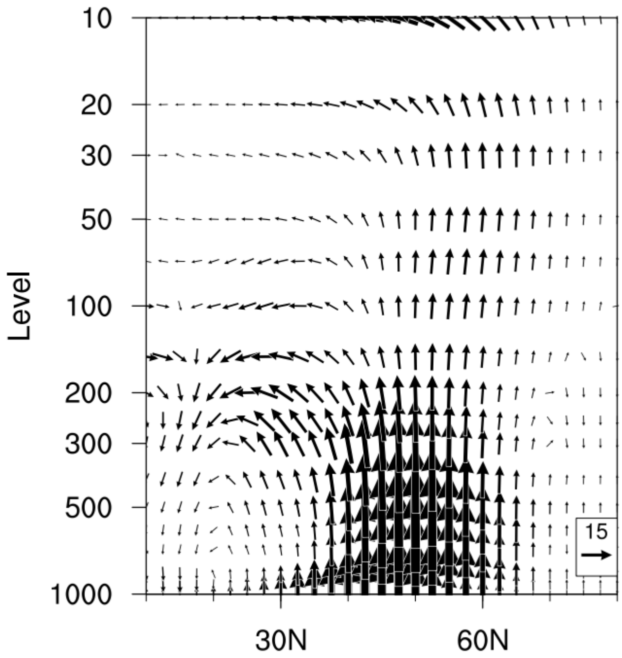

Figure 2. E-P flux cross sections (vector scale: m^3 s^{-2}; *Y*-axis denotes vertical levels, units: hPa) of quasi-stationary planetary waves averaged for 60 winters from the NCEP/NCAR [30] reanalysis data for 1961–2020.

2.3. Study on the Propagation of Quasi-Stationary Planetary Waves in the Three-Dimensional Atmosphere during Boreal Summer

There are few studies on the propagating characteristics of quasi-stationary planetary waves in the three-dimensional atmosphere during boreal summer. Huang and Gambo [31] studied the three-dimensional propagating characteristics of quasi-stationary planetary waves in the actual flow during boreal summer using the wave refraction index and E-P flux and noted that quasi-stationary planetary waves can propagate quasi-horizontally from the subtropical region to the middle and high latitudes during boreal summer, but not to the stratosphere.

3. The Guiding Role of Theory of Rossby Wave Energy Dispersion in the Study on the Dynamical Processes of the Variabilities of the East Asian Summer Monsoon System

Under the guidance of the theory of Rossby wave energy dispersion, the research on the dynamical processes of the variabilities of the East Asian summer monsoon system has been in recent years, especially on the interannual and interdecadal variabilities of the EAP pattern and "Silk Road" teleconnection wave trains and their effects on the variability of summer monsoon precipitation in eastern China.

3.1. The Guiding Role of the Theory of Rossby Wave Energy Dispersion in the Study on the Dynamical Processes of the Interannual Variability of the East Asian Summer Monsoon System

3.1.1. Dynamical Influence of the EAP Pattern Teleconnection Wave Train on the Interannual Variability of the East Asian Summer Monsoon System

In summer, the monsoon is prevalent in East Asia. Due to the obvious interannual variability of the monsoon, severe droughts and floods often occur in the eastern part of China.

Therefore, the causes of the interannual variability of the East Asian summer monsoon system and summer monsoon precipitation in China are important research topics.

The dynamical processes of the interannual variability of the East Asian summer monsoon system have been an interesting research topic for many scholars in East Asia since the 1980s. Nitta [13] firstly proposed that there is an anti-correlated oscillation, or the Pacific-Japan (PJ) oscillation, between the summer atmospheric circulation anomalies over the tropical western Pacific around the Philippines and those around Japan. Kosaka and Nakamura [20,32] also investigated the dynamics of the PJ oscillation. Under the guidance of the theory of Rossby wave energy dispersion, our research group [14–17,33] systematically studied the influence of strong heat sources formed by convective activities and the SST in the tropical western Pacific Ocean around the Philippines on the East Asian summer monsoon system and summer precipitation in eastern China from observational facts, theory and numerical simulations, respectively. These studies show that there is a distribution of teleconnection wave train of atmospheric circulation anomalies over the tropical western Pacific Ocean through East Asia and the Okhotsk Sea to Alaska and the west coast of North America in summer, which is referred as the East Asia/Pacific (EAP) pattern teleconnection wave train. These studies revealed that, as shown in Figure 3a, when the western Pacific warm pool is in a warm state and the convective activities over the tropical western Pacific around the Philippines are strong, there is a cyclonic circulation anomaly over the tropical western Pacific around the Philippines. Meanwhile, there is an anticyclonic circulation anomaly over Japan and the Yangtze and Huaihe River basins in China, i.e., the western Pacific subtropical high shifts northward. There is a cyclonic circulation anomaly that extends from north China towards the Okhotsk Sea. Under this condition, the plum rains over the Yangtze and Huaihe River basins are weak. In contrast, when the western Pacific warm pool is in a cold state and the convective activities over the tropical western Pacific around the Philippines are weak, as shown in Figure 3b, there is an anticyclonic circulation anomaly around the Philippines. There is a cyclonic circulation anomaly over Japan and the Yangtze and Huaihe River basins in China; that is, the West Pacific subtropical high shifts southward. In this configuration, strong plum rains often cause floods in the Yangtze River and Huaihe River basins. Due to the EAP pattern teleconnection wave train, the summer monsoon precipitation anomalies in eastern China often show a distribution of "+, −, +" or "−, +, −" tripole pattern wave train from south to north.

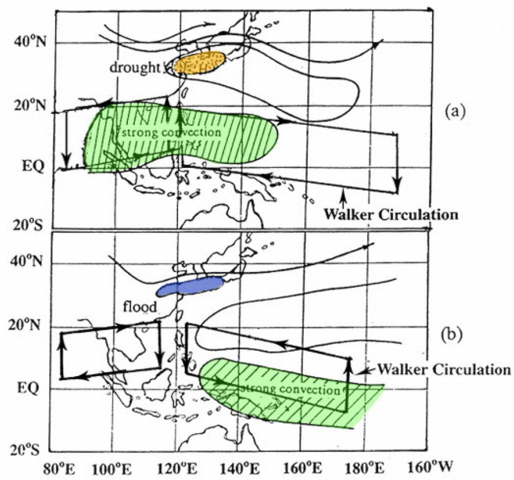

Figure 3. Schematic map of the relationships among the thermal state of the West Pacific warm pool (0°–14° N, 130°–150° E), the convective activities around the Philippines, the West Pacific subtropical high and the summer monsoon rainfall anomaly in the Yangtze River and the Huai River valleys in the (**a**) warm and (**b**) cooling states of the West Pacific warm pool (From Huang and Sun [17]).

It can also be studied from the EOF analysis of summer monsoon precipitation that the distributions of summer precipitation anomalies in eastern China are similar to the EAP pattern teleconnection. Our research group recently conducted the EOF analysis of the summer precipitation in eastern China using data for 60 years from 1961 to 2020. Figure 4a–d show the spatial distribution and corresponding temporal coefficients of summer precipitation in eastern China from 1961 to 2020, respectively. As shown in Figure 4a, the first mode of summer precipitation in eastern China shows a meridional tripole structure, which is similar to the EAP pattern. Additionally, as shown in Figure 4c, the first main mode of the variability of summer monsoon precipitation in eastern China shows a 2–3 year period. This is closely related to the meridional tripole distribution of the first mode of zonal water vapor transports in East Asia in summer [34].

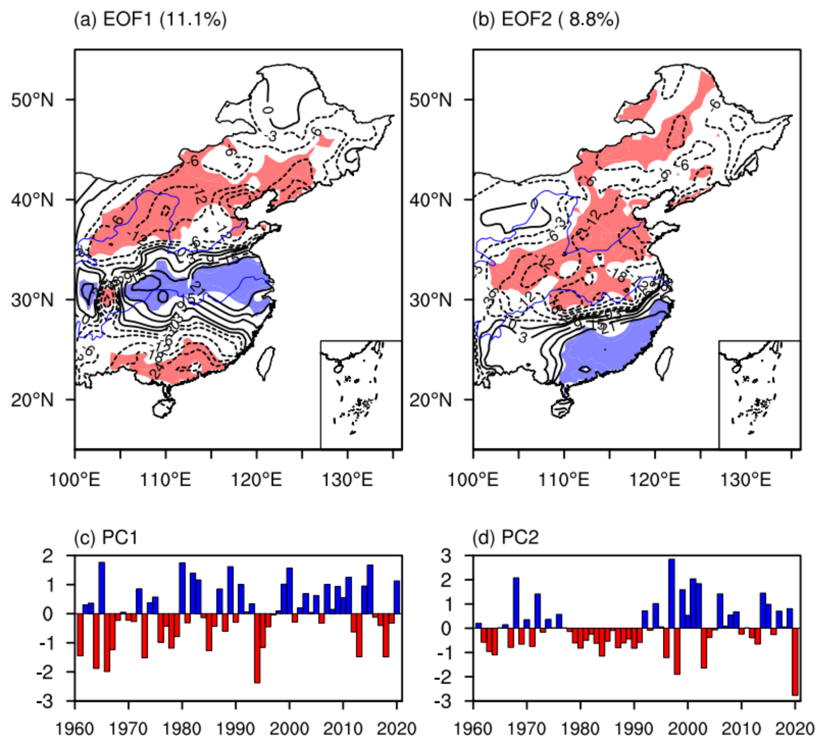

Figure 4. (**a**,**b**) Spatial distributions and (**c**,**d**) corresponding time coefficient series of the first and second components of EOF analysis of summertime (JJA) rainfall in eastern China for 1961–2020. The sold and dashed lines in Figure 4a,b indicate positive and negative values, respectively, and EOF1 and EOF2 explain 11.1% and 8.8%, respectively.

Huang et al. [35] used the EAP pattern teleconnection of atmospheric circulation anamolies to further explain the causes of the interannual variability of the summer precipitation in eastern China. This study showed that the spatial distribution of the variabilities of summer precipitation and East Asian summer monsoon water vapor transport fluxes in eastern China appears a meridional tripole distribution with a quasi-biennial period. The interannual variability with the quasi-biennial period maybe caused by the planetary wave train (i.e., EAP pattern teleconnection wave train) generated by the interannual variation of thermal forcing over the tropical western Pacific warm pool. Figure 5 shows the distribution of 500 hPa geopotential height anomalies regressed from the PC1. As shown in Figure 5, we can see that the summer monsoon circulation anomalies over East Asia and the tropical western Pacific exhibit a meridional tripole structure from south to north, and this distribution resembles the EAP pattern teleconnection wave train.

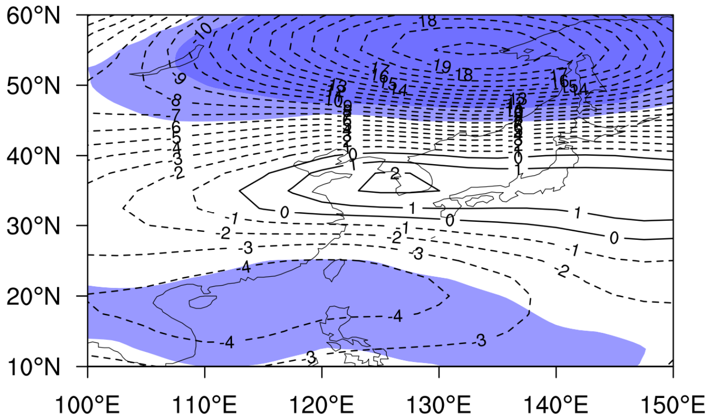

Figure 5. Distribution of summertime 500 hPa height anomalies over East Asia regressed by the time coefficients of EOF1 of summertime 500 hPa height for 1961–2020. Solid and dashed lines indicate positive and negative height anomalies, respectively, and areas with confidence level over 95% are shaded. Data of geopotential height fields is from the NCEP/NCAR reanalysis data [30].

To reflect the interannual variability of the EAP pattern teleconnection wave train and its influence on the interannual variability of summer monsoon precipitation in the Yangtze and Huaihe River basins, Huang G. [36] defined an EAP index from the distribution of the EAP pattern teleconnection wave train. This index is calculated with the standardized seasonal-mean (June-July-August) 500 hPa height anomaly at three different grid points (20° N, 125° E; 40° N, 125° E; 60° N, 125° E), which can well measure the strength of the East Asian summer monsoon and describe the interannual variability of summer rainfall and surface air temperature in East Asia. This index has a significantly negative correlation not only with summer monsoon precipitation in the Yangtze and Huaihe River basins in China but also with summer precipitation in Korea. Moreover, this index has a positive correlation with summer precipitation in North and South China. This shows that this index can describe the interannual variability of precipitation caused by East Asian summer monsoon. Figure 6 shows the wavelet analysis of the EAP index for 60 summers (June to August) recently calculated by using the definition of Huang G. [36] and the NCEP/NCAR reanalysis data from 1961 to 2020. From Figure 6, it can be seen that this index shows the interannual variability with the 2–3 year period from the 1970s to the late 1990s and from 2015 onward, which indicates that the interannual variability of East Asian summer monsoon precipitation with the 2–3 year period is closely related to the interannual variability of the EAP pattern teleconnection wave train.

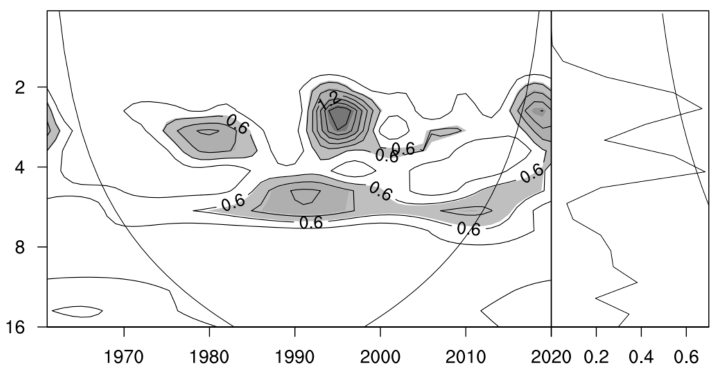

Figure 6. Wavelet analysis (*Y*-axis denotes periods, units: year; the curve on the right panel denotes the global wavelet spectrum; shading depicts power spectrum significant beyond 95% level based on the Chi-square test) of the EAP index calculated by using the definition in Huang G. [36] and 500 hPa height fields of the NCEP/NCAR reanalysis data [30] for 1961–2020.

3.1.2. Dynamical Influence of the "Silk Road" Pattern Teleconnection Wave Train on the Interannual Variability of the East Asian Summer Monsoon System

The variability of the East Asian summer monsoon system is influenced not only by the heat of the tropical western Pacific but also by the subtropical jet over Asia. The results studied by previous studies [18,19,21] demonstrated the existence of a wave train in the meridional wind variability in the upper troposphere from West Asia to East Asia. Later, Enomoto et al. [37] referred to this teleconnection wave train as the "Silk Road" pattern teleconnection. Therefore, the anomalies of East Asian summer monsoon precipitation with the meridional tripole or meridional dipole distribution may be influenced not only by the EAP pattern teleconnection but also by the Silk Road pattern teleconnection propagating along the upper tropospheric subtropical jet stream from West Asia to East Asia. Tao and Wei [38] suggested that the "Silk Road" pattern teleconnection has an important influence on the northward or southward movement of the western Pacific subtropical high and the East Asian summer monsoon rainfall belt. Hsu and Lin [39] and Kosaka et al. [40] also suggested that the Silk Road pattern teleconnection has an important influence on the western Pacific subtropical high and the northward or southward movement of and the summer monsoon rainfall belt. Hsu and Lin [39] and Kosaka et al. [40] further noted that the distribution of the summer precipitation anomalies with the tripole pattern is related not only to the EAP pattern teleconnection but also to the Silk Road pattern teleconnection propagating along the subtropical jet over Asia. Huang et al. [41] studied the dynamical processes of the variability of East Asian summer monsoon precipitation in terms of water vapor transports and showed that the variability of the East Asian summer monsoon precipitation is driven by a combination of the EAP pattern teleconnection wave train and the Silk Road pattern teleconnection wave train.

3.2. The Guiding Role of the Theory of Rossby Wave Energy Dispersion in the Study on the Dynamical Processes of the Interdecadal Variability of the East Asian Summer Monsoon System

The East Asian summer monsoon system not only has significant interannual variability but also obvious interdecadal variability. Due to the influence of interdecadal variability of the East Asian summer monsoon system, there is significant interdecadal variability in summer precipitation in eastern China. The result studied by Huang et al. [41] showed that the summer monsoon precipitation in eastern China experienced three significant interdecadal variations from the 1970s to the beginning of the 21st century. Recently, our research group analyzed the interdecadal variability of summer precipitation in eastern China using the summer precipitation data from 1961 to 2020 (Figure 7). The result shows that during 1961–1976, the summer precipitation anomalies in eastern China exhibited a "+, −, +" meridional tripole distribution from south to north, i.e., there was more precipitation in southern and northern China and less precipitation in the Yangtze River basin. However, during 1978–1992, the summer precipitation anomalies in eastern China appeared to have the opposite meridional distribution to those during 1961–1976. In the period from 1977 to 1992, the summer precipitation anomalies in eastern China appeared to have the opposite distribution of the meridional tripole pattern from 1961 to 1977, i.e., the meridional tripole pattern of "−, +, −", when the summer precipitation in southern and northern China decreased, while the summer precipitation in the Yangtze River basin increased. However, from 1999 to 2010, the summer monsoon precipitation anomaly in eastern China changed from a meridional tripole distribution to a meridional dipole distribution, i.e., appeared a feature with floods in southern China and droughts in northern China. Recently, our analysis also shows that there has been an additional variation in the interdecadal variability of summer precipitation pattern in eastern China since 2011, the summer precipition anomalies appear a meridional "+, −, +" tripole, i.e., more summer precipitation in northern and southern China and less summer precipitation in the Yangtze and Huaihe River basins.

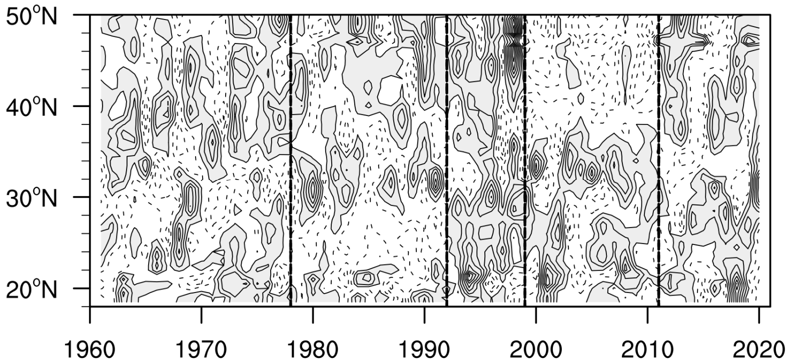

Figure 7. Distribution of summertime (JJA) rainfall anomalies (percentage) averaged for 110°–120° E in eastern China with latitude and time. Solid and dashed lines indicate positive and negative anomalies, respectively, and positive anomalies are shaded. Data of precipitation is from the dataset of precipitations at 822 observational stations in China.

Huang et al. [41] investigated the dynamic process of the interdecadal variability of summer precipitation in eastern China and noted that the interdecadal variability of summer precipitation in eastern China is closely related to the interdecadal variability of the teleconnection wave trains of the summer atmospheric circulation anomalies over East Asia, especially in regards to the interdecadal variability of the EAP pattern teleconnection wave train, which plays an important role in the variabilities of summer precipitation in eastern China. Recently, it is analyzed that the interdecadal variability of summer whole-layer water vapor transport fluxes between 1000 and 300 hPa using the NCEP/NCAR reanalysis data of water vapor transport fluxes over the Eurasian region from 1961 to 2020. Figure 8a–d show the 1000–300 hPa whole-layer water vapor transport fluxes averaged for the summers of 1977–1992, 1993–1998, 1999–2010, and 2011–2020, respectively. In Figure 8a, the anomalies of water vapor transport fluxes over Southeast Asia and East Asia appeared as a “cyclone-anticyclone-cyclone” tripole anomaly pattern during 1977–1992, i.e., there was an EAP-like pattern teleconnection wave train. And there was a strong southward water vapor transport anomaly in the eastern part of China. This finding indicates that the East Asian summer monsoon weakened. In addition, the anomalies of water vapor transport fluxes from the Caspian Sea through central Asia to North China appeared the distribution of “cyclone-anticyclone-cyclone”, those are similar to the distribution of the Silk Road-like pattern teleconnection wave train. In contrast, the anomalies of summer water vapor transport fluxes over East Asia during 1993–1998 (see Figure 8b) showed a somewhat different distribution from Figure 8a, i.e., anomalies of water vapour transport fluxes over Southeast Asia and East Asia appeared the dipole pattern distribution of “anticyclone-cyclone”. This finding indicates that the East Asian summer monsoon became stronger during this period. Moreover, the “anticyclone-cyclone-anticyclone-cyclone” pattern anomalies of water vapour transport fluxes from the Caspian Sea to North China were similar to the Silk Road pattern teleconnection wave train. However, comparing Figure 8c with Figure 8a,b, it is obvious that the distributions of the anomalies of water vapor transport fluxes along the zonal direction over Eurasia or along the meridional direction over East Asia significantly changed during the period from 1999 to 2010. During this period, the anomaly distribution of water vapor fluxes over East Asia appeared the meridional dipole pattern, and the anomaly distribution of water vapor fluxes over Eurasia showed an “anticyclone-cyclone-anticyclone-cyclone” pattern, which is similar to the Silk Road pattern teleconnection wave train. In addition, Figure 8c shows that there was the southward water vapor transport flux anomalies extending from the northeast region to the southwest region of China, which indicates that the East Asian summer monsoon became weak again during this period, which weakens the water vapor transport to the northeast and north China. Therefore, the persistent droughts occurred in these regions in different degrees during summer. However, there was a strong northward water vapor transport flux anomaly from the southeast coastal area of China to the east of the Huaihe River basin, which caused significant increase of the summer precipitation and severe floods in these regions during this period. Recently, the result analyzed by our research group shows that during 2011–2020, as shown in Figure 8d, the southward water vapor transport flux anomalies over the northeast to southwest region of China were smaller than those during 1999–2011, while the northward water vapor transport fluxes over the southeast coast of China to the Yellow River and Huaihe River regions in China were strengthened. This caused the increase of the summer precipitation in northern China and the water vapor transport flux anomalies from Southeast Asia to the northeast region of China along the eastern part of China. The water vapor transport flux anomalies from Southeast Asia along the eastern part of China to the northeast part of China appeared the distribution of "anticyclone-cyclone-anticyclone", which is similar to the EAP-like pattern teleconnection wave train. And the water vapor transport flux anomalies from the Caspian Sea to East Asia appeared the "anticyclone-cyclone-anticyclone-cyclone" distribution, which is the Silk Road-like pattern teleconnection distribution.

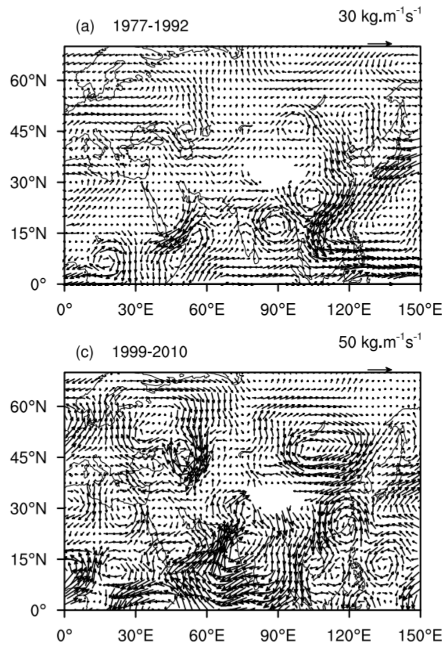

Figure 8. Anomaly distributions of summertime (JJA) water vapor transport fluxes integrated from 1000 hPa to 300 hPa over the Eurasian continent, averaged for (**a**) 1977–1992, (**b**) 1993–1998, (**c**) 1999–2010, and (**d**) 2011–2020. Data of water vapor and wind fields are from the NCEP/NCAR reanalysis data for 1961–2020 [30].

From the above analyses of the spatial distribution of the interdecadal variability of summertime water vapor transport fluxes over Eurasia, we can see that the interdecadal variability in summer monsoon precipitation over eastern China since the 1970s is closely related to not only the interdecadal variability of the distribution of the EAP pattern teleconnection wave train propagating along the meridional direction in East Asia but also related to the interdecadal variability of the Silk Road teleconnection wave train propagating along the subtropical jet in the upper troposphere over the Eurasian subtropics. Both wave trains are formed by the propagations of quasi-stationary planetary waves in the spherical atmosphere.

In summary, the interannual and interdecadal variabilities of summer monsoon precipitation and whole-layer water vapor transport in eastern China may be result of joint action of the interannual and interdecadal variabilities of the EAP pattern teleconnection wave train propagating along the meridional direction over East Asia and the Silk Road pattern teleconnection wave train propagating along the subtropical regions from West

Asia to East Asia. Therefore, the theory of Rossby wave energy dispersion proposed by academician Ye provides an important scientific basis for short- and medium-term weather forecasting but also a new idea for short-term summer climate prediction.

4. The Guiding Role of the Theory of Rossby Wave Energy Dispersion in the Study on the Dynamic Processes of the Variability of the East Asian Winter Monsoon System

The variability of the winter climate in China is controlled by the East Asian winter monsoon system. The interannual and interdecadal variabilities of the East Asian winter monsoon system is the main cause of winter rain, snow, and ice disasters in China [42]. However, there are few studies on the dynamic processes of interannual and interdecadal variabilities in East Asian winter monsoon system. Under the guidance of the theory of Rossby wave energy dispersion, some studies on the dynamic processes of the East Asian winter monsoon system have been carried out in recent years. Especially, some meteorogists in China have paid a special attention to the impacts of the interannual and interdecadal variations of quasi-stationary planetary waves in the three-dimensional spherical atmosphere on the East Asian winter monsoon system and the low-temperature rain, snow, and ice disasters in China.

4.1. The Guiding Role of the Theory of Rossby Wave Dispersion in the Study on the Dynamical Processes of the Interannual Variability of the East Asian Winter Monsoon System

The winter monsoon prevails in East Asia, and due to the interannual variability of the winter monsoon system, winter temperature and precipitation in China show the significant interannual variability. Occasionally, severe low-temperature and snow disasters frequently occur in winter, such as the freezing event occurred in January 2008. Due to the anomalously strong East Asian winter monsoon, the severe low-temperature and snow disasters occurred in southwest, central and southern China, which caused economic losses of more than 150 billion yuan [42].

The dynamical processes of interannual variability of the East Asian winter monsoon system are closely related to the interannual oscillations of these two propagating waveguides of quasi-stationary planetary waves during boreal winter. Previous studies [22,23,43] proposed that the variability of these two waveguides exists an opposite oscillation on the interannual time scale. The above studies suggest that the interannual variability of the East Asian winter monsoon system is significantly related to the interannual oscillation of the propagating waveguides of quasi-stationary planetary waves. When the polar waveguide strengthens, then the low-latitude waveguide weakens, and anomalously strong quasi-stationary planetary waves in the troposphere will propagate towards the stratosphere through the polar waveguide, while the propagation of quasi-stationary planetary waves towards the upper troposphere near the low latitudes through the low-latitude waveguide will be weakened. In contrast, when the polar waveguide weakens, then, the low-latitude waveguide strengthens, and anomalously strong quasi-stationary planetary waves in the troposphere will propagate from middle latitudes towards the upper troposphere at low latitudes through the low-latitude waveguide. In this case, the propagation of anomalously strong quasi-stationary planetary waves in the troposphere from middle to high latitudes towards the top of the troposphere over low-latitude region via the low-latitude waveguide is stronger, while the propagation of quasi-stationary planetary waves to the stratosphere through the polar waveguide is significantly weaker.

Huang et al. [24] studied the influence of the interannual oscillations of the propagating waveguides of quasi-stationary planetary waves in the three-dimensional atmosphere on the interannual variability of the East Asian winter monsoon system and analyzed the relationship between the East Asian climate anomalies and boreal quasi-stationary planetary wave activity during the winters of 2005 and 2006. In the winter of 2005, the temperature from Western Europe through the Urals to Siberia and East Asia was lower than normal, and the temperature in the east side of the Urals and the northwest side of the Mongolian Plateau was more than 2 °C lower than normal, which resulted in the cold winter and frequent cold waves outbreaked in China. This in turn led to anomalously strong snow in Northwest and Northeast China as well as strong precipitation in the Yangtze River basin. However, in the winter of 2006, the temperature in the Siberia and East Asia was higher than normal, and the temperature in Europe from the Urals to Baikal Lake was more than 2 °C higher than normal, resulting in a warm winter in China.

The obvious difference between the winter climate in Eurasia in 2005 and that in 2006 was closely related to the oscillation of the propagating waveguides of quasi-stationary planetary waves in the Northern Hemisphere during these two winters. Figure 9a,b show the E-P fluxes and the scatterplot distributions of the quasi-stationary planetary waves during the boreal winters of 2005 and 2006, respectively. As shown in Figure 9a, the polar waveguide of the boreal quasi-stationary planetary wave propagation in the winter of 2005 was strong, while the low-latitude waveguide was weak, i.e., the propagation of quasi-stationary planetary wave along the polar waveguide to the stratosphere was enhanced. This caused that the convergence of planetary wave E-P fluxes was enhanced in the upper troposphere at high latitudes and weakened the convergence of planetary wave E-P fluxes in the upper troposphere in the subtropics, i.e., enhanced divergence of the E-P fluxes in this region, which caused the weakening of the boreal polar frontal jet and the strengthening of the subtropical jet. This can facilitate the development of high pressure systems over the Siberia and the strengthening of the East Asian winter monsoon. As shown in Figure 9b, the polar waveguide of quasi-stationary planetary wave propagation in the winter of 2006 was weak, while the low-latitude waveguide was strong, i.e., the propagation of quasi-stationary planetary waves along the low-latitude waveguide was enhanced in the upper troposphere at low latitudes. This caused that the convergence of planetary wave E-P fluxes was enhanced in the upper troposphere in the subtropical region, while the convergence of planetary wave E-P fluxes in the upper troposphere at high latitudes was weakened, i.e., the divergence of the E-P fluxes was enhanced. This caused the strengthening of the boreal polar jet and the weakening of the subtropical jet, which was detrimental to the development of the Siberian high and brought about the weakening of the East Asian winter monsoon. As shown in Figure 9c, the difference between the propagations of quasi-stationary planetary waves in these two boreal winters was also evident.

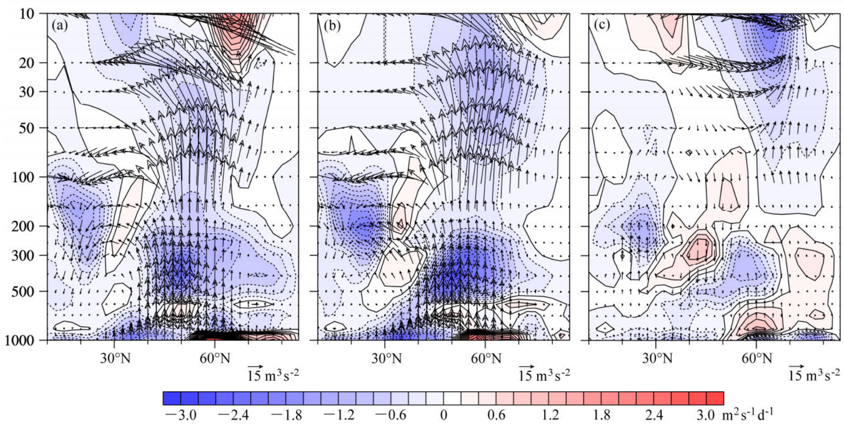

Figure 9. Composite distributions of the E-P fluxes (multiplied by ρ^{-1} for displaying purpose) (vectors, units: $m^3\ s^{-2}$) of quasi-stationary planetary waves for wavenumbers 1–3 and their divergence (shaded, units: $m^3\ s^{-1}\ d^{-1}$; *Y*-axis denotes vertical levels, units: hPa) over the Northern Hemisphere in the winters of (**a**) 2005 (December 2005 to February 2006) and (**b**) 2006 (December 2006 to February 2007), and (**c**) the difference between them. Solid and dashed lines indicate positive (divergence) and negative (convergence) of planetary wave E-P fluxes, respectively. And the divergence/convergence regions of the E-P flux are shaded with red/blue colors (from Huang et al. [24]).

4.2. The Guiding Role of the Theory of Rossby Wave Energy Dispersion in the Study on the Dynamic Processes of the Interdecadal Variability of the East Asian Winter Monsoon System

Wang et al. [25] have proposed that the East Asian winter monsoon system has not only significant interannual variability but also significant interdecadal variability. From the 1970s to the beginning of the 21st century, winter temperatures in China experienced two significant interdecadal variations. During the period from 1976 to 1987, the East Asian winter monsoon was strong, the winter temperature in China was generally low, and the frequency of cold wave outbreaks in China was high. However, during the period from 1988 to 1998, the East Asian winter monsoon was weak, the winter temperature in China was generally high, the frequency of cold wave outbreaks was significantly low, then, the warm winter frequently occurred. The result studied by Huang et al. [42] showed that during 1999–2010, winter temperatures in China changed significantly again, the colder temperature occurred in north China and warmer temperature appeared in south China. Moreover, temperature changed to a meridional oscillation pattern, and the interannual variability of winter temperatures changed from a 3–4 year cycle to a 2–8 year cycle. Our recent analysis shows that the variability of the East Asian winter monsoon during 2011–2020 was roughly similar to that during 1999–2010, and no a significant interdecadal variability occurred. During this period, several cold waves occurred in China, such as 21–25 January 2016, and 28–31 December 2020, where many regions in China experienced severe cooling and occurred low-temperature and snow disasters. These disasters caused severe economic losses.

The dynamic processes of interdecadal variability of winter climate in China and the East Asian winter monsoon system have been studied [25,42]. The results showed that the interdecadal variability of the East Asian winter monsoon system occurred in the mid-late 1980s and late 1990s, which was closely related to the interdecadal oscillation of the propagating waveguides of quasi-stationary planetary waves in boreal winter. Recently, it is analyzed that the interdecadal oscillations of propagating waveguides of quasi-stationary planetary waves in the Northern Hemisphere using the NCEP/NCAR reanalysis data from 1961 to 2020. Figure 10a–c show the composite distributions of the E-P fluxes of quasi-stationary planetary waves for wavenumber 1–3 and their divergences over the Northern Hemisphere averaged for the winters of 1976–1987, 1988–1998, and 1999–2020, respectively. From Figure 10a, it can be seen that during the period of 1976–1987, the polar waveguide of quasi-stationary planetary waves for the boreal winters was strong, i.e., the propagation of planetary waves was strong along the polar waveguide up to the stratosphere over 60° N and weak along the low-latitude waveguide to the upper troposphere over low latitudes. These caused strong convergence of the E-P flux of planetary waves in the troposphere and stratosphere over high latitudes of the Northern Hemisphere and weak divergence of the E-P fluxes in the middle and upper troposphere over the subtropical region near 30° N. Moreover, as shown in Figure 10b, during the period of 1988–1998, the propagation of the boreal winter quasi-stationary planetary waves changed. Compared with Figure 10a, the polar waveguide of the boreal winter quasi-stationary planetary waves was weak during this period, while the low-latitude waveguide became strong. In other words, the propagation of planetary waves towards the stratosphere along the polar waveguide over high latitudes became weaker in the winters of 1988–1998, comparing with that in the winters of 1976–1987. And the propagation of planetary waves to the upper troposphere over low latitudes along the low waveguide became stronger, comparing with that in the winters of 1976–1987, which caused the E-P fluxes of the quasi-stationary planetary waves over high latitudes during winters of 1988–1998 were weaker than those during 1976–1987. This means that there was a positive difference of the divergence. But the divergence of the E-P fluxes of quasi-stationary planetary waves in the upper troposphere over the subtropical region became stronger in the winters of 1988–1998 than that in the winters of 1976–1987. In addition, as shown in Figure 10c, the polar waveguide of propagation of the boreal quasi-stationary planetary waves was again stronger and the low-latitude waveguide was weaker in the winters from 1999 to 2020. This means that the propagation of planetary waves became stronger along the polar waveguide up to the stratosphere at high latitudes and weaker towards the upper troposphere of the subtropical region near 30° N via the low-latitude waveguide. The convergence of E-P fluxes of planetary waves in the upper troposphere and stratosphere at high latitudes was stronger than that in the winters of 1988–1998, but the divergence of planetary wave E-P fluxes in the upper troposphere over the subtropical region near 30° N was weaker than that in the winters of 1988–1998.

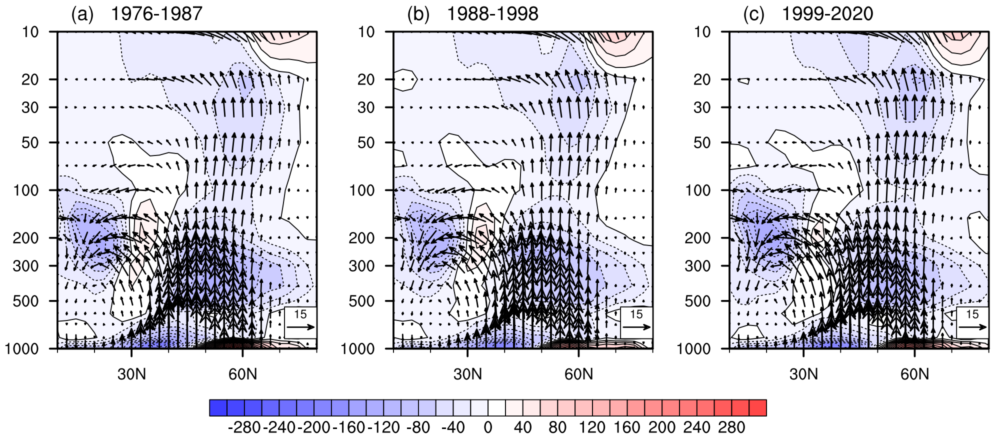

Figure 10. Composite distributions of E-P fluxes of quasi-stationary planetary waves for wave numbers 1–3 and their divergences (shaded, units: $m^3\ s^{-1}\ d^{-1}$; Y-axis denotes vertical levels, units: hPa) over the Northern Hemisphere averaged for the winters of (**a**) 1976–1987, (**b**) 1988–1998 and (**c**) 1999–2020. Solid and dashed lines indicate positive (divergence) and negative (convergence) divergence of E-P fluxes. Data of wind fields and temperature are from the NCEP/NCAR reanalysis data [30].

4.3. Dynamic Effect of the Propagating Waveguide Oscillations of Quasi-Stationary Planetary Waves on the Variability of the East Asian Winter Monsoons

The above results show that the boreal winter quasi-stationary planetary waveguides in the three-dimensional atmosphere have not only significant interannual oscillations but also significant interdecadal oscillations. Moreover, two significant interdecadal oscillations of the propagating waveguides of the boreal winter quasi-stationary planetary waves occurred since the 1970s. These oscillations of the propagating waveguides of quasi-stationary planetary waves caused the variability of the divergence or convergence of the E-P fluxes of quasi-stationary planetary waves. According to the wave-flow interaction equation for the spherical atmospheric planetary waves derived by Edmon et al. [29], the variation of the divergence of the E-P fluxes of quasi-stationary planetary waves will cause the variation of the zonal mean flow during boreal winter and the variation of the Arctic Oscillation (AO) index. According to previous studies [44,45], if the AO index is negative in a winter, the winter monsoon in East Asia is strong in the winter; conversely, if the AO index is positive in a winter, then the winter monsoon in East Asia is weak in the winter. Therefore, the interannual and interdecadal oscillations of the propagating waveguides of quasi-stationary planetary waves in the boreal winter will affect the interannual and interdecadal variabilities of the East Asian winter monsoon system.

It may see from the above studies that under the guidance of academician Ye's theory of Rossby wave dispersion, some studies on the dynamic processes of the variabilities of the East Asian winter monsoon system have been carried out. In particular, the study on the dynamic processes of the influence on the interannual and interdecadal oscillations of the propagating waveguides of quasi-stationary planetary waves on the East Asian winter monsoon variations has achieved an important progress.

5. Conclusions and Discussion

The theory of Rossby wave energy dispersion proposed by academician Ye in the 1940s not only improves the study on the characteristics of two-dimensional and three-dimensional propagations of quasi-stationary planetary waves in the spherical atmosphere but also provides a scientific basis for the study on the mechanisms related to the anomalies of global atmospheric circulation. And this theory also lays the theoretical basis for the study on the dynamic processes of tropospheric-stratospheric interactions and their mechanisms. This paper reviews the guiding role of the theory of Rossby wave energy dispersion in the studies on the characteristics of three-dimensional propagation of quasi-stationary planetary waves in the spherical atmosphere and their impacts on the dynamic processes of the interannual and interdecadal variabilities of the East Asian summer and winter monsoon systems. In particular, this paper reviews the impacts of the interannual and interdecadal variabilities of the EAP pattern teleconnection wave train propagating along the meridional direction over East Asia and the Silk Road pattern teleconnection wave train propagating along the zonal direction in the subtropical jet from West Asia to East Asia on the variabilities of the East Asian summer monsoon system. This paper also reviews the studies on the dynamical processes of the impacts of the interannual and interdecadal oscillations of the propagating waveguides of quasi-stationary planetary waves on the variabilities of the East Asian winter monsoon system.

The energy dispersion of waves is an important theoretical problem in the fluid dynamics, academician Ye first applied it to the study on the mechanisms of atmospheric circulation variability. His research inspired the study on the dynamics of the two- and three-dimensional spherical propagations of quasi-stationary planetary waves, and guides the study on the dynamical processes of the variabilities of the East Asian winter and summer monsoon systems.

Under the guidance of academician Yeh's theory of Rossby wave energy dispersion, our research group has investigated the dynamical processes of the interannual and interdecadal variabilities of the East Asian winter and summer monsoon systems. The results show that the variabilities of the East Asian winter and summer monsoon systems are the variablities of circulation seeing from their phenomena, but these variabilities are also the variations of quasi-stationary planetary waves according to their mechanisms. Currently, this theory is developing and expanding, and it has wide applications not only in the study on atmospheric circulation dynamics at middle and high latitudes but also in the study on the dynamics of typhoon genesis and evolution in tropical regions [46–51]. Moreover, the nonlinear effects of the energy dispersion of Rossby wave in atmosphere and the nonlinear interactions of different quasi-stationary planetary wave trains also need to be further investigated.

Author Contributions: Conceptualization, R.H.; validation, R.H., J.H., Y.L. and R.L.; writing—original draft preparation, R.H. and J.H.; writing—review and editing, R.H., J.H. and Y.L.; visualization, Y.L., J.H. and R.H.; supervision, R.H. and R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (41721004).

Data Availability Statement: The NCEP/NCAR reanalysis data can be found in the website: [https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html (accessed on 5 July 2021)]. The daily observational precipitation datasets in mainland China are provided by the National Meteorological Information Center of Chinese Meteorological Administration, which can be achived in the website: [https://data.cma.cn/ (accessed on 20 March 2021)].

Acknowledgments: We are thankful to the NCEP/NCAR and other scientific agencies for providing the datasets for our analysis. The authors are grateful for the comments and suggestions provided by the editor and anonymous reviewers.

Conflicts of Interest: The authors declare no conflict of interest.

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