Spatiotemporal characteristics and water budget of water cycle elements in different seasons in northeast China*

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In this paper, we study the spatiotemporal characteristics of precipitable water, precipitation, evaporation, and water–vapor flux divergence in different seasons over northeast China and the water balance of that area. The data used in this paper is provided by the European Center for Medium-Range Weather Forecasts (ECMWF). The results show that the spatial distributions of precipitable water, precipitation, and evaporation feature that the values of elements above in the southeastern area are larger than those in the northwestern area; in summer, much precipitation and evaporation occur in the Changbai Mountain region as a strong moisture convergence region; in spring and autumn, moisture divergence dominates the northeast of China; in winter, the moisture divergence and convergence are weak in this area. From 1979 to 2010, the total precipitation of summer and autumn in northeast China decreased significantly; especially from 1999 to 2010, the summer precipitation always demonstrated negative anomaly. Additionally, other elements in different seasons changed in a truly imperceptible way. In spring, the evaporation exceeded the precipitation in northeast China; in summer, the precipitation was more prominent; in autumn and winter, precipitation played a more dominating role than the evaporation in the northern part of northeast China, while the evaporation exceeded the precipitation in the southern part.

The Interim ECMWF Re-Analysis (ERA-Interim) data have properly described the water balance of different seasons in northeast China. Based on ERA-Interim data, the moisture sinks computed through moisture convergence and moisture local variation are quite consistent with those computed through precipitation and evaporation, which proves that ERA-Interim data can be used in the research of water balance in northeast China. On a seasonal scale, the moisture convergence has a greater influence than the local moisture variation on a moisture sink, and the latter is variable slightly, generally as a constant. Likewise, in different seasons, the total precipitation has a much greater influence than the evaporation on the moisture sink.

Keywords: ERA-Interim data, water cycle, moisture budget, spatiotemporal characteristic

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1. Introduction

As the global atmospheric circulation abruptly changed on a planetary scale in the late 1970s,[1,2] regional climate changed a lot, which resulted in serious floods in south China and severe droughts in the north.[3,4]

Northeast China is regarded as one of the largest commodity grain bases and most potential agriculture production areas in China.[5] It is also believed that summer is the primary season for northeast crops to grow, with frequent precipitation which affects the yield significantly as well as its distribution. Thus, the research into the summer precipitation is fairly crucial.

Lian *et al.*[6,7] set up the standard of generation and retreat of East Asian summer monsoon (EASM) and ascertained the corresponding index in northeast China, after studying the influence of EASM on summer precipitation in the northeast. They found that before and after EASM generated in (retreated from) the northeast, the precipitation increased (decreased) substantially. Meanwhile, the intensity index was positively correlated with the precipitation in July and August over most parts of the northeast. Shen *et al.*[8] used the observational data from 79 stations in the northeast and the 40-yr ECMWF Re-Analysis (ERA-40) data, and studied the characteristics of large-scale circulation affecting the interannual variation of precipitation in all summer months over this region. Results showed that a cold vortex was prominent in affecting the precipitation in June, EASM in July, while the summer monsoon and mid-high-latitude northeast Asian were blocking together in August. Cui[9] chose the data between 1981 and 1986 from 18 air sounding stations to study the moisture input and output of all edges of the northeast, and to analyze the water budget above this region. Results showed that the moisture input was larger than the output around the whole year in northeast China, and, summer was the only season in which the input was much greater than the output. However, discrepancy may partly be spurious because the number of stations was small, thereby leading to the spatial inaccuracy of such data unable to meet the requirements, and a large number of data processed in a simple way differing from the reality. Gao[10] analyzed

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National Centers for Environmental and Prediction (NCEP) daily reanalysis data from 1948 to 2006 to review the precipitable water in the northeast China, the spatial characteristics of meridional and zonal transport of moisture, total moisture transport, and moisture divergence flux, and interannual and interdecadal variation of surrounding moisture transport. He ultimately discovered that the precipitation appeared on a diminishing scale from the south to the north of northeast China. As we can see from the above studies, meteorologists were aware of the importance of the water cycle early enough; however, a great many studies were still only on single element characteristics of the water cycle, which were lacking in comprehensive study of the elements; besides, some work was accomplished a long time ago, excluding recent data or any study on interrelation of these elements. Lately, ECMWF has released abundant meteorological data whose accuracy is much improved,[11,12] enabling us to compute and study the characteristics of all elements and the water budget in northeast China in a comprehensive, systematic, and quantificational way. Based on this, this paper discusses the relation of all elements of the water cycle and the water budget relationship in northeast China, attempting to provide more accurate reference information for summer precipitation predictions over the northeast based on our existing summer rainfall prediction methods.[13–23]

2. Data and method

This paper employs the ERA-Interim data, where the elements include u and v wind fields and specific humidity field that were measured four times a day and eight vertical layers, which are 1000 hPa, 925 hPa, 850 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa, 300 hPa, respectively; monthly average precipitation and evaporation from 1979 to 2010, with horizontal resolution of $2.5^\circ \times 2.5^\circ$. In this paper, the precipitable water and horizontal moisture flux divergence respectively represent the mean values of their corresponding values of spring (March–May), summer (June–August), autumn (September–November), and winter (December–next February). The precipitation and evaporation accounts for their total amounts of each season (three months per season). In addition, the grid-point precipitation data from ECMWF reflects the observational precipitation in different seasons from the stations in the northeast more clearly. We choose such data for further computation and procession. Full-layer precipitable water, full-layer zonal and meridional moisture flux are the integrals of 300 hPa from above the terrain.[24] The equation to compute full-layer atmospheric precipitable water is

$$Q(x,y,t) = -\frac{1}{g}\int_{p_s}^{300} q(x,y,p,t)\mathrm{d}p; \tag{1}$$

the equations to compute full-layer zonal and meridional moisture flux are respectively

$$Q_u(x,y,t) = -\frac{1}{g}\int_{p_s}^{300} q(x,y,p,t)\cdot u(x,y,p,t)\mathrm{d}p, \tag{2}$$

$$Q_v(x,y,t) = -\frac{1}{g}\int_{p_s}^{300} q(x,y,p,t)\cdot v(x,y,p,t)\mathrm{d}p; \tag{3}$$

the equation to compute horizontal moisture flux divergence is

$$MC(x,y,t) = -\nabla\cdot\boldsymbol{Q}(x,y,t), \tag{4}$$

where

$$\boldsymbol{Q}(x,y,t) = Q_u(x,y,t)\boldsymbol{i} + Q_v(x,y,t)\boldsymbol{j}. \tag{5}$$

Here, Q is the atmospheric precipitable water of the full layer integration, Q_u and Q_v are respectively the zonal and meridional moisture flux of the full layer integration, MC is the horizontal moisture flux divergence, and Q is the horizontal moisture flux vector of the full layer integral, g is the gravitational acceleration (taking 9.8 $\mathrm{kg\cdot m\cdot s^{-2}}$), p_s is the surface atmospheric pressure, q is specific humidity, u and v are the zonal and meridional wind speed respectively.

Moisture flux divergence represents the moisture converging to or diverged from per unit volume in per unit time. The fact that moisture input exceeds the output (divergence is negative) is referred to as "moisture convergence", indicating that the convergence of moisture advected from the periphery towards this area, and such an area is called a "moisture sink"; the fact that moisture input is less than the output (divergence is positive) is referred to as "moisture divergence", indicating that the divergence of moisture advected from this area towards the periphery, and such an area is called a "moisture source". As a result, the spatial distribution of moisture flux convergence (divergence) can be used to describe that of the "moisture sink (moisture source)". Moisture flux divergence in this paper is calculated by integrating the full-layer moisture flux above this terrain and then computing divergence.

3. Spatiotemporal characteristics of water cycle elements in different seasons

From Fig. 1, precipitable water (Fig. 1(a)), precipitation ((Fig. 1(e)), and evaporation (Fig. 1(i)) in spring in the southeast are more than in the northwest. The maximum precipitation and evaporation occur in the area adjacent to the Liaoning Peninsula where moisture flux divergence (Fig. 1(m)) changes into convergence. The precipitable water (Fig. 1(b)), precipitation ((Fig. 1(f)), and evaporation (Fig. 1(j)) in summer are greater than in spring, with the area under the precipitation and evaporation of high values extending, and the moisture convergence intensified around areas near the Liaoning Peninsula (Fig. 1(n)). Compared the case in summer, the precipitable water (Figs. 1(c) and 1(d)), precipitation ((Figs. 1(g) and 1(h)), and evaporation (Figs. 1(k) and 1(l)) in autumn and winter are

less, characterized by the fact that such values in the southeast are greater than in the northwest in general. For moisture flux divergence, it plays a dominant role in the northeast of China in autumn (Fig. 1(o)), while neither convergence nor divergence occurs conspicuously in winter (Fig. 1(p)). Overall, a strong convergence zone is identical with the area of maximum precipitation and evaporation in summer in the northeast of China.

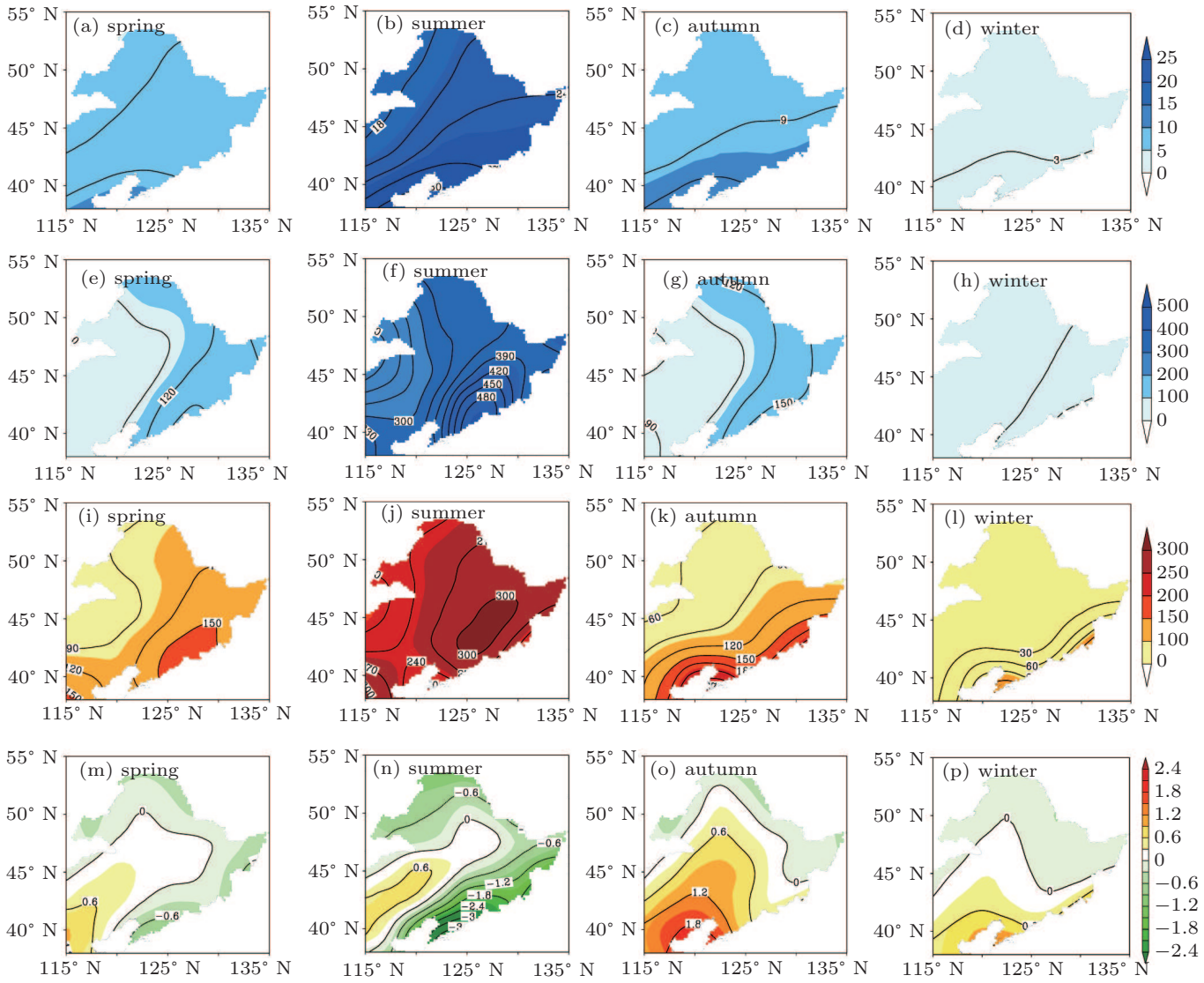


Fig. 1. (color online) The spatial distributions of water cycle elements in northeast China in different seasons. Panels (a)–(d) represent the spatial distributions of the atmospheric precipitable water in spring, summer, autumn, and winter in mm; panels (e)–(h) are similar to panels (a)–(d), only except that they represent the precipitation in mm; panels (i)–(l) are similar to panels (a)–(d), only except that they represent the evaporation in mm; panels (m)–(p) are similar to panels (a)–(d), only except that they represent the moisture flux divergences in 10^{-5} mm.

Figure 2 shows the interannual variations of water cycle elements in northeast China in different seasons, in which the precipitable water, precipitation, and evaporation are the mean values in this area. From Fig. 2 and Table 1, the precipitable water (Fig. 2(a)) and precipitation (Fig. 2(e)) do not change drastically, the evaporation (Fig. 2(i)) increases and moisture flux divergence (Figs. 2(f) and 2(g)) goes downwards, each with no significant variation. In summer and autumn, the precipitation (Figs. 2(f) and 3(g)) in the northeast of China trends downward distinctly, which is in accordance with the results of Huang Gang[25] and Liu Yong,[26] moisture flux divergences (Figs. 2(n) and 2(o)) are on a rise. Precipitable water (Figs. 2(b) and 2(c)) and evaporation (Figs. 2(j) and 2(k)) do not seem to be obvious. In winter, the evaporation (Fig. 2(l)) decreases, the variations of precipitable water (Fig. 2(d)), precipitation (Fig. 2(h)), and moisture flux divergence (Fig. 2(p)) are all fairly small. In general, the variations of moisture flux divergence in the northeast all through the year resembles that of precipitation. When precipitation declines, moisture flux divergence goes upward, leading to the moisture convergence weakening and divergence intensifying, which together contribute to the disadvantage of precipitation.

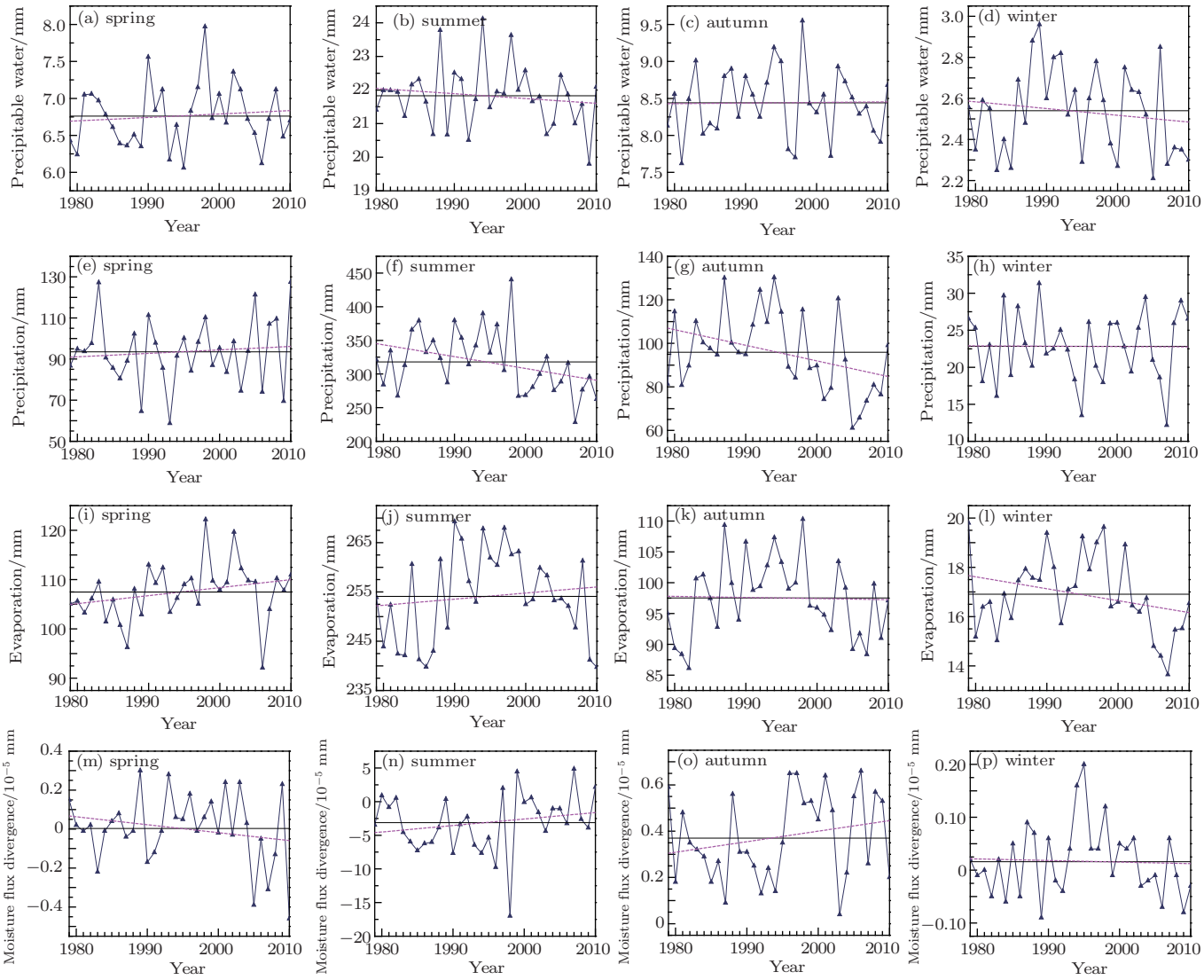


Fig. 2. (color online) The interannual variations of water cycle elements in northeast China in different seasons (1979–2010). Panels (a)–(d) represent the interannual variations of the precipitable water in spring, summer, autumn, and winter in mm; panels (e)–(h) are similar to panels (a)–(d), only except that they represent precipitation in mm; (i)–(l) are similar to (a)–(d), only except that they represent evaporation in mm; panels (m)–(p) are similar to panels (a)–(d), only except they represent moisture flux divergence in 10^{-5} mm. The curves represent the interannual variation lines, the dotted lines denote the trend lines; the straight lines refer to the mean values.

Table 1. Trend coefficients of water cycle factors in different seasons.

	Atmospheric precipitable water	Precipitation	Evaporation	Moisture flux divergence
Spring	0.10	0.10	0.26	–0.21
Summer	–0.15	–0.36[a]	0.13	0.21
Autumn	0.02	–0.37[a]	–0.03	0.23
Winter	–0.15	0.01	–0.29	–0.04

Note: [a]represents a 95%-confidence level.

4. Interrelations of different elements

4.1. Relations between precipitation, evaporation and moisture transport

On a global scale, the evaporation and precipitation within or more than a year are balanced. As to a region, however, the conclusion may not hold true due to moisture transport. If the precipitation of a region exceeds the evaporation within a certain period, moistrue input should occur to balance the water budget in this area. If the pattern goes to the contrary, there must be moisture output. To investigate the relation between precipitation and evaporation in northeast China, the spatial distributions of differences (evaporation minus precipitation) between total precipitaition and evaporation in different seasons are given in Fig. 3.

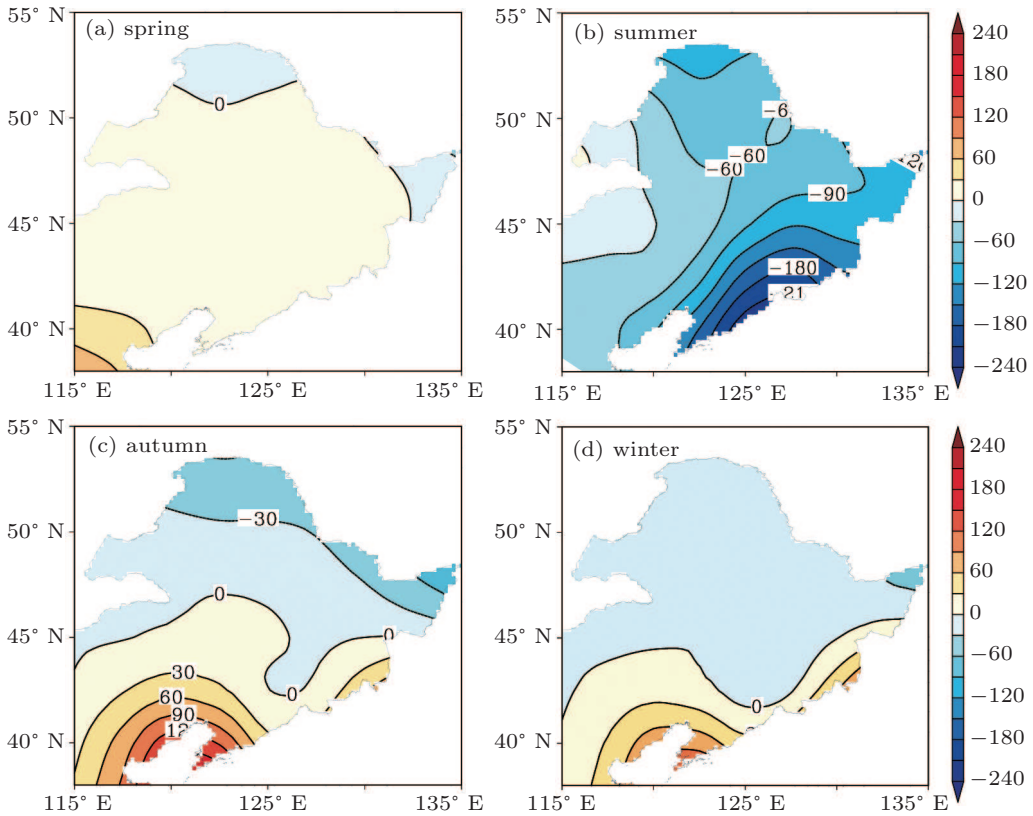


Fig. 3. (color online) Spatial distributions of the differences between precipitation and evaporation (evaporation minus precipitation) in northeast China (in unit: mm).

In spring, except for a few regions in the north and east of Heilongjiang, other areas have positive values, i.e., the evaporation of northeast China exceeds the precipitation, which means that the moistrue output occurs. In summer, the precipitation over the whole region exceeds the evaporation (all the values acquiring through evaporation minus precipitation are below zero), indicating that there exists moisture input, which appears totally in the opposite manner to that in spring. The difference between precipitation and evaporation in Liaodong Peninsula and Changbai Moutain area reaches the highest values (the precipitaton and evaporation of these areas are also the largest values), then the north of Heilongjiang becomes the second largest; the difference in the Inner Mongolia area is unconspicuous. In autumn and spring, the differences across the whole region fail to remain positive or negative, instead, different states exist. In autumn, the precipitation exceeds evaporation over the area north to 45° N, while it stands in contrast in the area south to 45° N; in winter, the 0 mm isoline of difference value between evaporation and precipitation roughly overlaps the border line of the Inner Mongolia Autonomous Region, the north of which area is dominated by precipitation exceeding evaporation, and the south of that area is dominated by the opposite.

In conclusion, in spring, the evaporation of northeast China goes over the precipitation with moisture output; in summer, the precipitation overwhelms evaporation with moisture input; in autumn, the area north to 45° N is dominated by precipitation with moisture input, while the area south to 45° N by evaporation with moisture output; in winter, evaporation is less than precipitation in northeast China in most parts, but there are still a few parts of the southern region where evaporation exceeds precipitation. This is partly different from Cui's[9] research results. In Ref. [9], Cui pointed out summer as the only season in which moisture input exceeded its output; however, summer is not the only season with moisture input in this paper, and moisture input in the north of northeast China also occurs in autumn and winter. The closer to the sea the area, the more significant the difference between evaporation and precipitation will be.

4.2. Water balance in northeast China

The water balance equation is written as

$$P - E = Q_{\text{in}} - Q_{\text{out}} - \Delta W, \tag{6}$$

where P and E are the total precipitation and total evaporation, respectively, and P–E represents the moisture sink of northeast China calculated through precipitation and evaporation, denoted as $I_{\text{P-E}}$; Q_{in} and Q_{out} are the input and output of moisture in northeast China, respectively, and $Q_{\text{in}} - Q_{\text{out}}$ represents the moisture convergence of this region, denoted as I_{CV}; ΔW is the variation of atmospheric precipitable water. The spring variation is the result of precipitable water at 18:00 on May

31 minus that at 0:00 on March 1; the summer one at 18:00 on August 31 minus that at 0:00 on June 1; the autumn one at 18:00 on November 30 minus that at 0:00 on September 1; the winter one at 18:00 on the next year's February 28 (common year) or February 29 (leap year) minus that at 0:00 on December 1, noted as I_{W}.

The method similar to that in Ref. [27] is used to compute the moisture convergence of northeast China. A rectangular region covering northeast China is selected, with the scope of 115° E–135° E, 37.5° N–55° N. The moisture net inputs of all edges are first calculated, then the moisture convergence of the whole area is calculated. The equations are

$$Q_{\mathrm{W}} = \int_{\varphi_1}^{\varphi_2} Q_{\mathrm{u}}(\lambda_1, \varphi, t)\mathrm{d}\varphi, \tag{7}$$

$$Q_{\mathrm{E}} = \int_{\varphi_1}^{\varphi_2} Q_{\mathrm{u}}(\lambda_2, \varphi, t)\mathrm{d}\varphi, \tag{8}$$

$$Q_{\mathrm{S}} = \int_{\lambda_1}^{\lambda_2} Q_{\mathrm{v}}(\lambda, \varphi_1, t)\mathrm{d}\lambda, \tag{9}$$

$$Q_{\mathrm{N}} = \int_{\lambda_1}^{\lambda_2} Q_{\mathrm{v}}(\lambda, \varphi_2, t)\mathrm{d}\lambda, \tag{10}$$

where Q_{W}, Q_{E}, Q_{S}, and Q_{N} denote the moisture inputs of the western, eastern, southern, and northern boundary, respectively; Q_{u} and Q_{v} represent the meridional and zonal moisture flux of the full layer integrations, respectively; $\varphi_1 = 37.5°$ N, $\varphi_2 = 55°$ N, $\lambda_1 = 115°$ E, and $\lambda_2 = 135°$ E. The moisture convergence of the whole area can be calculated through

$$Q_{\mathrm{in}} - Q_{\mathrm{out}} = Q_{\mathrm{W}} - Q_{\mathrm{E}} + Q_{\mathrm{S}} - Q_{\mathrm{N}}. \tag{11}$$

If $Q_{\mathrm{in}} - Q_{\mathrm{out}} > 0$, moisture convergence occurs in the region; if $Q_{\mathrm{in}} - Q_{\mathrm{out}} < 0$, moisture divergence occurs.

Equation (6) can be simplified into $I_{\mathrm{P-E}} = I_{\mathrm{CV}} - I_{\mathrm{W}}$, further, $I_{\mathrm{CV}} - I_{\mathrm{W}}$ can be denoted as I_{A}, the moisture sink of northeast China is computed by local moisture variation I_{W} and moisture convergence I_{CV}.

Figure 4 shows the variations of moisture sink I_{A} and $I_{\mathrm{P-E}}$ in different seasons in northeast China. It can be seen that the variations of I_{A} and $I_{\mathrm{P-E}}$ in each season are extremely consistent, and their correlation coefficients reach 0.84, 0.82, 0.83, and 0.68 respectively. The results basically match Eq. (6), proving that ERA-Interim data can properly describe the water budgets in different seasons in northeast China. Concerning different seasons, northeast China is a moisture source in spring and autumn, with the total moisture sinks of -1.87×10^{13} kg and -0.22×10^{13} kg respectively, indicating that the moisture transports from the ground into the atmosphere in the two seasons; northeast China is the moisture sink in summer and winter, with the total moisture sinks of 8.55×10^{13} kg and 0.79×10^{13} kg, respectively, indicating that the moisture transports from the atmosphere to the ground.

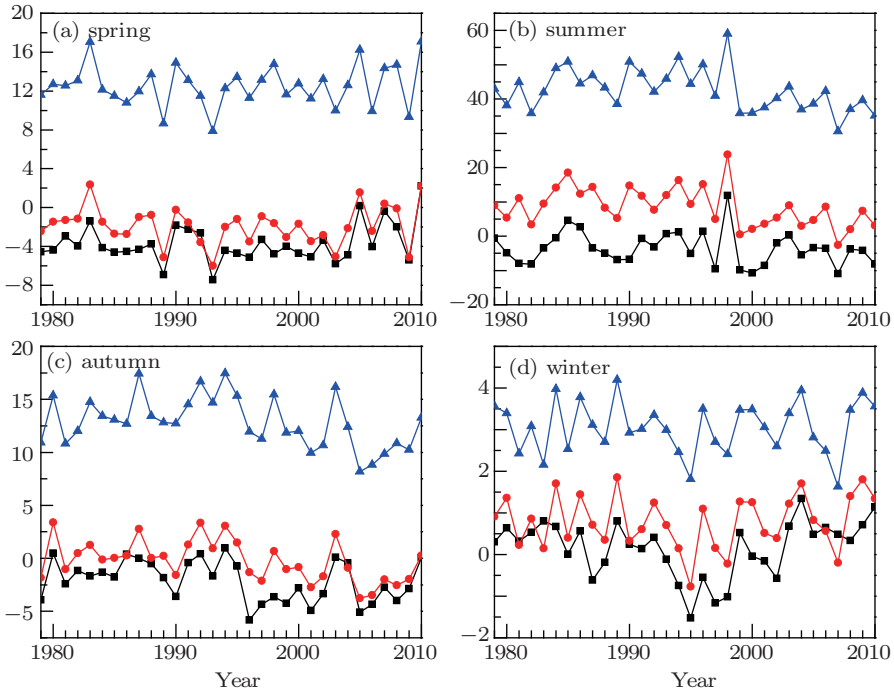


Fig. 4. (color online) Variations of moisture sink I_{A} (line with solid rectangles), $I_{\mathrm{P-E}}$ (line with solid circles) and regional total precipitation P (line with solid triangles) in northeast China (in unit: 10^{13} kg).

Figure 5 shows the variations of moisture sink I_{A}, moisture convergence I_{CV}, and local moisture variation of northeast China. It can be seen that in different seasons the variations of moisture convergence I_{CV} and moisture sink I_{A} correspond to each other properly, and their correlation coefficients are 0.98, 0.99, 0.97, and 0.95, respectively, which means that moisture convergence has a great influence on the moisture sink. In addition, the range of the local moisture variation I_{W}, which is far smaller than that of

the moisture sink I_A and moisture convergence I_{CV}, almost remains constant. In summer and winter, the local moisture variation I_W fluctuates above and below 0 and the fluctuation range is fairly small, which shows that the local moisture in summer and winter remains unchanged and the local moisture variation can be ignored; in spring, the local moisture variation is 2×10^{13} kg with moisture increasing; in autumn, the local moisture variation is -2×10^{13} kg with moisture decreasing. Thus, the moisture variation in northeast China in a whole year is 0, which means that the amount of moisture remains unchanged.

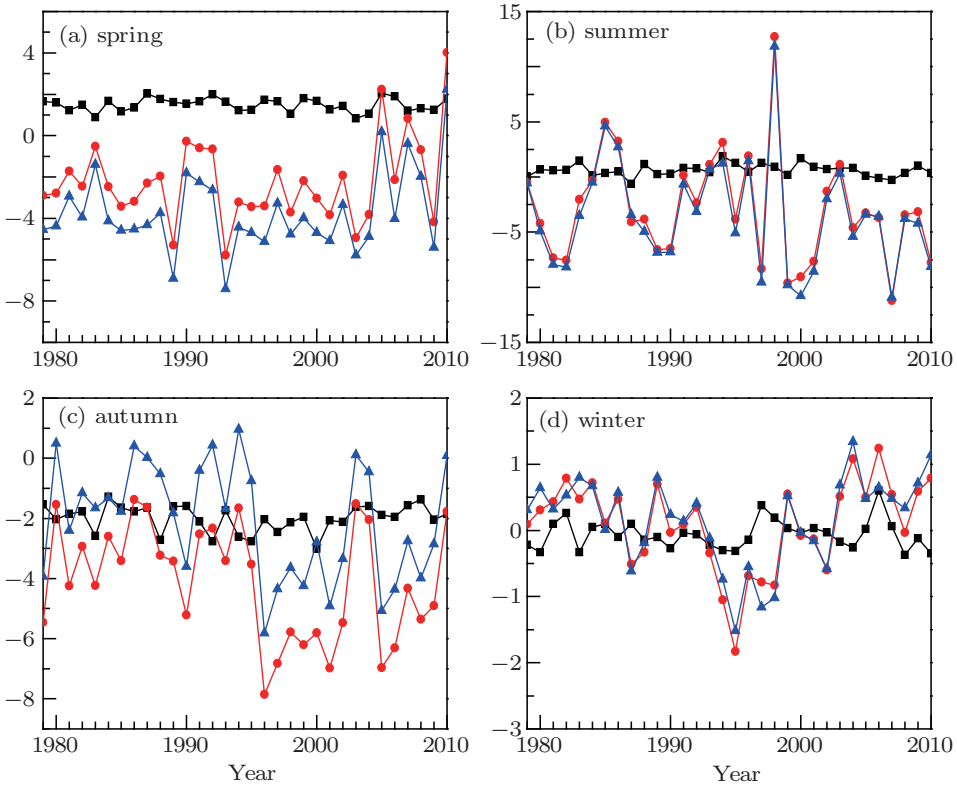


Fig. 5. (color online) Variations of the moisture sink I_A (line with solid triangles), moisture convergence value I_{CV} (line with solid circles), and local moisture variation I_W (line with solid rectangles) in northeast China (in unit: 10^{13} kg).

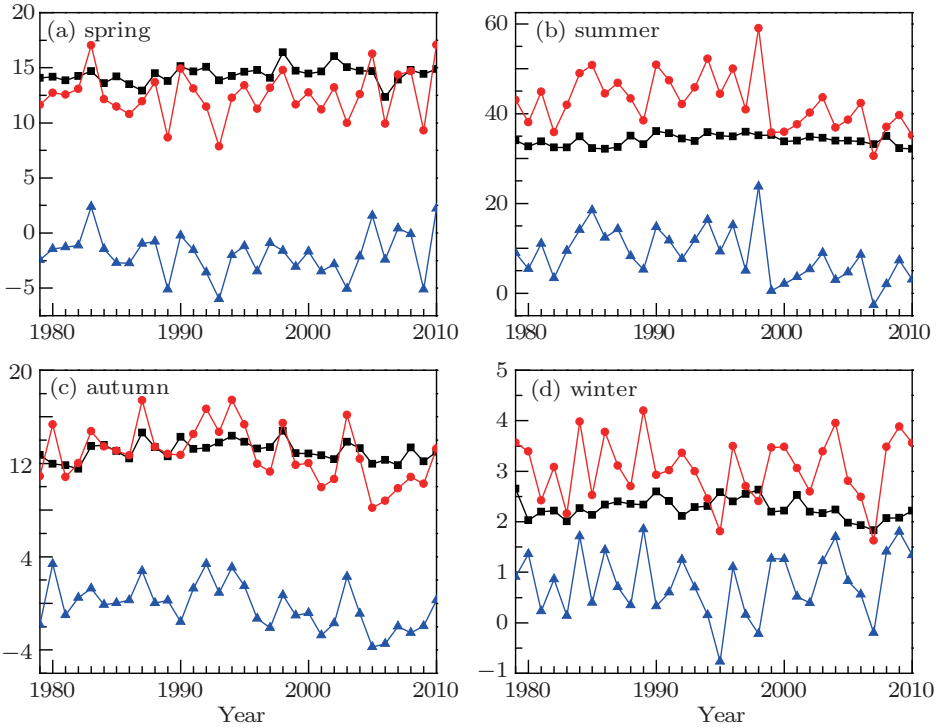


Fig. 6. (color online) Variation of the moisture sink I_{P-E} (line with solid triangles), regional total precipitation P (line with solid circles), and regional total evaporation E (line with solid rectangles) in northeast China (in unit: 10^{13} kg).

Figure 6 shows the variation of moisture sink I_{P-E}, total precipitation P, and total regional evaporation E of northeast China. It is found that the phases and the amplitudes of the precipitation P and moisture sink I_{P-E} in different seasons are in accordance with each other, and precipitation P and moisture sink I_{P-E} are in significant positive correlation, whose correlation coefficients are 0.94, 0.98, 0.95, and 0.95, respectively. The amplitude of evaporation E is far smaller than precipitation P and moisture sink I_{P-E}, accounting for that on a seasonal scale, the total precipitation P in northeast China exerts a greater influence on moisture sink I_{P-E} than the evaporation E. The fact that the precipitation is predominant over the moisture sink to some extent compensates for the lack of evaporation generated by surface runoff which is neglected in the analysis.

5. Conclusions and discussion

In this paper the ERA-Interim data from ECMWF is used to analyze the spatial distribution and temporal variation of the precipitable water, precipitation, evaporation, and divergence of moisture flux of northeast China and the water balance of that area. From the present study we draw some conclusions as follows.

(i) The spatial distributions of precipitable water, precipitation, and evaporation feature that the values of these elements in the southeastern area are all larger than those in the northwestern area; in summer, much precipitation and evaporation occur in the Changbai Mountain region as a strong moisture convergence region; in spring and autumn, moisture divergence dominates the northeast China; in winter, the moisture divergence and convergence are weak in this area.

(ii) From 1979 to 2010, the total amount of precipitation of summer and autumn in northeast China decreased markedly; especially from 1999 to 2010, the summer precipitation was always shown as a negative anomaly. Additionally, other elements in different seasons change in a truly imperceptible way.

(iii) In spring, evaporation exceeds precipitation in northeast China with moisture output; in summer, the precipitation is more prominent with moisture input; in autumn and winter, the precipitation plays a more dominant role in the northern part of northeast China, featuring that moisture input exists, but the evaporation exceeds the precipitation in the southern part with moisture output occuring; the closer to the sea the areas, the greater the difference between evaporation and precipitation will be.

(iv) ERA-Interim data has properly described the water balance between different seasons in northeast China. Based on ERA-Interim data, the moisture sinks computed through moisture convergence and moisture local variation are quite consistent with those computed through precipitation and evaporation, which proves that ERA-Interim data can be used in studying the water balance in northeast China.

(v) On a seasonal scale, the moisture convergence has a greater influence than the local moisture variation on the moisture sink, and the latter is variable slightly, generally it is a constant. Likewise, in different seasons, the total precipitation has a much greater influence on moisture sink than the evaporation.

Although ERA-Interim data can properly describe the moisture balance of different seasons in northeast China, there exist some deviations. This could be caused by the embodiment of the assimilation system for evaporation. Because of the complexity of the land surface process, the analysis data do not include enough information about the land-atmospheric exchange, which leads to a larger uncertainty of the estimation of evaporation.[28,29] This problem should be noticed in the research of regional water cycle balance.

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