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ORIGINAL PAPER

Changes in the characteristics of precipitation over northern Eurasia

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Abstract Based on observed daily precipitation data, this study investigates the changes in the characteristics of precipitation over northern Eurasia during 1951–2010. Over the majority of northern Eurasia (east of 20° E), the light precipitation days and amounts decrease, but those for the moderate, heavy, and very heavy precipitation increase. Moreover, the precipitation intensity increases, which is responsible for the decrease in light precipitation days and amount and increase in relatively more intense precipitation since there is no significant trend in total precipitation days. However, the precipitation characteristics are opposite over the Iberian Peninsula. We find that the changes in precipitation characteristics are possibly due to the changes in static stability. In the majority region (the Iberian Peninsula), the static stability weakens (strengthens) during 1951–2010. When static stability weakens (strengths), the upward motion increases (decreases) and thus the precipitation intensity increases (decreases). Accordingly, the light precipitation events decrease (increase) and heavy precipitation events increase (decrease).

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1 Introduction

The global mean temperature has experienced conspicuous warming since the beginning of the twentieth century especially during the period after the 1970s (Trenberth and Jones 2007). Global warming is expected to have a considerable impact on the global and regional hydrocycle (Trenberth 1999; Held and Soden 2006; Trenberth 2011). Under global warming, moisture content in the atmosphere increases, which in turn may lead to increase in total precipitation amount and heavy precipitation events (Trenberth 1999; Karl and Trenberth 2003; Trenberth et al. 2003; Allan and Soden 2008).

Based on observed precipitation data, the changes of total precipitation in many countries and regions have been studied for the periods ranging from century to several decades (Dai et al. 1997; Karl and Knight 1998; Zhang et al. 2000; Klein Tank et al. 2002; Zhai et al. 2005; Trenberth and Jones 2007; Niedźwiedź et al. 2009; Tošić et al. 2013). In general, there were increases in land precipitation at higher latitudes since the beginning of the twentieth century, and deceases at the subtropics and tropics outside of the monsoon trough after about 1970 (Trenberth and Jones 2007; Trenberth 2011). Precipitation over the USA, Canada, and Northern Europe increased significantly in the twentieth century (Karl and Knight 1998; Zhang et al. 2000; Trenberth and Jones 2007). In contrast, precipitation in the Mediterranean, including the central-western Mediterranean basin, Italy, and Spain, decreased in latter half of the twentieth century (Piervitali et al. 1998; Romero et al. 1998; Norrant and Douguédroit 2006; Trenberth and Jones 2007). In China, the trend of total precipitation is weak during 1951–2000 (Zhai et al. 2005).

Besides the total precipitation, the changes in precipitation characteristics are also important. Heavy precipitation may cause flood and runoff. Moderate and light precipitation can directly soak into the soil, and thus the decrease in less intense precipitation may lead to drought. Hence, changes in the characteristics of precipitation are very important for agriculture, hydrology, and water resources. Trenberth et al. (2003) argued that the characteristics of precipitation are just as vital as the total amount, and they are more apt to change as climate changes.

Several studies have revealed the changes in the characteristics of precipitation in different regions. Over the USA, there were century-long increasing trends for annual precipitation frequencies and amounts in all intensity categories (Karl and Knight 1998). Although there were regional and seasonal different changes in the characters of precipitation, the decreasing trends in annual precipitation frequencies and amounts in all intensity categories were obvious over the northern China for 1960–2000 (Liu et al. 2005). Over India, the heavy precipitation events increased at the cost of moderate precipitation events for monsoon seasons (Goswami et al. 2006; Dash et al. 2009). Over Europe, the changing characteristics of precipitation have been documented for some countries, like UK (Osborn et al. 2000), Italy (Brunetti et al. 2004), Spain (Romero et al. 1998).

There are large areas over northern Eurasia. However, the large-spatial-scale changes in the characteristics of the precipitation over there have not been reported. European Climate Assessment and Data (ECA&D) project has released a daily station rain gauge precipitation dataset (Klein Tank et al. 2002). This dataset covers most of Europe and the Asian part of Russia. Based on this dataset, we investigate the changes in the precipitation characteristics. Moreover, we suggest a possible connection between the changes in the characteristics of precipitation and the static stability by using reanalysis data and WRF model.

The rest of this paper is organized as follows: Section 2 introduces the data, model, and experimental design. Section 3 describes the changes in the characteristics of precipitation in northern Eurasia. The possible mechanism for the impact of the changes in static stability on the changes in the characteristics of precipitation is discussed in Section 4. Finally, a summary is given in Section 5.

2 Data and model

2.1 Data

Daily precipitation data for 2,565 stations from European Climate Assessment and Dataset (ECA&D) project (Klein Tank et al. 2002) are used. ECA&D project has checked the dataset and detected data errors such as erroneous outliers and negative values. Every observed value is accompanied with quality label in the dataset. Quality labels indicate the observed precipitation values valid, suspected or missing. In order to ensure the reliability of the results, suspected values are treated as missing values and only valid data are used here. In this study, a year with no missing value is classified as usable year. Stations with no less than 50 usable years during 1951–2010 are accepted in this analysis. As a result, a number of 1,022 stations are selected.

Atmospheric data used in this study, including monthly mean temperature and potential height fields, are derived from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) atmospheric reanalysis dataset (Kalnay et al. 1996). The data have a 2.5°×2.5° horizontal resolution and extends from 1,000 to 10 hPa with 17 pressure levels in vertical, and is available from January 1948.

2.2 Model and experimental design

This study utilizes the Advanced Research Weather Research Forecasting (ARW-WRF) model version 3.4.1 developed by NCAR, NCEP, and others. We use a 30-km horizontal grid resolution, and 28 terrain-following vertical layers. The model domain, covering a large part of Northern Eurasia, is centered at 55° N and 30° E and consists of 201 (west-east)×111 (south-north) grid points. The model's initial conditions and outmost lateral boundary conditions are obtained from the NCEP global final (FNL) analysis dataset (National Centers for Environmental Prediction 2000) at 1°×1° resolution and 6-h intervals.

The following three experiments are performed using the above model: control experiment EXP_CTL and sensitivity experiments EXP_WEA and EXP_STR. In the EXP_CTL run, the initial conditions and lateral boundary conditions for the model are derived from NCEP-FNL analysis data. The initial conditions and lateral boundary conditions in EXP_STR and EXP_WEA are the same as those in EXP_CTL except for the temperature field. In the EXP_WEA runs, the temperatures from 1,000 to 200 hPa in the initial conditions and lateral boundary conditions are added 1.8 to 0.0 K at an interval of 0.1 K, which make the lapse rate increase and the static stability weaken. By contrast, in the EXP_STR runs, the temperatures from 1,000 to 200 hPa in the initial conditions and lateral boundary conditions are added 0.0 to 1.8 K at the interval of 0.1 K, which makes the lapse rate decrease and the static stability strengthen. Every experiment consists of 30 runs and every run is integrated for 24 h starting from 0000 UTC of every day in July except for 31 July.

3 Changes in the characteristics of precipitation over northern Eurasia

We class daily precipitation rates based on percentile for each station. Following Allan and Soden (2008), daily precipitations are classed into four categories, including light (<30th), moderate (30–60th), heavy (60–90th), and very heavy (≥90th).

The spatial patterns of trends in annual precipitation days of the four intensities during 1951–2010 are shown in Fig. 1. There are striking features for the trends of light precipitation days. The majority of northern Eurasia exhibit downward tendency. Almost all the stations east of 20° E have a significant decreasing trend (Fig. 1a). The significances of trends for most stations exceed 95 % confident levels according to Student's *t* test. The regional-averaged light precipitation days are reduced by 5.3 % per decade over the area east of 20° E during 1951–2010 (Fig. 2a, averaged over 20° E–180° E, 40°

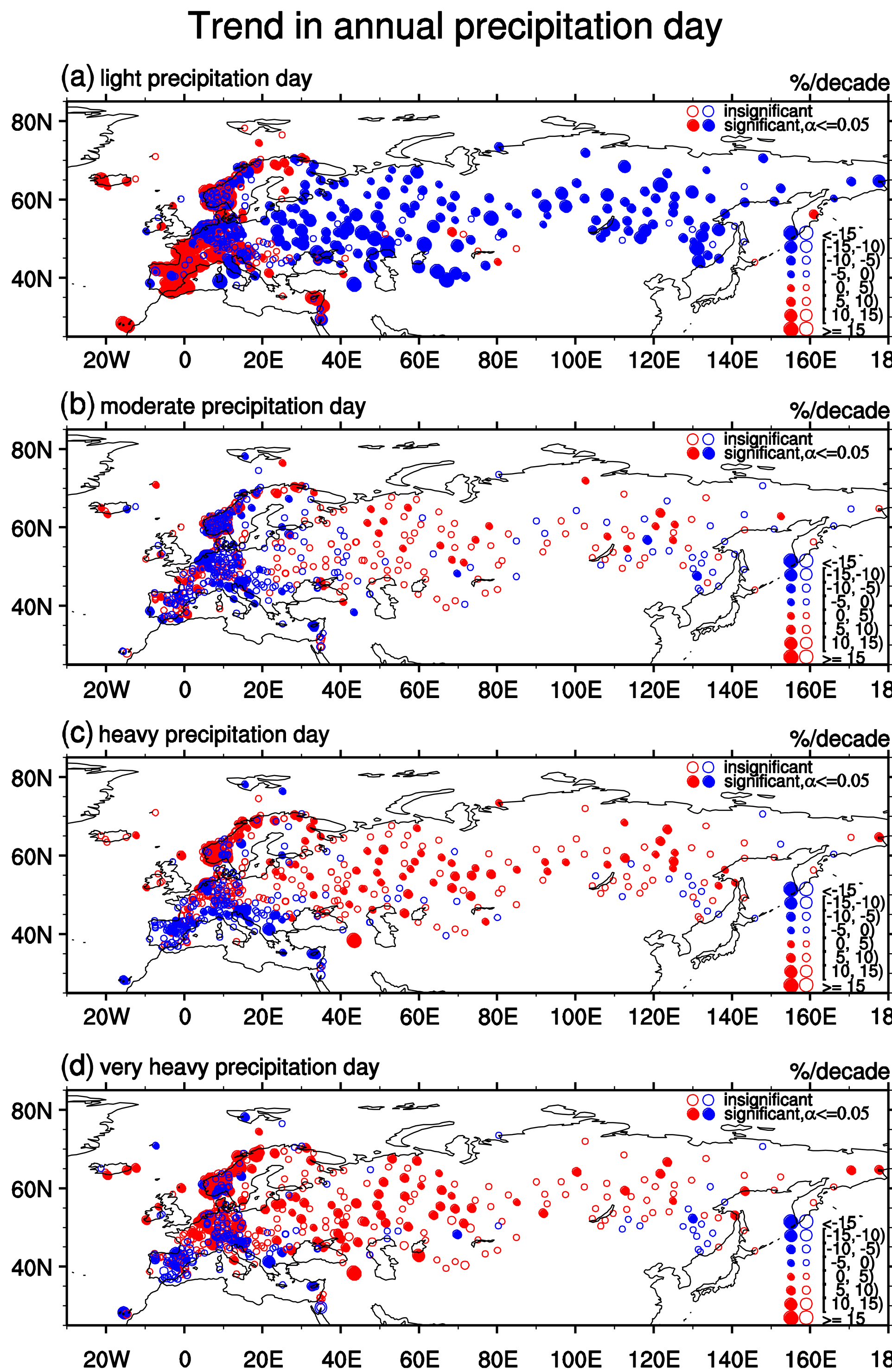


Fig. 1 Trends (%/decade, relative to climatology, which is the mean during 1961–2000; climatology period is the same hereafter) in annual **a** light, **b** moderate, **c** heavy, and **d** very heavy precipitation days over northern Eurasia during 1951–2010. *Red and blue colors* represent the positive and negative trends, respectively. *Dots and circles* denote that the trends are significant and insignificant at the 0.05 level according to Student's *t* test, respectively

N–75° N). However, the Iberian Peninsula is an exception. On the contrary, most of the stations over the Iberian Peninsula have a conspicuous upward trend. The regional-averaged light precipitation days are increased by 6.6 % per decade over the Iberian Peninsula (Fig. 2e, averaged over 15° W–5° E, 35° N–45° N).

Opposite to the changes of light precipitation days, there are increasing trends in moderate (Fig. 1b), heavy (Fig. 1c) and very heavy (Fig. 1d) precipitation days over the majority of northern Eurasia, especially the area east of 20° E. Although the significances and magnitudes are less than those for light precipitation days, the increasing trends in moderate, heavy, and very heavy precipitation days are widespread among the stations east of 20° E. The regional consistencies of the trends in heavy and very heavy precipitation days are more obvious than those in moderate days. In addition, the regional-averaged heavy and very heavy precipitation days increase by 2.0 % (Fig. 2c) and 3.2 % (Fig. 2d) per decade over the area east of 20° E, which are larger than increasing trend of moderate precipitation days (0.8 % per decade, Fig. 2b). Interestingly, similar with the trends in light precipitation days, the trends in moderate, heavy, and very heavy precipitation days are contrary between the area east of 20° E and the Iberian Peninsula. The decreases in moderate, heavy, and very heavy precipitation days are prevalent among the stations over the Iberian Peninsula. However, the trends in

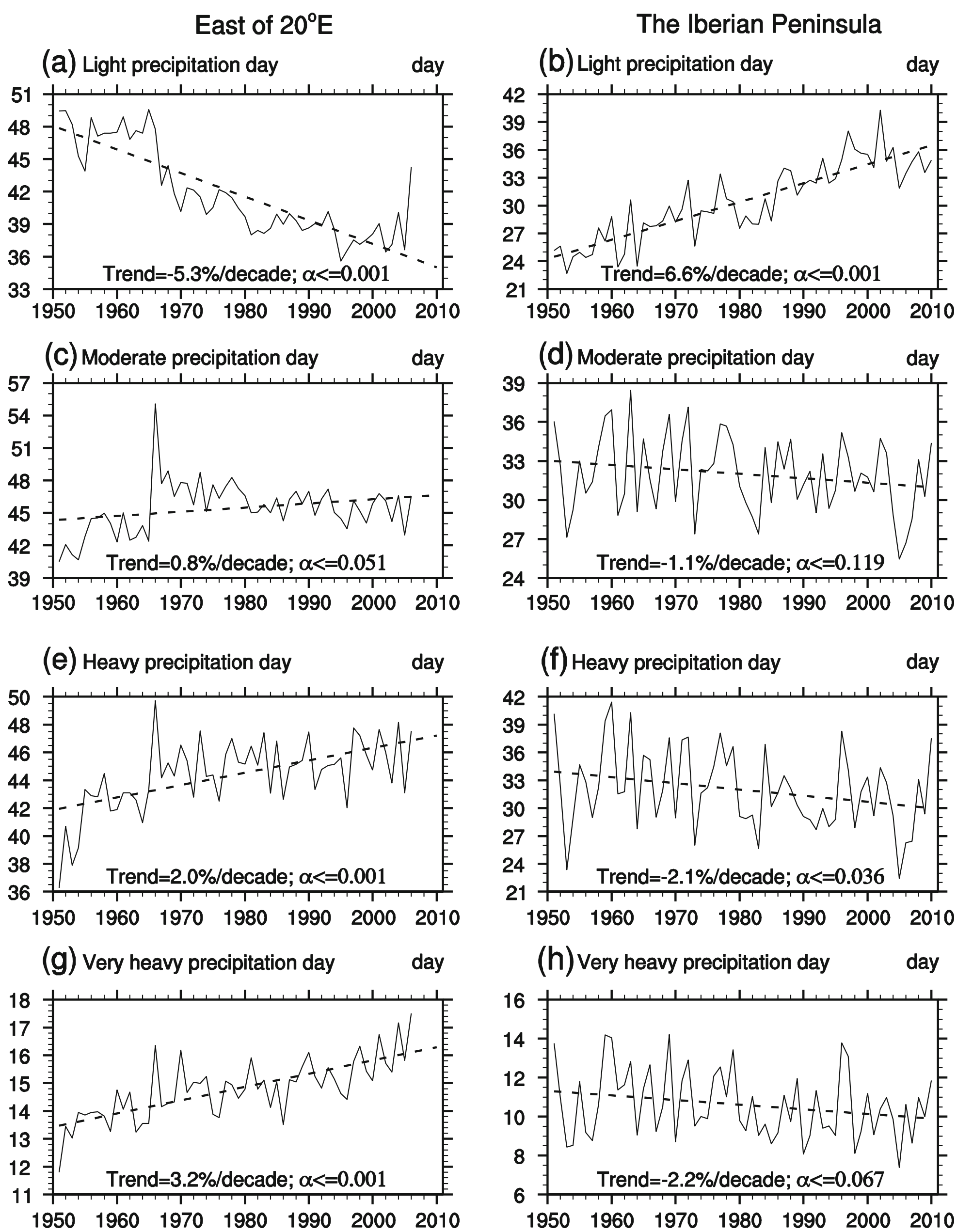
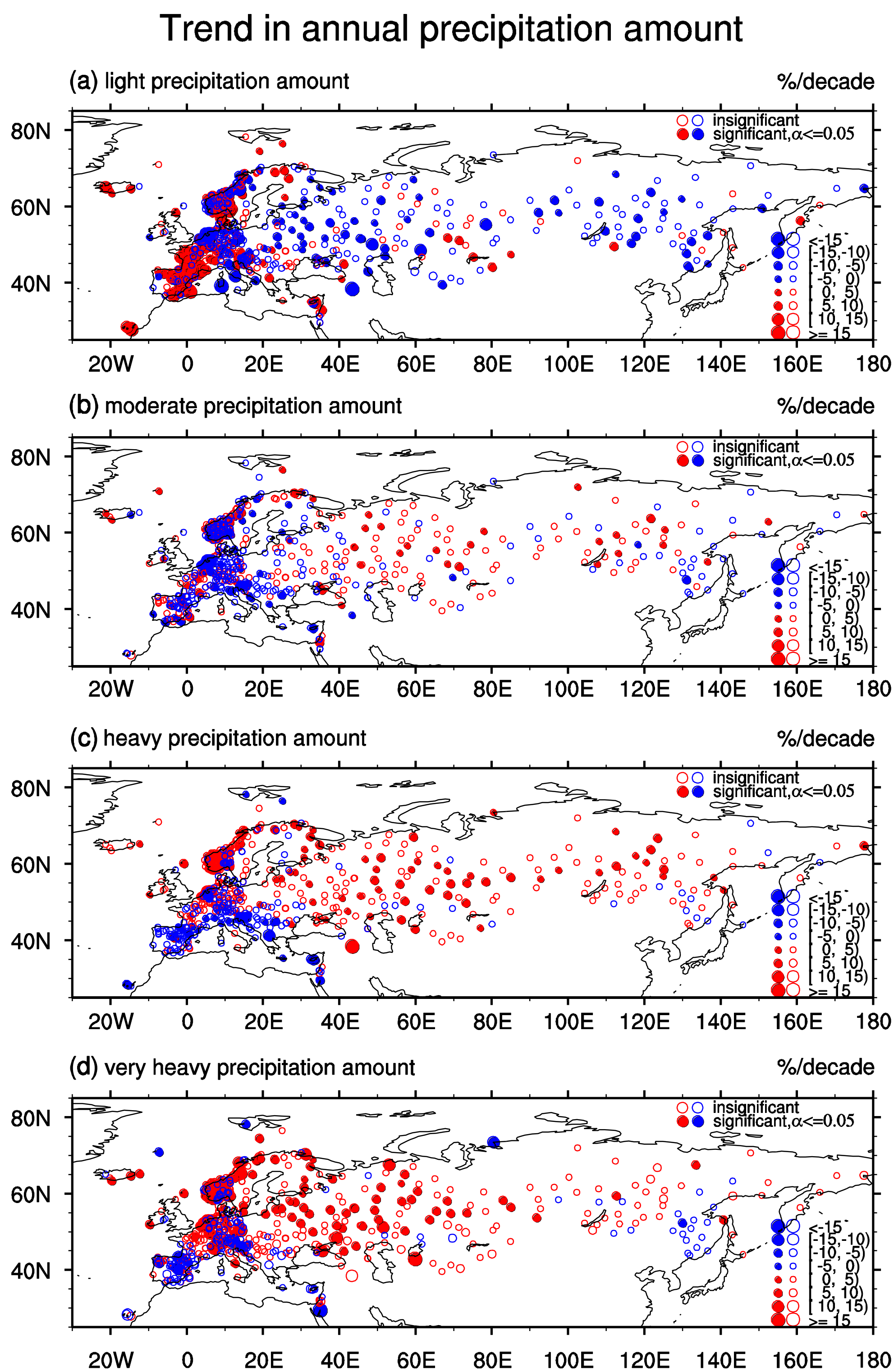


Fig. 2 Regional-averaged annual light (*top row*), moderate (*second row*), heavy (*third row*) and very heavy (*bottom row*) precipitation days (day) over the area east of 20° E (*left column*) and the Iberian Peninsula (*right column*) during 1951–2010. *Dashed lines* represent the trends (%/decade)

regional-averaged heavy (−2.1 % per decade, Fig. 2g) and very heavy (−2.2 % per decade, Fig. 2h) precipitation days are also more considerable and significant than those in moderate (−1.1 % per decade, Fig. 2f) precipitation days.

The spatial patterns of trends for the annual precipitation amount of the four intensities, shown in Fig. 3, are similar to those for annual precipitation days. Light precipitation amounts (Fig. 3a) decrease, but moderate (Fig. 3b), heavy (Fig. 3c), and very heavy (Fig. 3d) precipitation amounts increase for most of the stations over the area east of 20° E. The light precipitation amount is decreased by 1.7 % per decade (Fig. 4a) over the area east of 20° E, and the moderate,

Fig. 3 Same as Fig. 1, but for the precipitation amount



heavy, and very heavy precipitation amounts are increased by 0.4 % (Fig. 4b), 1.4 % (Fig. 4c), and 2.7 % per decade (Fig. 4d), respectively. By contrast, light (Fig. 3a) precipitation amounts increase, but moderate (Fig 3b), heavy (Fig. 3c), and very heavy (Fig. 3d) precipitation amounts decrease for most of the stations over the Iberian Peninsula. The trends in regional-averaged light, moderate, heavy, and very heavy precipitation amounts are 2.0 % (Fig. 4e), −1.4 % (Fig. 4f), −2.2 % (Fig. 4g) and −2.6 % (Fig. 4h) per decade, respectively.

The inverse trends in precipitation days and amounts between lower and higher intensity indicate that the precipitation probability distributions may change over northern Eurasia during 1951–2010. However, the changes are opposite between the area east of 20° E and the Iberian Peninsula.

Considering the seasonality of precipitation, we also analyze the change in the seasonal characteristics of precipitation, which is shown in Fig. 5. The spatial patterns of the trends in seasonal light precipitation days for winter (DJF, Fig. 5a), spring (MAM, Fig. 5b), summer (JJA, Fig. 5c), and autumn (SON, Fig. 5e) are all similar with those for annual light precipitation days. The majority of northern Eurasia has decreasing tendency for the light precipitation days in the four

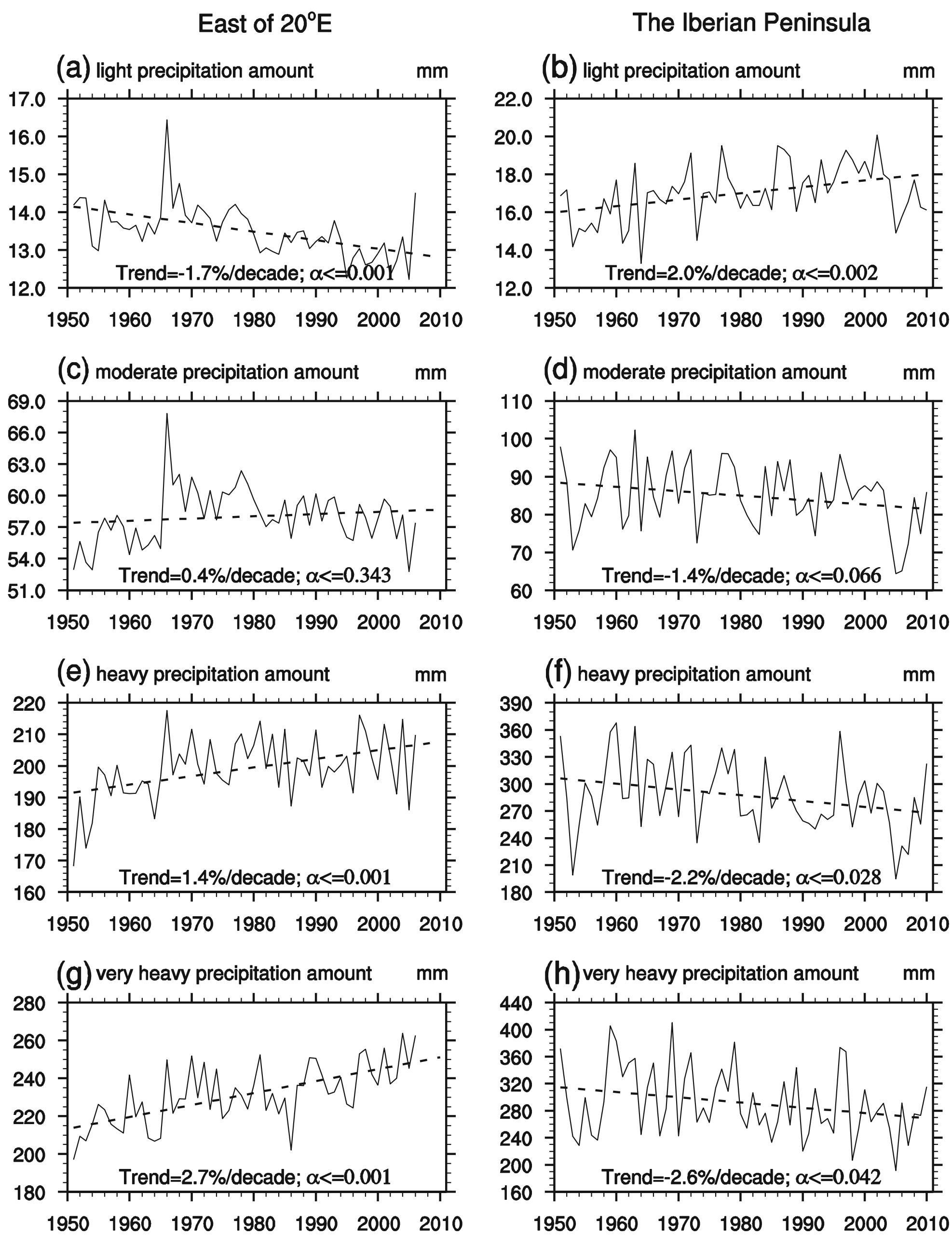


Fig. 4 Same as Fig. 2, but for the precipitation amount

seasons. Most of the stations east of 20° E have a decreasing trend. On the contrary, most of the stations over the Iberian Peninsula have an increasing trend in every season. However, the same as annual result, the precipitation events at the right side of precipitation probability distribution are opposite to those at the left side. There are increasing trends in very heavy (Fig. 5e–h) precipitation days in all the seasons over the majority of northern Eurasia, especially the area east of 20° E. Upward trends in very heavy precipitation days are widespread among the stations east of 20° E. To the opposite, downward trends in very heavy precipitation days are prevalent among the stations over the Iberian Peninsula. The same changes of light and very heavy precipitation in different seasons over northern Eurasia indicate that there are little seasonal differences in the changes of precipitation characteristics.

4 Possible reasons for the changes in the characteristics of precipitation over northern Eurasia

The changes in precipitation are largely affected by static stability (Peppler and Lamb 1989; Richter and Xie 2008; Johnson and Xie 2010). In this section, we discuss the changes in static stability over northern Eurasia in recent decades and their impacts on the changes in precipitation characteristics.

4.1 Changes in the static stability over northern Eurasia

The trends in seasonal temperature lapse rate between 1,000 and 700 hPa for winter (Fig. 6a), spring (Fig. 6b), summer (Fig. 6c), autumn (Fig. 6d) over northern Eurasia are shown in Fig. 6. The seasonal differences of spatial pattern of trends are small. Upward tendencies are evident for temperature lapse

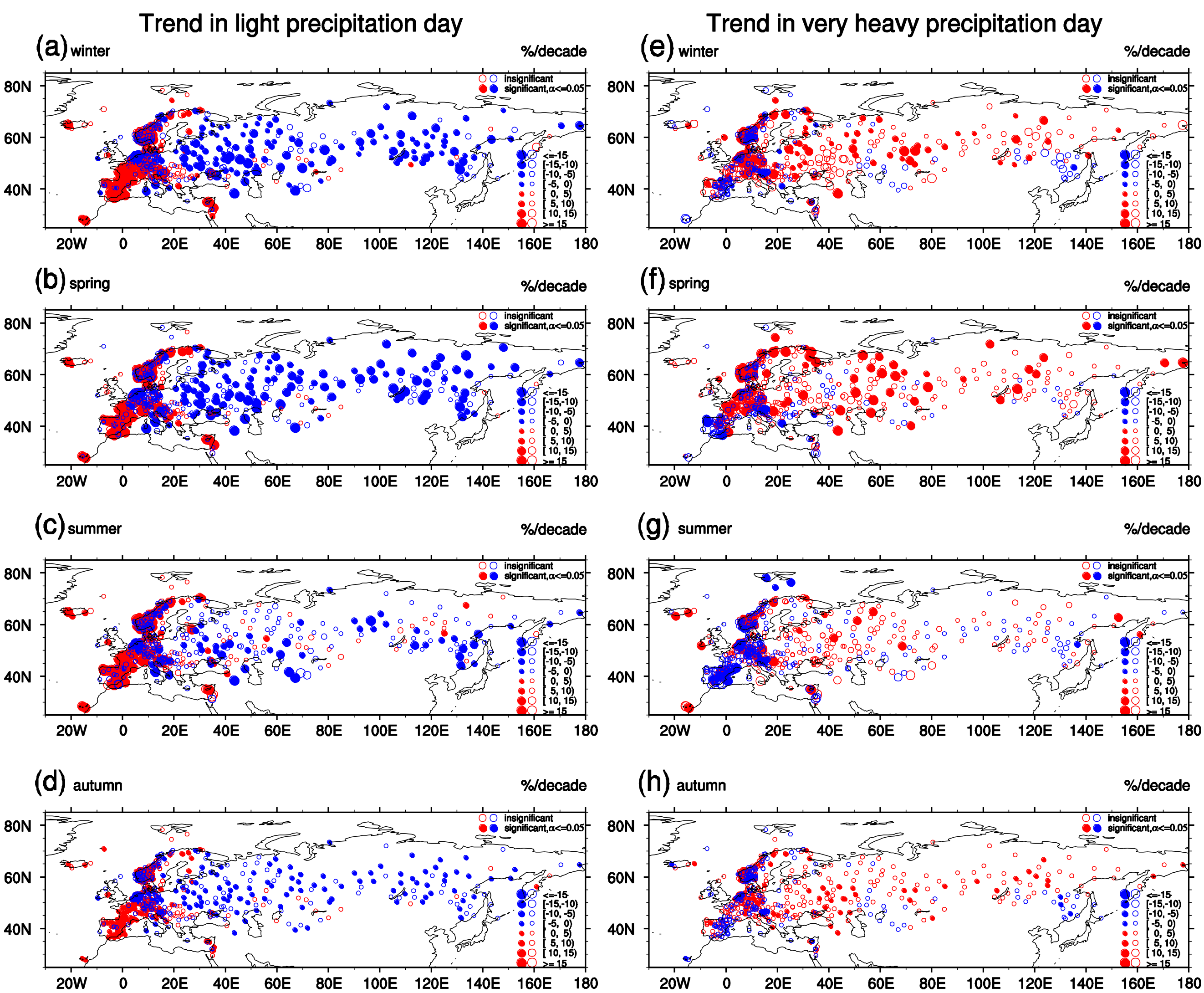


Fig. 5 Trends (%/decade) seasonal light (*left column*) and very heavy (*right column*) precipitation days over northern Eurasia for winter (DJF, *top row*), spring (MAM, *second row*), summer (JJA, *third row*) and autumn (SON, *bottom row*) during 1951–2010. *Red and blue colors* represent the positive and negative trends, respectively. *Dots and circles* denote that the trends are significant and insignificant at the 0.05 level according to Student's *t* test, respectively

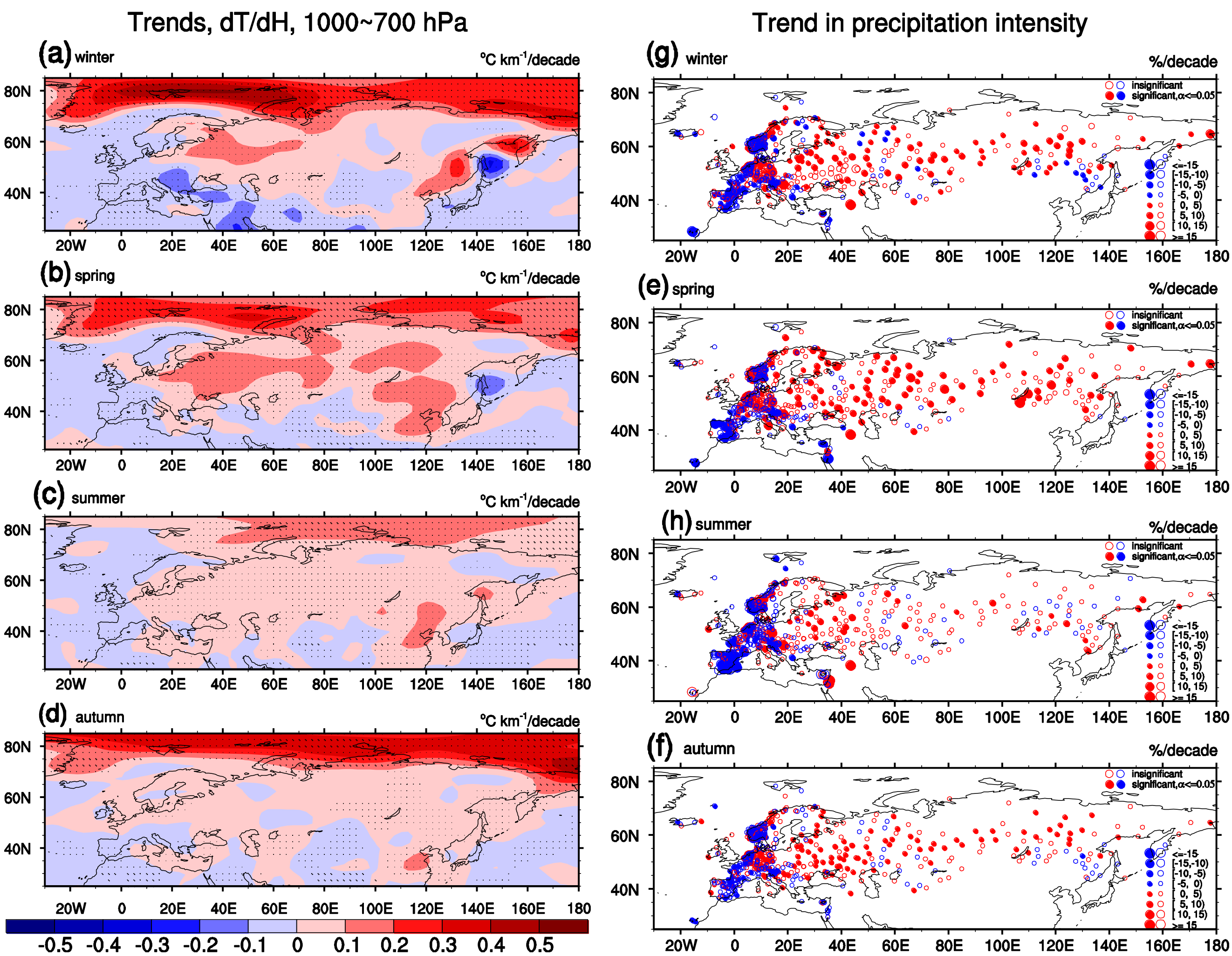


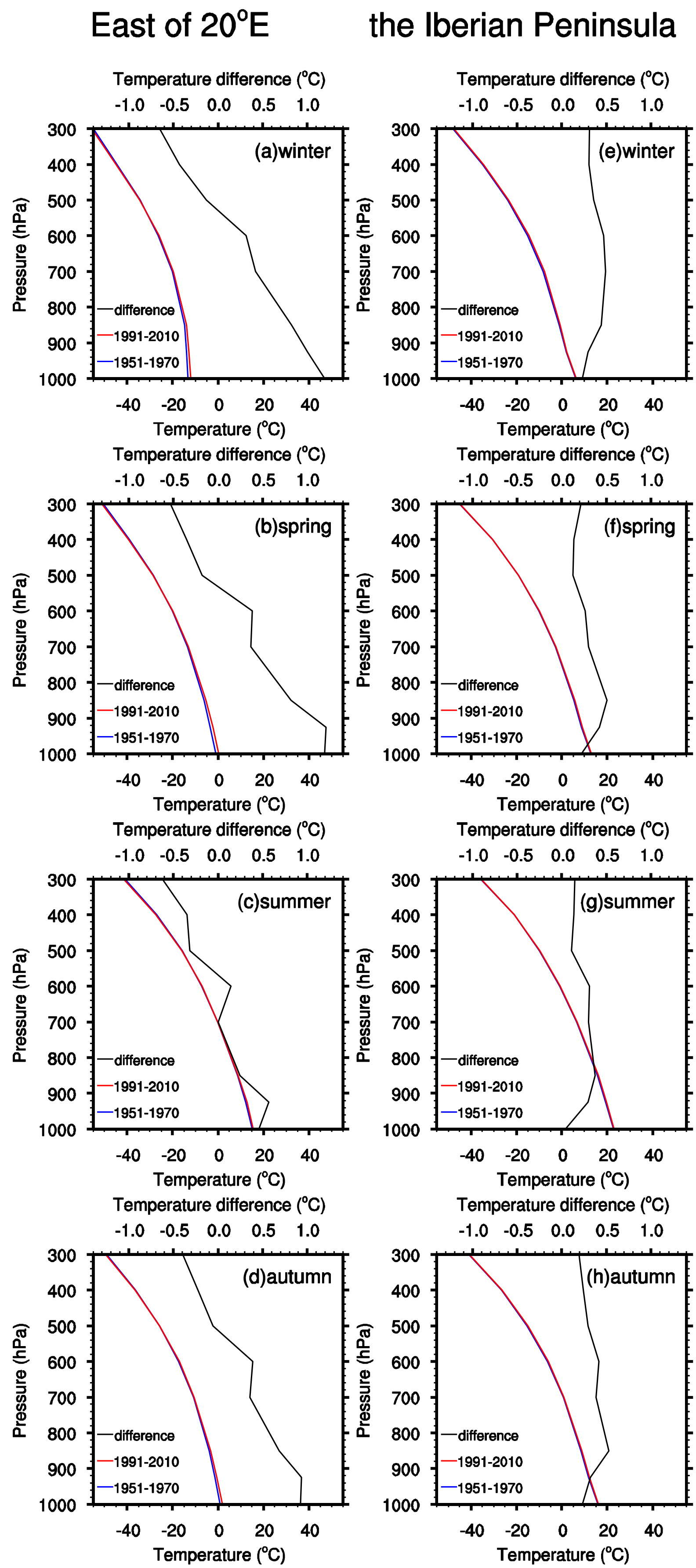
Fig. 6 Trends (°C km^{-1}/decade) in seasonal temperature lapse rate (dT/dH) between 1,000 and 700 hPa level from NCEP-NCAR reanalysis data (*left column*) and trends (%/decade) in seasonal precipitation intensity (*right column*) over northern Eurasia for winter (*top row*), spring (*second row*), summer (*third row*), autumn (*bottom row*). *Dots in the right column* denote the grid points where the trend is significant at the 0.05 significance level according to Student's *t* test

rate over the majority of northern Eurasia, especially the area east of 20° E in four seasons. The increase in temperature lapse rate indicates that the static stability weakens and the atmospheric stratification becomes less stable. By contrast, the temperature lapse rate has a downward tendency over the Iberian Peninsula. The decrease in temperature lapse rate implies that the static stability strengthens and the atmospheric stratification becomes more stable.

We can also see the temporal changes in the seasonal static stability over the two areas from the mean vertical temperature profiles during the first and last 20 years in 1951–2010. Figure 7 shows the mean vertical temperature profiles for 1951–1970 (blue line) and for 1991–2010 (red line) as well as their difference (black line) between the two periods. The temperatures increase for the mid-low level of troposphere (below 500 hPa), and the temperatures decrease for the high level (above 500 hPa) over the area east of 20° E (Fig. 7a–d). Besides, the warming at mid-low level of troposphere is reduced as altitude increases. The vertical temperature profiles over the area east of 20° E have the same changing pattern in four seasons. The changing patterns of vertical temperature profiles indicate that the lapse rate increases and the static stability weakens. As for the Iberian Peninsula, the tropospheric temperatures increase for almost all the levels (Fig. 7e–h) in four seasons. However, the low level (1,000–700 hPa) gets less warmer than the mid-high level (above 700 hPa, Fig. 7e–h). The warming at low level of troposphere grows as altitude increases. Thus, the lapse rate decreases, especially for the low level, and the static stability strengthens.

The different changes in the temperatures at different levels make the static stability change. The inverse changes in static stability lead to the facts that the atmospheric stratifications become less stable over the area east of 20° E and more stable over the Iberian Peninsula.

Fig. 7 The mean seasonal tropospheric temperature profiles (°C) in winter (*top row*), spring (*second row*), summer (*third row*), autumn (*bottom row*) for 1951–1970 (*blue line*) and for 1990–2010 (*red line*), and their differences (°C, *black line*) during two periods over the area east of 20° E (*left column*) and the Iberian Peninsula (*right column*)



4.2 Impact of static stability on precipitation

The occurrence of precipitation is generally accompanied with upward motion. The vertical motion is usually associated with the atmospheric stratification. Unstable atmospheric stratification favors upward motion and heavy precipitation, while stable atmospheric stratification suppresses the upward motion and is favorable for less intense precipitation. Therefore, when the static stability weakens, the upward motion strengthens so that the precipitation intensity increases. Accordingly, the increase in precipitation intensity leads to less light precipitation events and more heavy precipitation events. While the atmospheric stability strengthens, the upward motion abates so that the precipitation intensity decreases and light precipitation events increase and heavy precipitation events decrease.

Associated with the weakening of static stability, the precipitation intensity in four seasons increases significantly over the area east of 20° E (Fig. 6e–h). Furthermore, the trends in total precipitation days are quite small and not significant there (figure not shown). Therefore, the increase in precipitation intensity leads to less light precipitation events and more heavy precipitation events. On the contrary, the strengthening of static stability results in decrease in precipitation intensity over the Iberian Peninsula (Fig. 6e–h). There are also no significant trends for total precipitation days there (figure not shown). Hence, light precipitation events increase and heavy precipitation events decrease.

However, the changing pattern of associated vertical velocity is not same as that of the static stability (figure not shown). It is because the monthly vertical velocity is the monthly mean of daily values. The daily vertical velocity is upward when precipitation events occur and is usually downward when there are no precipitation events. Both the upward and downward motions enhance (reduce) when static stability weakens (strengths). Therefore, the influence of changing in static stability on upward motion associated precipitation does not appear on monthly vertical velocity field.

Therefore, we employ a model to examine the impact of static stability on precipitation intensity through upward motion. The used model and the experimental design have been mentioned above in Section 2. We present the model results

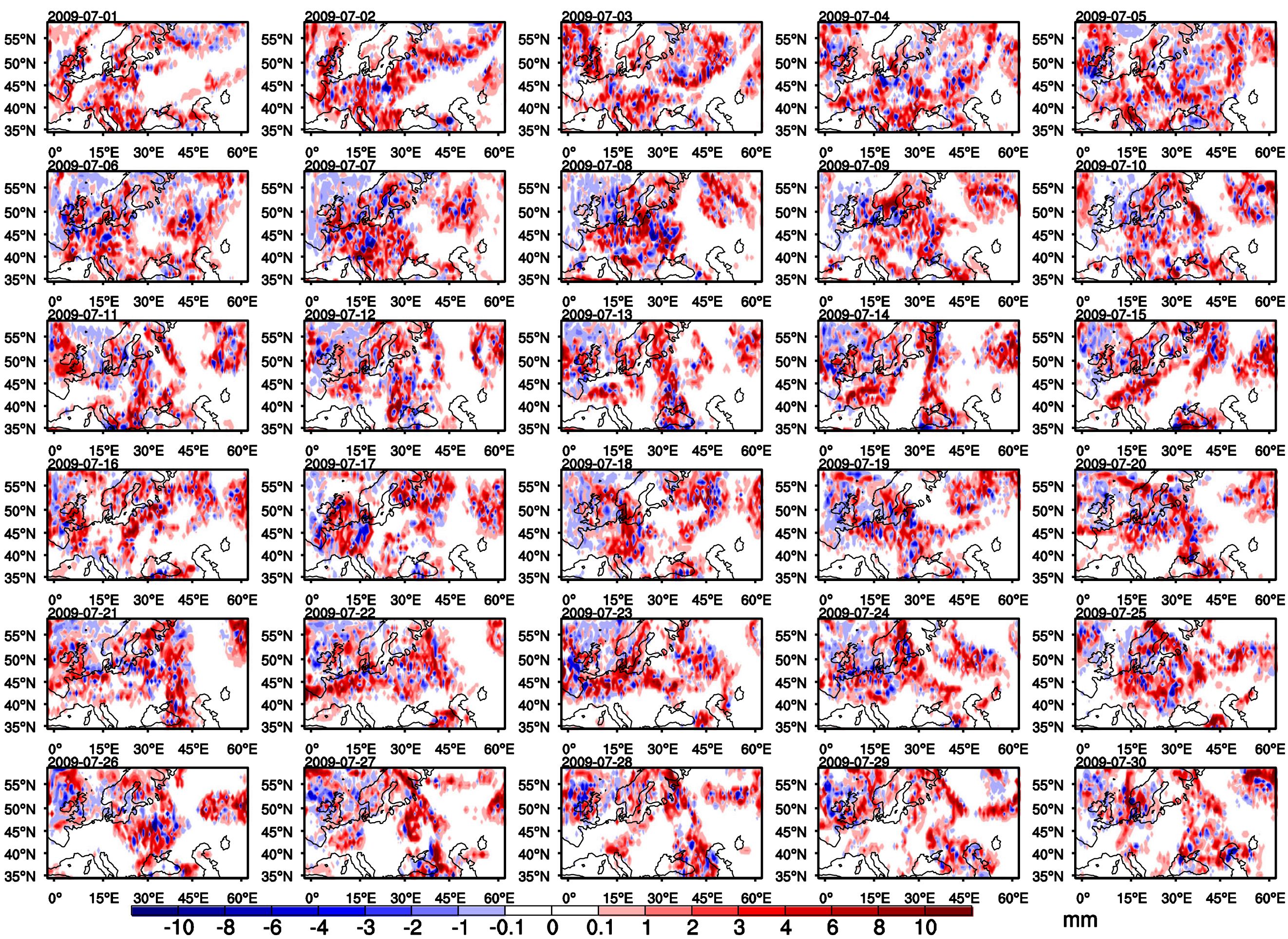


Fig. 8 The precipitation differences (mm) between the experiment EXP_WEA and EXP_CTL

here. Figure 8 shows the precipitation differences between the static stability weakening experiment (EXP_WEA) and control experiment (EXP_STR) for 30 days. Increases in most of the precipitation indicate that the precipitation intensity increases when static stability weakens. The precipitation differences between the static stability strengthening experiment (EXP_STR) and control experiment (EXP_CTL) are shown in Fig. 9. Decreases in most of the precipitation imply that the precipitation intensity decreases when static stability strengthens. The regional-averaged precipitations (averaged over an area with daily precipitation above 0.1 mm) in the three experiments for the 30 days clearly reflect that precipitation intensity (Fig. 10f) increases (decreases) when static stability weakens (strengthens). The vertical velocities in the experiments also change significantly as static stability changes. The vertical velocities increase (decrease) when static stability decreases (increases) at low and mid levels of troposphere (Fig. 10a–d), especially at the 500 hPa level (Fig. 10d). The model results indicate that static stability can affect the precipitation intensity through upward motion. The precipitation intensity increases for the increase in upward motion when static stability weakens, and vice versa.

5 Summary and discussion

In this study, we investigate the changes in the characteristics of precipitation over northern Eurasia. The annual light precipitation days and amounts decrease over the majority of northern Eurasia, especially the area east of 20° E, but the moderate, heavy, and very heavy precipitation days and amounts increase. In addition, the precipitation intensity increases there. Since there is no significant trend in the total precipitation days, the increase in precipitation intensity is responsible for the decrease in light precipitation events and increase in more intense precipitation events. However, the precipitation characteristics over the Iberian Peninsula are opposite to those in the area east of 20° E. The light precipitation days and amounts increase, but the moderate, heavy, and very heavy precipitation days and amounts decrease over the Iberian Peninsula, which are accompanied with the decrease in precipitation intensity. It is interesting that the change in light precipitation is opposite to moderate, heavy, and very heavy precipitation. Another interesting feature is that there are inverse changing tendencies for precipitation characteristics between the area east of 20° E and the Iberian Peninsula.

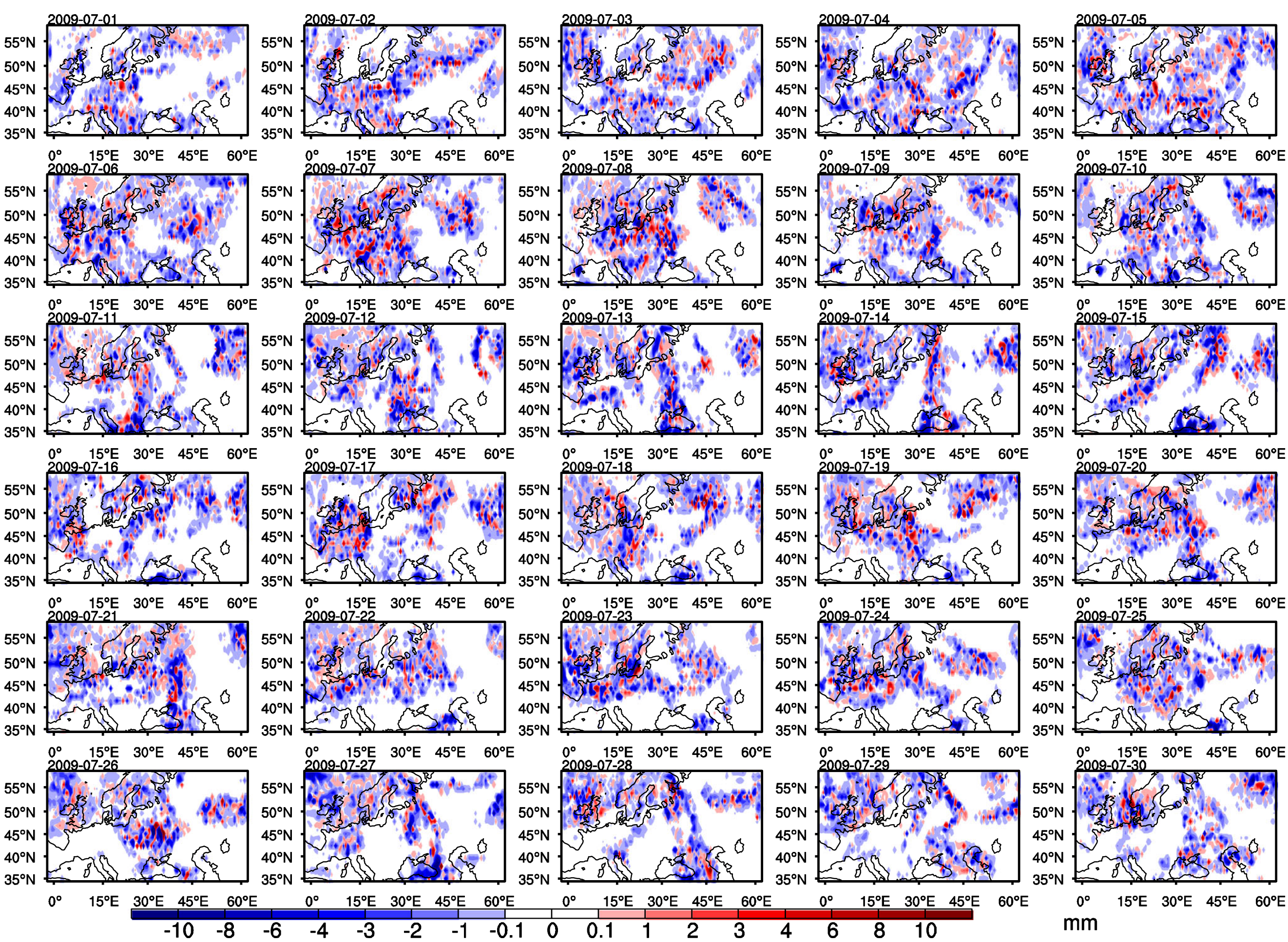


Fig. 9 Same as Fig. 8, but for the experiment EXP_STR and EXP_CTL

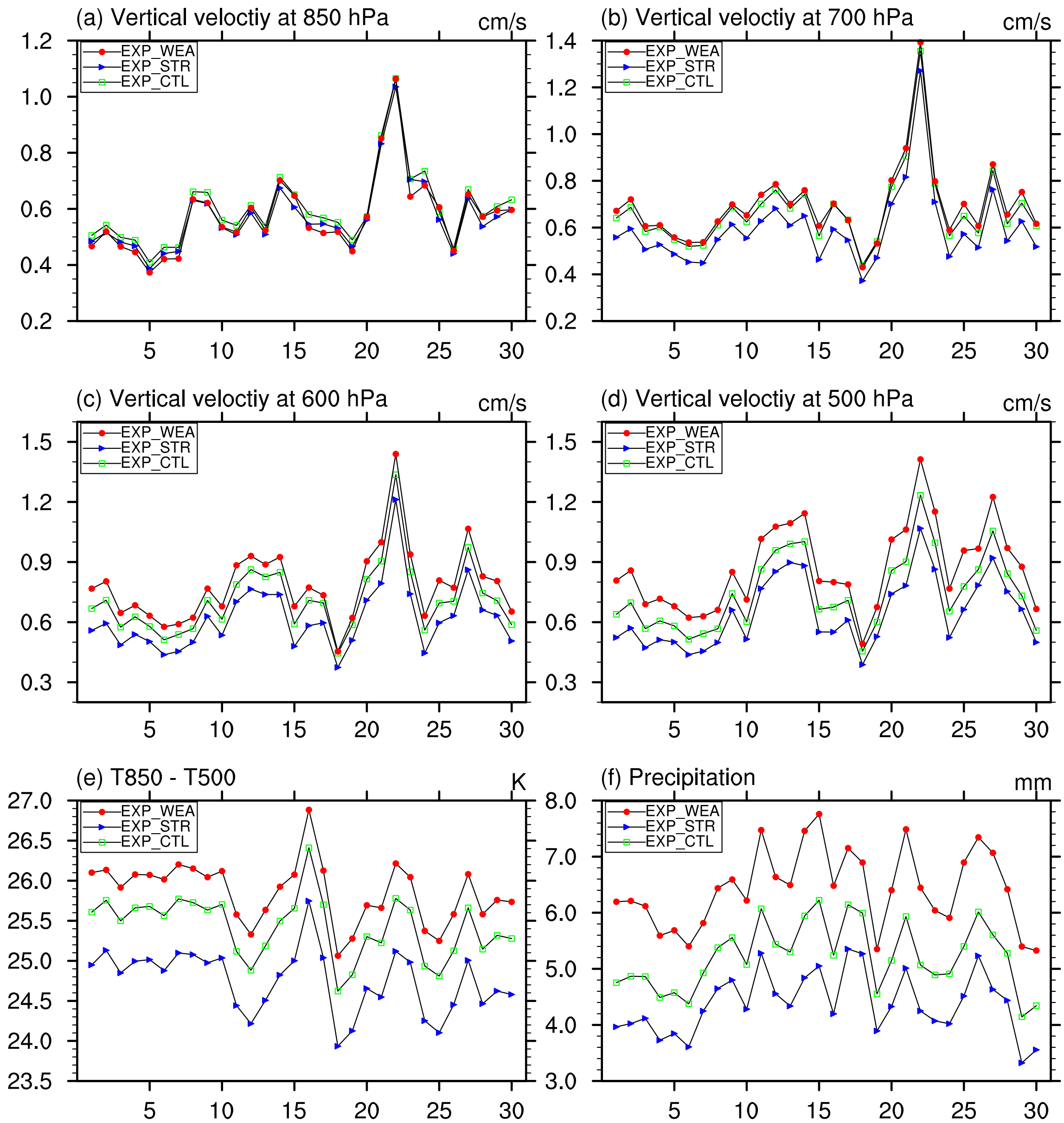


Fig. 10 The regional-averaged vertical velocity (cm/s) at **a** 850 hPa, **b** 700 hPa, **c** 600 hPa, **d** 500 hPa, **e** temperature differences (°C) between 850 and 500 hPa and **f** precipitation (mm) over the areas with daily precipitation above 0.1 mm in 30 simulated days of each experiment. *Blue*, *green* and *red lines* and markers denote experiment EXP_STR, EXP_CTL, EXP_WEA, respectively

The changing characteristics in winter, spring, summer, and autumn are similar with the annual result. There are small seasonal differences in the change of precipitation characteristic.

The changes in the characteristics of precipitation are possibly due to the changes in static stability over northern Eurasia. The same as the changes in precipitation characteristic, the static stability exhibits inverse changes between the area east of 20° E and the Iberian Peninsula. The static stability weakens (strengthens) and the atmospheric stratification becomes less (more) stable over the area east of 20° E (the Iberian Peninsula). When the static stability weakens (strengthens), the upward motion increases (decreases) so that the precipitation intensity increases (decreases). The increase (decrease) in precipitation intensity leads to less (more) light precipitation events and more (less) intense precipitation events. This mechanism is supported by model experiments.

Water vapor is one of the important factors affecting the precipitation characteristics. However, we have not found believable connection between them over northern Eurasia. There are decreasing trends in total column water vapor over the majority of northern Eurasia. This changing pattern could not explain the increases in moderate, heavy, and very heavy precipitation days and amounts over the area east of 20° E.

Besides, we have not explained why the static stability weakens over the area east of 20° E and strengths over the Iberian Peninsula. Those are possibly associated with the change in atmosphere circulation. We will investigate this issue in the near future.

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