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Relative importance of water vapor and air temperature in the interannual variation of the seasonal precipitation: a comparison of the physical and statistical methods

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Abstract
The necessary condition for forming precipitation is the saturation of the atmosphere, and thus precipitation can be influenced by both water vapor and air temperature. Using the data from three reanalysis datasets for the recent 39 years, we examine the relative importance of water vapor and air temperature in the interannual variability of precipitation. Two methods are used to estimate the relative importance. One is the physical method, which is based on the very tight relationship between the seasonal precipitation and relative humidity as well as the definition expression of the relative humidity. The other is the statistical method, which uses linear regression and can be applied generally for many of the relationship issues. The goal of this study is to find out whether these two methods can obtain consistent results. For each method, an indicator is constructed to determine the relative importance of the water vapor and air temperature. The indicators of the two methods are calculated for each of the grid points. Comparisons include both their overall spatial distribution patterns and the spatial correlation of the two fields. It is found from the three datasets that over most of the grid points in the globe, the physical method and the statistical method can truly provide consistent results for the relative importance assessment. Both methods reveal that for every season, precipitation is majorly dominated by water vapor over the globe, with the dominance being mostly over the middle-low latitudes. However, there are still many areas where precipitation is dominated by air temperature, which appears especially over the middle-high latitudes.

Keywords Dominance · Interannual variability · Seasonal precipitation · Water vapor · Air temperature

1 Introduction

The intensity, duration, and frequency of the precipitation over different regions in the globe display large interannual variations in the warming climate (e.g., Räisänen 2002; Neelin et al. 2003; Douville et al. 2006; Sato et al. 2007; Chen et al. 2011; Seager et al. 2012; James and Washington 2013; Berg and Hall 2015; Xu et al. 2016; Pendergrass et al. 2017; Ni and Hsu 2018; Giorgi et al. 2019; Mishra 2019). These variations are generally attributed to the interannual abnormalities in the atmospheric circulations (e.g., Haston and Michaelsen 1997; Smith et al. 1998; Lenters and Cook 1999; Dünkeloh and Jacobeit 2003; Zhang et al. 2008; Bothe et al. 2012; Tao et al. 2014). Since water vapor is the material of the precipitation, the effect of the atmospheric circulation in transporting the water vapor has been emphasized in the previous studies (e.g., Chen et al. 1988; Berbery and Collini 2000; Bretherton et al. 2004; Evans and Smith 2006; Feng and Zhou 2012).

However, while water vapor is important, the necessary condition for the formation of precipitation is the saturation of the atmosphere, which depends on both water vapor and air temperature. The horizontal motion of the atmosphere can influence the transport of the water vapor and the warm/cold air, and thus the convergence of the moisture and heat flux. The vertical motion is related to the atmospheric instability and may lead to the ascending or lifting of the air. For the formation of the precipitation of

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a region, the ultimate (or total) effect of the three-dimensional atmospheric circulation is to change the local water vapor content and the local air temperature, which finally makes the air become saturated, at least at certain (condensation) levels. It has been found that, for the interannual variations, the seasonal precipitation total holds a very strong positive relation with the seasonal mean relative humidity of the atmosphere (e.g., Bretherton et al. 2004; Lu and Zeng 2005; Lu and Takle 2010). Compared with specific humidity, relative humidity can better indicate the interannual variation of the seasonal precipitation (Lu and Takle 2010).

Based on the physical relation of precipitation with relative humidity, along with the definition expression of the relative humidity, Lu and Takle (2010) designed a simple method to examine the concurrent effects of the water vapor and air temperature in the interannual variation of the seasonal precipitation. With defining the "change of water vapor" and the "change of air temperature" from a (composite) dry year to a wet year, the contributions of these two different quantities can be separated, and their relative importance to the variation of precipitation can be revealed from the comparison. This physical method can be used to identify whether the more precipitation of the wet year, relative to the dry year, is dominated by the more water vapor in the air, or the lower air temperature, or both of them. The method has also been applied to investigate whether the lack of moisture or the warm air temperature is more important to the formation of the severe drought events (Lu et al. 2011; 2014a).

For most issues in the climate (and other scientific) studies, the variation of the quantity examined may be influenced by two (or more) factors, but the relation cannot be expressed with a formula that is physically rigorous and mathematically determined. For these issues, we may also need to estimate, in the variation of the quantity, the relative importance of the different influencing factors. For example, when examining the interannual hydrological variations, Lu et al. (2010) explored which of the changes in the near-surface temperature and the precipitation is more important to the interannual variations of the streamflow, evapotranspiration, and snowmelt.

Statistical method can be used for such empirical linkages. Using a multiple linear regression, Lu et al. (2010) constructed the measures for comparing the relative importance of the different quantities. When fitting with the linear regression, the contribution of an influencing factor can be estimated with the coefficient of the factor, which indicates the change rate, multiplied by the standard deviation of its variation, which indicates the amplitude of the perturbation. This statistical method was later used to analyze the relative importance of the factors influencing the land surface energy balance (Hua and Chen 2011), the drought severity (Li 2012), the summer extreme precipitation (Lu et al. 2014b), and the total summer rainfall (Lu et al. 2016).

In the present study, the above two methods are both used for the specific issue of examining the relative importance in the interannual variation of precipitation. In the physical method, through the physically-sound relation of precipitation with relative humidity, precipitation can be physically linked to the water vapor and air temperature. In the statistical method, as for many other issues, we simply link the precipitation itself, directly, to the water vapor and air temperature. What we feel curious here is that, for the precipitation issue, whether the statistical method can provide consistent results with the physical method, regarding the relative importance of the water vapor and air temperature in the interannual variation of the precipitation. Inter-comparisons are performed for all the grid points over the globe in each season by using three reanalysis datasets.

The data used in this study are introduced in Sect. 2. The physical method, which includes the separation of the contributions of the water vapor and air temperature, the patterns of their concurrent effects, and the indication of the relative importance, is presented in Sect. 3. Shown in Sect. 4 is the statistical method, which presents the measures for estimating the contributions of the two influencing factors through the linear regression, and the indicator of the relative importance. The results of the relative importance of water vapor and temperature revealed from the two methods are compared in Sect. 5. One dataset is utilized as an example in Sects. 3, 4, 5 to narrate the applications of the two methods. Other two datasets are used in Sect. 6 for the inter-model comparisons of the results. Summary and discussion are given in Sect. 7.

2 The datasets used

The ERA-Interim Reanalysis (Berrisford et al. 2015), provided from the European Centre for Medium-Range Weather Forecasts (ECMWF), is utilized in Sects. 3, 4, 5 as an example to describe the details of the physical and statistical methods. The output of the model is over a Gaussian grid of T255. The data are converted into different horizontal resolutions, and a version of the dataset with a resolution of $2.5° \times 2.5°$ in latitude and longitude is adopted in this study. The data used include the monthly specific humidity, air temperature, and relative humidity. Two additional reanalysis datasets are used for further inter-model comparisons in Sect. 6. One is the JRA-55 Reanalysis (Kobayashi et al. 2015; Harada et al. 2016), developed by the Japan Meteorological Agency (JMA). The model output is over a Gaussian grid of TL319, and a dataset with resolution of $1.25° \times 1.25°$ is used in our analysis. The other is the NCEP-DOE Reanalysis 2 (Kanamitsu et al. 2002), from the National Centers for Environmental Prediction (NCEP) and the Department of Energy (DOE), with a horizontal resolution of 2.5° × 2.5° in latitude and longitude.

The CPC (Climate Prediction Center) Merged Analysis of Precipitation (CMAP) (Xie and Arkin 1997), with a resolution of 2.5° × 2.5°, is used in this study to determine the wet and dry years in the physical method and link the precipitation amount to the water vapor and air temperature in the statistical method. Before the use of the pressure-level data from the three reanalysis datasets, as a preliminary step, the precipitation data contained in the three datasets are compared with the CMAP data. Plots indicate that the precipitation data of the three datasets are fairly consistent with the CMAP precipitation, both in spatial patterns and in magnitudes (figures not shown).

We use the data from March 1979 to February 2018 for all the three reanalysis datasets and the CMAP precipitation. The results of the study are for the four seasons, with the MAM (March–April–May), JJA (June–July–August), SON (September–October–November), and DJF (December–January–February) representing the boreal spring, summer, fall, and winter, respectively.

3 The physical method

3.1 The physical linkage between precipitation and relative humidity

From the physics of precipitation, as mentioned above, since water vapor is the material of precipitation, sufficient moisture is generally required for forming precipitation. However, the necessary condition for the formation of precipitation is the saturation of the atmosphere, at least at certain (condensation) levels. This is true for a single synoptic precipitation process. At the seasonal timescale, it has been revealed that the seasonal-mean relative humidity can also be used to indicate the interannual variations of the seasonal precipitation total (Lu and Takle 2010).

Figure 1 shows the correlations of the seasonal precipitation amount with the seasonal-mean temperature, specific humidity, and relative humidity of each grid point (all plots in Sects. 3, 4, 5 use the ERA-Interim reanalysis). The correlation of precipitation with specific humidity is positive at most of the grid points over the globe for all

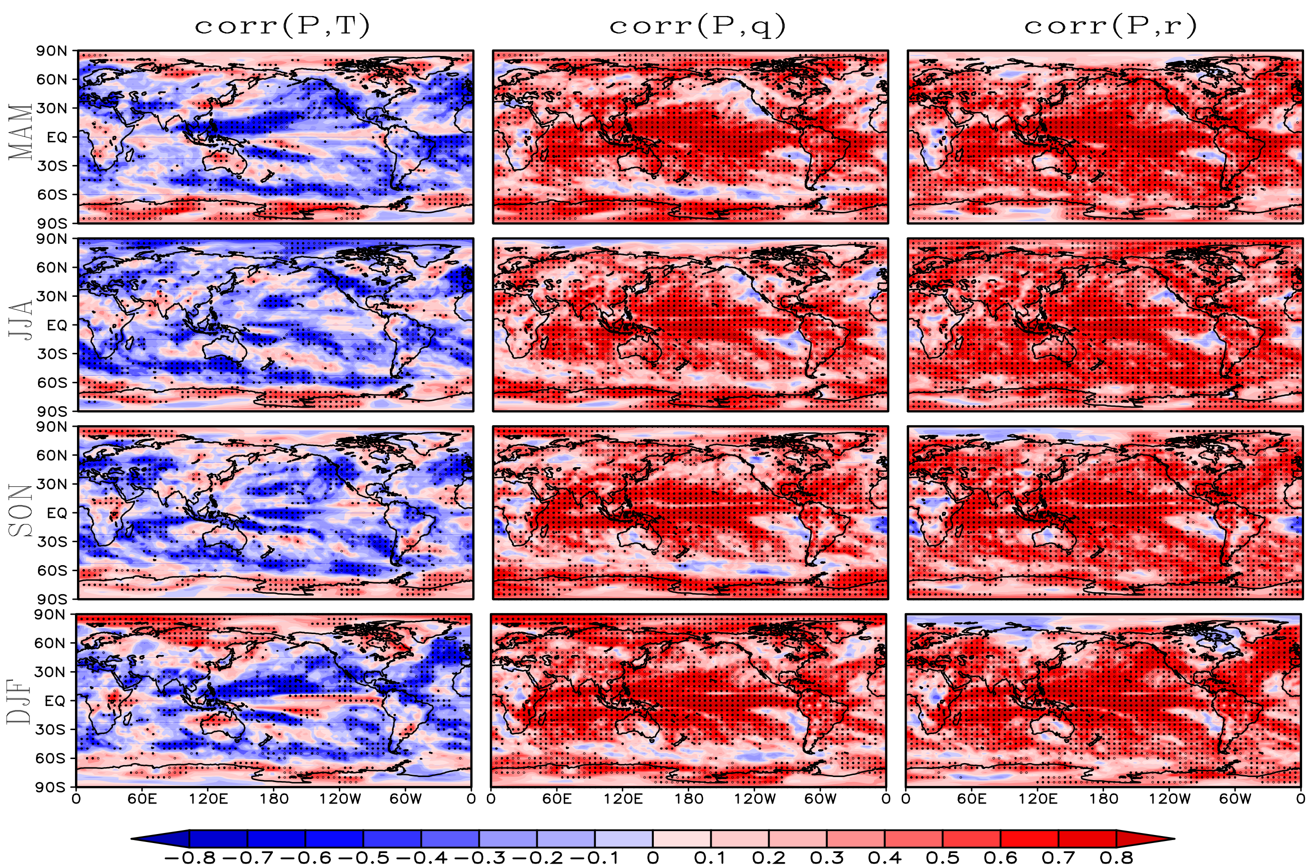

Fig. 1 Distributions of the correlations of the CMAP precipitation with the air temperature (left), specific humidity (middle), and relative humidity (right) at 600-hPa from the ERA-interim dataset for the period Mar 1979–Feb 2018. The grid points where the correlation is significant at the 95% confidence level are highlighted with the dots

seasons, suggesting that specific humidity can reflect the interannual variation of the precipitation. The correlation of precipitation with the air temperature is majorly negative, overall from the globe. This suggests that the air temperature may also, to some extent, reflect the interannual variation of the precipitation.

However, when using the relative humidity, which combines both water vapor and air temperature, it can better indicate the interannual variation of the precipitation, better than using the air temperature or the specific humidity alone. The correlation of precipitation with the relative humidity shows that, compared with the correlation with specific humidity, the relation is positive at more grid points, and the correlation is more significant at most of the grid points. This suggests that although water vapor can well indicate the variability of precipitation, relative humidity is much better in indicating the interannual variability of the precipitation.

The correlation of the precipitation with relative humidity is positive and can be significant at the 95% confidence level at most of the grid points over the globe for all seasons. The overall very tight positive relationship of the seasonal precipitation and relative humidity may allow us to explore the concurrent variations of the water vapor and air temperature in the interannual variation of the seasonal precipitation.

3.2 The contributions from water vapor and air temperature

For the concurrent variations of the water vapor and air temperature, Lu and Takle (2010) proposed two physically-based measures to compare the changes of the two different quantities between the (composite) wet year and the dry year. In the present study, we use different definitions and notations, so that we may conveniently compare the contributions from the changes of the water vapor and air temperature to the interannual variation of the relative humidity, and thus the variation of the precipitation.

For each grid point, with the seasonal precipitation of the total 39 years, we make composites of the 13 wettest years and the 13 driest years. Then, a contrast is performed between the composite wet year and the composite dry year. With the increase of precipitation from the (composite) dry year to the wet year ($P_{wet}/P_{dry} > 1$), the increase in relative humidity at a level can be denoted as $r_{wet}/r_{dry} > 1$. It can be written as

$$C_r > 0, \tag{1}$$

where $C_r \equiv \ln\left(r_{wet}/r_{dry}\right)$ measures the change of relative humidity between the dry and wet years.

Express relative humidity as $r = q/q_s(T)$, where q is specific humidity and $q_s(T)$ is the saturation specific humidity at temperature T. Then we can obtain $C_r = C_q + C_T$, where

$$C_q \equiv \ln\left(q_{wet}/q_{dry}\right), \tag{2}$$

and

$$C_T \equiv \ln[q_s(T_{dry})/q_s(T_{wet})]. \tag{3}$$

Then relation (1) can be written as

$$C_q + C_T > 0. \tag{4}$$

The C_q and C_T are the measures of the "contributions" from the water vapor and air temperature, because of their changes, to the change of the relative humidity between the dry and wet years.

Figure 2 shows the distributions of the C_q and C_T, which measure the contributions of the water vapor and air temperature to the change of the relative humidity, and thus the precipitation, from the dry year to the wet year. Overall, for the four seasons, water vapor has a positive contribution over most of the grid points in the globe. It may have large contributions, and the largest contributions are over the middle-low latitudes, especially over the tropical oceans. The air temperature may have positive contributions as well as negative contributions, depending on the location. The magnitudes of the contributions from the air temperature are relatively weak, compared with the strongest contributions from the water vapor. However, for each specific grid point, whether water vapor or air temperature is more important needs to be further analyzed.

3.3 The patterns of the concurrent contributions

According to relation (4), with the condition of $C_r > 0$, the concurrent variations and effects (or contributions) of the water vapor and air temperature can be categorized into three patterns. In the first pattern, $C_q > 0 > C_T$ while $C_q > \left|C_T\right|$. This means that corresponding to the increase of precipitation from the dry year to wet year, air temperature increases and thus has a negative contribution. Meanwhile, water vapor also increases, which has a positive contribution. Also, the contribution of the water vapor is greater than that of the air temperature in magnitude. This is the "moistening" pattern. In the second pattern, $C_T > 0 > C_q$ while $C_T > \left|C_q\right|$. This means that, corresponding to the increase of precipitation, water vapor decreases and thus has a negative contribution. However, air temperature also decreases, which has a large positive contribution. This is an interesting pattern. Corresponding to the more precipitation of wet year, there is less water vapor in the atmosphere; the more precipitation is due to the much lower air temperature. This is the "cooling" pattern. The third is the "moistening-cooling" pattern, in which $C_q > 0$ and $C_T > 0$. Corresponding to the increase of precipitation, water vapor increases while air

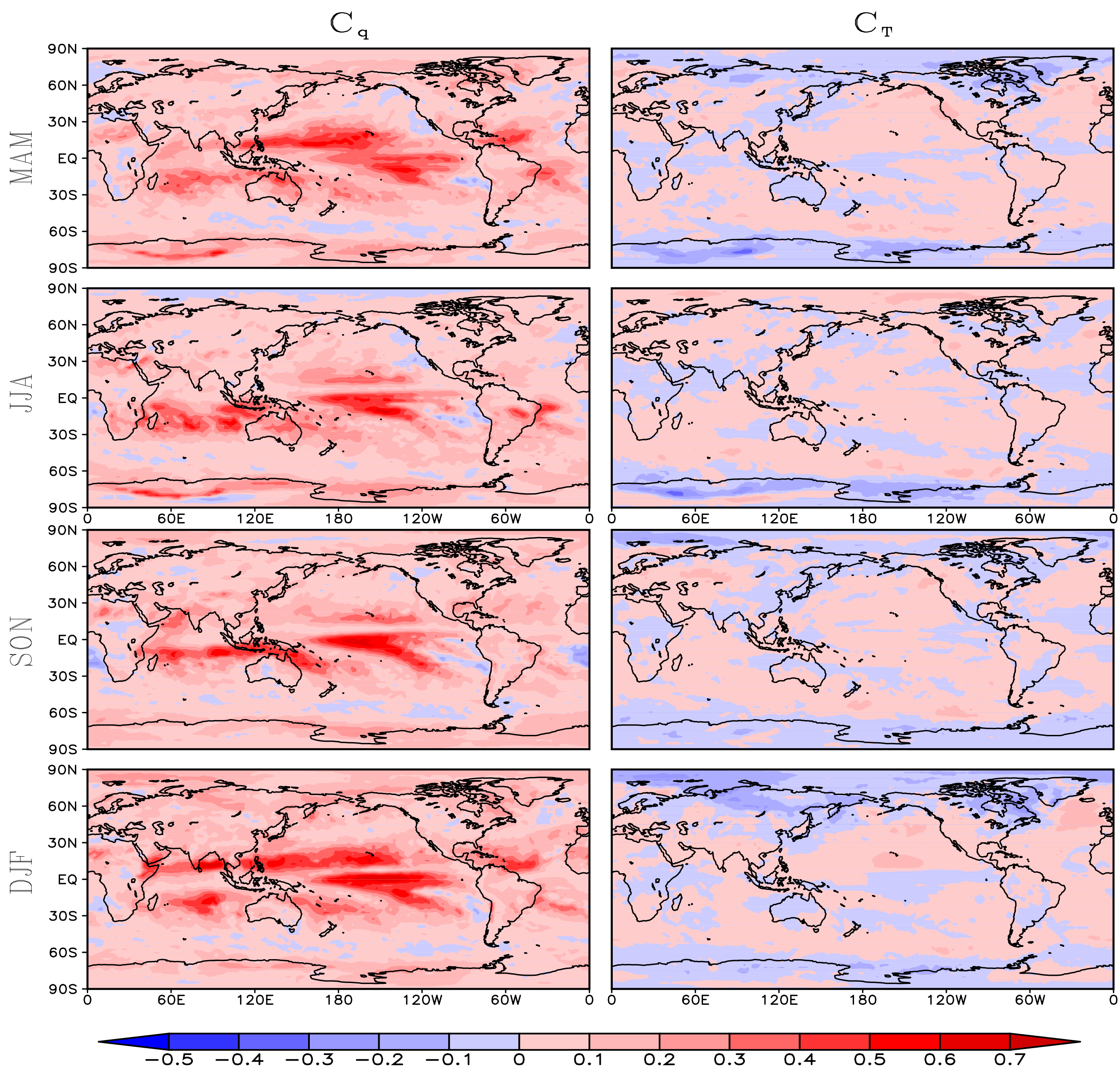

Fig. 2 Distributions of the C_q (left) and C_T (right) at 600-hPa (with ERA- interim), which measure the contributions of the water vapor and air temperature to the change of the relative humidity between the wet and dry years

temperature decreases, and thus both have positive contributions. This is the more general situation.

Figure 3 shows the distributions of the three patterns for the concurrent contributions from water vapor and air temperature for the four seasons, corresponding to the change of the relative humidity. Relative humidity increases from dry year to wet year ($C_r > 0$) over most of the grid points in the globe for all seasons. These grid points with the increasing relative humidity is classified in Fig. 3, in terms of the above three patterns that stress the different concurrent effects of the water vapor and air temperature.

Overall, for the four seasons, the cooling pattern (blue) mainly appears in the middle-high latitudes of both hemispheres. The moistening pattern (red) and the moistening-cooling pattern (yellow) may appear in all latitudes. In addition, the distribution of the patterns, especially the cooling pattern, displays a seasonal transition along the north-south direction. Over the wide regions with the moistening-cooling pattern, water vapor and air temperature both have positive contributions. Their relative importance can further be examined.

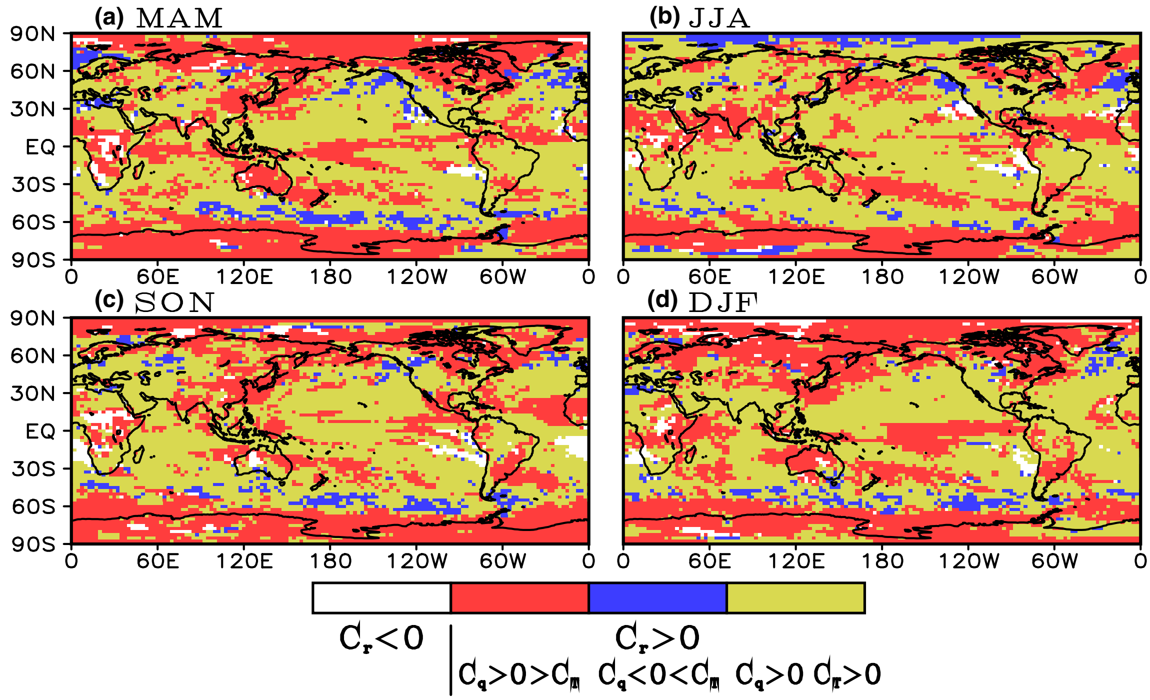

Fig. 3 Distributions of the three patterns of the concurrent effects (contributions) from the water vapor and air temperature at 600-hPa (with ERA-interim) corresponding to the change from the dry year to the wet year: The moistening pattern (red, $C_q > 0 > C_T$ and $|C_q| > |C_T|$), the cooling pattern (blue, $C_T > 0 > C_q$ and $|C_T| > |C_q|$), and the moistening-cooling pattern (yellow, $C_q > 0$ and $C_T > 0$). Grid points with $C_r < 0$ are not plotted

3.4 The dominance indicator of the physical method

Over most of the grid points where the physical linkage of seasonal precipitation with relative humidity is valid, the increase of the relative humidity can be contributed from both water vapor and air temperature, as long as the relation $C_q + C_T > 0$ is satisfied. Over the regions with the moistening pattern, whose condition can be written as $|C_q| > |C_T|$, the warmer air has a negative contribution, and the more precipitation of wet year is dominated by the more water vapor. It is interesting that over the areas with the cooling pattern, whose condition can be written as $|C_T| > |C_q|$, the more precipitation of wet year is not because of the more water vapor in the atmosphere; it is simply dominated by the much lower air temperature. Over the regions with the moistening-cooling pattern, which is the most popular one over the globe, the more precipitation is due to both the more water vapor and the lower air temperature. For this pattern, whether water vapor or air temperature dominates the change of precipitation can be determined through comparing the $|C_q|$ and $|C_T|$.

Therefore, for the dominance analysis, all the grid points with the three patterns can finally be classified into two types, according to the comparison between the $|C_q|$ and $|C_T|$. One is the type for $|C_q| > |C_T|$. The change of precipitation is dominated by water vapor. In Fig. 3, this includes the grid points of the moistening pattern (red) and partial grid points of the moistening-cooling pattern (yellow). The other is the type for $|C_T| > |C_q|$. The change of precipitation is dominated by air temperature. It includes the grid points of the cooling pattern (blue) and the remaining grid points of the moistening-cooling pattern.

The relative importance of the water vapor and air temperature in the interannual variations of the seasonal precipitation can hence be determined through comparing the values of the $|C_q|$ and $|C_T|$. The indicator of relative importance for this physical method is thus defined as

$$Q_p = |C_q| / (|C_q| + |C_T|). \quad (5)$$

This indicator ranges from 0 to 1. When $Q_p > 0.5$, the change of water vapor is more important, and dominates the interannual variation of the seasonal precipitation. When $Q_p < 0.5$, the change of air temperature is more important. The results of the indicator will be presented and compared in Sect. 5.

4 The statistical method

4.1 The linear fitting and the relative importance

In our previous studies, a statistical method was initially used in Lu et al. (2010) to analyze the relative importance of the different influencing factors. Lu et al. (2016) then demonstrated the reasonability and reliability of the method. For the general issue in which a quantity Z can be influenced by variables X and Y, we express the relation as $Z = Z(X, Y)$. As suggested in their studies, it would be convenient to analyze the relative importance of the two influencing variables if we could simplify the relation linearly as

$$Z = a \cdot X + b \cdot Y + c. \tag{6}$$

This relation, i.e., the three coefficients, can be determined with the data (time series) of the X, Y, and Z.

The meaning of the a and b can be illustrated by expressing them as $a = \partial Z/\partial X$ and $b = \partial Z/\partial Y$. They represent, respectively, the change rates of the Z with respect to X and Y, or the amount of the changes in Z corresponding to a unit increase in X and Y.

We may then use the measures $I_X \equiv |\partial Z/\partial X| \cdot \sigma_X$ and $I_Y \equiv |\partial Z/\partial Y| \cdot \sigma_Y$ to indicate the relative contributions to the Z from the X and Y. Here, σ_X and σ_Y are the standard deviations of the X and Y, which reflect respectively the scales of the year-to-year perturbations of the X and Y.

With the coefficients fitted from the regression, the two measures can be expressed as

$$I_X \equiv |a| \cdot \sigma_X \tag{7}$$

and

$$I_Y \equiv |b| \cdot \sigma_Y. \tag{8}$$

4.2 Linking precipitation to water vapor and air temperature

The present issue of linking precipitation to the water vapor and temperature can also be treated as one of the general issues mentioned above, and we may simply establish the linkage directly, and use a linear regression to fit the relation. Water vapor (specific humidity) and air temperature are two different quantities, and they have different units. For the convenience to compare their changes (as well as the change of the precipitation), the three quantities of the seasonal-mean specific humidity and air temperature as well as the seasonal total of precipitation are first normalized, based on their 39-year time series (samples), before establishing the relation using Eq. (6). Finally we obtain

$$P = A \cdot q + B \cdot T + C, \tag{9}$$

where P, q, and T are, respectively, the normalized seasonal precipitation, specific humidity, and air temperature. Because of the normalizations of the input quantities, the coefficients A and B fitted with the data can be compared in their magnitudes, and the constant C may go to zero. The fitting is performed for every grid point over the globe and for all seasons.

Significance tests are made to the linear regression to ensure the reliability of the direct linkage of the precipitation to the water vapor and air temperature. Figure 4 shows the distributions of the coefficient of determination for the linear regression of the seasonal precipitation with water vapor and air temperature, which is the square of the multiple-correlation coefficient (Cohen et al. 2013). The multiple correlation between the observed precipitation and the precipitation fitted from (9) is significant at the 95% confidence level at most grid points over the globe in every season.

Because of the normalizations of the input quantities, we have $\sigma_q = 1$ and $\sigma_T = 1$. Then the two measures can be expressed as

$$I_q \equiv |A| \tag{10}$$

and

$$I_T \equiv |B|. \tag{11}$$

This means that when we use the normalized quantities to fit the linear relation, the coefficients of the regressed relation can fundamentally reflect, with their absolute values, the relative importance of the two influencing factors.

The distributions of the coefficients A and B obtained from the linear regression of the normalized precipitation with the normalized water vapor and temperature are displayed in Fig. 5. The A is positive at most of the grid points in the globe for all the seasons. The B is negative at most of the grid points in every season. In most regions over the globe, precipitation increases with water vapor (A is positive) but decreases with the air temperature (B is negative).

However, the situation can be different over some tropical ocean areas. In addition to the positive values of coefficient A, the coefficient B there also has positive values. Over these regions, precipitation increases with the air temperature at the condensation (600-hPa) level, according to the regression. This may be due to the strong vertical consistency of the air temperature. The air temperature at the condensation levels may have a strong positive correlation with the near-surface air temperature, which reflects the surface evaporation. The higher air temperature at the level may suggest, indirectly, a higher surface air temperature, and thus a stronger evaporation. Through the evaporation, the atmosphere at the condensation levels may gain much more water vapor. Hence, finally, the positive effect of the warm surface air temperature, which favors the evaporation,

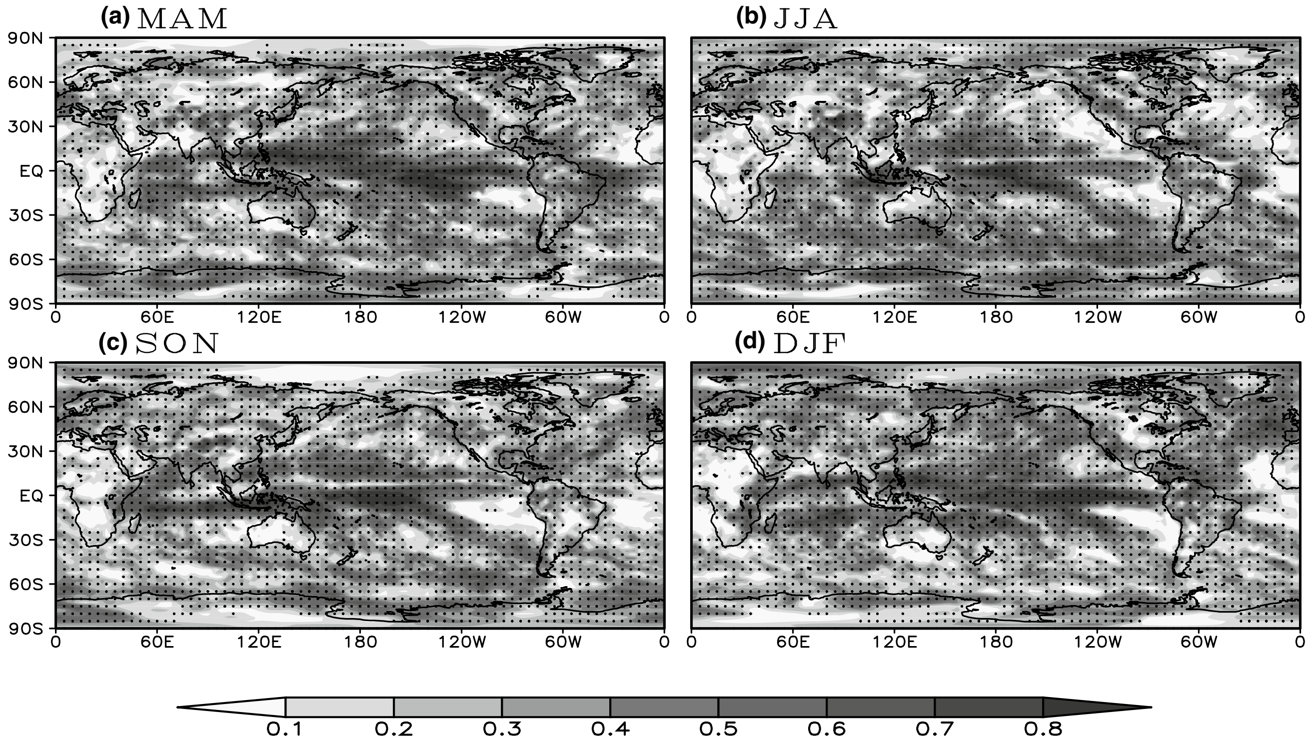

Fig. 4 Distributions of the coefficient of determination (R^2) for the linear regression of the seasonal precipitation with the water vapor and air temperature at 600-hPa (with ERA-interim). The grid points where the coefficient of the multiple-correlation (R) is significant at the 95% confidence level are highlighted with the dots

might be stronger than the negative effect of the warm air temperature at the condensation level, which enhances the water vapor holding capability of the atmosphere and thus does not favor the precipitation. The net effect leads to a positive relation between the precipitation and the air temperature at the condensation level.

4.3 The dominance indicator of the statistical method

Since they are normalized, these two different quantities can be directly compared. The relative importance of the water vapor and air temperature in the interannual variation of the seasonal precipitation can thus be determined with this statistical method through defining the

$$Q_s = I_q \big/ (I_q + I_T). \quad (12)$$

This indicator also ranges from 0 to 1. When $Q_s > 0.5$, the change of water vapor is more important, and dominates the interannual variation of the seasonal precipitation. When $Q_s < 0.5$, the change of air temperature is more important, which dominates the variation of the precipitation. The large values of the Q_s suggest a more contribution from the water vapor. The results of this indicator will be presented, and compared with that of the physical method, in Sect. 5.

5 Comparison of the results from the two methods

Figure 6 presents the results of the relative importance of water vapor and air temperature in the interannual variation of precipitation revealed respectively from the physical method and the statistical method for each of the four seasons. Two aspects will be examined here to illustrate the consistency of the results obtained from the two methods. One is the overall spatial distribution patterns of their indicators, which may provide a general idea of the regional characteristics of the relative importance. The other is the spatial correlation of the two fields, which may provide an idea whether and how the results of the relative importance from the two methods are locally consistent.

It is shown from Fig. 6 that over the wide regions in the globe, the distribution patterns of the two methods are fairly consistent. Overall, for the four seasons, the results of the two methods illustrate that the grid point where Q_p and Q_s are greater than 0.5, and thus the seasonal precipitation there is dominated by the water vapor, though can appear in all

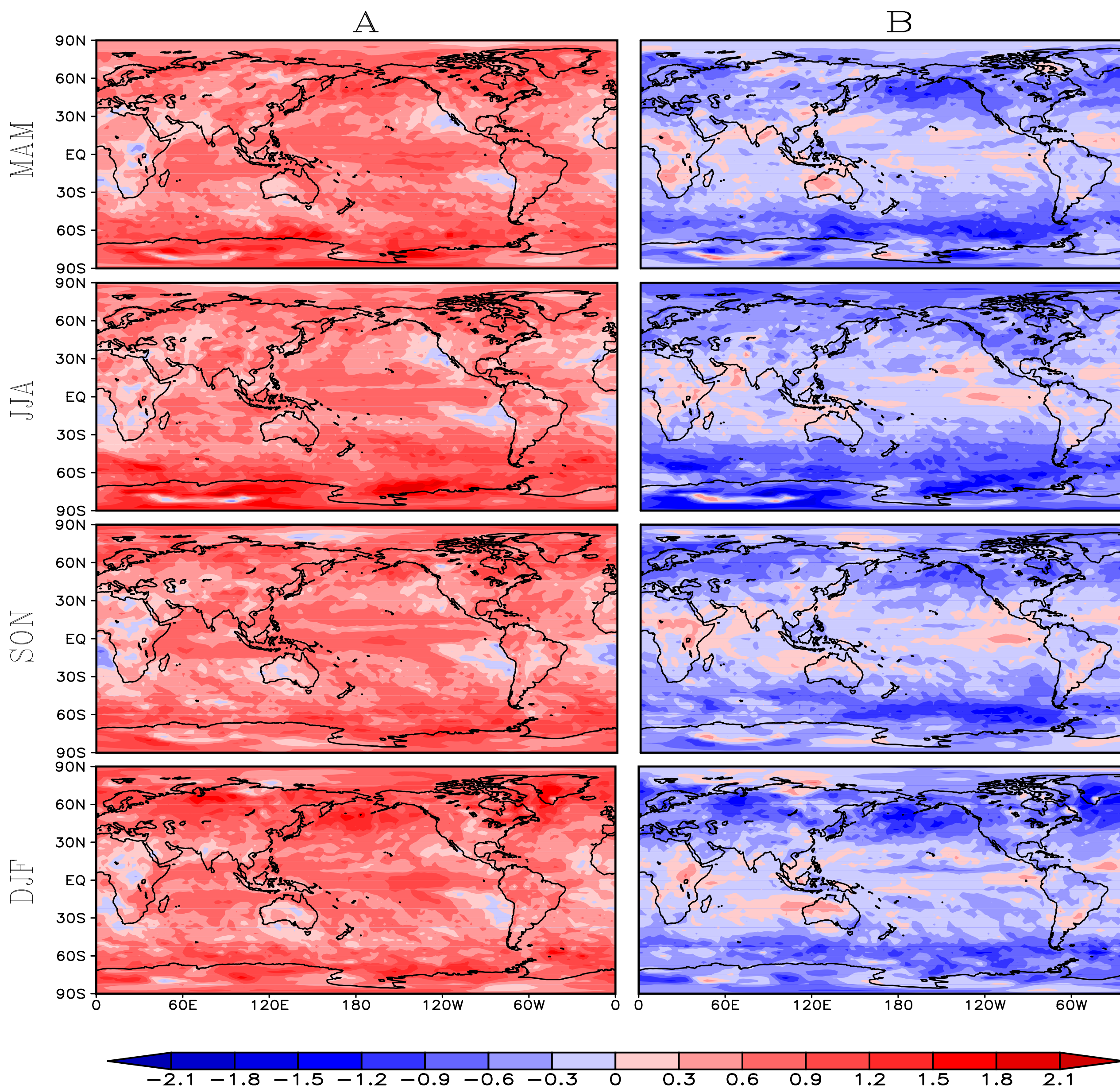

Fig. 5 Distributions of the coefficients *A* (left) and *B* (right) obtained from the linear regression of the normalized precipitation with the normalized water vapor and temperature at 600-hPa (with ERA-interim)

latitudes, is mostly over the tropics and subtropics. The grid point where Q_p and Q_s are less than 0.5, and thus the corresponding precipitation is dominated by air temperature, is mainly distributed in middle-high latitudes of the two hemispheres.

We notice that, in Fig. 6, the red and blue colors in the plots of the statistical method (the right panel) are lighter than that of the physical method (the left panel). The reason is that in the physical method, we simply contrast the two ends of the total 39-year samples. That is, with dropping those normal years, we composite the 13 wettest years and the 13 driest years and then contrast the composite wet and dry years. Differently, in the statistical method, the total 39-year samples are included for establishing the regressions. The inclusion of the samples of those normal years may weaken the fitted relations, although the classification for the composites in the physical method is based on the precipitation, with no particular consideration of the water vapor and air temperature. In the statistical method, we may also fit the relation using just the 26 samples, i.e., the 13 wettest years plus the 13 driest years. Spatial distributions (not shown) illustrate that the relations fitted from the 26 samples can be, in general, stronger than that originally obtained from the

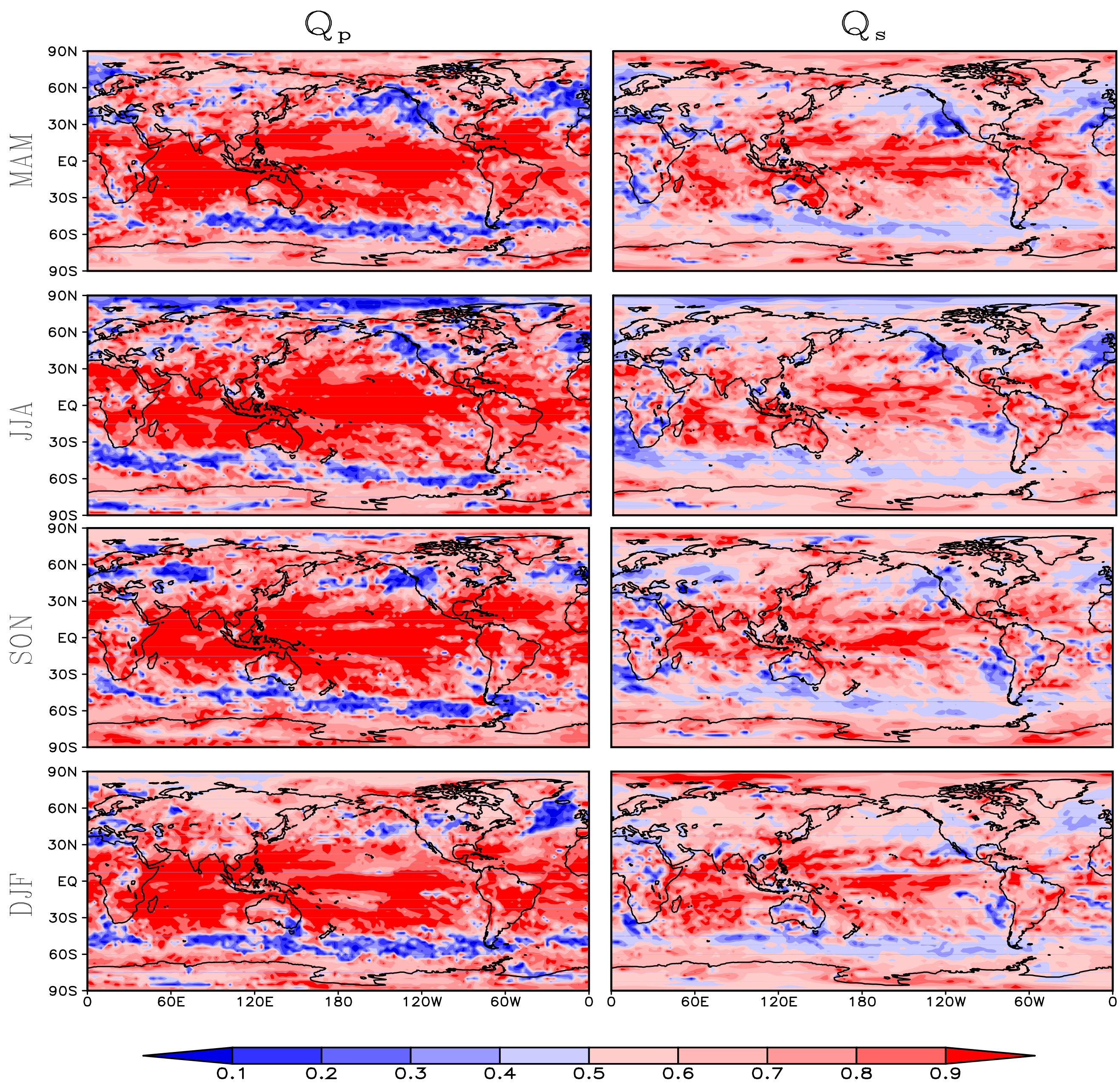

Fig. 6 Distributions of the Q_p (left) and Q_s (right), the two measures defined respectively for the physical method and the statistical method to indicate the relative importance of the water vapor and air temperature at 600-hPa (with ERA-interim). The grid points where precipitation is dominated by water vapor (air temperature) are marked in red (blue)

total 39 samples, and thus the corresponding red and blue colors can be deeper in the plots.

In addition to the comparison of the spatial patterns of the relative importance from the two methods, a point-to-point comparison is also performed to the two fields. Table 1 presents the coefficients of the correlation between the spatial fields of the Q_p and Q_s. The coefficients of the spatial correlation between Q_p and Q_s can be 0.656, 0.652, 0.654, and 0.588 for the four seasons, which are significant, considering the large number of the spatial samples. This demonstrates that the two fields of the indicators for the two methods are truly very consistent in indicating the relative importance.

6 Some further intercomparisons

Precipitation is related to the saturation of the moist air. In both the physical method and the statistical method, precipitation needs to be linked to the water vapor and air temperature of the saturation levels. In the above analysis (Sects. 3,

Table 1 The coefficients of the spatial correlations between the Q_p and Q_s, calculated with all the grid points over the globe, for the three vertical levels and for the four seasons. The Q_s is based on the linear regression of the data from the total 39 years

		MAM	JJA	SON	DJF
ERA-Interim	500 hPa	0.670	0.671	0.664	0.612
	600 hPa	0.656	0.652	0.654	0.588
	700 hPa	0.661	0.655	0.658	0.615
JRA-55	500 hPa	0.697	0.699	0.682	0.698
	600 hPa	0.684	0.685	0.683	0.712
	700 hPa	0.650	0.669	0.679	0.710
NCEP-DOE	500 hPa	0.581	0.594	0.569	0.567
	600 hPa	0.580	0.599	0.587	0.570
	700 hPa	0.596	0.625	0.609	0.625

4, 5), the 600-hPa is taken as a representative level for presenting all the distributions. In addition to this level, we have also plotted all the figures, the same as shown in Figs. 1, 2, 3, 4, 5, 6, for other pressure levels. Figures 7 and 8 show, respectively, the final results for the Q_p and Q_s at the 700- and 500-hPa levels, calculated with the same ERA-Interim reanalysis. Comparisons indicate that the distributions of the Q_p at the 500-, 600-, and 700-hPa are very similar, and the distributions of the Q_s at the three levels are also very similar. Table 1 presents the spatial correlations of the Q_p and Q_s for all the three levels of this reanalysis. Similar to the results of the 600-hPa, the correlations of the two fields for the 700- and 500-hPa levels are also very strong for all the seasons.

In addition to the ERA-Interim reanalysis, which is used as an example in the above analysis (Sects. 3, 4, 5) for describing the applications of the physical and statistical methods, we also use the JRA-55 reanalysis and the NCEP-DOE reanalysis in the present study to further demonstrate the consistency of the two methods in indicating the relative importance of the water vapor and air temperature to the seasonal precipitation. Using these two reanalysis datasets, we reproduce all the plots, as displayed in Figs. 1, 2, 3, 4, 5, 6, including the 500-, 600-, and 700-hPa levels. What presented in Fig. 9 is an example of the results, which shows the distributions of the Q_p and Q_s of the 600-hPa calculated with the JRA-55 reanalysis. Intercomparisons of the three datasets illustrate that all the distributions of the Q_p, at the 500-, 600-, and 700-hPa levels with the ERA-Interim, the JRA-55, and the NCEP-DOE reanalysis, are very similar. All the distributions of the Q_s at the three levels for the three reanalysis datasets are also very similar. Table 1 presents all the spatial correlations of the Q_p and Q_s for the three levels and the three reanalysis datasets. The correlations of the two fields are all very strong for the four seasons.

The goal of the present study is to compare the behaviors of the physical and statistical methods in indicating the dominance of the water vapor and air temperature in the interannual variation of the precipitation. All the above intercomparisons, among the different reanalysis datasets, different condensation levels, and different seasons, demonstrate that the two methods can truly provide consistent results in reflecting the relative importance of the water vapor and air temperature in the interannual variation of the precipitation.

7 Summary and discussion

Dominance analysis is required in nature (and even social) sciences. A quantity we examine may be influenced by two (or more) factors. For example, in the climate study, the summer precipitation over East China may be influenced by the sea surface temperature over the Pacific Ocean and the thermal effect of the Tibetan Plateau, along with other factors. We may need to assess which of these factors is more important than the others in the year-to-year variation of the summer precipitation. Generally, for the issues with multiple influencing factors, we may use statistical method to analyze the relative importance. In our previous studies, a simple statistical method has been used to determine whether the near-surface air temperature or the precipitation is more important in the interannual variation of the hydrological quantities (Lu et al. 2010), as well as whether the rainy days or the averaged precipitation intensity is more important in the interannual variation of the seasonal precipitation total (Lu et al. 2016).

When examining the relative importance of the water vapor and air temperature in the interannual variation of the seasonal precipitation amount, we may also use the statistical method. However, for this special issue, we happen to be able to develop a physical method to analyze the relative importance. The goal of this study is to compare the two methods, and find out whether the two methods can provide consistent results. The physical method is physically-based, and is thus more robust. The consistency of the two methods may give us more confidence in using the simple regression-based statistical method to assess the relative importance for other scientific issues.

The key of the physical method for this special issue is that, based on the precipitation physics, the atmosphere needs to be saturated for forming precipitation. At seasonal timescale, the precipitation-relative humidity relation is valid over most of the grid points in the globe. So, compared with water vapor alone, the relative humidity that combines water vapor and air temperature can better indicate the interannual variation of the precipitation. The physical expression of the relative humidity enables us to examine the concurrent effects of the water vapor and air temperature, and further compare their contributions and relative importance.

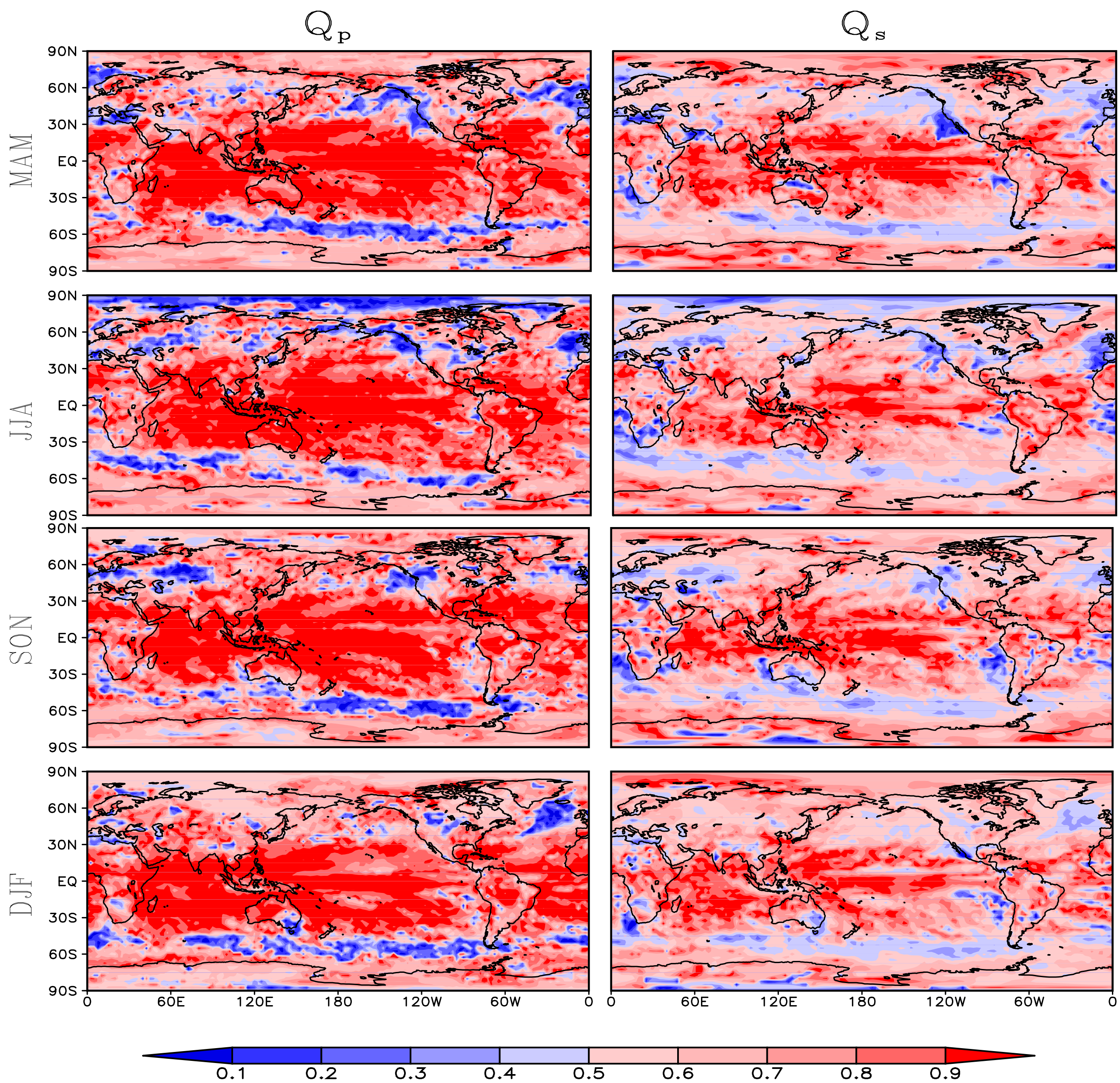

Fig. 7 Distributions of the Q_p and Q_s at 700-hPa (with ERA-interim)

With the derivations in this study, the effects (or contributions) from the water vapor and air temperature can be linearly separated. By using the defined measures C_q and C_T, the concurrent effects are classified into three patterns. The moistening pattern shows that the more precipitation of a wetter year is due to the particularly more water vapor, while air temperature is higher and thus plays a negative role. The cooling pattern reveals an interesting situation. Corresponding to the more precipitation, there is less water vapor in the atmosphere. The key is that the air temperature is extremely low, and thus dominates the more precipitation of the wetter year. The moistening-cooling pattern is a very common situation. The more water vapor and the lower air temperature both play positive roles to the more precipitation of the wetter year, and their relative importance can be further compared with the two measures. For all these three patterns, analysis indicates that the relative importance of the water vapor and air temperature can be concluded through comparing the absolute values of the two measures.

When using the statistical method, the seasonal precipitation is directly linked to the water vapor and air temperature, with a linear regression. For general issues, the two

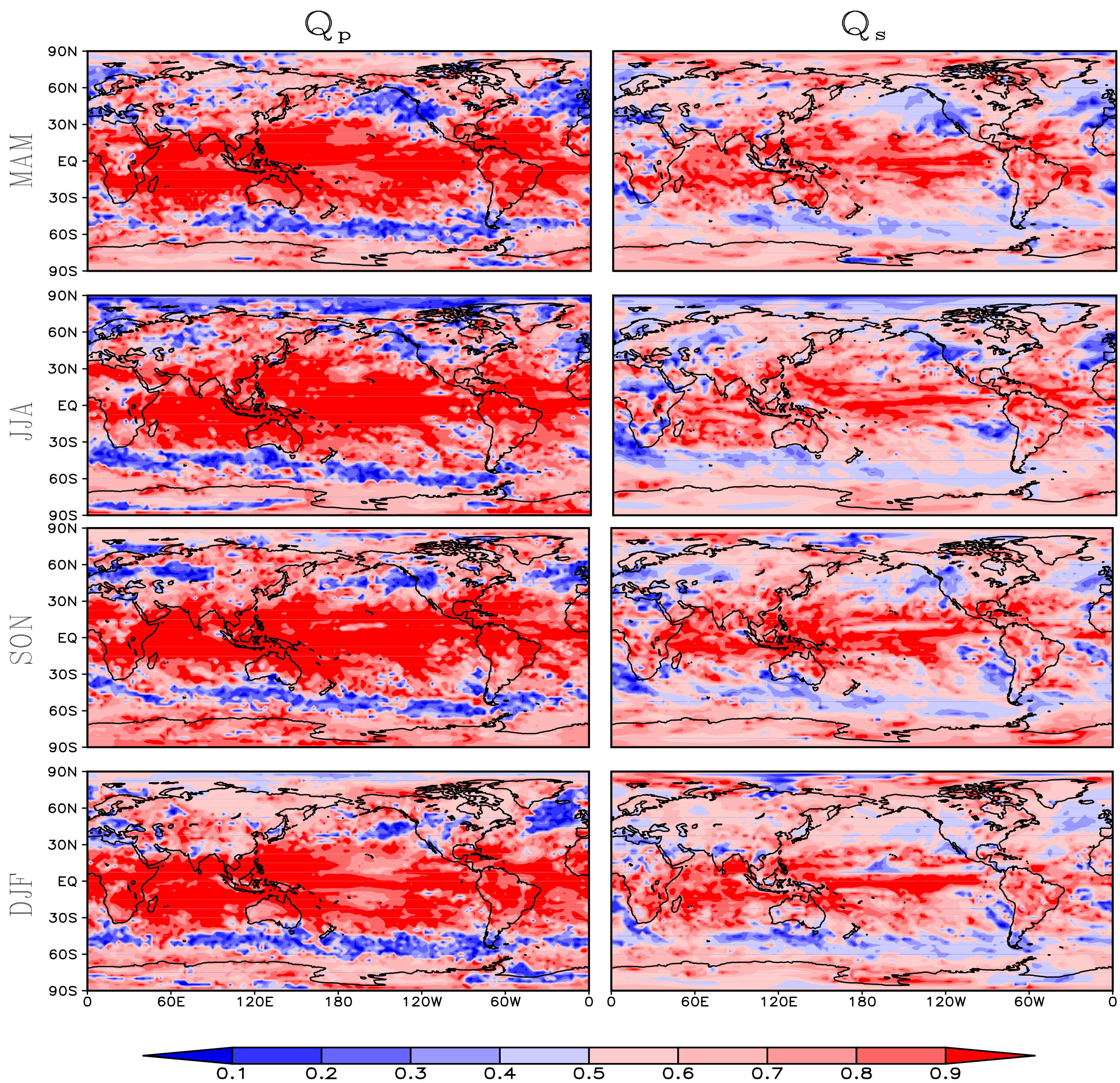

Fig. 8 Distributions of the Q_p and Q_s at 500-hPa (with ERA-interim)

measures I_X and I_Y, which estimate the contributions from the two influencing factors, are designed with considering the change rates and the perturbation scales. In the present study, the three input quantities of the regression are all normalized, and thus the measures I_q and I_T actually become the absolute values of the two coefficients fitted from the corresponding regression. Results of the fitting show that, for all seasons, coefficient A is positive and coefficient B is negative at most grid points over the globe. This suggests that, at most grid points over the globe, the seasonal precipitation increases with water vapor but decreases with air temperature. Although it is simply obtained from the statistical method, the conclusion is reasonable and is consistent with the physical understanding.

The relative importance determined from the physical method, characterized with the indicator Q_p, and the relative importance obtained from the statistical method, characterized with the indicator Q_s, are compared, from both the patterns of their spatial distributions and the correlations of their spatial fields. In addition, intercomparisons are performed among three vertical levels and four seasons, by using the three reanalysis datasets. The results of these

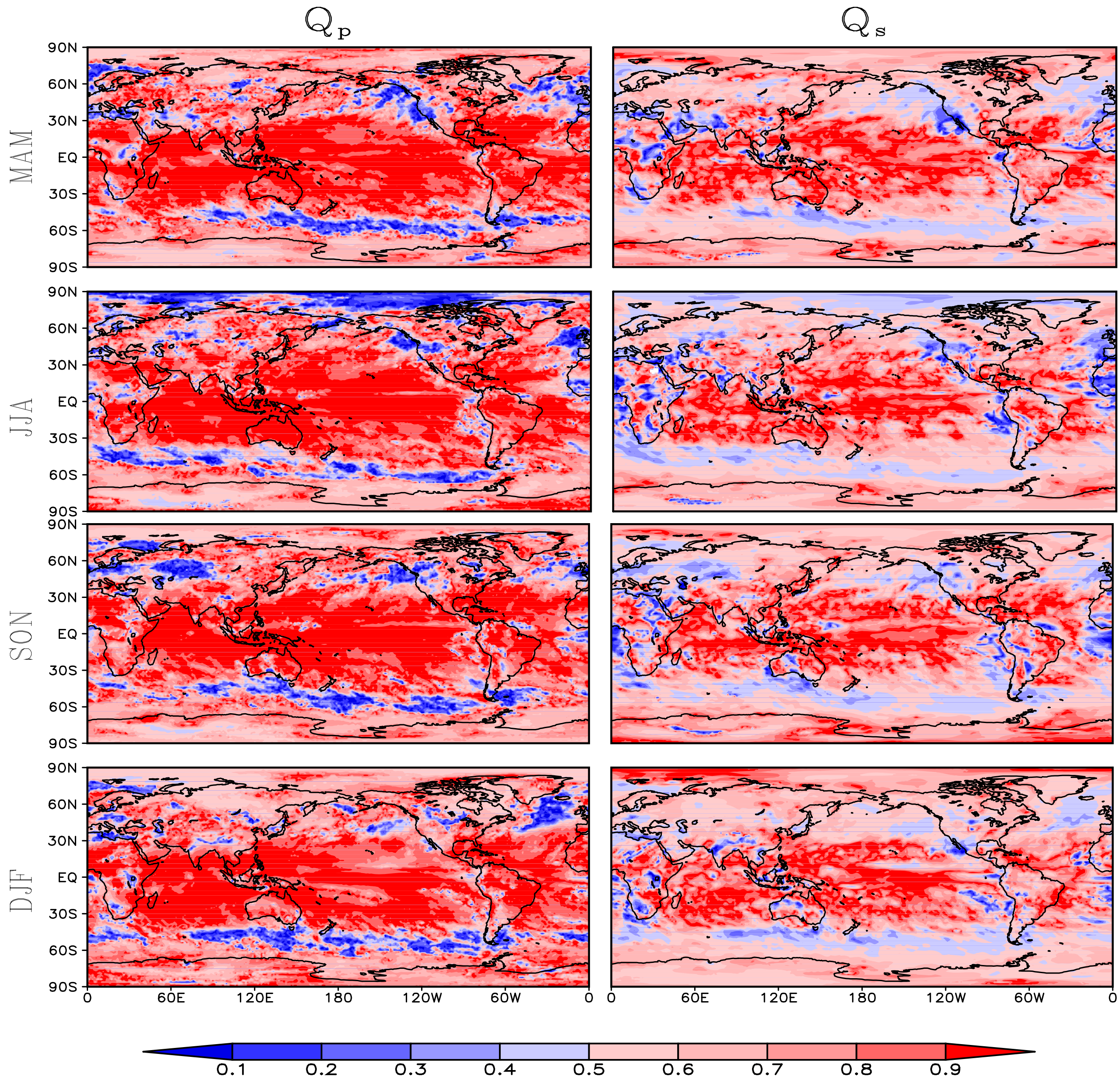

Fig. 9 Distributions of the Q_p and Q_s at 600-hPa (with JRA-55)

intercomparisons, as displayed in Table 1, demonstrate that the physical and statistical methods can truly provide consistent results in revealing the relative importance of the water vapor and air temperature in the interannual variation of the precipitation.

The physical method is based on the tight interannual relationship between the seasonal precipitation and relative humidity, which is sound in physics from the perspective of the formation of precipitation, along with the definition expression of the relative humidity. The results derived from the physical method are thus relatively more reliable. The statistical method is a more general approach, which links precipitation directly to the two influencing factors, i.e., the water vapor and air temperature, and the formula involved are not physically determined. Hence, as the goal of the present study, the results obtained from the statistical method should be compared with that from the physical method. The above comparison of the two methods with the different datasets suggests that qualitatively, as assessed from the globe, the results of the statistical method are consistent with the results of the physical method. The consistency supports the reliability of the statistical method, suggesting that this simple method is also capable in indicating the relative importance, and thus might be used for other scientific issues.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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