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Concurrent variations of water vapor and temperature corresponding to the interannual variation of precipitation in the North American Regional Reanalysis

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The concurrent variation patterns of water vapor and temperature corresponding to the interannual variation of winter precipitation and the roles of change in atmospheric circulation are studied with the North American Regional Reanalysis. A very tight positive relationship between precipitation and relative humidity at interannual time scale is found from the large spatially sampled data set. On the basis of this relationship, the concurrent variations of water vapor and temperature between the wettest and the driest years are categorized into three patterns. The distribution of the patterns shows that more winter precipitation of wetter years corresponds to more water vapor but not lower temperature (moistening pattern) in high latitudes, lower temperature but not more water vapor (cooling pattern) in midlatitudes, and both more water vapor and lower temperature (moistening-cooling pattern) in low latitudes. The characteristics and roles of change in atmospheric circulation from the driest years to the wettest years are analyzed for two selected areas. It is found that, around the selected cooling pattern (moistening pattern) area, the field of wind difference between the wettest years and the driest years is divergent (convergent). Dominated by this, the fields of differences in both heat flux and water vapor flux are divergent (convergent). This leads to the decreases (increases) of the heating and moistening rates and, thus, the characteristics of the cooling pattern (moistening pattern) area with cooling and drying (warming and moistening) from the driest years to the wettest years. This study suggests that, for interannual prediction of precipitation, temperature, in addition to water vapor, should also be considered.


1. Introduction

Interannual variability of precipitation is evidenced by severe floods and droughts that may occur at different places in different years, causing major societal impact, as in the 1988 drought and 1993 flood over the Midwest United States [e.g., Changnon, 1989; Kunkel et al., 1994; Trenberth and Guillemot, 1996]. This variability can be affected by external forces of the atmosphere such as sea surface temperature [e.g., Wu and Liu, 1992; Ting and Wang, 1997; Montroy et al., 1998; Mo and Paegle, 2000; Bates et al., 2001; Markowski and North, 2003; Lyon and Barnston, 2005; Yang et al., 2007] and snow cover [e.g., Namias, 1985; Karl et al., 1993; Lo and Clark, 2002]. Changes in atmospheric circulation, which are due to both the internal changes in the atmosphere and the external forces, are the more direct cause of interannual variability of precipitation [e.g., Haston and Michaelsen, 1997; Smith et al., 1998; Lenters and Cook, 1999].

The roles of atmospheric circulation in the formation of precipitation are to transport water vapor [e.g., Chen et al., 1988; Schmitz and Mullen, 1996; Berbery and Collini, 2000; Evans and Smith, 2006], create convergence, and induce atmospheric instability and ascending motion. These roles can be different from place to place. Regardless of location, forming precipitation requires that the atmosphere becomes saturated. The ultimate effect of atmospheric circulation is to change the local water vapor and temperature (through advection and convection of water vapor and heat) to saturate the air. Bretherton et al. [2004] pointed out that precipitation and column relative humidity hold strong positive relationships at seasonal and daily time scales. Lu and Zeng [2005] also revealed a close precipitation–relative humidity relationship at seasonal time scale. It is found in the present study that, at interannual time scale, precipitation and relative humidity also possess a tight positive relationship.

Increase in relative humidity with precipitation from drier to wetter years can be due to more water vapor in the air and/or lower air temperature. One purpose of this study is
to locate regions where more precipitation of wetter years corresponds to more water vapor, to lower temperature, and to both. The linkage of more water vapor and/or lower temperature with more precipitation of wetter years in different regions, revealed from the concurrent variation patterns of water vapor and temperature, will help improve the interannual prediction of precipitation. The second purpose of this study is to understand the possible roles of change in atmospheric circulation; that is, how the change in circulation from drier to wetter years contributes to maintain more water vapor and/or lower temperature associated with more precipitation of wetter years.

The data used and the composites are described in section 2. The spatially tight positive relationship between interannual precipitation and relative humidity is revealed in section 3. By using this relationship, three concurrent variation patterns of water vapor and temperature in the interannual variation of precipitation and spatial distribution of the patterns are presented in section 4. In section 5, the roles of change in atmospheric circulation in causing more water vapor and/or lower temperature of wetter years are analyzed. Summary and discussion are presented in section 6.

2. Data and Composites

2.1. Data

Precipitation, specific humidity, temperature, and wind components used in this study are taken from the North American Regional Reanalysis (NARR), which was developed by National Centers for Environmental Prediction (NCEP). Data are available at 3 h increments, and we use the monthly mean data set. The horizontal spacing is 32 km, and the domain of the NARR includes 349 × 277 grid points. There are 29 layers in vertical. The NARR starts from 1979, and 28 years (March 1979 to February 2007) are included in this study. Observed precipitation is assimilated in the NARR. Other details of the NARR can be found in the works of Mesinger et al. [2006] and Bukovsky and Karoly [2007].

2.2. Composites

For each grid point, the nine wettest years and the nine driest years of the total 28 years are determined with its seasonal mean precipitation. Spatial coherence leads to closely spaced grid points having more common wet and dry characteristics than spatially separated points. Composites of seasonal mean specific humidity, temperature, and relative humidity are made for each grid point over its wettest years and driest years. Grid-point-based composites provide large spatial samples (grid points) to evaluate the interannual relationships of precipitation with other quantities. To analyze the fields of changes in wind and the related water vapor and heat fluxes, two small areas are selected for determining the wettest years and the driest years, and the entire fields are composited in terms of the area-based wettest and driest years.

3. Tight Interannual Precipitation–Relative Humidity Relationship

Bretherton et al. [2004] revealed from the observed data that precipitation and column relative humidity hold a tight positive relationship at seasonal time scales. Lu and Zeng [2005] also found the seasonal precipitation–relative humidity relationship from the NARR data and used the relationship to understand why precipitation can have different seasonality regimes in spite of the increases in both water vapor and temperature everywhere from winter to summer. At the synoptic time scale, Bretherton et al. [2004] pointed out that the precipitation–relative humidity relationship is also positive and strong. But is there a strong positive relationship at the interannual time scale? Lu and Zeng [2005] calculated the precipitation–relative humidity correlations for winter and summer of three different places using the NARR data for 25 years (1979–2003). They found that the correlations are all positive at levels below 300 hPa, suggesting that relative humidity can well reflect the interannual variations of precipitation in these places. This interannual relationship will be further studied in this section by using the same NARR data. Lu and Zeng [2005] showed (in their Figure 3) that the interannual precipitation–relative humidity correlations are, in general, much stronger at 600 hPa than other levels for all the analyzed seasons and places. Plots at this level are presented herein, although figures of other levels were also plotted and analyzed.

Figure 1c presents significances and values of changes in winter (December–January–February) specific humidity and temperature at 600 hPa from the driest years to the wettest years. With precipitation increases from the driest years to the wettest years, water vapor increases at most grid points and temperature decreases at most grid points. So overall (considering the large spatial samples), the interannual precipitation can have a strong positive relationship with water vapor and a strong negative relationship with temperature. However, there are still considerable grid points where water vapor decreases with precipitation and temperature increases with precipitation. This means that relationships of precipitation with both water vapor and temperature are not so spatially fixed. Thus, neither water vapor nor temperature alone can well describe the interannual variation of precipitation.

Changes in winter surface evaporation, cloud cover, and meridional wind and vertical velocity at 600 hPa between the wettest years and the driest years at each grid point are also analyzed (figures not shown). Over a major portion of the domain, more surface evaporation, more
Figure 1. Differences of winter (a) specific humidity (g kg\(^{-1}\)), (b) temperature (K), and (c) relative humidity (100%) at 600 hPa between the wettest years and the driest years. (right) The difference values. (left) The significances of the differences, in which red and blue colors represent the positive and negative differences, respectively, and the dark and light colors represent the significant and insignificant differences at the 95% level, respectively.
extensive cloud cover, stronger north wind, and stronger ascending motion accompany more precipitation of wetter years, indicating that these factors all well relate to precipitation. However, there are still areas where there are less evaporation, less cloud cover, weaker north wind, and weaker ascending motion. Compared with water vapor, temperature, and all these quantities, relative humidity is most reliable in describing the interannual variation of precipitation.

4. Concurrent Variation Patterns of Water Vapor and Temperature

[12] With the increase in precipitation from the driest years to the wettest years \(P^{wet} > P^{dry}\), the increase in relative humidity at a level can be denoted as

\[
r_{wet} > r_{dry}.
\]

[13] With relative humidity expressed as \(r = q/q_s(T)\), where \(q\) and \(q_s(T)\) are specific humidity and saturation specific humidity at temperature \(T\) in the same pressure level, respectively, relation (1) can be written as

\[
C_{vap} > C_{tem}.
\]

where

\[
C_{vap} \equiv \frac{q^{wet}}{q^{dry}}
\]

and

\[
C_{tem} \equiv \frac{q_s(T^{wet})}{q_s(T^{dry})}
\]

are termed as the change in water vapor and the change in temperature from the driest years to the wettest years, respectively.

[14] \(C_{vap}\) is the amplification of specific humidity from the driest years to the wettest years. \(C_{tem}\) reflects the change in temperature from the driest years to the wettest years through a projection or transformation with the increasing function \(q_s(T)\). When evaluating the variation of relative humidity, we need to know whether water vapor or temperature “varies more” [e.g., Gaffen et al., 1992; Dai, 2006], and the comparison can now be easily made with the concepts of \(C_{vap}\) and \(C_{tem}\). For example, the statement by Dai [2006] that “A large increasing trend of relative humidity results from a large increase of water vapor coupled with a moderate warming” can simply be expressed as \(C_{vap} > C_{tem} > 1\).

[15] Relation (2) shows that, with definitions (3) and (4), the change in water vapor from the driest years to the wettest years is always larger than the change in temperature. The concurrent variations of water vapor and temperature can be categorized into the following three patterns: (1) moistening pattern: water vapor and temperature both increase from the driest years to the wettest years, and water vapor increases more \((C_{vap} > C_{tem} > 1)\); so more precipitation of wetter years corresponds to more water vapor but not lower temperature; (2) cooling pattern: water vapor and temperature both decrease from the driest years to the wettest years, and temperature decreases more \((1 > C_{vap} > C_{tem})\); so more precipitation corresponds to lower temperature but not more water vapor; (3) moistening-cooling pattern: water vapor increases but temperature decreases from the driest years to the wettest years \((C_{vap} > 1 > C_{tem})\); thus, more precipitation corresponds to both more water vapor and lower temperature.

[16] Figure 2 shows the distribution of the concurrent variation patterns of water vapor and temperature at 600 hPa, corresponding to the interannual variation of winter precipitation. The change in temperature in equation (4) is calculated by averaging the temperature over the seasons of all the wettest years and driest years first and then computing the saturation specific humidity. The calculation was also made by computing the saturation specific humidity at a monthly mean temperature first and then averaging over the seasons of the wettest years and driest years, and results indicate that there is almost no perceivable difference in the two calculations. The 3 h data are not used, but it can be expected that the results from them will also not make perceivable difference because of the relatively weak non-linearity of the saturation vapor pressure. Figure 2 suggests that relative humidity increases from the driest years to the wettest years \((r^{wet} > r^{dry})\) over almost the entire domain, and there are almost no grid points at this and other middle and lower levels where it decreases \((r^{wet} < r^{dry})\). The differences between the averages of both precipitation and relative humidity of the nine wettest years and that of the nine driest years are significant at the 95% level in a fairly large portion of the domain (shown as dark colors). The almost-entire domain of increasing relative humidity \((C_{vap} > C_{tem})\) can be divided to illustrate the distribution of the three concurrent variation patterns of water vapor and temperature. The moistening pattern (blue) mainly appears in the high latitudes north of 45°N. So more winter precipitation of wetter years there corresponds to more water vapor but not to lower temperature. The cooling pattern (red) mainly appears in the midlatitudes around 45°N, suggesting that more winter precipitation of wetter years in those areas does not correspond to more water vapor but to lower temperature; therefore, attention should be paid to temperature when predicting the year-to-year variation of precipitation of such area. The moistening-cooling pattern (yellow) mainly appears in the low latitudes south of 30°N, where more winter precipitation relates to both more water vapor and lower temperature. Because of the contributions from both moistening and cooling, the increase in relative humidity from the driest years to the wettest years is generally larger in the wide moistening-cooling pattern regions than in regions of other patterns, especially over the oceans and at middle and lower latitudes (Figure 1c). Correspondingly, the increase in precipitation is also larger in moistening-cooling pattern regions, especially over oceans and at middle and lower latitudes (figure not shown).

[17] The distributions of the concurrent variation patterns for precipitation of other seasons are also plotted (figures not shown). For summer precipitation, the distribution of the patterns is very different from that for winter precipitation. The cooling pattern is mainly in mid to high latitudes, the moistening pattern is mainly in low latitudes, and the moistening-cooling pattern can appear in all latitudes. Over the North American monsoon region (Southwest United States and Mexico), the moistening-cooling pattern prevails in lower levels while the moistening pattern prevails in mid
to upper levels, suggesting that in lower levels both more water vapor and lower temperature relate to the summer monsoon precipitation, but in mid to upper levels only more water vapor relates to the summer monsoon precipitation. The distributions of the patterns for precipitation in fall and spring both display transitions between the distribution for summer precipitation and that for winter precipitation.

The changes in water vapor and temperature from the driest years to the wettest years have strong consistency among vertical levels. Figure 3 presents the profiles of the changes in winter water vapor and temperature from the driest years to the wettest years at three locations, each representing a concurrent variation pattern. The profiles of the moistening pattern at a high-latitude location (62°W/50°N) imply that the increase in water vapor from the driest years to the wettest years is always greater than the increase in temperature in the atmospheric column. The profiles of the cooling pattern at a midlatitude location (35°W/50°N) suggest that the decrease in temperature is always greater than the decrease in water vapor in the atmospheric column. So in wetter winters of this area, there is no more water vapor in the atmospheric column and more precipitation relates to the lower temperature of the air column. For the moistening-cooling pattern at a low-latitude location (135°W/15°N), more precipitation corresponds to both more water vapor and lower temperature in the column. For precipitation of other seasons (figures not shown), there are also places where each concurrent variation pattern controls the entire atmospheric column.

The concurrent variations of water vapor and temperature in an atmospheric layer \((p_1, p_2)\) from the driest years to the wettest years can be evaluated by defining the relative humidity of the layer as

\[
r = \frac{W}{W_s},
\]

where \(W = \int_{p_1}^{p_2} q(T, p) dp\) is the total water vapor of the layer while \(W_s = \int_{p_1}^{p_2} q_s(T, p) dp\) (in which \(q_s\) also varies with pressure \(p\) and \(g\) is gravitational acceleration) is the water vapor holding capacity of the layer, which is determined by the vertical profile of temperature. The changes in water vapor and temperature in the layer are then defined, respectively, as

\[
C_{\text{vap}} = \frac{W_{\text{wet}}}{W_{\text{dry}}},
\]

and

\[
C_{\text{tem}} = \frac{W_{\text{wet}}}{W_{\text{dry}}}.\]

Figure 2. Distribution of the three concurrent variation patterns of winter water vapor and temperature at 600 hPa. Moistening pattern (blue, \(C_{\text{vap}} > C_{\text{tem}} > 1\)), cooling pattern (red, \(1 > C_{\text{vap}} > C_{\text{tem}}\)), and moistening-cooling pattern (yellow, \(C_{\text{vap}} > 1 > C_{\text{tem}}\)). Grid points with \(C_{\text{vap}} < C_{\text{tem}}\) are not plotted. Darkly colored are grid points where differences of precipitation, relative humidity, as well as specific humidity (for moistening pattern), temperature (for cooling pattern), or both (for moistening-cooling pattern) between the wettest years and the driest years are all significant at the 95% level. Locations (a), (b), and (c) are labeled for use in Figure 3.
[20] Figure 4 shows the distribution of the three concurrent variation patterns of the winter water vapor and temperature in the 850–500 hPa layer, which roughly represents the major condensation layer. The distribution of the patterns for the 1000–100 hPa layer, representing the entire atmospheric column, is also plotted (figure not shown). The distribution features for the layer and column are very close, both being similar to that in Figure 2, with more water vapor in the layer or column in wetter winters of high latitudes, lower temperature in midlatitudes, and both in low latitudes. The concurrent variations of the layer or column water vapor and temperature are less significant than the variations at 600 hPa, and this may be due to the effect of the offset within the different levels. The interannual precipitation–relative humidity correlations that are, in general, strongest at 600 hPa [Lu and Zeng, 2005] suggest that, although for a specific year the relative humidity in condensation layer (e.g., 700–850 hPa) is more important than that at other levels to the precipitation for the year, the year–to–year variation of the relative humidity at 600 hPa is more important to the year–to–year variation of precipitation.

[21] The results of this section remind us that, when predicting precipitation at the interannual time scale, we need to take into account the situations of both water vapor and temperature. Water vapor has always been stressed. However, attention should be paid to temperature or both in a vast region.

5. Characteristics and Roles of Change in Atmospheric Circulation

[22] As mentioned above, the purpose of determining the wettest years and the driest years for each individual grid point is to expose the tight precipitation–relative humidity relationship from the large spatial samples. The wettest years and the driest years can be different from place to place. The field of change in atmospheric circulation between the wettest and the driest years and its roles in maintaining a concurrent variation pattern of water vapor and temperature should be examined with the wettest years and the driest years being determined for each specific place (a grid point or a limited area) of interest. In this section, as examples, we examine the roles of changes in atmospheric circulation for the cooling and moistening patterns of winter precipitation in two areas at 600 hPa, which are marked in Figure 5. They are 3° longitude × 2° latitude and contain 44 and 45 grid points, respectively (Table 1). The nine wettest years and the nine driest years of each area are determined based on the seasonal precipitation averaged over the area. Table 1 shows that, compared with the precipitation in the moistening pattern area, the precipitation in the cooling pattern area is very large, even in its driest years. The area–averaged water vapor and temperature both decrease from the driest years to the wettest years in the cooling pattern area and increase in the moistening pattern area. This is also the case at other levels (figure not shown).

[23] Figure 6 shows the differences in winter geopotential height and wind at 600 hPa between the area–based wettest and driest years. There are two noteworthy characteristics in the difference fields. First, the cooling pattern area is in the center of the region where the pressure difference is negative. The moistening pattern area is in the region where the pressure difference is positive, and the center of the region is east of the area. We notice that, although in a specific year the place that is horizontally low in pressure is favorable for precipitation, more precipitation of wetter years of the place does not have to, although it may, be accompanied by lower pressure. Second, corresponding to the negative pressure difference system around the cooling pattern area, the field of wind difference is divergent, although it is cyclonic. For the positive pressure difference system around the moistening pattern area, the field of wind difference is convergent and anticyclonic. These characteristics also exist in other major levels.

[24] The lower mean air temperature of a season is the result of the smaller seasonal mean heating rate of the atmosphere. The heat equation can be written in flux form as
\[
\frac{\partial T}{\partial t} = -\nabla \cdot (TV^*) - \partial (T \omega)/\partial p + S_T,
\]
where \( S_T \) is the heat source, including mainly the long-wave and short-wave radiation and the latent and sensible heat [Pielke, 2002]. The heating rate is contributed by the convergence of the horizontal and vertical heat fluxes as well as the heat source. Here we analyze the roles of horizontal atmospheric circulation.

[25] We denote the heating rate induced by the convergence of the horizontal \((h)\) heat flux as

\[
\left( \frac{\partial T}{\partial t} \right)_h = -\nabla \cdot (TV).
\]

[26] The left side of equation (7) is the seasonal mean of the heating rate. On the right side, it is better to use the three hourly data of temperature and wind components to calculate the horizontal heat flux and then average the flux over the season. Here we use the seasonal means of \( T \) and \( V \) to calculate the stationary heat flux \( TV \) and study the effect of the seasonal mean circulation. The transient eddy heat flux is not considered and can be included in the source term. Averaging equation (7) over the area-based wettest and driest years, the increase in the heating rate from the driest years to the wettest years can be written as

\[
\left( \frac{\partial T}{\partial t} \right)_{h}^{\text{wet}} - \left( \frac{\partial T}{\partial t} \right)_{h}^{\text{dry}} = -\nabla \cdot \left[ (TV)_{\text{wet}} - (TV)_{\text{dry}} \right].
\]

[27] The water vapor equation in flux form is \( \partial q/\partial t = -\nabla \cdot (qV) - \partial(q \omega)/\partial p + S_q \), where \( S_q \) is the moisture source, including mainly evaporation and sublimation (negative for condensation and deposition). The moistening rate contributed by the convergence of the horizontal water vapor flux is denoted as \( \left( \frac{\partial q}{\partial t} \right)_h = -\nabla \cdot (qV) \). Similarly, the increase in the moistening rate from the driest years to the wettest years can be written as

\[
\left( \frac{\partial q}{\partial t} \right)_{h}^{\text{wet}} - \left( \frac{\partial q}{\partial t} \right)_{h}^{\text{dry}} = -\nabla \cdot \left[ (qV)_{\text{wet}} - (qV)_{\text{dry}} \right].
\]

[28] Equations (8) and (9) indicate that the convergences (divergences) of the increases in horizontal heat flux and water vapor flux from the driest years to the wettest years have contribution to the increases (decreases) in heating rate and moistening rate from the driest years to the wettest years.

[29] Figure 7 displays the differences of winter temperature and heat flux as well as the differences of specific humidity and water vapor flux at 600 hPa between the area-based wettest and driest years. The cooling pattern area is truly in the region where the temperature difference is negative, although the center of the region is to its west (Figure 7a). The cooling pattern area is exactly in the center of the region where the field of difference in heat flux between the wettest years and the driest years is divergent, which is dominated by the divergent wind difference. According to equation (8), the divergence of the difference in heat flux leads to the decrease in the heating rate of this area from the driest years to the wettest years. Similarly, the
cooling pattern area is in the region where water vapor difference is negative, and the center of the region is to its west (Figure 7b). The cooling pattern area is also exactly in the center of the region where the field of difference in water vapor flux is divergent, and this, based on equation (9), results in the decrease in the moistening rate of this area from the driest years to the wettest years. The roles of circulation for the moistening pattern area are opposite. The moistening pattern area is in a warming region and the region where the field of difference in heat flux is slightly convergent, although the warming and convergence centers are both northeast of the area (Figure 7c). The moistening pattern area is also in the region where water vapor difference is positive and the region where the field of difference in water vapor flux is convergent, and the centers of these regions are both to its northeast (Figure 7d). The convergences of the differences of water vapor flux and heat flux have contributions to the moistening and warming of the area.

6. Summary and Discussion

[30] The concurrent variation patterns of water vapor and temperature associated with the interannual variation of precipitation and the roles of change in atmospheric circulation in the maintenance of the different patterns are studied by using the NARR. Exploring and understanding the relationship between the variations of water vapor and temperature and the interannual variation of precipitation are helpful to the prediction of precipitation at the interannual time scale. Special attention should be paid to temperature in

<table>
<thead>
<tr>
<th>Table 1. Cooling Pattern Area and Moistening Pattern Area</th>
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<td>C_vap</td>
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*The locations (Lat, latitude; Lon, longitude) of the selected cooling pattern area and moistening pattern area, the numbers (N) of grid points contained in them, the winter precipitation (P), and the specific humidity (q) and temperature (T) at 600 hPa averaged over each of the areas and the nine area-based wettest or driest years.*
regions where more precipitation of wetter years relates to lower temperature.

[31] The variations of water vapor and temperature are linked to the variation of precipitation through the interannual precipitation–relative humidity relationship. It has been previously revealed that precipitation and relative humidity hold strong positive relationships at both seasonal and daily time scales. It is found in this study that precipitation and relative humidity also possess a very tight positive relationship at the interannual time scale. This conclusion is reached by comparing the changes in relative humidity and precipitation from the driest years to the wettest years over all grid points, in which the wettest years and the driest years are determined for each grid point by its precipitation. The consistency of the changes based on the very large spatial samples suggests the tight relationship.

[32] The increase in relative humidity with precipitation from the driest years to the wettest years can be obtained by increasing water vapor, lowering temperature, or both. With this, the concurrent variations of water vapor and temperature corresponding to the interannual variation of precipitation are classified into moistening, cooling, and moistening–cooling patterns. For winter precipitation, the moistening pattern mainly appears in high latitudes north of 45°N. So the more precipitation of wetter years there corresponds to more water vapor but not lower temperature. The cooling pattern mainly appears in the midlatitudes around 45°N; thus, the more precipitation of wetter years there does not correspond to more water vapor but lower temperature. The moistening–cooling pattern mainly appears in low latitudes south of 30°N, where more precipitation relates to both more water vapor and lower temperature.

[33] The changes in the local water vapor and temperature from its driest years to the wettest years can be attributed to the change in atmospheric circulation. A cooling pattern area and a moistening pattern area of winter precipitation are selected for analyzing the characteristics and roles of change in atmospheric circulation. Around the cooling pattern area, the pressure difference between the wettest years and the driest years is negative, and the field of wind difference is cyclonic and divergent. Dominated by the divergent wind difference, the fields of differences of both heat flux and water vapor flux between the wettest years and the driest years are divergent. These lead to a negative heating rate and a negative moistening rate, thus the cooling and drying characteristics of the cooling pattern. Around the moistening

Figure 6. Differences of winter geopotential height (gpm; shaded) and wind (m s\(^{-1}\); vector) at 600 hPa between the area-based wettest and driest years. The cooling pattern area (C) and moistening pattern area (M) are marked in white.
Figure 7. Differences of 600 hPa winter temperature (K; shaded) and heat flux (K m s\(^{-1}\); vector) for (a) cooling pattern area and (c) moistening pattern area, as well as specific humidity (g kg\(^{-1}\); shaded) and water vapor flux (g kg\(^{-1}\) m s\(^{-1}\); vector) for (b) cooling pattern area and (d) moistening pattern area between the area-based wettest and driest years.
pattern area, the pressure difference is positive and the field of wind difference is anticyclonic and convergent. The fields of differences of water vapor flux and heat flux are both convergent, and these result in the positive moistening and heating rates, thus moistening and warming characteristics of the moistening pattern.

[34] For every specific location, the roles of change in atmospheric circulation in the changes in local water vapor and temperature should be analyzed with the wettest years and the driest years determined specifically for this location. The analysis of this study only focuses on the seasonal mean circulation, and the transient eddy effect is not examined. As illustrated from the heat and water vapor equations, the vertical fluxes and all those factors included in the source terms are not investigated, and they may also have contributions to the changes in the heating rate and moistening rate.

[35] The interannual relationships of precipitation with water vapor and temperature have been studied from observed data and model output [e.g., van Loon and Williams, 1978; Zhao and Khalil, 1993; Trenberth and Shea, 2005], and it was found that these relationships can be positive and negative in different regions. The tight positive relationship of interannual precipitation with relative humidity revealed in this study can be used to unify the above two relationships. In most regions, precipitation can have a positive interannual relationship with water vapor, which corresponds to a relatively small interannual variation of temperature. However, there are regions where precipitation has a negative interannual relationship with water vapor. In this case, we should be aware that, behind this relationship, there is a more important negative interannual relationship between precipitation and temperature. Similarly, in most regions, precipitation can have a negative interannual relationship with temperature, corresponding to a relatively small interannual variation of water vapor. In those regions where precipitation has a positive interannual relationship with temperature, there may have been a stronger positive interannual relationship between precipitation and water vapor.

[36] The cooling pattern found in this study is majorly over the midlatitude oceans, with one in the Pacific and one in the Atlantic close to the coastal, although it may also appear over some land areas (e.g., in South Dakota). The cooling pattern over the oceans suggests that, in wetter years, there is less water vapor and lower temperature, and lower temperature is more important than less water vapor. Less water vapor contained in the atmosphere may be associated with lower temperature due to the smaller water vapor holding capacity of the air. The purpose of this study is to understand the dynamic roles of atmospheric circulation in the formation of the different concurrent variation patterns relating to the interannual variation of precipitation with the NARR, which provides three-dimensional data set for all the required quantities. The reason for studying the cooling pattern over the ocean for winter season is that the concurrent variations of water vapor and temperature in this area are very strong and have large spatial coherence. The variation patterns of different areas of land and different seasons can be analyzed with the same methodology. We noticed that, in the NARR, the precipitation over land is assimilated from observations and the precipitation over ocean needs to be verified when observations are also available. Studies for other regions over the globe may also be made.

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