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RESEARCH ARTICLE

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Relative importance of surface air temperature and density to interannual variations in monthly surface atmospheric pressure

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Abstract

The spatial inhomogeneity of air pressure drives the atmospheric circulation. The interannual variation of the pressure can be affected by both air temperature and density. The goal of this study is to identify, for the near-surface air, whether the variation of the density or temperature is more important in the interannual variation of the pressure. The physical relation of the pressure (P) with density (D) and temperature (T), denoted as $P = D \cdot T$ for simplicity, is nonlinear. To be convenient for estimating the relative importance, a normalized linear regression is used to fit the relation, which is finally written as $P = AD + BT$. Tests show that the linear fitting is robust; it is perfect everywhere in the globe. Because of the normalizations, the D and T are in magnitude of 1, but can be positive or negative. Derivations and calculations indicate that the coefficients A and B are both positive. What they reflect are the partial correlations of the pressure with the D and T, which are both equal to 1 across the entire field. For the normalized fitting, the A and B can be used to estimate the contributions of the D and T to the variation of the pressure. The linear fitting method can provide quantitative results for the dominance. The original nonlinear relation, due to the special form for the issue, can be used to qualitatively deduce the dominance. Comparisons suggest that the results obtained from the linear fitting are consistent with those qualitatively reached from the nonlinear physical relation. The consistency is true, no matter what the relation is between the two influencing factors. Corresponding to the negative relation between the density and temperature, there are two patterns. One is that the pressure increases with density but decreases with temperature. In this case, density dominates the variation of pressure. The second is that the pressure increases with temperature but decreases with density, and thus temperature dominates the variation of pressure. The third pattern is for the positive relation between density and temperature. In this case, density and temperature both have positive contributions to the variation of pressure, and which of them is more important can further be assessed with the linear fitting method.

KEYWORDS

air density, air temperature, dominance factors, interannual variability, surface air pressure

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1 | INTRODUCTION

Atmospheric pressure is one of the most important quantities of the climate system. Many investigators explored the observations, spatial distributions, climatic anomalies, and long-term changes of the atmospheric pressure (e.g., Arctowski, 1944; Barnett, 1985; Canavero and Einaudi, 1987; Trenberth *et al*., 1987; Bannon *et al*., 1997; Chen *et al*., 1997; Mass and Madaus, 2014; Anderson *et al*., 2016). Along with the change of the pressure, the warming as well as the changes in air density were also extensively studied (e.g., Wood and Spreen, 1963; Polyakov *et al*., 2003; Bayr and Dommenget, 2013; You *et al*., 2017).

According to the equation of motion, the spatial inhomogeneity of pressure is fundamentally responsible for driving the atmospheric circulation. The influences of the pressure on the circulation at various temporal and spatial scales were focused (e.g., Martín *et al*., 2001; Raible *et al*., 2005; Carrera and Gyakum, 2007; You *et al*., 2010). The changes in the spatial distribution patterns of the pressure, especially the low- and high-pressure systems, were examined (e.g., Li *et al*., 2009; Pickart *et al*., 2009; Dong *et al*., 2017; Ren *et al*., 2019). The anomalies in the atmospheric circulation may lead to occurrences of the hydrological extremes, for example, the severe floods and droughts, which appear more frequently in the warming climate (e.g., Seager *et al*., 2012; Makarieva *et al*., 2014; Costa-Cabral *et al*., 2016). As an interaction, the atmospheric circulation may also have influences on the pressure fields (e.g., Liu and Darkow, 1989; Zhang and Tian, 2019).

Atmospheric pressure can also affect the oceans, which is another important component of the climate system. Studies revealed that the anomalous spatial distribution of the atmospheric pressure may lead to changes in the ocean circulations (e.g., Harzallah *et al*., 1993; Ponte, 2009). In addition to the influences on the atmospheric and oceanic circulations, changes in the atmospheric pressure can have more direct impacts on the human's future. Numerous researches pointed out that the sea level of many coasts can be significantly altered by the changes in the atmospheric pressure (e.g., Traon and Gauzelin, 1997; Dorandeu and Traon, 1999; Yan and Zhu, 2001).

The gas law tells us that the atmospheric pressure can be affected, in a nonlinear manner, by both air density and air temperature. Fundamentally, there may be two approaches to make the air pressure change. One is that air temperature does not change (or does not change much), and the change of the pressure is caused by the change in air density. The other is that air density does not change (or does not change much), and the change of pressure is due to the change in air temperature. The more real situation is that both the air density and air temperature have changes. For these two quantities, one may change more, and one may change less. Over the globe, the situations can be different, depending on geographical region.

The goal of this study is to make clear, overall for the globe and specifically for each region, whether the interannual variation of the pressure is caused more by the change in air density or caused more by the change in air temperature, that is, which of them is more important and thus has more contribution. Density and temperature are two different quantities. The key here is that we need to have an appropriate method to compare the changes of these two different quantities, and then assess their contributions or relative importance to the variation of the pressure. In this study, we focus on near-surface air, for each grid point over the globe, and examine the interannual variations of the monthly mean pressure, density, and temperature.

For the issues that have multiple influencing factors, we may always need to know the dominance of these factors, with estimating their relative contributions and assessing the relative importance (e.g., Budescu, 1993; Azen and Budescu, 2003; Gromping, 2007). In our previous studies, a simple method was used to explore the corresponding relative importance. We examined whether precipitation or surface air temperature dominates the variations of the stream flow and other hydrological quantities (Lu *et al*., 2010), as well as whether the rainy days or the average rainfall intensity dominates the variation of the rainfall total amount (Lu *et al*., 2016). Based on linear regression, two measures were constructed for estimating the contributions of the two influencing factors, which consider the change rates, for example, the two coefficients fitted from the regression, and the scales of the changes, which can be represented with the standard deviations of their variations.

We hope that this linear-fitting-based method can also be used for the issue of the present study, so that we may conveniently compare the relative importance of the density and temperature in the interannual variation of the pressure. As will be demonstrated in the text, the nonlinear physical relation can truly be simplified, and fitted perfectly with the linear regression. The robustness of the linearization is illustrated in the study, and the feasibility is due to the special form of the physical relation, that is, the form of the gas state equation.

The linear fitting method can provide quantitative results for the dominance. While obtaining the results, we still hope that these results obtained from the statistical calculations can be verified or further interpreted. We notice that the original nonlinear physical relation, although it is not convenient for providing a quantitative assessing, it can be used to perform a qualitative analysis for the dominance, and this is also due to the special form of the physical relation for the present issue. With the nonlinear gas law, the correlations among the three quantities can be easily inferred. The density and temperature, the two influencing factors, can be independent or related, and their correlations can be positive or negative. Comparisons reveal that the results of the dominance determined from the linear fitting are reasonable and reliable, no matter what the correlation is between the two influencing quantities.

As an example for the investigation, the National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) Reanalysis I (Kalnay *et al.*, 1996) is used in this study. The data used include the monthly surface air temperature and pressure, with a horizontal resolution of 2.5° × 2.5° in latitude and longitude over the 71 years from 1948 to 2018. The monthly surface air density is then calculated with the ideal gas law.

In Section 2, we demonstrate that, as a key step, the nonlinear gas law can be linearized robustly with a regression, which is convenient for analysing the relative importance. It is revealed in Section 3 through derivations that the coefficients of the regression are linked to partial correlations, not simple correlations. In Section 4, we introduce the measures for the general analysis of the relative importance, and show that for this special issue they simply become the two coefficients of the normalized regression. It is shown in Section 5 that the results of the dominance, which are classified into three patterns, obtained from the linear fitting method are consistent with the conclusions qualitatively reached from the original nonlinear relation. Summary and discussion are given in Section 6.

2 | THE LINEAR FITTING AND ITS ROBUSTNESS

2.1 | The normalized linear fitting

Atmospheric pressure (p) is linked to air density (ρ) and temperature (T) with the gas state equation $p = \rho RT$, where R is the specific gas constant. In this study, as an example, we examine the near-surface air, analysing the dominance in the relation among interannual variations of the monthly means of the near-surface pressure (P), density (D), and temperature (T). For simplicity, we write the relation of the three quantities as $P = D \cdot T$.

For this nonlinear relation, we hope that a linear regression

$$P = AD + BT + c \tag{1}$$

can be used to approximate it. Also, since pressure, density, and temperature are different quantities, in order to compare their changes, these three quantities are first normalized before establishing the linear regression. So finally in Equation (1), the P, D, and T denote, respectively, the normalized surface pressure, density, and temperature of each grid point, which are calculated from the monthly means of the multi-year time series of each month.

The coefficients A, B, and c are then determined with the data. The linear fitting is performed for each grid point over the globe. Because of the normalizations of the three input quantities, the c obtained is close to zero, compared with the other two terms in the right-hand side of Equation (1). Thus, the linear relation can be written as $P = AD + BT$. The spatial distributions of the coefficients A and B calculated from the regression are presented in Figure 1.

Figure 2 is one of the plots displayed in the right column of Figure 1, which shows the ratio of the two coefficients (B/A) for February. Based on the characteristics in the distribution, five representative areas are selected, including the areas over the Tibetan Plateau, Greenland, the Antarctic, the tropical Pacific, and the North Pacific. These areas are used below, as examples, to provide details for further analyses. In the calculations, each area is treated as a single point. For each area, the pressure and temperature are averaged over the area. The gas law is then used to calculate the air density of the area. The three input quantities are normalized, and then a linear fitting is performed, which provides the corresponding coefficients A and B for the area.

2.2 | The robustness of the linear fitting

To be sound in statistics, the feasibility of the linearization for the original nonlinear physical relation needs to be verified with a significance test, and this is a key step to the dominance analysis of this study. For the purpose of the significance test, the coefficient of the multiple correlation, which is the correlation of the pressure observed with the pressure computed by using the fitted formula, is calculated for each grid point. With the results of the A and B displayed in Figure 1, the fitted pressure is calculated. It is interesting that the coefficient of the multiple correlation is very close to 1, for all the grid points over the globe and for all the 12 months (figures not shown). In the plot of February, for example, the correlation is greater than 0.975 over the entire field.

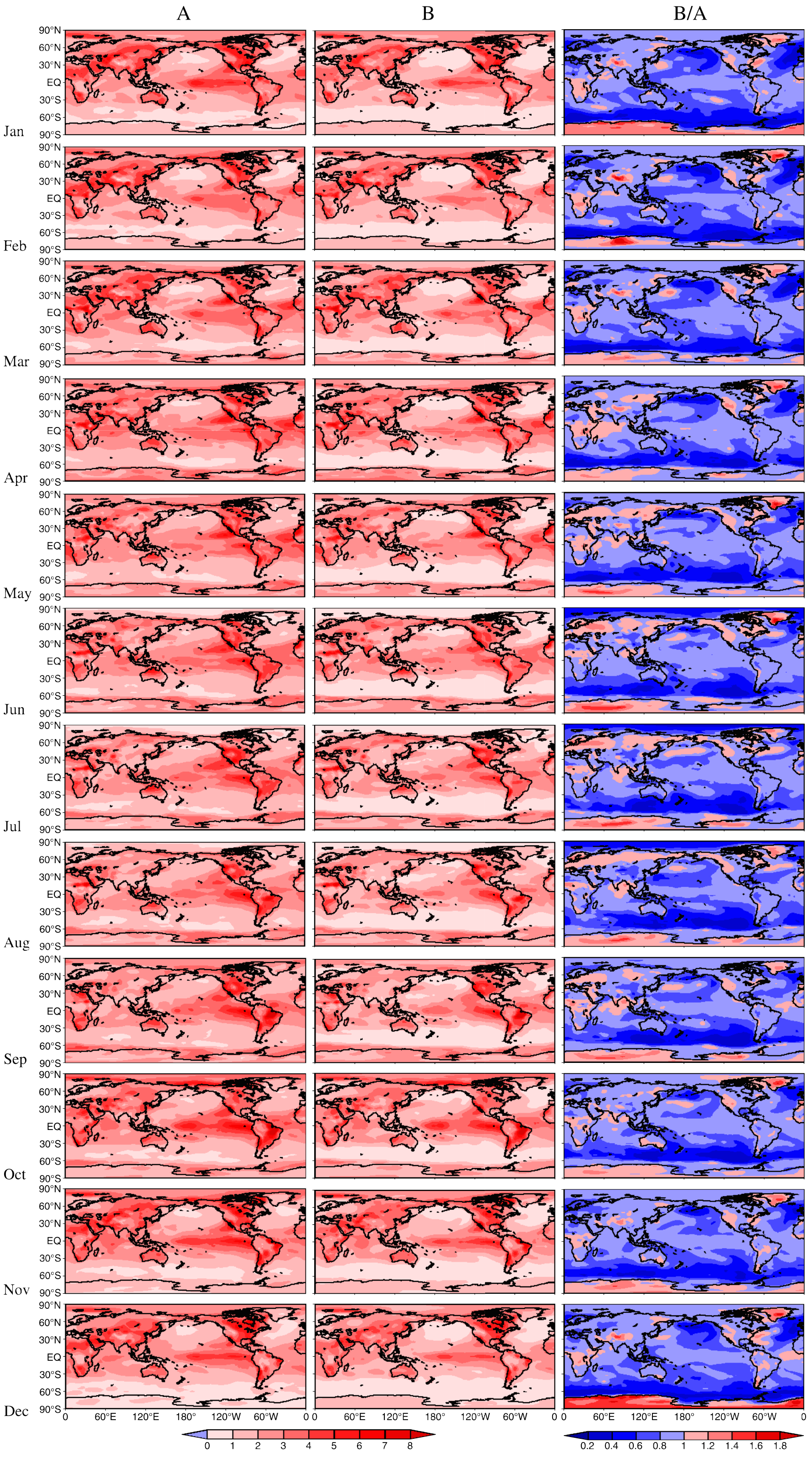

FIGURE 1 Distributions of the coefficients *A* (left) and *B* (middle), calculated from the normalized linear regression, as well as their ratio *B*/*A* (right) for the 12 months [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 3 shows the interannual variations of the normalized pressure, density, temperature, along with the pressure computed from the fitted linear relation, for February and for the five areas. Since these quantities are all normalized or calculated from them, they can be compared directly with each other. These examples indicate that although the curve of the observed pressure may have great differences from the curves of either the density or the temperature, it is very consistent with the curve of the pressure fitted from the regression, which is

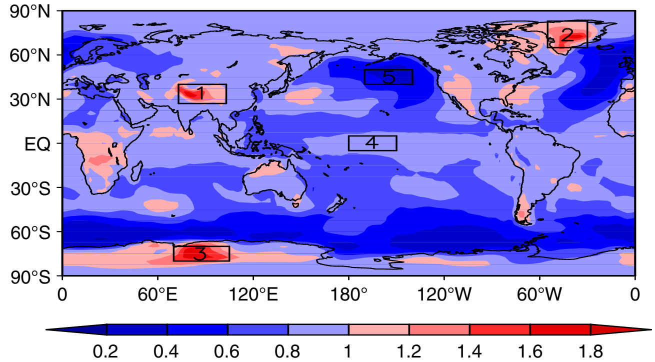

FIGURE 2 Using the distribution of the B/A for February in Figure 1 to select five representative areas, including Area 1 (73°–103°E, 27°–40°N) for the Tibetan Plateau, Area 2 (30°–55°W,65°–83°N) for Greenland, Area 3 (70°–105°E,70°–80°S) over the Antarctic, Area 4 (150°–180°W, 5°S–5°N) over the tropical Pacific, and Area 5 (140°–170°W,40°–50°N) over the North Pacific [Colour figure can be viewed at wileyonlinelibrary.com]

a linear combination of the density and temperature. These consistencies are true for every grid point.

These results demonstrate that the nonlinear physical relation, the gas law, can truly be linearized, perfectly for every grid point in the globe, by using the linear fitting. The feasibility of the linearization may be due to the inherent characteristic of the original physical relation; namely, the special function form of the relation $P = D \cdot T$, and this will be further analysed in Section 6. The robustness of the linearization ensures that we can further use the results of the A and B, presented in Figure 1, to investigate the contributions and the relative importance of density and temperature to the variation of the pressure.

3 | THE COEFFICIENTS AND THE PARTIAL CORRELATIONS

3.1 | Expressing the coefficients with the correlations

Figure 1 indicates that, for the specific issue of the present study, the coefficients A and B obtained from linear regression are both positive over the entire field. The distribution patterns of the A and B are in general very similar. They are both geographically dependent. Overall, their values are large over lands and tropical oceans. They are large over North and South Americas, Australia, South Africa, and the eastern tropical Pacific all year round, and over Euro-Asia during the cold months. The A and B are small over the North Pacific, North Atlantic, and the ocean belt north of the Antarctic. The meaning of the coefficients A and B can be better understood with the following derivations, which link them to partial correlations.

In terms of the simple correlation coefficients and standardized deviations, as similarly illustrated in the appendix of Lu *et al.* (2016), the A and B can be expressed as

$$A = \left(\frac{r_{PD} - r_{PT} r_{DT}}{1 - r_{DT}^2}\right)\left(\frac{\sigma_P}{\sigma_D}\right) \tag{2}$$

and

$$B = \left(\frac{r_{PT} - r_{PD} r_{DT}}{1 - r_{DT}^2}\right)\left(\frac{\sigma_P}{\sigma_T}\right). \tag{3}$$

3.2 | Linking the coefficients to the partial correlations

The coefficient of the partial correlation of P with D can be expressed, with the simple correlations among the three quantities, as

$$R_{PD} = \frac{r_{PD} - r_{PT} r_{DT}}{\sqrt{1 - r_{PT}^2} \cdot \sqrt{1 - r_{DT}^2}}. \tag{4}$$

The comparison of (2) and (4) shows that the A is proportional to the coefficient of the partial correlation between P and D. Thus, what coefficient A reflects in (2) is actually their partial correlation, not the simple correlation. The implication of the partial correlation here is that the influence from T is removed. Similarly, what coefficient B reflects in the regression is the partial correlation of P with T, in which the influence from D is removed.

By using the expressions of the partial correlations R_{PD} and R_{PT}, the (2) and (3) become

$$A = R_{PD}\sqrt{\frac{1 - r_{PT}^2}{1 - r_{DT}^2}}\left(\frac{\sigma_P}{\sigma_D}\right) \tag{5}$$

and

$$B = R_{PT}\sqrt{\frac{1 - r_{PD}^2}{1 - r_{DT}^2}}\left(\frac{\sigma_P}{\sigma_T}\right). \tag{6}$$

These indicate that the signs of the A and B depend on the signs of the R_{PD} and R_{PT}.

The distributions of the simple correlations and the partial correlations of pressure with density and

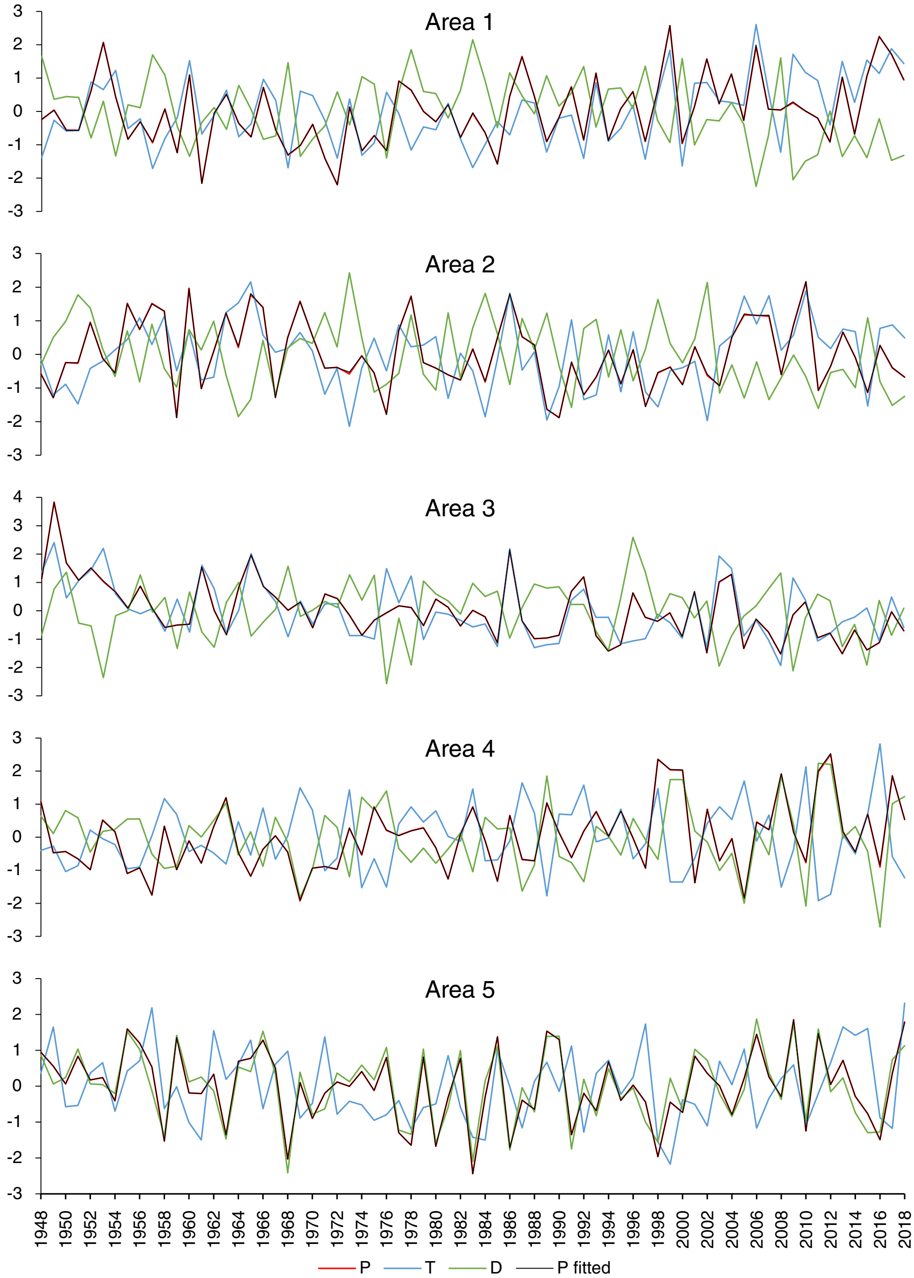

FIGURE 3 Interannual variations of four quantities of February for the five areas, including the normalized pressure, density, and temperature, along with the pressure computed from the fitted linear relation [Colour figure can be viewed at wileyonlinelibrary.com]

temperature, calculated for each grid point and for February as an example, are presented in Figure 4. For the simple correlation with density (Figure 4b), it is positive over most grid points in the globe. However, it can be negative in some areas over the lands, including the grid points over the Tibetan Plateau, the Africa, North Australia, Greenland, West America, the southern portion of South America, and the Antarctic. For the simple correlation with temperature (Figure 4c), it can be negative over more regions. Differently, it is positive over the Tibetan Plateau, Africa, Greenland, and the Antarctic. It is also positive over some of the oceans, including the North Pacific, the North Atlantic, and the ocean belt north of the Antarctic.

However, nevertheless the both positive and negative simple correlations, Figure 4d,e show that the partial correlations R_{PD} and R_{PT} are both positive everywhere in the globe, and both are almost equal to 1 everywhere. In the plots for February, they both can be greater than 0.975 for all the grid points. The small difference from 1 might be caused by the numerical truncations in the computations. The reason that the partial correlations R_{PD} and R_{PT} are both positive and equal to 1 everywhere can be interpreted from the physical relation $P = D \cdot T$. Because of the partial correlation, we may treat one of the two quantities (say, D) as a constant, and then P has a linear relation with the T. Thus, P and T have a positive correlation, and the correlation coefficient can be expected to be 1.

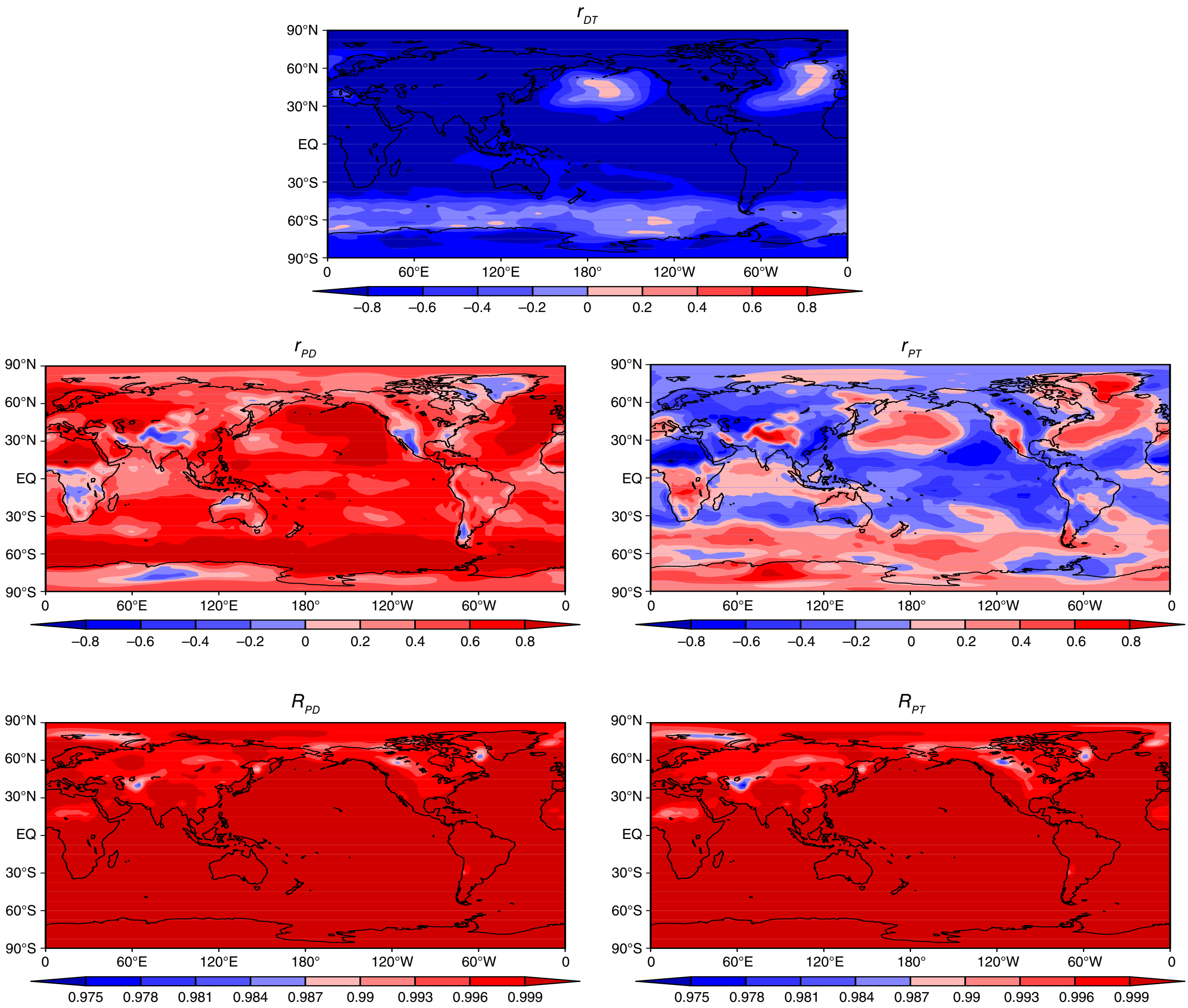

FIGURE 4 Distributions of the simple correlation between density and temperature (upper), along with the simple correlations (middle) and partial correlations (lower) of the pressure with the density and temperature for February [Colour figure can be viewed at wileyonlinelibrary.com]

4 | THE MEASURES FOR ESTIMATING THE CONTRIBUTIONS

4.1 | The method for general relationship issues

In our previous studies, with performing linear regression, measures were constructed for estimating the contributions and comparing the relative importance of the influencing factors (Lu *et al.*, 2010; Lu *et al.*, 2014; Lu *et al.*, 2016). In regression Equation (1), the meaning of the A and B can be illustrated by expressing them as $A = \partial P/\partial D$ and $B = \partial P/\partial T$. They represent, respectively, the change rates of P with respect to D and T, or the amount of the changes in P corresponding to a unit increase in D and T. Meanwhile, we can use σ_D and σ_T, the standard deviations of the D and T determined from the data, to indicate, respectively, the scales of the year-to-year perturbations of the D and T.

Then, the products of the change rates and the corresponding variation scales, that is, $|\partial P/\partial D| \cdot \sigma_D$ and $|\partial P/\partial T| \cdot \sigma_T$, can be used to measure, respectively, the scales of the change in P induced by the variations of D and T. With the A and B obtained from the fitting, the two measures for estimating the contributions are defined as

$$S_D = |A| \cdot \sigma_D \tag{7}$$

and

$$S_T = |B| \cdot \sigma_T. \tag{8}$$

In order to have a better understanding, the above two measures can be expressed by using the simple and partial correlation coefficients. With relations (5) and (6), we obtain

$$S_D = |R_{PD}| \sqrt{\frac{1-r_{PT}^2}{1-r_{DT}^2}} \cdot \sigma_P \tag{9}$$

and

$$S_T = |R_{PT}| \sqrt{\frac{1-r_{PD}^2}{1-r_{DT}^2}} \cdot \sigma_P. \tag{10}$$

With the two estimated contributions, the relative importance can be reflected from the ratio

$$\frac{S_T}{S_D} = \left|\frac{R_{PT}}{R_{PD}}\right| \sqrt{\frac{1-r_{PD}^2}{1-r_{PT}^2}}. \tag{11}$$

4.2 | The measures for the present special issue

In this study, when establishing regression (1), the three input quantities are all normalized, so we have $\sigma_D = 1$, $\sigma_T = 1$, and $\sigma_P = 1$. Because of the special form of the physical relation $P = D \cdot T$, we conclude that coefficients A and B, as two change rates, are both positive. This is also demonstrated by the calculations as displayed in Figure 1 for all the months. Thus, from (7) and (8), the two measures for estimating the relative importance become $S_D = A$ and $S_T = B$, suggesting that the two coefficients obtained from the linear regression, when the input quantities are normalized, can directly reflect the relative importance of the two influencing factors.

Also, because of the special form of the relation $P = D \cdot T$ in this issue, as revealed above, we have $R_{PD} = 1$ and $R_{PT} = 1$. So, from (5) and (6), the two coefficients can be written as $A = \sqrt{1-r_{PT}^2}/\sqrt{1-r_{DT}^2}$ and $B = \sqrt{1-r_{PD}^2}/\sqrt{1-r_{DT}^2}$. The relative importance of the density and temperature to variation of pressure can be determined with $S_T/S_D = B/A = \sqrt{1-r_{PD}^2}/\sqrt{1-r_{PT}^2}$. This can further be written as $B/A = Q_T/Q_D$, where $Q_D \equiv 1/\sqrt{1-r_{PD}^2}$ and $Q_T \equiv 1/\sqrt{1-r_{PT}^2}$. Here, Q_D increases with r_{PD}^2, and Q_T increases with r_{PT}^2. So, for this special issue, the relative importance can simply be determined through comparing the magnitudes of the r_{PD} and r_{PT}, the coefficients of the simple correlations of the pressure with density and temperature.

Figure 5 shows the seasonal variations of the Q_D and Q_T for the five areas. Over Greenland (Area 2) and the Antarctic (Area 3), Q_D is smaller than Q_T in almost all the months, and thus the variation of the temperature is more important. Over the tropical Pacific (area 4) and the North Pacific (Area 5), Q_D is greater than Q_T in almost all the months, and thus the variation of the density is more important. Over the Tibetan Plateau (area 1), the relative importance exhibits a seasonal change. Temperature is more important during the cold months, while density is more important during the warm months.

5 | PATTERNS OF THE DOMINANCE AND THE REASONABILITY OF THE RESULTS

5.1 | The results of dominance assessed with the method

For the purpose of conveniently assessing the dominance of density and temperature in the variation of pressure, a linear regression is used to fit the relation. The measures are then constructed to estimate the contributions of the two influencing factors. As suggested above, when normalized quantities are used to establish the fitting, the two measures become simply the A and B, the two coefficients fitted from the linear regression. The relative importance, or the dominance, of the density and temperature can thus be indicated with B/A, the ratio of the two coefficients. Figure 1 (right column) presents the results of the dominance for all the months.

The spatial distributions for all the months show that, over the globe, there are more areas where B/A is less than 1, suggesting that in the interannual variation of the pressure, the variation of density is more important than the variation of temperature. This is the case especially over the North Pacific, North Atlantic, and the ocean belt north of the Antarctic. Oppositely, there are also areas where B/A is greater than 1, indicating that temperature dominates the variation of pressure. This is the case over the Antarctic and the Greenland for all the months. Over the Tibetan Plateau, temperature is more important during the cold months, especially in February, while during the warm months density is more important.

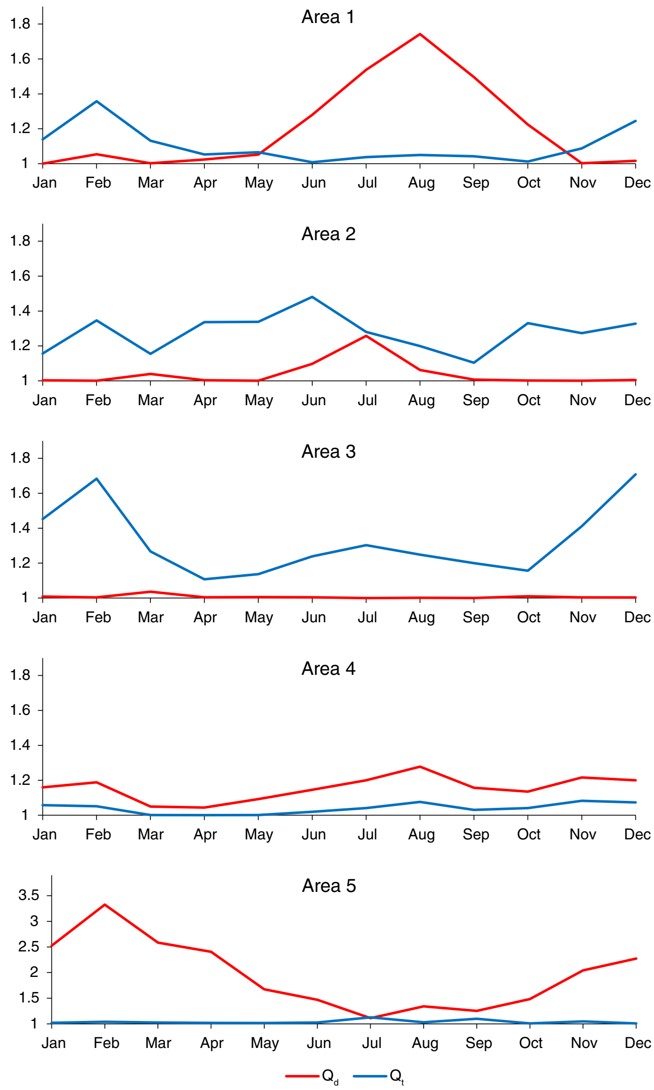

FIGURE 5 Seasonal variations of the Q_D (red) and Q_T (blue) calculated for the five areas [Colour figure can be viewed at wileyonlinelibrary.com]

5.2 | The regional correlations of the two influencing factors

The gas law suggests that for the change of the pressure, density and temperature are two independent variables. Globally, from the data, they may truly be treated as independent quantities, since their correlation has different signs at different places. However, regionally, their data may display certain correlation patterns, and this may be caused by the interactions among the land, ocean, and atmosphere at both regional and large scales.

Figure 4a shows that the two influencing factors, the density and temperature, have weak positive correlations ($r_{DT} > 0$) over the North Pacific, North Atlantic, and the ocean belt north of the Antarctic. Over the wide remaining area in the globe, especially over the northern hemisphere and the tropics, density and temperature are negatively correlated ($r_{DT} < 0$), and the correlation is strong. Further, these wide areas with negative correlation between density and temperature can be divided into two parts. One is the areas where pressure has negative correlation with density but positive correlation with temperature ($r_{PD} < 0$ and $r_{PT} > 0$). The other is the areas where pressure is positively correlated with density but negatively correlated with temperature ($r_{PD} > 0$ and $r_{PT} < 0$).

Based on these three patterns with the different simple correlations between the two influencing factors as well as the simple correlations of the pressure with them, in the following section, we analyse the reasonability of the results obtained from the simple method for assessing the dominance of the two influencing factors in the variation of pressure.

5.3 | The dominance patterns and their reasonability

As mentioned above, the original physical relation of the three quantities is the gas law ($P = D \cdot T$), which is a nonlinear relation. In order to be convenient to assess the dominance of the two influencing factors, we instead use the normalized linear fitting ($P = AD + BT$). What we obtain in Figure 1 (right column) are simply the final results of the dominance, based on the quantitative calculations of the linear regression method. The reasonability of the results for the dominance from the statistical method needs to be interpreted. The gas law, as a physical relation, is simple, and is easy for understanding qualitatively the relations among the quantities. It is used here for illustrating the reasonability of the results for the following three patterns.

The first pattern of the dominance is, within the wide areas in the globe in Figure 4a with the negative correlation between density and temperature ($r_{DT} < 0$), for those regions in Figure 4b,c where pressure has negative correlation with density ($r_{PD} < 0$) but positive correlation with temperature ($r_{PT} > 0$), including the Tibetan Plateau, the Africa, North Australia, Greenland, West America, the southern portion of South America, and the Antarctic. The correlation of the pressure with temperature there is stronger, in magnitude, than the correlation with density ($r_{PT} > |r_{PD}|$).

The meaning of the two correlations is that corresponding to the large value of the pressure in a specific year, the density is relatively low, but the temperature is much high. In other words, based on the physical relation $P = D \cdot T$, the large positive contribution from the temperature can overcome the negative contribution from the density. This suggests that the temperature, of the two influencing factors, dominates the variation of the pressure.

For the pattern of these regions, same conclusion can be obtained from the statistical method. In linear regression $P = AD + BT$, since input quantities are normalized, D and T are both in magnitude of 1, while they can be positive or negative. The decrease of pressure with density ($r_{PD} < 0$) can be denoted with $D = -1$, and the increase of pressure with temperature ($r_{PT} > 0$) can be denoted with $T = 1$. Thus the increase of the pressure can be expressed as $P = -A + B > 0$, where A and B are both positive. The dominance relation of the $B/A > 1$, we reach here from the statistical method, indicates that for this pattern, the change of temperature always dominates the variation of the pressure, and the density here plays a negative role.

The second pattern of the dominance is also within the wide areas in Figure 4a with negative correlation between density and temperature ($r_{DT} < 0$), but for the regions where pressure has positive correlation with density ($r_{PD} > 0$) in Figure 4b while negative correlation with temperature ($r_{PT} < 0$) in Figure 4c. The meaning of the two correlations is that corresponding to the large value of the pressure in a specific year, the density is large, but the temperature is relatively low. Based on the physical relation $P = D \cdot T$, the positive contribution from density overcomes the negative contribution from temperature, suggesting that the density, of the two influencing factors, dominates the variation of the pressure.

The conclusion of this pattern can also be reached from the statistical method. In the normalized linear regression $P = AD + BT$ for the regions with this pattern, the increase of pressure with density ($r_{PD} > 0$) can be denoted with $D = 1$, and the decrease of pressure with temperature ($r_{PT} < 0$) can be denoted with $T = -1$. The increase of the pressure can thus be expressed as $P = A - B > 0$. The dominance relation of the $B/A < 1$ obtained from the statistical method also indicates that for this pattern, the change of density dominates the variation of the pressure; the temperature here plays a negative role.

The third pattern of the dominance is for the areas where density and temperature are positively correlated ($r_{DT} > 0$), including the north Pacific, north Atlantic, and the ocean belt north of the Antarctic (Figure 4a). It is shown in Figure 4b,c that over these regions, pressure has positive correlations with both density ($r_{PD} > 0$) and temperature ($r_{PT} > 0$). According to the physical relation $P = D \cdot T$, density and temperature of these regions both have positive contributions to the change of the pressure. For this pattern, we hope to determine whether density or temperature contributes more to the interannual variation of the pressure.

The statistical method can reach the same conclusion for the dominance of this pattern, and can easily determine which influencing factor is more important. In the linearly fitted relation $P = AD + BT$ for the regions of this pattern, the positive correlation of pressure with density ($r_{PD} > 0$) is indicated with $D = 1$, and the positive correlation with temperature ($r_{PT} > 0$) is denoted with $T = 1$. Thus the increase of pressure can be expressed as $P = A + B > 0$. For this pattern, the relative importance of the two influencing factors needs to be determined, through comparing the values of the A and B, which are both positive. For the regions with $B/A > 1$, temperature dominates the variation of the pressure. For the regions with $B/A < 1$, density dominates the variation.

In sum, for all the three patterns, the linear regression-based quantitative method can reach the same conclusion as obtained from the qualitative analysis of the original nonlinear physical relation. The B/A, the ratio of the two coefficients calculated from the fitting, can be used to determine the relative importance of the two influencing factors. The two factors can have both positive and negative correlations, depending on the location, and these can be used to better understand the meaning of the results for the dominance. When density and temperature are negatively correlated ($r_{DT} < 0$), there can be two situations. One is that in some regions density plays a negative role, and temperature dominates the change of the pressure, so we have $B/A > 1$. The other is that in some regions temperature plays a negative role, and density dominates the change of the pressure, thus we have $B/A < 1$. When density and temperature are positively correlated ($r_{DT} > 0$), they both have positive contributions to the change of the pressure, and their contributions can further be compared. For the regions where $B/A > 1$, temperature is more important. For the regions where $B/A < 1$, density is more important.

6 | SUMMARY AND DISCUSSION

Atmospheric pressure is an important quantity for atmospheric circulation and climate system. The variability and changes of the atmospheric pressure need to be further investigated. In the present study, we focus on near surface air, and examine the interannual variation of the pressure. The gas law shows that pressure can be affected by density and temperature. We then explore whether density or temperature dominates the variation of the pressure.

Density and temperature are nonlinearly linked in the gas state equation. To be convenient to compare the contributions of the two influencing factors and assess their relative importance, we apply a linear method, which utilizes normalized linear regression. The key of the method is the reliability of the linearization. Significance tests, which are performed for each grid point, show that the method is robust, and the linear fitting is perfect everywhere over the globe.

The reason of the feasibility is that, for obtaining a given pressure, density and temperature are linked in form of a hyperbolic relation $D \cdot T = P$. For the density and temperature of a grid point, their joint distributions may fall into the two types. One is that the density varies greatly but, relatively, the temperature does not have much change. The other is that the temperature varies greatly but density changes a little. For these two types, the scatter plots of the two quantities may both be retrograded, so that a linear fitting can well reflect their joint effects.

In the normalized linearly-fitted relation $P = AD + BT$, the D and T are in magnitude of 1, and their values can be positive or negative. Calculations show that, for this issue, the coefficients A and B are both positive everywhere in the globe. Derivations indicate that the two coefficients link to the partial correlations, not simple correlations. Calculations suggest the partial correlations of the pressure with D and T are both positive and equal to 1 everywhere in the globe. This is consistent with what we deduce from the original physical relation $P = D \cdot T$.

For the normalized fitting, we can simply use the two coefficients A and B to measure the contributions from the D and T. The results of the B/A, for the entire field and for all the months, are presented in this study to illustrate the relative importance of the density and temperature. The linear regression method can provide quantitative results of the dominance. Since this is a statistical method, we still hope that the results can be verified or further interpreted.

The nonlinear issue of the present study is a special case, which provides an opportunity for us to examine the reliability of the linear-regression method. The original nonlinear relation $P = D \cdot T$ can be used to qualitatively deduce the dominance, through considering the relation between the two influencing factors as well as the relations of the pressure with the two factors. The results of the dominance are classified into three patterns, and the behaviours of the linear fitting method are compared. It is shown that for all the three patterns, the results of the dominance quantitatively determined with the linear fitting method are consistent with the results qualitatively reached from the original nonlinear relation.

The first two patterns are corresponding to the negative correlation between density and temperature. Based on the relation $P = D \cdot T$, the pressure can be positively correlated with one of the two influencing quantities, while negatively correlated with the other. Thus, by nature, the variation of the pressure is dominated by the one that is positively correlated with the pressure. The third pattern is corresponding to the positive correlation between density and temperature. Based on the nonlinear relation, they both have positive correlations with the pressure, and thus both have positive contributions to the variation. Whether density or temperature dominates the variation needs to be determined with the linear fitting method through comparing the two measures.

It is therefore demonstrated that for the specific issue of this study, the normalized linear fitting method is robust. The results of the dominance quantitatively determined from the linear method are reasonable and reliable, for all the grid points that may belong to the different patterns. The two influencing factors, the density and temperature, can be independent, positively or negatively correlated. The determinations of the dominance are not affected by the relation of the two influencing factors. The two coefficients of the linear fitting, which determine the dominance, are linked with the partial correlations.

Although there may exist interactions among the three quantities, which will be further analysed in our next work, the variation of the pressure with the density and temperature is a more fundamental issue. It reflects, respectively, the dynamic and thermodynamic effects of the atmospheric circulation in the change of the pressure, that is, the contributions from the mass transport and the heat transport because of the circulation.

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