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PARTITION OF SEASON BASED ON MULTIELEMENTS AND THE DECADAL CHANGE OF SEASON DURATION IN CHINA

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Abstract: Using the multielements similarity measurement method and 1950-2017 NCEP/NCAR gridded daily reanalysis datasets, we analyzed season duration in China during 1950-2016, and we defined the element with maximum absolute sensitivity as the key impact element at each point using the sensitivity analysis method. The decadal change of season duration and its key impact element before and after 1980 were studied. The results indicated obvious meridional and zonal differences in the distribution of season duration for the 67-year average, and that the key impact element has the same distribution characteristics as season duration. In addition, complementary relationships were found between the durations of spring and summer, autumn and winter, and the cold and warm seasons. Among them, the complementary relationship between the durations of spring and summer was strongest and the regions of complementarity were numerous. The complementary regions of autumn and winter durations were found mainly in western China. In the cold and warm seasons, the complementary regions were widespread and the complementary relationship was generally weak. Comparison of the periods before and after 1980 revealed an east-west difference in the interdecadal variation of season duration. Interdecadal variation in spring and summer was found concentrated in northern and western regions, while that in autumn and winter was concentrated in the western region. Areas of significant interdecadal variation of the key elements were found concentrated in northern and western regions, corresponding well to the areas of significant interdecadal variation of season duration.

Key words: multielements similarity measurement method; season duration; key impact element; decadal change
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1 INTRODUCTION

Increasing concentrations of greenhouse gases in the atmosphere and rising global temperature have prompted increasing attention from the academia, the public, and governments on environmental problems related to global climate change (Qin [1]). The Fifth Assessment Report of the IPCC claims that evidence of the warming of the climate system is irrefutable. Global combined land and ocean temperature data show an increase of approximately 0.85℃ during 1980 –2012, which is considered the warmest period since the Industrial Revolution (IPCC5 [2]). The Second National Assessment Report on Climate Change states that annual mean ground temperature in China increased by 1.38℃ during 1960 –2009, which is much lower in the Northern Hemisphere (Second National Assessment Report on Climate Change[3]). Since the late 1970s, the main areas of warming in China have been in the northwest, northeast, and northern China (Shi et al. [4]). Global climate change has had an important impact on the interdecadal change of the seasons in China (Gong et al.[5]; Zhang et al.[6]; Shen et al. [7]). Therefore, studying season duration in China could clarify its spatial characteristics, elucidate its sensitivity to meteorological elements, and reveal its interdecadal variation, which will help determine the impact of global climate change on the characteristics of the seasons in China. This will be beneficial for improving societal adaptability to global climate change, and for achieving sustainable and harmonious socioeconomic and environmental development (Lu et al. [8]).

Seasons can be distinguished based on astronomical, phenological, climatological, and meteorological classification systems (Zeng et al. [9]). In meteorological research, the study of seasons focuses primarily on two considerations: atmospheric circulations and meteorological elements. Each perspective has its specific rationality and limitations. Dividing seasons using atmospheric circulations can better explain the dynamic mechanism and abrupt change of each season, but this method is specific to individual regions and the outcome is not very accurate. Dividing seasons using meteorological elements can produce results for each region that are more accurate, but they can be difficult to

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explain in terms of theory and dynamic mechanisms. In addition, the influence of the climate system on season duration is a complex, highly nonlinear, scale-free, multilevel, and forced dissipative system (Guo et al.[10]; Hao et al.[11]), the variation of which is a nonstationary process (Gong et al.[5]; Li et al.[12]). Thus, existing methods for dividing seasons have certain limitations in terms of comprehensive and accurate assessment of the response of climate change to global warming (Zhang et al.[13]).

Many studies have been undertaken regarding the division of seasons in China. Previous studies based on atmospheric circulations (e.g., Zhu[14]; Tu et al.[15]; Ye et al.[16]; Zhang et al.[17]; Yuan et al.[18]; Fan et al.[19]) have focused mainly on monsoons and other large-scale circulations and their division standards have tended to be qualitative. Earlier studies based on meteorological elements (e.g., Zhang[20]; Zhu[21]; Zhang et al.[22]; Liao et al.[23]) have used a single element or multiple elements. Such studies have tended to focus on the seasonal variation of certain meteorological elements, e.g., temperature, from which they might have artificially derived some quantitative division standards. Thus, these methods might be incapable of comprehensively revealing the main characteristics of seasonal variation, and generalizations alone cannot predict climatic change scientifically (Liu et al.[24]).

By considering the shortcomings of both approaches, Zeng et al., Zhang et al. and Xue et al. have all proposed adopting the similarity measurement method for the division of seasons to obtain results that are more objective and quantitative[9, 25, 26]. Based on the similarity measurement method, Sun et al. and Hou et al. suggested a new approach to the division of seasons using multielements to structure the climate fields[27, 28], which makes the division more accurate and comprehensive. However, the sensitivity of season duration to meteorological elements in China has not been studied previously, and related studies on the interdecadal variation of regional seasonal characteristics are lacking. In this study, we divided the seasons during 1950–2016 in Chinese mainland using NCEP/NCAR gridded daily reanalysis datasets and the multielements similarity measurement method. Moreover, we also investigated the sensitivity of season duration to the meteorological elements. In addition, we analyzed the interdecadal variation of season duration in China and its key impact element. The results provide a unique picture of climate change characteristics in China from the prospective of season duration.

2 DATA AND METHODS

2.1 *Data*

To investigate season duration in Chinese mainland and its key impacting element, we used 1950–2017 NCEP/NCAR gridded (2.5°×2.5°) daily reanalysis surface datasets of temperature (T), relative humidity (R_H), pressure (P), zonal wind (U), and meridional wind (V). In this study, data acquired on February 29 of leap years were removed so that each year comprised of 365 days and 73 pentads.

2.2 *Regional division*

According to our research needs and China's Physical Geography (1995), China was divided into eight areas, as shown in Fig. 1. Area 1 covered northeast China (42°–54°N, 110°–135°E), including Heilongjiang, Jilin, Liaoning and the northeastern parts of Inner Mongolia, and it incorporated 55 and 35 grid points within and near China, respectively. Area 2 encompassed northern China (34°–42°N, 110°–128°E), including Hebei, Shandong, eastern Shanxi, Beijing, and Tianjin, and it included 21 and 17 grid points within and near China, respectively. Area 3 was central China (27°–34°N, 110°–123°E), including Jiangsu, Zhejiang, Anhui, Henan, Hubei, and some adjacent regions, and it included 18 and 15 grid points within and near China, respectively. Area 4 covered southern China (18°–27°N, 110°–123°E), including Guangdong, eastern Guangxi, the annexes, southwestern Jiangxi, southern Hunan, Hainan, and Taiwan, and it incorporated 18 and 12 grid points within and near China, respectively. Area 5 encompassed eastern parts of northwest China (37°–45°N, 95°–110°E), including the middle part of Inner Mongolia, western and northern Shaanxi, Ningxia, and northern Gansu, and it covered 18 grid points in China. Area 6 included western parts of northwest China(37°–49°N, 73°–97°E), including Xinjiang, and it encompassed 40 and 31 grid points within and near China, respectively. Area 7 covered southwest China (22°–37°N, 97°–110°E), including Yunnan, Guizhou, western Guangxi, Sichuan, Chongqing, western Hunan, and southern Shaanxi, and it included 30 and 29 grid points within and near China, respectively. Area 8 was Tibet (27°–37°N, 78°–97°E), including southwestern Tibet and Qinghai, and it incorporated 28 and 25 grid points within and near China, respectively.

2.3 *Method used for season division*

The multielements similarity measurement method, adopted in this study to divide seasons, was implemented as follows. (1) Five days were taken as a pentad and 365-day daily mean data of the five climate elements were obtained to form 73-pentad pentad mean datasets, from which we constructed a climate state function $F(\theta, \lambda, p, t)$ of time t at (θ, λ, p, t),

$$F(t)=(P, T, R_H, U, V) \tag{1}$$

where P, T, R_H, U and V represent pressure, temperature, relative humidity, zonal wind, and meridional wind, respectively. $F(t)$ is a vector field formed by the five climate elements that vary with time. (2) Based on the similarity measurement method, we recorded the mean fields of January (winter) and July (summer) as F_W and F_S, respectively. Eliminating the mean of the two fields, $F^*=(F_W+F_S)/2$, we obtained the typical fields of winter and summer, $F_W^{'}$ and $F_S^{'}$, respectively. (3) At every pentad, we eliminated F^* to obtain the deviation of pentad mean

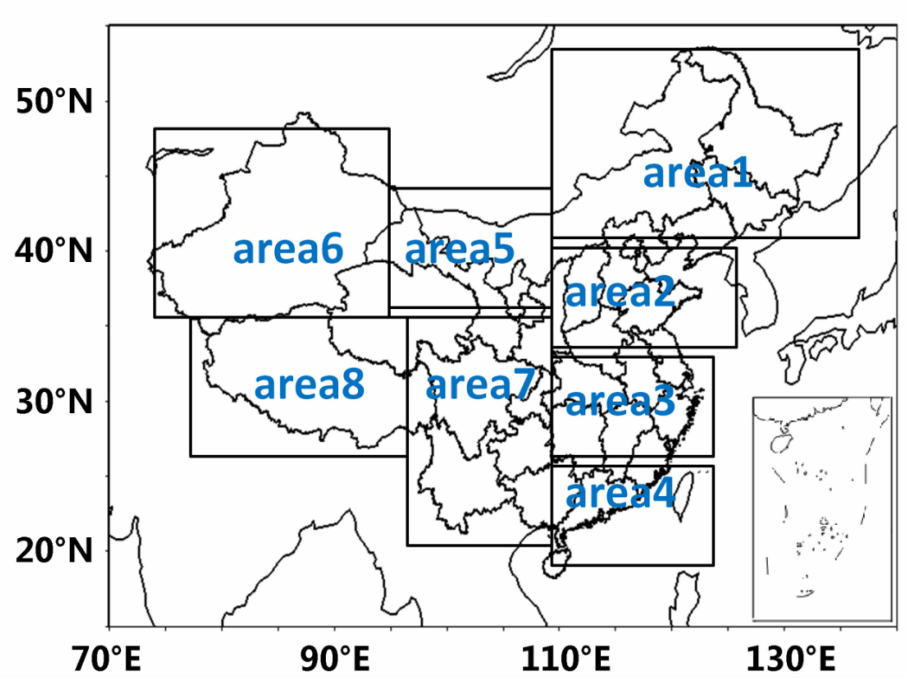

Figure 1. Division of study regions in China.

typical field $F'(t)$, $F'(t)=F(t)-F^*$. (4) Finally, we calculated the similarity coefficient $R(t)$ between $F'(t)$ and F'_W (or F'_S) of each pentad:

$$R(t)=(F'(t), F'_W)/[\ \| F'(t) \| \cdot \| F'_W \|\ ]. \tag{2}$$

In Equation (2), each variable on the right is a vector, so the inner product and norm are those of the vector. Here, F'_W and F'_S are two opposite vectors, so only F'_W or F'_S need to be used to calculate $R(t)$. Here, $R(t)$ characterizes the similarity between the climate anomaly field and the typical field of winter (or summer) in each pentad. When the similarity is above/below a certain threshold, we can consider the season to have changed.

According to the projection angle of $R(t)$, $\theta=\arccos R_w(t)$; therefore, the following criteria for season division are derived, following Xue et al.[26]:

$$\begin{cases} 0\leqslant\theta\leqslant\pi/4 & \text{(winter)} \\ 3\pi/4\leqslant\theta\leqslant\pi & \text{(summer)} \\ \pi/4<\theta<3\pi/4 & \text{(spring or autumn)} \end{cases}$$

2.4 *The complementarity index*

We examined the complementary relationship between the lengths of two seasons in China. The complementarity index is used in economics to measure the degree of coincidence between the export products of one country and the import products of another country. Based on the complementarity index proposed by the economist Drysdale[29], we made a simple modification to the calculation to obtain an index that could express the complementarity relationship between the durations of two seasons:

$$\mathrm{C_{ab}}=-k\cdot[\mathrm{LT_a}-\mathrm{LT}_{\bar{\mathrm{a}}}/\mathrm{LT}_{\bar{\mathrm{a}}}]\cdot[\mathrm{L}T_\mathrm{b}-\mathrm{LT}_{\bar{\mathrm{b}}}/\mathrm{LT}_{\bar{\mathrm{b}}}] \tag{3}$$

where $\mathrm{C_{ab}}$ represents the complementarity of season duration between season a and season b; $\mathrm{LT_a}$ and $\mathrm{LT_b}$ represent the duration of season a and season b at grid points, respectively; $\mathrm{LT}_{\bar{\mathrm{a}}}$ and $\mathrm{LT}_{\bar{\mathrm{b}}}$ represent the average duration of season a and season b in China, respectively; k is a constant. If $\mathrm{C_{ab}}$ is positive, it means that the durations of seasons a and b are complementary, and the larger the value of $\mathrm{C_{ab}}$, the stronger the complementarity. If $\mathrm{C_{ab}}$ is negative, it means that the durations of seasons a and b do not have complementarity.

2.5 *Sensitivity analysis*

Sensitivity analysis is an effective method with which to understand and evaluate a model, i.e., by keeping other elements the same, the effects caused by a change of one parameter can be analyzed (Yi et al. [30]). Sensitivity analysis was adopted to determine the key impact element of regional season duration, which might help explain the derived changes of season duration. Sensitivity of season duration (SD) to meteorological element (X) can be obtained using partial derivatives, i.e., $\partial SD/\partial X$. Because of the different dimensions and scales of different elements, we first needed to nondimensionalize the variable (McCuen[31]):

$$S=\frac{\partial SD}{\partial X}\cdot\frac{|X|}{SD} \tag{4}$$

A simple and effective method for calculating the relative sensitivity coefficient is to use an approximate solution of the finite difference of the Taylor series expansion (Hupet and Vanclooster [32]; Lenhart and Eckhardt[33]):

$$S=\frac{\Delta SD}{\Delta X}\cdot\frac{|X|}{SD} \tag{5}$$

where ΔX is the change of a meteorological element, and ΔSD is the change of season duration caused by ΔX. The greater the absolute value of S, the higher the sensitivity of season duration (SD) to X, and the greater the impact of X on season duration (SD). The relative sensitivity coefficient is dimensionless; therefore, it is convenient for comparing the impacts of different meteorological elements on season duration (Yi et al.[30]).

In this study, each time we changed one meteorological element with value μ and kept the other elements the same, we calculated SD and S. By comparing the absolute value S of different meteorological elements, we defined the meteorological element with the greatest absolute value S as the key impact element. Normally, the value of μ is not constant and it should be adjusted. Based on many experiments, we choose a value of μ= 20% in this study (Goyal[34]). To illustrate the sensitivity of season duration to meteorological elements, certain figures in this paper use different colors to represent different meteorological elements, and circles and triangles are used to reflect positive and negative values of the sensitivity of the key elements, respectively. A positive value indicates that the key element has positive effect on season duration, and an increase of that element would lead to an increase of season duration, and vice versa.

3 SPATIAL DISTRIBUTION OF SEASON DURATION IN CHINA AND KEY IMPACT ELEMENTS

3.1 *Season duration*

Most previous related studies (e.g., Zhang et al.[13]; Xue et al.[26]; Huang et al.[35]) have focused mainly on the time of the onset of specific seasons and thus regional season duration has not been studied extensively. Here, we analyze the spatial distribution of season division in Chinese mainland during 1950–2016 (Fig. 2) using the multielements similarity measurement method. In the Liaodong Peninsula and the north, southwest, and eastern parts of northwest China, spring duration is above 17 pentads (Fig. 2a) and much longer than in other regions of the country. Areas in which spring has an obviously shorter duration (<10 pentads) are distributed mainly in southern China, northern parts of northeast China, western parts of the Tibet Plateau, and Xinjiang. Spring duration shows obvious north-south and east-west differences. Similar differences exist in summer (Fig. 2b) but with a converse distribution of areas with longer and shorter duration. The duration of summer on the Liaodong Peninsula, in northern China, and in eastern parts of northwest and southwest China is much shorter (<20 pentads) than in other areas, whereas summer duration is above 27 pentads in southern China, on the Tibet Plateau, and in Xinjiang. Comparison of Fig. 2a and 2b reveals an opposite relationship between the duration of spring and summer in most regions of China. It means that in a region where spring duration is long, summer duration will be short, and vice versa.

The definitions of warm and cold seasons are slightly different for different regions (Lin et al.[36]; Lin et al.[37]; Shi et al.[38]). Shi et al. defined the sum of normal spring and summer as the warm season, and the sum of

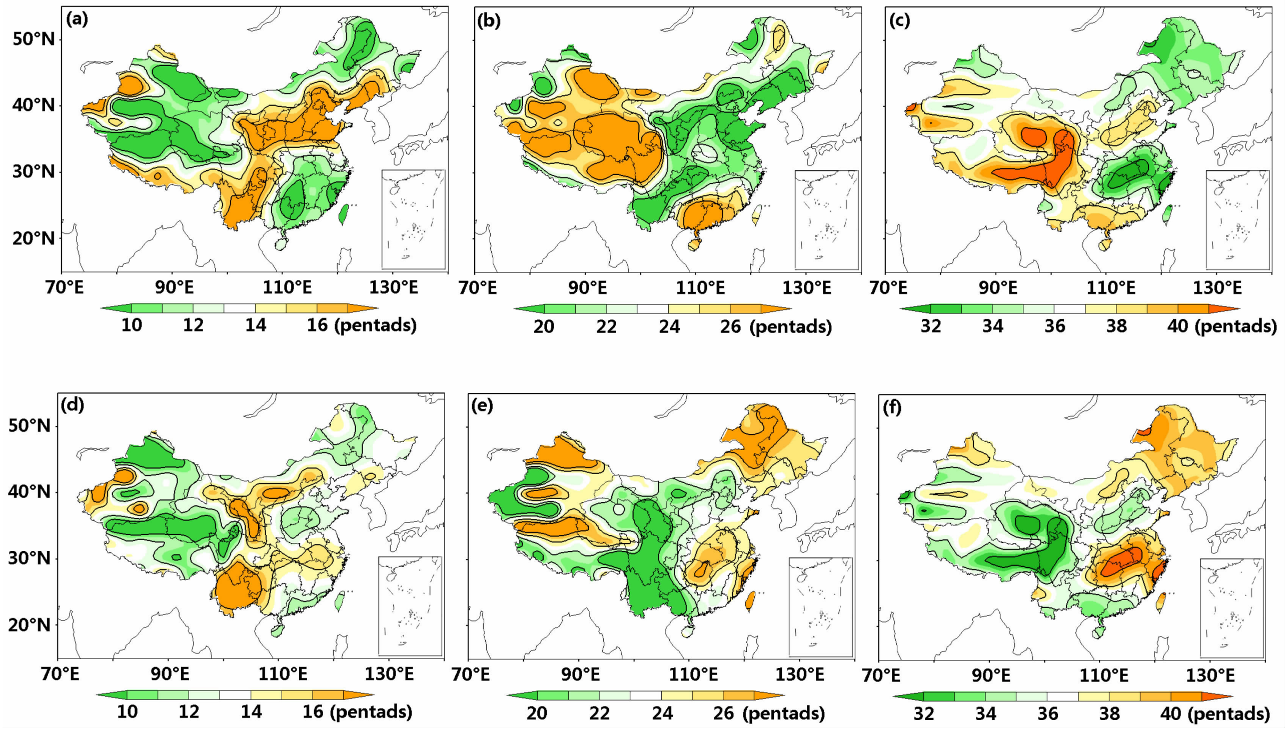

Figure 2. Spatial distribution of 1950–2016 mean season duration in China: (a) spring, (b) summer, (c) warm season, (d) autumn, (e) winter, and (f) cold season.

normal autumn and winter seasons as the cold season in east China [38]. Other earlier studies have also roughly defined the warm and cold seasons as extending from March to August and from September to February, respectively. However, few studies have focused on the durations of warm and cold seasons defined using an objective division method. The spatial distributions of the duration of the warm and cold seasons in China during 1950–2016, defined using the similarity measurement method, are shown in Fig. 2c and 2f, respectively. As the results are averages of many years, the durations of the warm and cold seasons are reasonably fixed, which leads to almost opposite spatial distributions of duration between the two seasons. The spatial distribution of warm season duration shows obvious zonal differences, i.e., shorter in eastern areas and longer in the west. The distribution features are obviously opposite for the cold season. Furthermore, the duration distribution also presents obvious meridional differences in east China, reflecting a short-long-short-long pattern in warm season duration from north to south, but a long-short-long-short pattern in cold season duration. These differences are likely due to both the different dominant elements affecting season duration in each region and the seasonal variation characteristics of meteorological elements.

3.2 *Interseasonal complementarity index in China*

We also calculated the complementarity index between spring and summer durations, between autumn and winter durations, and between warm and cold season durations. Except for some regions (i.e., middle and lower reaches of the Yangtze River, northern parts of northeast China, and southeastern parts of Tibet), the complementarity of season durations in spring and summer is significant (Fig. 3). The regions with strong complementarity of season duration in autumn and winter are concentrated mainly in western regions (i.e., west of 110° E), including western Xinjiang, northern Tibet, southwest China, and eastern parts of northwest China, while there is no complementarity in eastern regions. The spatial distribution characteristics of complementarity are consistent with the spatial distribution characteristics of season duration shown in Fig. 2, indicating that the complementarity coefficient can well reflect the complementary characteristics of the seasons. Because of the complementarity illustrated in Fig. 3a and 3b, the duration of the warm (cold) season shown in Fig. 2 varies slightly in most parts of China. The regions with longer and shorter (shorter and longer) seasons in Fig. 2c (2f) correspond well with those without complementarity in Fig. 3a (3b). Because the sum of the durations of the cold and warm seasons is reasonably constant, complementarity between the cold and warm seasons exists throughout the entire country, although it is generally weak. The regions with longer and shorter (shorter and longer) warm (cold) seasons correspond well with those with strong complementarity in Fig. 3c. Evident complementarity of season duration exists between spring and summer, autumn and winter, and the cold and warm seasons and, to a certain extent, it can explain the spatial distribution characteristics of season duration.

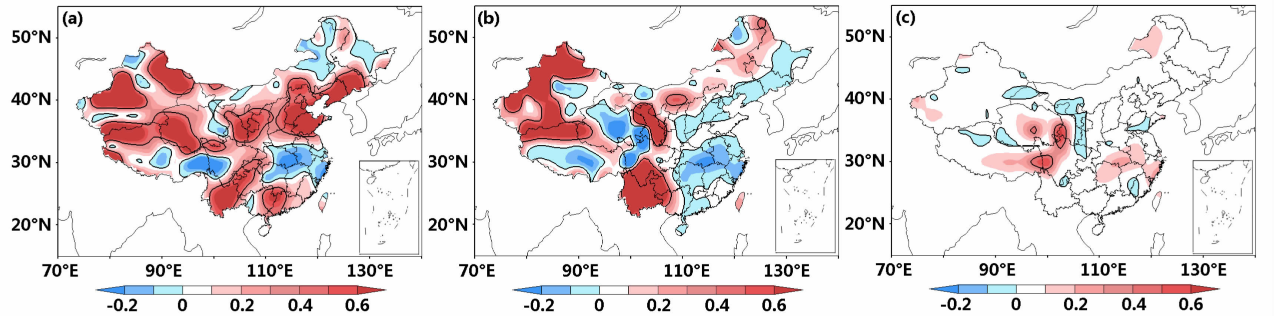

Figure 3. Spatial distribution of complementary index between two seasons. (a) Complementary index between spring and summer; (b) between autumn and winter; (c) between warm and cold seasons. Black solid line indicates significant complementarity.

3.3 *Key impact elements*

We investigated the sensitivity coefficient of season duration to meteorological elements, and we defined the one with the maximum absolute value as the key impact element. The results are presented in Fig. 4. In accordance with the definition of regions in section 2.2, the first two main elements affecting season duration are listed in Table 1.

The main element affecting spring duration in China is pressure (Fig. 4a), while other elements have relatively small impact. The impact of each element on spring duration is largely positive, indicating that an increase of any element would lead to an extension of the duration of spring. Regionally (Table 1), the second major element affecting spring duration in the eastern region is temperature, while the second major element affecting spring duration in western region is meridional wind. Among all regions, spring duration in northeast China is affected mostly by pressure; conversely, spring duration in northern China is affected least by pressure and influenced more by temperature and relative humidity.

Throughout the entire country, summer duration is affected greatly by relative humidity and pressure, while the influence of meridional wind is relatively small and confined mainly to central China. The effects of air pressure and meridional wind on summer duration are both negative, while the effect of relative humidity is positive. In regions other than northern China and central China (Table 1), the effects of air pressure and relative humidity are reasonably strong. In northern China, the influence of relative humidity on summer duration is the greatest. In central China, the influence of relative humidity on summer duration is the smallest, but the influence of meridional wind is enhanced.

Figure 4c shows that autumn duration in northwest China and Tibet is affected mainly by relative humidity and temperature; the effect of temperature is positive, while that of relative humidity is negative. Autumn duration in east and southwest China is affected mainly by pressure, and the effect of pressure in east China is negative. In addition, the influence of relative humidity is reasonably strong in all regions except central and south China (Table 1).

The main characteristics of the distributions of the key elements affecting winter duration (Fig. 4d) are that winter duration in Tibet is affected mainly by relative humidity, while that in other areas is affected mainly by pressure. In northern China, winter duration is also affected by temperature. The effects of relative humidity and air pressure are mainly positive, while the effect of temperature is mainly negative. Winter duration in southern China is affected mostly by pressure; thus, winter duration would increase as pressure increases.

In conclusion, there are obvious regional differences in the spatial distributions of the key elements affecting season duration in China. In summer, autumn, and winter, regional differences are obvious and the key impact elements exhibit evident differences between eastern and western China, consistent with the regional differences of season duration. Eastern China is characterized as a monsoon area; thus, the key impact element on season duration has a clear meridional distribution. Western China encompasses the monsoon marginal zone, westerly climate zone, and plateau climate zone; thus, the climate is more complex. In addition, the underlying surface condition has clear regional differences, and there is greater variety in the key elements that affect season duration in this area. Therefore, the spatial distribution is reasonably scattered, and the sign of the sensitivity of season duration to the key impact element is different in the western region. Furthermore, to a certain extent, the distribution of the key elements affecting season duration shown in Fig. 4 corresponds to the spatial distributions of season duration shown in Fig. 2. If we consider the seasonal variation of meteorological elements and the distributions of the key elements concurrently, we can infer the season duration in each region. The distributions of the key elements affecting season duration can explain, to a certain extent, the spatial distribution of season duration.

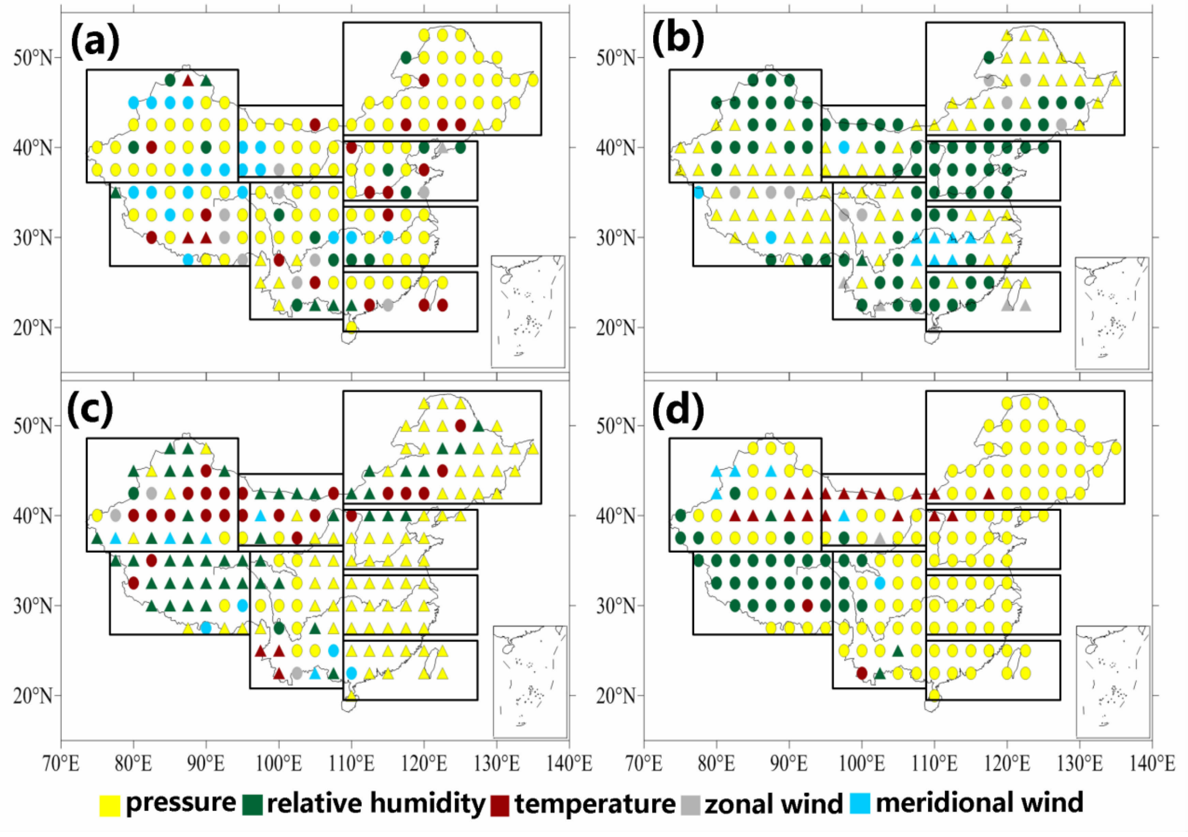

Figure 4. Spatial distribution of key impact elements on season duration: (a) spring, (b) summer, (c) autumn, and (d) winter. Circles (triangles) indicate that sensitivity coefficient is positive (negative).

Table 1. Percentage of the first two main elements affecting the duration of the four seasons in China. P: barometric pressure, R: relative humidity, T: temperature, U: zonal wind, and V: meridional wind. Positive (negative) values mean positive (negative) sensitivity.

		Spring	**Summer**	**Autumn**	**Winter**
Area 1	1st	+P(82.86%)	−P(65.71%)	−P(62.86%)	+P(94.29%)
	2nd	+T(11.43%)	+R(22.86%)	−R(22.86%)	−T(5.71%)
Area 2	1st	+P(41.18%)	+R(100%)	−P(76.47%)	+P(88.24%)
	2nd	+T,+R(23.53%)	0	−R(17.65%)	−T(11.76%)
Area 3	1st	+P(66.67%)	−P(46.67%)	−P(100%)	+P(100%)
	2nd	+R,+V(13.33%)	−V(33.33%)	0	0
Area 4	1st	+P(58.33%)	+R(50%)	−P(91.67%)	+P(100%)
	2nd	+T(25%)	−P,−U(25%)	+V(8.33%)	0
Area 5	1st	+P(66.67%)	+R(50%)	+T(33.33%)	+P(44.44%)
	2nd	+V(22.22%)	−P(44.44%)	−R(33.33%)	−T(38.89%)
Area 6	1st	+P(58.06%)	+R(58.06%)	−R(32.26%)	+P(48.39%)
	2nd	+V(22.58%)	-P(41.94%)	+T(29.03%)	−T(19.35%)
Area 7	1st	+P(41.38%)	−P(41.38%)	+P(31.03%)	+P(68.97%)
	2nd	+R(13.79%)	+R(34.48%)	−P(27.59%)	+R(17.24%)
Area 8	1st	+P(44%)	−P(68%)	−R(68%)	+R(80%)
	2nd	+V(24%)	+R,+U(12%)	−P(12%)	+P(16%)

4 INTERDECADAL CHANGE OF SEASON DURATION AND ASSOCIATED KEY IMPACT ELEMENTS

4.1 *Change of season duration*

To analyze the decadal change of season duration, we used anomaly histograms of season duration in China over the past 67 years (Fig. 5). The 9-point smoothing curves shown in Fig. 5 reveal obvious interdecadal variation in season duration during the late 1970s and early 1980s.

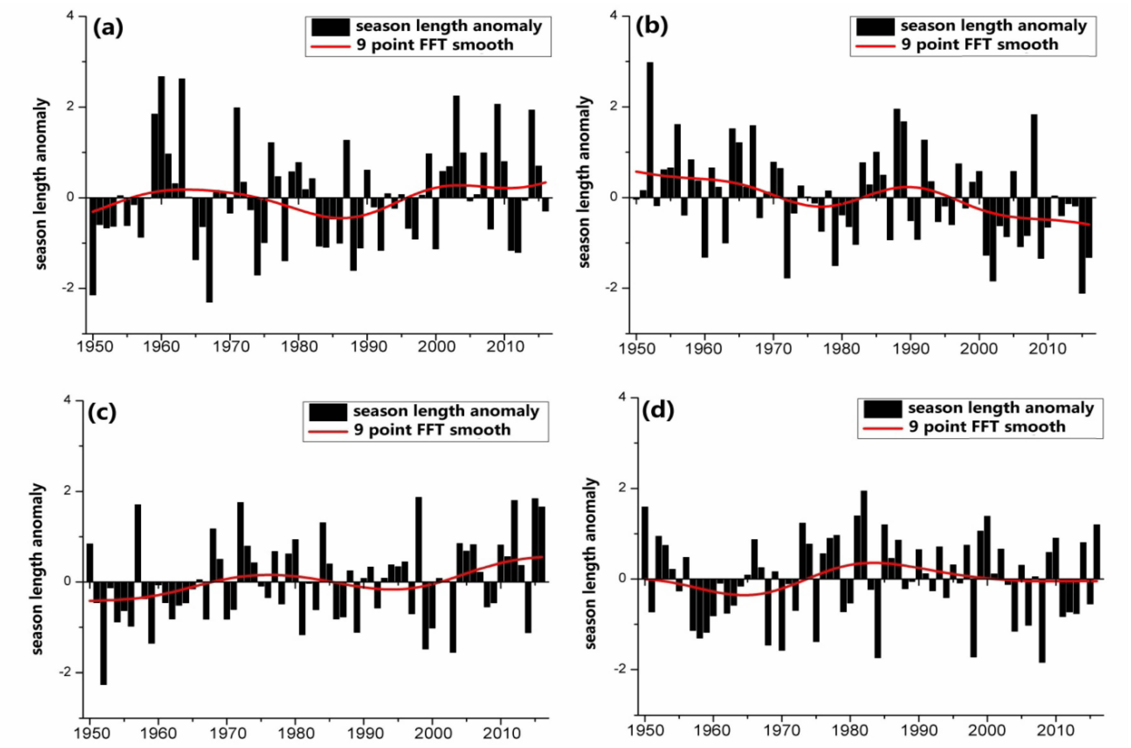

Figure 5. Annual variation of season duration in China during 1950−2016: (a) spring, (b) summer, (c) autumn, and (d) winter. Red curve is the 9-point FFT smooth curve.

Following previous research (e.g., IPCC [2]; Shi et al. [39]; Zhao et al. [40]; He et al. [41]; Gong et al. [42]), we compared the season durations of the two periods of 1950–1980 (period 1) and 1981–2016 (period 2). The differences of season duration between the two periods are presented in Fig. 6. Fig. 6a shows that the change of spring duration shows obvious meridional differences after 1980, i.e., spring duration in the eastern region increases, while that in the western region decreases. The increased high-value areas include northern parts of northeast China, eastern parts of northern China, eastern parts of northwest China, and South China. The decreased high-value areas cover almost the entire western region. The change of spring duration in each of the above areas is greater than two pentads. The meridional differences are the same(Fig. 6b) but the pattern is the opposite. Summer duration increases in the eastern region and decreases in the western region. In southern and eastern Tibet, summer duration increases most. In northern parts of northeast China, northern China, and eastern parts of northwest China, summer duration decreases most. The change of summer duration in each of the above areas is greater than two pentads. The changes of spring and summer durations after 1980 show obvious differences between areas to the west and east of 105° E (Fig. 6a and 6b, respectively). This difference in distribution corresponds well with the regional differences of the key impact elements, and it suggests the regional differences of duration changes might be related to the regional key impact elements. There is a reasonable complementary relationship between the changes of spring duration and summer duration. It means that in a region where spring duration increases, summer duration might decrease correspondingly, and vice versa. Because of this complementary relationship, changes in the duration of the warm season in most areas of China are reasonably small (Fig. 6c); however, overall, the warm season duration is shortened.

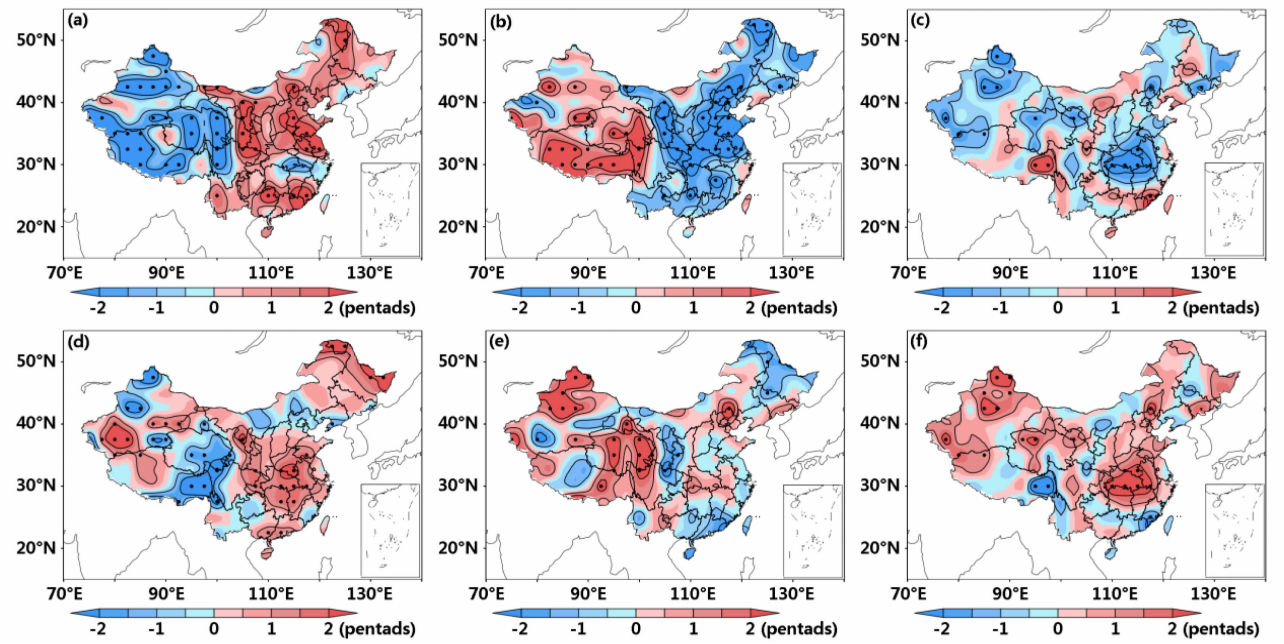

Figure 6. Difference (period 2 minus period 1) of season duration between 1950–1980 (period 1) and 1981–2016 (period 2): (a) spring, (b) summer, (c) warm season, (d) autumn, (e) winter, and (f) cold season. Shading indicates area of significant change.

Although the changes of autumn and winter durations have meridional differences, they occur mainly in western parts and are smaller than in spring and summer. The areas of significant increase in autumn duration are northern parts of northeast and central China and some western parts of northwest China. The areas of significant decrease in autumn duration are eastern Tibet and some western parts of northwest China. Overall, autumn duration is decreased in the west and increased in the east. The areas of significant increase in winter duration are eastern Tibet and northern Xinjiang. Thus, winter duration is increased in the west and decreased in the east. Furthermore, although the cold season duration (Fig. 6f) is increased, its change is reasonably small in most parts of China.

From the above, we know that the interdecadal variation between spring and summer durations is different to that between autumn and winter durations. Furthermore, the meridional differences of the interdecadal variation are obvious. The interdecadal variation in spring and summer is concentrated in northern and western regions. In autumn and winter, the interdecadal variation does not show obvious meridional differences, and it occurs mainly in northern and western regions. The regions of significant interdecadal change in our study are like those found in other research (e.g., Zhou et al.[43]). In addition, the interdecadal variations of cold and warm season durations are different. Overall, the warm season duration China decreased and the cold season duration increased. Because the sum of the cold and warm season durations is reasonably fixed, the areas of significant change in cold and warm season durations are similar, i.e., concentrated mainly in the area of the middle and lower reaches of the Yangtze River and northern Xinjiang. Sections 3.1 and 3.3 highlighted that the distributions of season duration are related closely both to the distributions of the key elements and to the changes of the meteorological elements. Without considering the interdecadal variations of the meteorological elements, the interdecadal variations of the key elements affecting season duration will have greater impact on the variation of season duration. The interdecadal variations of the key elements affecting season duration are discussed in the following paragraphs.

4.2 *Changes of key impact elements*

To further explore the interdecadal variation of season duration in different regions, we determined the differences of the key impact elements before and after 1980 (Fig. 7). We also calculated the changing percentage (period 2 minus period 1) of five elements affecting

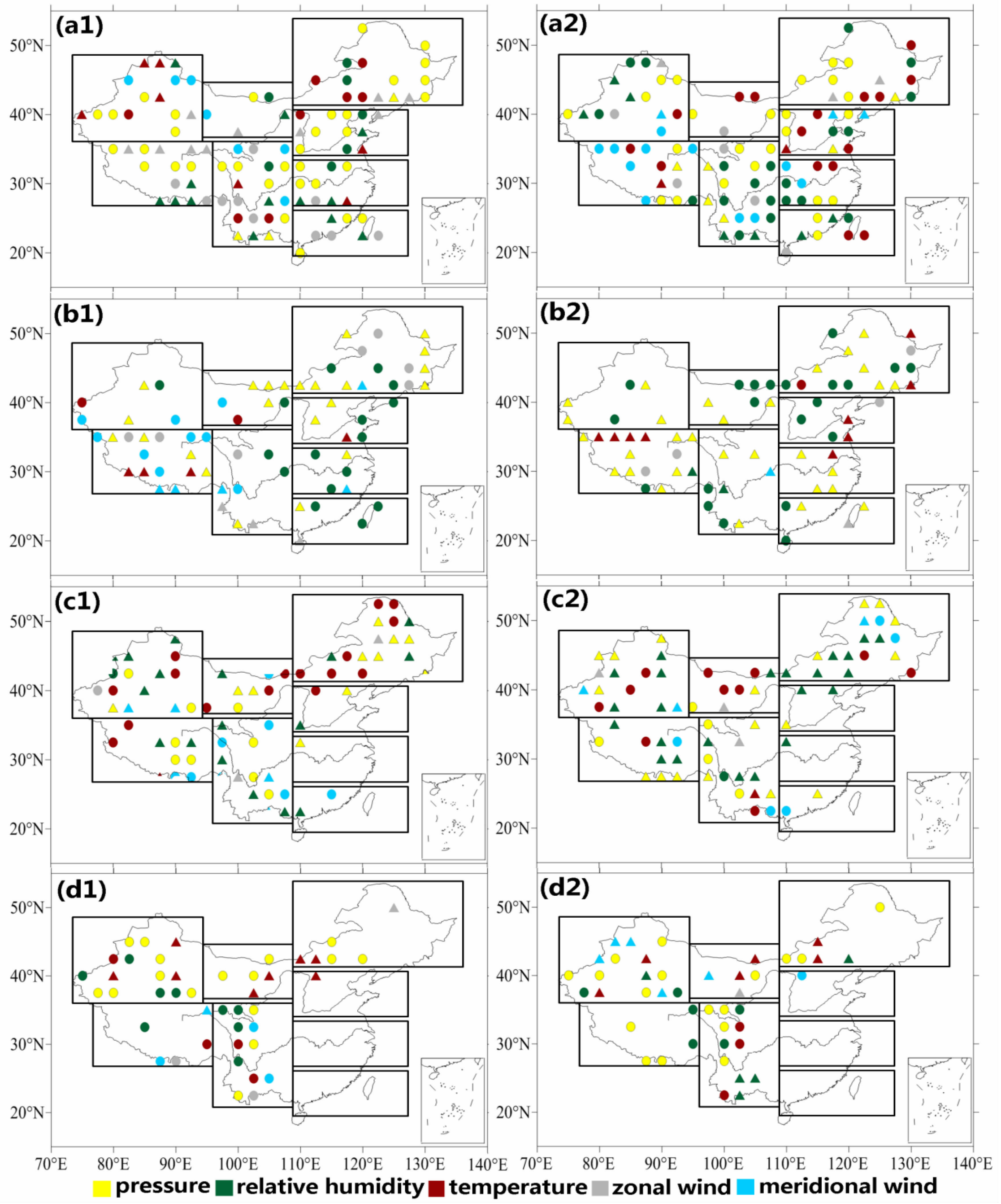

Figure 7. Distributions of the key elements affecting season duration before 1980: (a1) spring, (b1) summer, (c1) autumn, and (d1) winter and after 1980: (a2) spring, (b2) summer, (c2) autumn, and (d2) winter. Circles (triangles) indicate that sensitivity coefficient is positive (negative).

season duration in each region.

The key elements affecting the durations of spring and summer in China changed markedly between the two periods and the regions affected are distributed throughout the country (Fig. 7). The key elements affecting the durations of autumn and winter in China are mainly in the western region, while the key element affecting autumn is mainly in the northeastern region. For ease of comparison of the changes of the key elements in the two periods, Table 2 shows the change percentage of first key element between the two periods in each of the eight regions. The regions in which the key elements changed markedly are distributed reasonably widely in spring and summer, whereas they are concentrated mainly

Table 2. Percentage changes of the elements affecting season duration in China before 1980 (1950–1980) and after 1980 (1981–2011). P: barometric pressure, R: relative humidity, T: temperature, U: zonal wind, and V: meridional wind. Positive and negative values are sensitivity coefficients. Black (red) bold values indicate a change that is >10% (>20%).

	Element	D value			
		Spring	Summer	Autumn	Winter
Area 1	P	−2.86%	5.71%	0.00%	0.00%
	R	2.86%	5.71%	**−11.43%**	−2.86%
	T	0.00%	−2.86%	**−14.29%**	0.00%
	U	−2.86%	−8.57%	2.86%	2.86%
	V	0.00%	2.86%	2.86%	0.00%
Area 2	P	**−17.65%**	**11.76%**	0.00%	0.00%
	R	5.88%	0.00%	−5.88%	0.00%
	T	**11.76%**	−5.88%	−5.88%	5.88%
	U	**11.76%**	5.88%	0.00%	0.00%
	V	**−11.76%**	0.00%	0.00%	5.88%
Area 3	P	**−13.33%**	**−20.00%**	6.67%	0.00%
	R	**26.67%**	**−20.00%**	−6.67%	0.00%
	T	**20.00%**	−6.67%	0.00%	0.00%
	U	−6.67%	0.00%	0.00%	0.00%
	V	**13.33%**	6.67%	0.00%	0.00%
Area 4	P	−8.33%	−8.33%	−8.33%	0.00%
	R	8.33%	−8.33%	8.33%	0.00%
	T	**16.67%**	0.00%	0.00%	0.00%
	U	**−16.67%**	0.00%	0.00%	0.00%
	V	0.00%	0.00%	0.00%	0.00%
Area 5	P	5.56%	5.56%	5.56%	**−11.11%**
	R	0.00%	**16.67%**	0.00%	0.00%
	T	**11.11%**	−5.56%	5.56%	0.00%
	U	**11.11%**	0.00%	−5.56%	−5.56%
	V	−5.56%	−5.56%	−5.56%	−5.56%
Area 6	P	−3.23%	−6.45%	**−16.13%**	−3.23%
	R	0.00%	3.23%	−3.23%	−9.68%
	T	**12.90%**	−3.23%	0.00%	0.00%
	U	3.23%	0.00%	−3.23%	0.00%
	V	−9.68%	−6.45%	0.00%	**−12.90%**
Area 7	P	−6.90%	−6.90%	**−10.34%**	3.45%
	R	**20.69%**	0.00%	6.90%	**−17.24%**
	T	−3.45%	0.00%	0.00%	3.45%
	U	−6.90%	6.90%	0.00%	−3.45%
	V	−3.45%	−3.45%	−3.45%	−6.90%
Area 8	P	**−12.00%**	**−16.00%**	**−20.00%**	**12.00%**
	R	**20.00%**	0.00%	−8.00%	4.00%
	T	4.00%	**12.00%**	0.00%	−4.00%
	U	**12.00%**	0.00%	0.00%	−4.00%
	V	**24.00%**	**−12.00%**	−4.00%	0.00%

in the western region in autumn and winter. There is reasonable correspondence between the regions with large variation of the key elements and those with significant variation of season duration (section 4.1), indicating that the interdecadal variation of the key elements could explain for, to a certain extent, the interdecadal variation of season duration.

It can be seen from Fig. 7a1, 7a2, and Table 2 that spring is the season in which the key elements change most. In all areas except northeast China, the key elements vary considerably, especially in central China, southwest China, and Tibet. Moreover, the range of the positive influence of temperature in the northern region widens, the area of positive influence of relative humidity in the southern region expands, and the influence of meridional wind in Tibet gradually increases. These changes might be attributable to increased sensitivity of global warming to winter end time and summer start time (i.e., spring duration can be calculated using winter end time and summer start time) in the north, which leads to greater influence of temperature over a wider range in spring. In southern China and Tibet, the increasing sensitivity of duration to relative humidity and meridional wind, respectively, is attributable to the decrease of precipitation and the reduction of meridional wind speed in spring (Zuo et al. [44]; Yao et al. [45]).

In summer, the regions in which the key elements change markedly are northern China, central China, eastern parts of northwest China, and Tibet (Table 2), and the region with significant change in the key elements is central China. It can be seen from Fig. 7b1 and 7b2 that the range of influence of relative humidity increases in the north and decreases in the south, which might be related both to the warming and drying of the north in summer and to increased precipitation in southern coastal areas in summer (Ren et al. [46]; Han et al. [47]; Jin et al. [48]; Liu et al. [49]; Zhang et al. [50]).

The regions in which the key elements change markedly in autumn are northeast China, western parts of northwest China, southwest China, and Tibet (Table 2), and the region with significant change in the key elements is Tibet. The effect of relative humidity on autumn duration in northeast China (Fig. 7c1, 7c2) is enhanced, which might be attributable to the decrease of autumn precipitation in this region (Liu et al. [51]). The change of the effect of pressure in Tibet and its surrounding areas might be related to the increase of high pressure after 1978 (Zhang et al.[52]). In winter, the changes of the key elements are concentrated mainly in the west; however, the changes are not significant and there are no obvious trends.

In summary, between the two periods, the changes of the key elements are concentrated mainly in the north and west, consistent with the results of previous studies (Shi et al. [4]; Zhou et al. [43]). The changes of the key elements in southern areas are mainly in spring and summer. The changes of the key elements in Tibet are reasonably large in all four seasons, consistent with the current interdecadal climate change on the Qinghai-Tibet Plateau (Lu et al.[8]; Jin et al.[48]; Liu et al.[49]; Peng[53]).

5 CONCLUSIONS AND DISCUSSION

In this study, we investigated season duration in China and we considered certain key impact elements during 1950–2016 using daily NCEP/NCAR reanalysis datasets. We also explored their interdecadal changes. The findings can be summarized as follows.

(1) Season duration in various regions of China shows obvious meridional and zonal differences, as well as close relationships with certain key impact elements. In most regions, the high-value (low-value) areas of spring duration correspond well with the low-value (high-value) areas of summer duration, especially in autumn and winter. The spatial distribution of warm season duration shows obvious zonal differences, i.e., shorter in the east and longer in the west; the spatial distribution of cold season duration shows the converse. The duration distribution presents obvious meridional differences in eastern China, reflecting a short-long-short-long pattern from north to south in the warm season, but a long-short-long-short pattern from north to south in the cold season.

(2) There are complementary relationships between spring and summer durations, between autumn and winter durations, and between cold and warm season durations, which can explain, to a certain extent, the spatial distribution characteristics of the durations of these seasons. The complementary relationship between spring and summer durations is the best and the regions of complementarity are widespread. The complementary regions of autumn and winter durations are concentrated mainly in the western region. The complementary regions of cold and warm season durations are widespread but their relationships are weak.

(3) There are obvious regional differences in the spatial distributions of the key elements affecting season duration in China. The regional differences found in summer, autumn, and winter are reasonably obvious and reflected mainly in east-west and north-south directions. To a certain extent, the spatial distributions of the key elements affecting season duration correspond to the spatial distributions of season durations.

(4) The interdecadal variation between spring and summer durations is markedly different to that between autumn and winter durations. The meridional differences of the interdecadal variation in spring and summer are obvious and concentrated in northern and western regions, whereas there are no obvious meridional differences in autumn and winter.

(5) The areas of significant interdecadal variation of the key elements are concentrated in northern and western regions, and they correspond well with the areas of significant interdecadal variation of season duration. Regions in which the key elements changed greatly are

reasonably widespread in spring and summer but concentrated mainly in the western region in autumn and winter.

There were two principal reasons for choosing the multielements method for this study. The first was that the method adopted produces a measure of similarity, reflecting the seasonal changes of the meteorological elements. When there are more elements, each element influences the result and the result is reasonably stable. When there are fewer elements, the effect of a single element increases; thus, the fluctuation of the division results increases and the accuracy decreases. The second reason was that the regional differences and the elements affecting the seasonal variations are not the same. For example, the differences in temperature and humidity between seasons are large in the north but small in the south, while the change of air pressure on the Qinghai-Tibet Plateau is obvious. Therefore, we used the similarity measure method and we selected the five basic meteorological variables that could best reflect the meteorological state in the process of season division. To better consider the dynamic effects in seasonal division, we also conducted an experiment only using zonal and meridional winds to divide the four seasons in China. Fig. 8 shows the corresponding season duration distributions of the two methods. The season durations of summer and winter obtained by the two methods have reasonable spatial similarity. The multielement partitioning method reflects the seasonal partitioning characteristics in the dynamic sense, because it already contains the wind element, which also demonstrates the effectiveness of the seasonal partitioning method. However, there are certain differences between the two methods in the western region and in northern China. This also shows that using temperature and relative humidity for seasonal division can also reflect, to a certain extent, the thermodynamic characteristics.

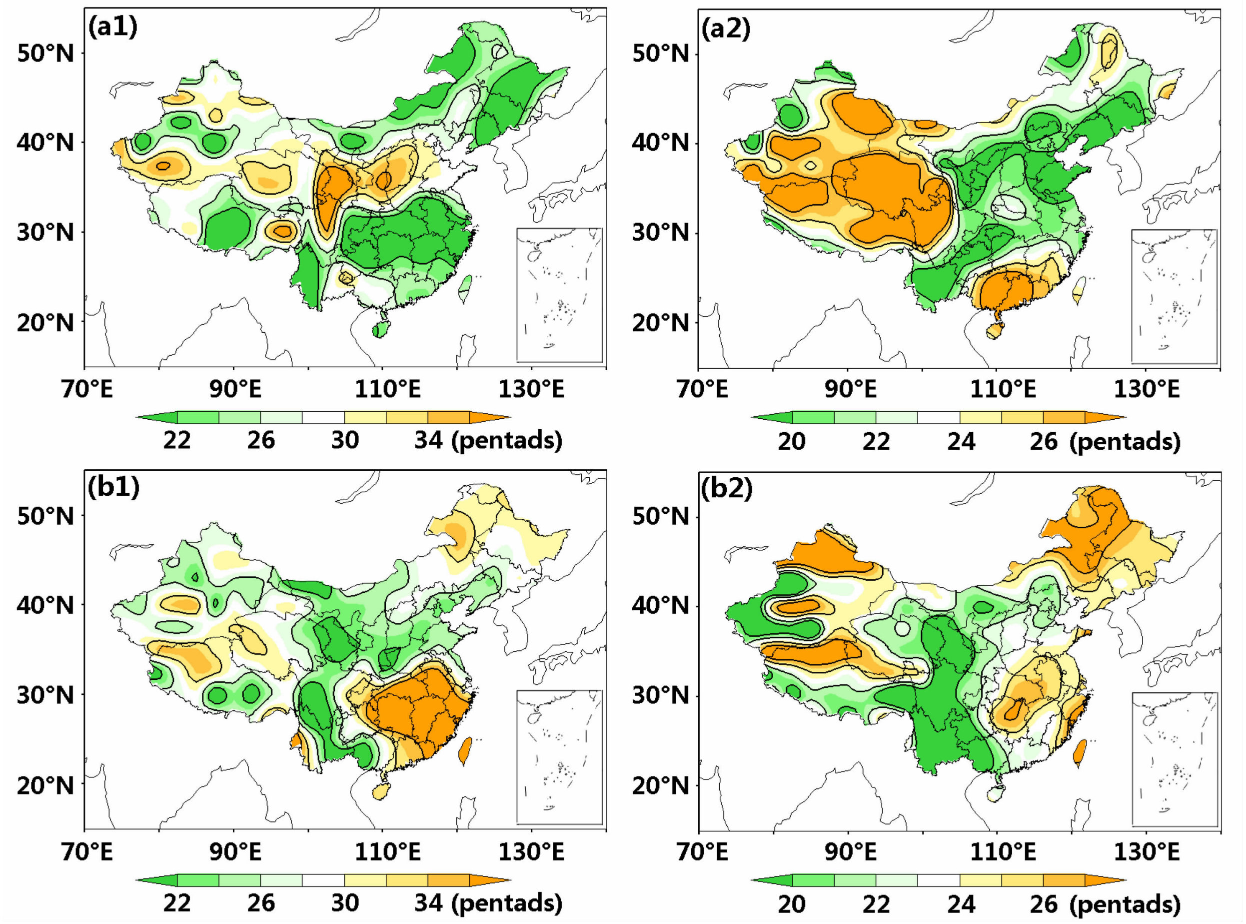

Figure 8. A comparison of season durations determined by (left) wind elements and (right) multielements similarity methods: (a1, a2) summer and (b1, b2) winter.

The results of season division obtained in this study are not the same as derived using traditional seasonal division methods. This is because our method focuses on the change of the atmospheric state, i.e., when changing from one stable atmospheric state to another.

We also investigated the interdecadal variation of season duration in China and its key impact elements. Such study can help elucidate the effects of global climate change on human life and provide important scientific support for studying regional climate change adaptation.

The interdecadal variation of season duration varies in different parts of China and the corresponding changes in regional meteorological elements are also different. Furthermore, the impact caused by each meteorological element varies over time, which could have even more influence on season duration in the relevant region than the key element itself. Further investigation is needed to understand the impact of such influence.

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