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New Evidences on the Climatic Causes of the Formation of the Spring Persistent Rains over Southeastern China

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ABSTRACT

The spring persistent rains (SPR) over southeastern China (SEC) are a unique synoptic and climatic phenomenon in East Asia. A former study has found that the southwesterly flow which lies on the southeastern flank of the Tibetan Plateau (TP) is one of the deflected westerly flows of the TP, and it is suggested to be the direct climatic cause of SPR. This study found that the southwesterly flow is also highly correlated with the sensible heating of the southeastern TP in interannual variability, in addition to having a high correlation in seasonal variability. These facts suggest that the thermal forcing of the TP is another important climatic cause of SPR. Numerical sensitivity experiments further prove that the mechanical and thermal forcings of the TP are the climatic causes of the formation of the SPR. On the other hand, the Nanling Mountains and Wuyi Mountains (NWM) over southeastern China not only increase the SPR precipitation amount evidently, but also make the SPR rain belt move to the south by blocking the strong southwesterly flow.

Key words: spring persistent rains, climatic causes, southwesterly flow, the Tibet Plateau, sensitivity experiments

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1. Introduction

The Tibetan Plateau (TP) is the highest and the steepest topography in the world. It is recognized that its mechanical forcing significantly influences the atmospheric circulation of the Northern Hemisphere (Queney, 1948; Hahn and Manabe, 1975; Hoskins and Karoly, 1981; Wu, 1984). Ye et al. (1957) pointed out that the TP is an intense heat source in summer but a heat sink in winter. Yanai and Song (1992) found that the heating of the TP is mainly in the form of sensible heating before the monsoon onset, but latent heating afterwards. In fact, in terms of sensible heating, the southeastern TP changes from a heat sink to a heat source at the very beginning of spring (figure not shown). Then, what is the role of the TP in the formation of spring circulation and rainfall over southeastern China?

It is well known in China that the spring persistent cloudiness and rains over most of southeastern China (SEC) are disasters to agriculture and transportation. Since the 1950s, studies have emphasized the spring rains in the synoptic and mid-short term forecast aspects (Li et al., 1977). Gao and Xu (1962) mentioned that the rain-belt over east China stays between the Yangtze River and the Nanling Mountains from mid-October to early May. However, few climatological studies have focused on the atmospheric circulation associated with it. Kato (1989) considered the rain belt to be associated with the winter monsoon circulation and to be related to the upper westerly jet stream. As a climatic concept, the spring persistent rains (SPR) present another rainy period besides the mei-yu or Plum rain periods in early summer over cen-

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tral China, and SPR was firstly introduced explicitly by Tian and Yasunari (1998). The climatic cause of SPR was thought to be the west-east land-sea thermal contrast between the Indo-China Peninsula and the western North Pacific, or in other words, the effect of the time-lag of seasonal warming in spring. However, Wan and Wu (2007) found that there is no SPR-like rain belt over southeastern America even though there is similar time-lag over southern North America in spring. So the time-lag mechanism is questionable. In addition, they revealed a possible mechanism responsible for the formation of SPR through climatological mean data analysis and numerical model sensitivity experiments. Specifically, SEC is located downstream of a southwesterly velocity center (SWVC) which lies on the southeastern flank of TP. As a result, there is strong southwesterly wind velocity convergence and moisture convergence over SEC. In spring, the seasonal evolution of the southwesterly velocity consists with that of the surface sensible heating over the southeastern TP, indicating that the formation of SPR is related to not only the southwesterly wind of mechanically deflected flow around the TP, but also that of a thermally forced cyclonic low-level circulation. Numerical sensitivity experiments demonstrate that, without the TP, both SWVC and the SPR rain belt would disappear. The southwesterly wind velocity increases almost linearly with the amount of the total diabatic heating with TP height, except for a rapid increase caused by deflected flow around the TP with height at early steps. Therefore, SWVC is the result of mechanical and thermal forcing of the TP. All these factors suggest that the presence of the TP plays a primary role in the climatic formation of SPR. In this paper, new data analyses and numerical model sensitivity experiments are presented to further support that theory.

2. Data

The monthly mean rainfall data are from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) (Xie and Arkin, 1997), which have $1^\circ\times1^\circ$ longitude-latitude grid resolution and span from 1979 to 2004. The National Center for Environmental Prediction (NCEP) reanalysis climatological monthly mean data (1968–1997), horizontal wind at 850 hPa, and surface sensible heat flux (Kalnay et al., 1996) are used.

3. Diagnostic analysis

Tian and Yasunari (1998) considered the 12th–26th pentads of the year as the SPR period. We chose March and April instead, in view of the data and model limitations, and this choice did not appear to affect our results. The mean rainfall in the SPR period over both East Asia and North America is shown in Figs. 1a, 1b. The spatial distributions of precipitation over the two southeastern continental regions are very different. Over the extra-tropical regions, the main rainfall belts are located over the western parts of the oceans and close to the east coasts of the continents. These rain belts are affirmatively ascribed to the polar front separating the cold air from the northern pole and warm air from the tropical oceans. It is noticeable that there is a rain belt with a central intensity exceeding 6 mm d^{-1} lying over the East Asia continent, i.e., the SPR. But there is no such similar heavy rain belt correspondingly appearing over southeastern America.

The mean spatial characteristics of the large-scale atmospheric circulation during the SPR period are examined from the fields of wind vectors at 850 hPa over both East Asia and North America (Figs. 1c, 1d). The wind vector fields are distinctly different. Due to the mechanically diffluent effect of the TP, the westerly jet in East Asia is split into two westerly jets, and then they meet near the east coast. A SWVC with a maximum of 7 m s^{-1} emerges at the southeastern flank of the TP. Consequently, downstream of the velocity center, the velocity convergence zone dominates most of SEC (Fig. 1c). On the contrary, there is only one westerly jet belt appearing over North America, centered over the west Atlantic. There is no SWVC upstream of southeastern America. Consequently, only strong wind divergence and a weak rainfall belt exist in southeastern America (Fig. 1b).

As we know, the topography of the TP, even its southeastern part, the Yungui Plateau, exceeds the critical height for lifting or deflection of flows (Wu, 1984). In spring, the westerly jet in middle latitudes is split into two branches by the TP. The southern one flows eastward along the south flank of the Himalayas and encounters the Yungui Plateau and then deflects (Fig. 1c). Therefore, the deflected southwesterly flow is one main part of the overall southwesterly pattern.

Wan and Wu (2007) found that from middle winter to middle spring, over the Eurasian continent at 850 hPa, the temperature difference between south and north decreases quickly, and the mean westerlies over the middle latitudes decrease, following thermal wind balance. The decrease of mean westerlies indicates that both the inflow and the deflected flow of the TP are decreasing. Unexpectedly, the southwesterly flow at the southeastern flank of the TP ($V_{\rm sw}$) can be regarded as the deflected flow of the TP, and increases remarkably from winter to early spring. So $V_{\rm sw}$ is produced not only by the deflected flow, but

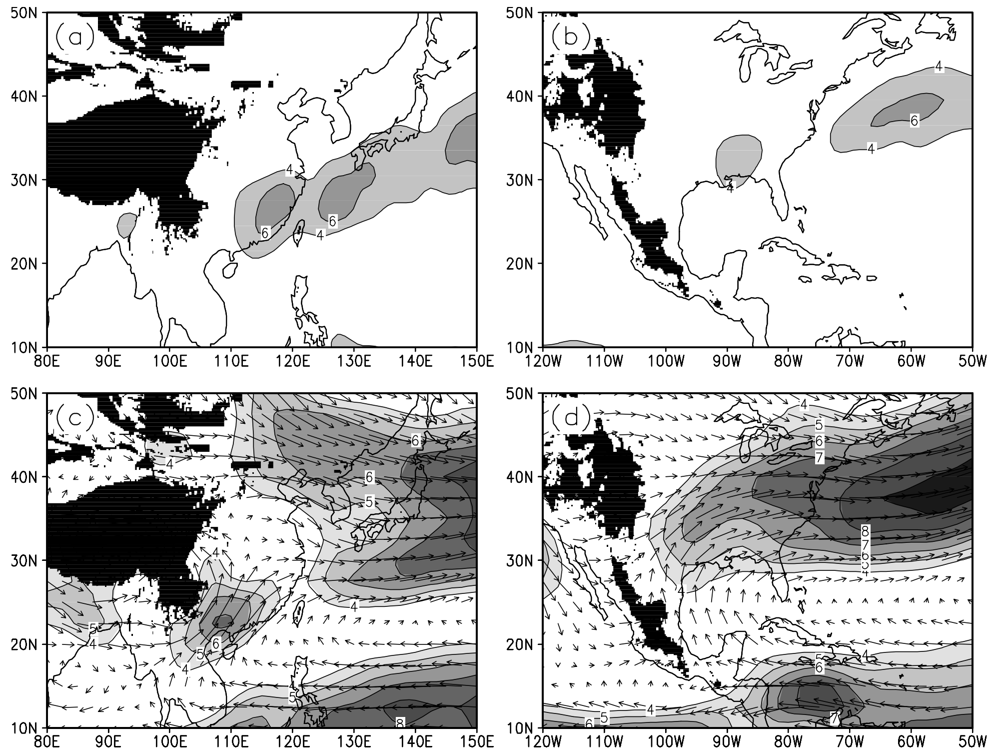

Fig. 1. Climatological mean fields of CMAP precipitation (1979–2004) (panels a and b), wind vector and wind velocity (contours) at 850 hPa (1968–1997) (panels c and d) in March–April over East Asia (panels a, c at left) and North America (panels b, d at right). The elevation of the dark-shaded regions exceeds 1500 meters. Units: mm d^{-1} in panels a and b, m s^{-1} in panels c and d.

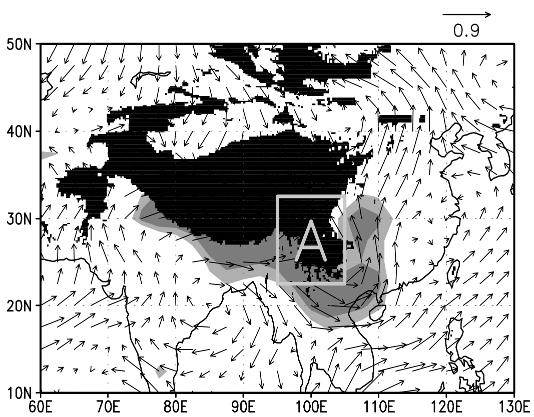

Fig. 2. Correlation between SH over region A and the wind at 850 hPa averaged in March–April (1965–1994). Vectors are composed of the correlations between SH and the u component and the v component of the wind at 850 hPa, respectively. Grey shaded areas are where the t-test is significant at the 95% and 99% levels respectively in the correlation coefficients between SH and the scalar velocity of the wind at 850 hPa. Black shaded regions are where the elevation exceeds 1500 meters.

also by other factors. At the same time, they found that the surface sensible heat flux (SH) over the southeastern TP is consistent with $V_{\rm sw}$ in seasonal evolution. According to the thermal adaptation theory of diabatic heating (Wu et al., 1999), the obvious consistency suggests that the thermally forced component of the southwesterly wind induced by SH over the southeastern TP is another main component of the southwesterly wind.

This can also be seen in the interannual correlation between SH over region A and the wind at 850 hPa, as shown in Fig. 2. In this figure, the correlation vectors are composed of the correlations between SH and the u component and v component of the wind at 850 hPa, respectively. The grey shaded areas are where the correlations between SH and the scalar velocity of the wind at 850 hPa are significant by a t-test. Obviously, there is a cyclonic-circulation-like correlation arrow around A region. It means that, in higher SH years, conditions are favorable for stronger cyclonic circulation around this region, and stronger southwesterly flow, and vice versa.

So the thermally-forced component of the southwesterly flow is a major part of the southwesterlies at the southeastern flank of the TP. Therefore, it is the combination of mechanically-forced deflected flow and thermally-forced low-level circulation of the TP that gives birth to the SWVC, and the TP is the climatic cause of the formation of SPR.

4. Sensitivity numerical model experiments

A global atmospheric spectral model (SAMIL-R42L9) (Wu et al., 2003) was employed for this study. This model can well reproduce the observed basic patterns of global circulation and precipitation (Wang et al., 2004).

4.1 *The effects of big plateaus*

Three experiments were conducted. In the control experiment, the topography is the real topography (CTL, hereafter). The other two experiments with Eurasia leveled to 0 m and western America lifted by 3 km are called the non-TP and higher North America experiments (NTP and HNA, respectively hereafter). The method of lifting North America is to lift the topographic height by 3 km in the region of (27.5°–40°N, 120°–90°W) where elevations exceed 200 m. All experiments integrate for 15 years, respectively, and the mean fields of March and April of the last 10 years are analyzed as the SPR period.

In the CTL experiment (Fig. 3a), the planetary westerlies at low levels (850 hPa) are split by the TP in spring. As a result, there are two westerly jets to the north and south of the TP, respectively. The velocity of the southwesteries at the southeastern flank of the TP exceeds 4 m s^{-1}, and a SWVC appears with a value over 6 m s^{-1}. Southeastern China is located the downstream of the velocity center and there is strong velocity convergence there. Another southwesterly velocity center appears over the northwest Pacific and at the junction of the two westerly jets. Accordingly, there is a strong rain belt over the area from SEC to the south of Japan. These are consistent with the observation shown in Fig. 1a on the whole. However, the SPR rain belt here locates 5° further north than in observations. This is related to the model topography. The model smoothes mountain heights in SEC and underestimates the blocking effect of the mountain chains on the warm and damp southwesterlies. So the SPR rain belt drifts north. When the model topography is adjusted appropriately, the rain belt shifts back to SEC and is consistent with observations (figure not shown).

The CTL model result for North America is shown in Fig. 3b. The splitting and deflecting of the planetary westerly jet is not obvious. A southwesterly velocity center is located over the northwest Atlantic. Southeastern America lies upstream and in the divergent velocity area. Accordingly, there is only weak rainfall in southeastern America. These results basi-

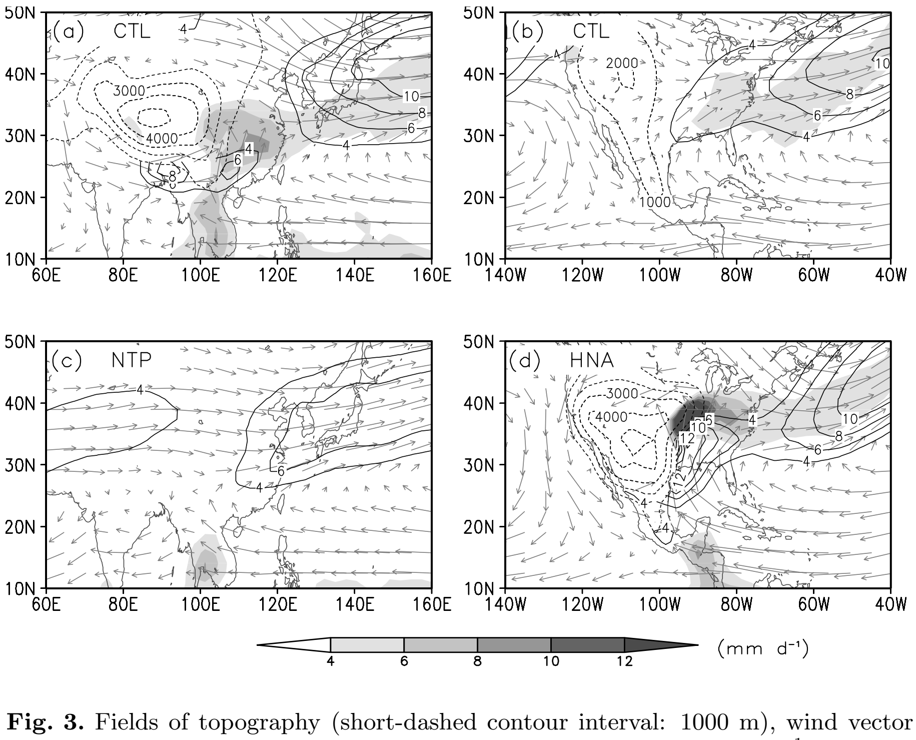

Fig. 3. Fields of topography (short-dashed contour interval: 1000 m), wind vector at 850 hPa and its southwesterly velocity (solid contour interval: 2 m s^{-1}) and rain (gray-shaded) of CTL, NTP, and HNA experiments averaged over March and April.

cally agree with observations (Fig. 1b).

But in the NTP experiment (Fig. 3c), there is no splitting and deflecting of the westerly jet and there is no SWVC at upstream of SEC; the rain from SEC to south of Japan decreases to below 4 mm d^{-1} and the SPR rain belt disappears. On the contrary, in the HNA experiment (Fig. 3d), when the topography height of western America is lifted by 3 km, a strong SWVC appears at the southeastern flank of the lifted region. A strong SPR-like rain belt appears over eastern America. The results of these experiments further demonstrate that the presence of the TP is the climatic cause of the formation of the SPR.

4.2 *The effects of high mountain chains in southeastern China*

There are the Nanling Mountains and the Wuyi-Mountains (hereafter NWM) in southeastern China (Fig. 4b). Zhou and Qian (1996) pointed out in their experimental study on the effects of topography on numerical synoptic prediction that topography not only contributes to the precipitation amount, but also evidently affects the distribution of rainfall to some extent. How do the NWM affect the SPR rainfall climatically?

Another set of numerical model sensitivity experiments was performed to answer this question, including three kinds of experimental schemes. The first used real model topography and was called the control (CTL) case. The second was with all mountains in southeastern China leveled to 0 m and was called the NNL (no Nanling mountains) case. The third was with these mountains lifted by 300 m and was called the HNL (high Nanling mountains) case. The other settings were the same as in section 4.1. The focus of this section is on comparisons and discussion of the effects of these mountains on SPR rainfall. The real and model topography and experimental rainfall results are shown in Fig. 4.

The comparison between the precipitation of the CTL case (Fig. 4a) and that of the real climatological mean (Fig. 4b) shows that the distribution pattern of the CTL rainfall resembles the real SPR rainfall on the whole, though the rains over the southeastern flank of the TP are much bigger than observed, possibly owing to the topographic height methodology in the model. This aspect will not be important in this discussion. When southeastern China is leveled to 0

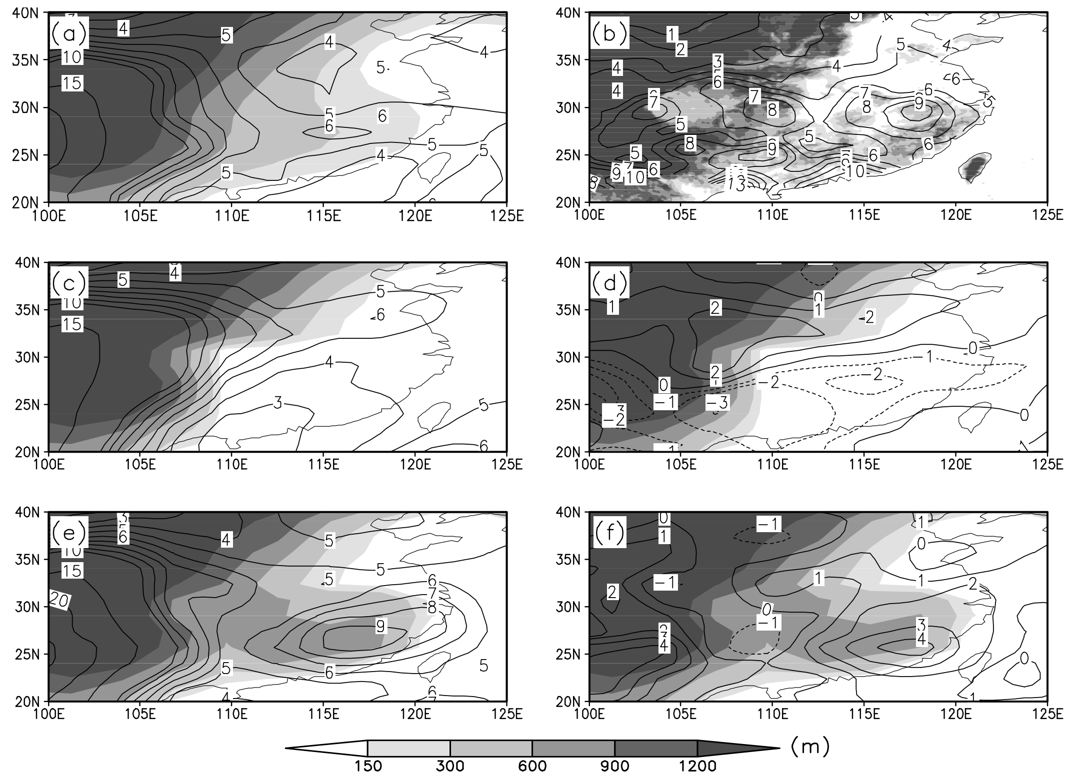

Fig. 4. Real and model topography and SPR rainfall (mean daily precipitation of March and April): (a) CTL case, (b) observations, (c) NNL case, (d) NNL–CTL, (e) HNL case (+300 m), and (f) HNL–CTL. Shading is for topography (units: m) and contours are daily mean precipitation (units: mm d^{-1}). Negative contours are in dashed lines.

m in the NNL case (Fig. 4c), the belt of the rainfall shifts to the north of the Yangtze valley, just at the junction of the two westerlies (see also Fig. 1c). Compared with the CTL case, the SPR rainfall decreases 1–3 mm d^{-1} (Fig. 4d). However, the rainfall over the South China coast and to the north of Yangtze valley increases in some fashion. That is, the whole rainfall of southeastern China decreases and the rainfall is distributed more evenly. On the contrary, when the NWM are lifted by 300 m (Fig. 4e), the center of the SPR rain belt shifts south to the NWM region and is consistent with the observed rain belt (Fig. 4b). The rainfall to the south of the Yangtze River increases obviously by 1–2 mm d^{-1} and decreases to the north (Fig. 4f). Thus, it can be seen that the existence of the NWM affects the distribution and amplitude of SPR rainfall remarkably. The NWM block the southwesterlies from the south and force flow to rise up, increasing the rainfall in the mountain areas. We can also deduce that the shift of the rain belt to the north in the CTL case may come from the underestimate of the topography in the CTL model process.

5. Conclusion and discussion

The low level circulation and precipitation comparison between East Asia and North America suggested a mechanism for the rainy season over SEC, climatologically. In spring, the presence of SWVC at the southeastern flank of TP is directly responsible for the climatic formation of SPR. Besides the deflected southwesterly flow formed by the mechanical effect of the TP, the significant high correlations in interannual variability between SH over the southeastern TP and the surrounding wind at 850 hPa further suggest that a thermally-forced low level cyclonic wind pattern is a major contributor to the southwesterly flow. A comparison of model sensitivity experiments proved further that the southwesterly flow is related to the deflected flow around the TP and the sensible heating over the southeastern TP. So the mechanical and thermal effects of the gigantic plateau region are the essential climatic causes of the formation of the SPR.

Mountain chains over southeastern China also have an important influence on the SPR. The NWM not only increase the SPR precipitation amount evidently, but also make the SPR rain belt move to the south by blocking the strong southwesterly flow.

This paper focuses only on the climatic origins of the SPR. In fact, the annual SPR is affected by many factors, such as the contemporary thermal contrast between the Indochina Peninsula and the western North Pacific low level temperature (Tian and Yasunari, 1998), ENSO events, etc. How to predict the annual variation of SPR rains is still a big challenge for meteorologists.

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