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- Multi-scale topographic control of southwest vortex formation
- Two topographically induced vorticity streams contribute to SWV formation
- The Tibetan Plateau and Hengduan Cordillera control the SWV location and scale

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Multi-scale topographic control of southwest vortex formation in Tibetan Plateau region in an idealized simulation

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Abstract The southwest vortex (SWV) is a lee vortex occurring on the leeside of the Tibetan Plateau in southwestern China, which is strongly affected by the different scale topography of the Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin. The roles of these topographic features in SWV formation were investigated by conducting simulations with dry dynamics in an idealized background flow. Two shallow topographically induced vorticity streams are found to be the main contributors to SWV formation. The first vorticity stream extends out from the southeastern Hengduan Cordillera and the second from the east side of the Tibetan Plateau conjoint with the Hengduan Cordillera and Sichuan Basin. The stretching, tilting, and friction play different roles in vertical vorticity generation along the two vorticity streams, in which the stretching of the planetary vorticity dominates other vertical vorticity sources at the upper level of the first vorticity stream. The SWV forms due to the combined effects of the topographic features. The Hengduan Cordillera turns the southwesterly airflow around the Tibetan Plateau to induce the first vorticity stream, and the Sichuan Basin enhances the second one, which is associated with the stretching and tilting of airflow from the top of the Tibetan Plateau. Moreover, the Sichuan Basin provides a natural site favorable for the merging of the two vorticity streams and then promoting SWV formation. The sensitivity experiments show that the location and scale of the SWV are controlled mainly by the Tibetan Plateau and Hengduan Cordillera, and the Sichuan Basin plays a secondary role.

1. Introduction

The topography of many mountain leeside regions provides a preferred location for cyclogenesis. Lee cyclogenesis often begins with a shallow leeside low or lee vortex and has been widely studied in the context of the synoptic-scale Rocky mountains [e.g., Bannon, 1992; Steenburgh and Mass, 1994; Davis, 1997; Schultz and Doswell, 2000] and the meso-scale European Alps [e.g., Speranza et al., 1985; Buzzi and Speranza, 1986; Tafferner, 1990; Aebischer and Schär, 1998; Kljun et al., 2001]. Rocky Mountain lee cyclogenesis is associated with the southward propagation of a low when crossing the Rockies followed by regeneration in phase with the arrival of an upper-level trough [Bannon, 1992; Schär, 2003]. Alpine lee cyclogenesis consists of two phases [Buzzi and Tiboldi, 1978; McGinley, 1982; Schär, 2003]: the first phase is associated with the retardation of a cold front by the Alps, inducing a shallow vortex over the Gulf of Genoa, and in the second phase the orographic vortex grows baroclinically through interaction with the upper-level trough associated with the original cold front [Aebischer and Schär, 1998]. The Tibetan Plateau lee vortex is frequently observed over southwestern China on the east and southeast flanks of the Tibetan Plateau and is known as the southwest vortex (hereafter SWV). The SWV is a sub-synoptic and mesoscale vortex system characterized by a horizontal scale of 300–500 km on weather charts at 700 and 850 hPa [Lu, 1986; He, 2012]. The SWV is one of the most important factors causing rainstorms in summer in China; it often induces local severe weather in the Tibetan Plateau leeside region [Kuo et al., 1986] and has a strong influence on precipitation systems downstream when it moves away from its original site [e.g., Fu et al., 2012]. The formation of the SWV is different from that of the Rocky Mountain leeside low or Alps lee vortex, due to the evidently different topography and regional atmospheric flows. The influence of the topography in the Tibetan Plateau region on SWV formation is poorly documented.

The Tibetan Plateau region has a more complex topography than the Rocky Mountains and Alps. Figure 1 shows the topography of China with the most important features in the Tibetan Plateau region highlighted: the Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin. Some earlier studies found
Figure 1. Regions with frequent southwest vortex (SWV) formation from Chen and Min [2000] and the main topographic features in the Tibetan Plateau region. The Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin are denoted by dashed circles. Region A of frequent SWV formation is over the southeast edge of the Hengduan Cordillera, region B is along the shared boundary between the Tibetan Plateau and Sichuan Basin, and region C is over the northeast of the Sichuan Basin.

that the SWV preferentially forms over the Sichuan Basin [Chung et al., 1976; Lu, 1986]. A statistical analysis covering the years 1983–1992 shows that there are three main regions with frequent SWV formation [Chen and Min, 2000], spatially related to the main topographic features in the Tibetan Plateau region. Region A lies over the southeast edge of the Hengduan Cordillera, region B lies along the shared boundary between the Tibetan Plateau and the Sichuan Basin, and region C is over the northeastern Sichuan Basin (Figure 1). A more recent study covering a longer period (1990–2004) confirmed that these regions exist not only on an annual basis but also in all seasons, except that regions A and B merge [Chen et al., 2007]. The positions of these regions suggest that SWV formation is linked to the three main topographic features in the Tibetan Plateau region, especially the Sichuan Basin, which connects with all three regions (Figure 1). Previous case studies indicate that the Sichuan Basin plays the most important role in SWV formation and controls the associated heavy rainfall within or near the basin [e.g., Kuo et al., 1986], whereas other studies [e.g., Fu et al., 2010] reported that the Sichuan Basin plays a secondary role in SWV formation. Therefore, the role of the Sichuan Basin in SWV formation needs further investigation. Interestingly, the climatological-mean SWV forms over the Sichuan Basin and has a scale comparable to that of the Sichuan Basin (Figure 1); however, it is not known whether the scale of the Sichuan Basin determines the scale of the SWV.

Many studies have shown that SWV formation is closely linked with the vorticity generation over the Tibetan Plateau leeside region [Kuo et al., 1988; Wu and Liu, 1999; Yasunari and Miwa, 2006; Fu et al., 2010]. Several mechanisms have been proposed based on the significant role of the Hengduan Cordillera in vorticity generation; that is, stretching of planetary vorticity [Kuo et al., 1988], and vorticity development as air parcels slide down the slanting isentropic surfaces on the lee side [Wu and Liu, 1999]. These mechanisms indicate that stretching is the most important vorticity source in this region, although friction has been traditionally emphasized as a primary mechanism [e.g., Lu, 1986]. Studies in other mountainous regions indicate that friction can create vorticity where the isentropic surfaces of airflow interact with the topography [e.g., Thorpe et al., 1993]. Therefore, there is some doubt whether friction or stretching plays the dominant role in vorticity generation, and in particular it is not clear how they interact.
The vorticity generation contributing to SWV formation is also associated with airflow over the Tibetan Plateau, which may carry a preexisting weather system. The vorticity of existing convergence lines or convective systems over the Tibetan Plateau can trigger intensive development of the SWV, when such systems move eastward over the Sichuan Basin and couple with the vorticity of the shallow SWV below [Yasunari and Miwa, 2006; Fu et al., 2010]. The shallow SWV is independent of the preexisting weather system over the Tibetan Plateau, and can be fed by the airflow over the Tibetan Plateau that pours into the Sichuan Basin even in the absence of such preexisting weather systems. However, it is unclear how this airflow obtains vorticity and how different this process is from the vorticity generation over the southeastern Tibetan Plateau region. In addition to this uncertainty about the mechanism of vorticity generation associated with the Sichuan Basin, Hengduan Cordillera, and Tibetan Plateau in the Tibetan Plateau leeside region, no previous study has clearly addressed how the vorticity sources are involved in the SWV circulation and how they are organized to create the SWV vorticity. The multi-scale topographic control and the individual roles of each of the main topographic features in SWV formation need further investigation.

The formation of the SWV is determined by the interaction of the topography in the Tibetan Plateau region with a favorable large-scale environmental airflow [Lu, 1986; He, 2012]. Climatically, summer is the most favorable season for the frequent formation of the SWV [Chen et al., 2007]. The purpose of this study is to investigate the multi-scale topographic control of SWV formation in an idealized background flow in summer. One focus of this study is to examine the characteristics of the SWV, including its evolution and structure. The second focus is on the vorticity generation associated with SWV formation controlled by the multi-scale topography in the Tibetan Plateau region and the pathways for the development of the SWV vorticity, especially the individual role of each of the main topographic features in the formation of the SWV.

The remainder of this paper is organized as follows. In section 2, the model and the experimental design are briefly described. The general evolution and structure of the SWV are analyzed in section 3. Section 4 further discusses the vorticity generation and its dynamics and the individual role of each of the main orographic influences. Finally, a summary and discussion are given in section 5.

2. Model Description and Experimental Design

Version 5 of the ARPS [Advanced Regional Prediction System; Xue et al., 2000, 2001] is used in this study. The ARPS is a three-dimensional, non-hydrostatic compressible model formulated in generalized terrain-following coordinates. The split-explicit scheme is used to integrate the sound-wave containing equations, and state-of-the-art physics parameterization schemes are included. The model with terrain-following coordinates and flexible surface physics options is suitable for performing numerical simulations to investigate orographic effects.

The computational domain is three dimensional and includes $635 \times 435 \times 35$ grid points in $x$, $y$, and $z$ directions, respectively, with a horizontal resolution of 10 km. In the vertical, the averaged resolution is 625 m, with the finest resolution of 50 m at the lowest model level. Aloft, the grid size is gradually stretched with the model top located at ~20 km where a radiation condition is used. An open radiation condition is applied on the lateral boundaries. The ARPS is used in its simple physics mode. The moist processes are switched off because only dry dynamic simulations are investigated in this paper. The radiation physics is not considered either. Surface fluxes are calculated using a 1.5-order turbulent kinetic energy (TKE)-based subgrid-scale turbulence parameterization and TKE-based non-local planetary boundary layer (PBL)-mixing parameterization, together with constant surface drag coefficients.

The realistic terrain for the simulations is interpolated from the USGS 30 arc second topography data sets and is smoothed moderately to clearly outline the main topographic features in the Tibetan Plateau region (Figure 2a). The smoothed topography is comparable to that used in several case studies [e.g., Kuo et al., 1988; Wang et al., 1993]. Furthermore, to investigate the effects of each of the main topographic features on SWV formation, sensitivity experiments are designed with different combinations of the three main topographic features in the Tibetan Plateau region (see Table 1), which are idealized according to the horizontal and vertical scales estimated by Wang and Tan [2006] (see Appendix A). The idealized topography captures the main characteristics of the real features in the Tibetan Plateau region (Figure 2).
The idealized background flow used to initialize the control experiment (CNTL; see Table 1) is the July mean flow averaged from the 65 year (1948–2012) monthly averaged NCEP/NCAR global reanalysis data on a 2.5° × 2.5° grid [National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, 1994]. The initial response to an impulsively switched on airflow can result in a “start-up” vortex or cyclonic circulation due to the initial subsidence created in the lee of the topography [e.g., Boyer et al., 1987; Peng et al., 1995], and the “start-up” vortex will progress steadily downstream. A supplementary experiment CNTL_96 is therefore carried out to verify the reliability of the SWV formed in the CNTL. In the CNTL_96, the mountain height is set to increase gradually during the initial 96 h of integration to reduce the initial response or “start-up” effect, as discussed by Peng et al. [1995]. The time span of 96 h is chosen rather than

<table>
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<th>Experiment</th>
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<tr>
<td>CNTL_96</td>
<td>Real topography with height gradually increased during the initial 96 h of integration</td>
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<td>CNTL_NF</td>
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Figure 2. The different terrains used in the numerical simulations. (a) Smoothed real terrain from the USGS 30 arc second topography data sets for the CNTL, CNTL_96, and CNTL_NF, (b) idealized terrain combined with the Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin for the IT_ALL, (c) idealized terrain combined with the Tibetan Plateau and Hengduan Cordillera for the IT_TH, and (d) idealized terrain of only Tibetan Plateau for the IT_TP. The terrains are outlined at 600, 900, 1200, 1500, 2000, 3000, and 4000 m, respectively. The dashed box in Figure 2a denotes the analysis region in Figure 3.
Three developmental phases can be identified associated with SWV formation and the evolution of the vorticity streams at 850 hPa. During the first phase before 6 h, vorticity is gradually generated above the leeside steep terrain among Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin. By 6 h, the leeside vorticity can already be identified as decreased geopotential height at 700 and 850 hPa (Figures 3d and 3g), or low perturbation pressure near the surface (Figure 3j). The low centered between the Hengduan Cordillera and Sichuan Basin is found coupled with the HVS at 6 h (Figure 3g). During the second phase in the following 6 h, the low grows and becomes broader. Cyclonic circulation is gradually established, associated with the low, and begins to draw in the TVS and HVS toward the low center. At the same time, the north winds associated with the circulation drive the HVS southward. Farther southward, a vorticity band associated with airflow around the Hengduan Cordillera develops and extends downstream toward the low. By 12 h (Figure 3h), the vorticity band has almost reached the low, where it begins to join and enhance the HVS that is also extending downstream. The HVS later merges with the vorticity band (Figure 3i). In the third phase over the next 12 h, the low and the SWV gradually break away from the Hengduan Cordillera and continue to develop. During this phase, animations of the simulation show that the vorticity from the HVS and TVS is gradually drawn into the SWV, as the low and the cyclonic circulation develop. By 24 h (Figure 3i), the SWV reaches a quasi-stationary stage, the circulation of the SWV is collocated with the low, and a solid core of vorticity is already established within the vortex.

At 700 hPa and above (Figures 3a–3f), no closed circulation is found associated with the SWV, while near the surface the solid core of vorticity within the SWV is established earlier at 12 h (Figure 3k). The low-level closed circulation associated with the SWV also forms earlier than at 850 hPa (Figure 3j). This shows that the SWV is a shallow circulation system developing from low levels. The vorticity streams are not as clear near the surface as that at 850 hPa (Figures 3j–3l), since they tend to extend into the above-surface airflow (Figures 3g–3i). The structure of the SWV is further analyzed in section 3.2. The generation of the vorticity that feeds the vorticity streams and the contribution of the vorticity streams to SWV formation are discussed in section 4.

3.2. Horizontal and Vertical Structure

Figure 4 shows an enlarged view of the structure of the quasi-stationary SWV in the region shown by the dashed box in Figure 3i. The vortex lies over the southeastern Sichuan Basin and connects with the
Figure 3. Formation of the SWV. Relative vorticity (shaded, ×10^5 s^-1), geopotential height (bold contours, 10 m), and horizontal wind fields (full barb represents 5 m s^-1, half barb 2.5 m s^-1) on (a, b, c) 500 hPa, (d, e, f) 700 hPa, (g, h, i) 850 hPa, and (j, k, l) near the surface. The pressure perturbation (dashed bold contours, Pa) is shown in the near-surface plots instead of geopotential height. The terrain in each of the plots is outlined at 600, 900, 1200, 1500, 2000, 3000, and 4000 m (thick gray contours). See context for the detail.
HVS (TVS) on its east to northeast (southwest) side (Figures 4a and 4b). The horizontal scale of the vortex, given by the maximum closed circulation, is about 400–500 km, which is comparable to the scale of the Sichuan Basin represented by the 600 m terrain contour (Figures 4a and 4b). The horizontal circulation associated with the shallow vortex vanishes above the 3 km level, and the vertical vorticity is concentrated primarily below this level (Figures 4c and 4d).

In the quasi-stationary state, downslope winds are found at low level over the steep terrain associated with the Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin (Figure 4a). The downslope winds flow around the SWV (Figure 4a) and are confined within a very shallow near-surface layer denoted by the regions of negative vertical velocity in Figures 4c and 4d. Above this layer, a prominent region of positive vertical velocity is found on the west side of the SWV (Figures 4b and 4d). The positive vertical velocity is associated with the cyclonic circulation of the vortex and its interaction with the surrounding airflow. In the vertical cross sections, the west wind associated with the TVS is shown surrounding the vortex near the surface (left side of Figure 4c). Following the vortex circulation, the west wind turns to the south on the east side of the vortex, and this south wind persists near the surface though at reduced strength (right side of Figure 4d).

Figure 4. Structure of the SWV. Enlarged view of the boxed region in Figure 3i. Shown in (a) near the surface and (b) 850 hPa are vertical vorticity (shaded, \( \times 10^5 \) s\(^{-1}\)), vertical velocity (red contours, negative values dashed), and horizontal winds (full barb represents 5 m s\(^{-1}\), half barb 2.5 m s\(^{-1}\)). The plots of Figures 4c and 4d are vertical cross sections along south-north and west-east lines in Figure 4b, respectively. In Figures 4c and 4d, shown are vertical vorticity (shaded, \( \times 10^5 \) s\(^{-1}\)), vertical velocity (red contours), potential temperature (purple contours), and horizontal wind perpendicular to the cross section (black contours). Terrain is outlined as thick gray contours in Figures 4a and 4b as that in Figure 3.
To the east side of the near-surface southerly is the stronger and thicker south wind (Figure 4d), which is evident at 850 hPa and is associated with the HVS (Figure 4b). Farther around the cyclonic circulation, the south winds near the surface and at 850 hPa merge on the northeast side of the vortex, and the merged wind becomes weaker east wind on the north side of vortex where it extends up to the 3 km level (right side of Figure 4c). This east wind then converges with and strengthens the stronger north wind along the steep terrain on the west side of the vortex (left side of Figure 4d). The strengthened north wind is also enhanced by the downslope wind that converges at low levels. Marked vertical velocity is evident directly over this converged north wind (Figure 4d).

The stronger north wind along the steep terrain on the leeside of the Tibetan Plateau was also simulated in the study by Murakami and Nakamura [1983] and was interpreted as resulting from the leeside strong north-south pressure gradient, associated with the anticyclone/cyclone generated on northeast/southeast edge of the Tibetan Plateau. The stronger north wind in this study is associated with the TVS (Figures 4b and 4d) and is also coupled with the enhanced pressure gradient along the steep leeside terrain in the Tibetan Plateau associated with the low (Figures 3i and 4d).

In general, the SWV induced by the topography in the idealized flow has comparable horizontal scale and similar quasi-stationary state to that of a real SWV in summer. For example, meso-scale analyses of the SWV that induced flooding during 11–15 July 1981 show that the SWV was quasi-stationary with a horizontal scale of about 500 km [Kuo et al., 1986, Figure 7]. The time-height section of vertical vorticity of the real SWV also shows the vortex formed with vorticity maximum established at 850 hPa and major vorticity confined below 700 hPa. Subsequently, an eastward-moving vortex over the Tibetan Plateau merged with the SWV and induced strong vertical development of the SWV, while the developed SWV still maintained a vorticity maximum at 850 hPa [Kuo et al., 1986, Figure 9a]. The vorticity structure of the real SWV before merger with this vortex is comparable to the SWV simulated in the CNTL. The major vorticity associated with the SWV that formed in the idealized flow lies mostly below 3 km (~700 hPa), and the vorticity maximum is at about 1 km (Figures 4c and 4d), slightly lower than the 850 hPa (~1.5 km) maximum for the real SWV. In addition, the vertical velocity associated with the real SWV before merger with the eastward-moving vortex is not strong [Kuo et al., 1986, Figure 9a], consistent with the weak vertical velocity of the SWV simulated in the idealized flow (Figure 4).

The well-developed SWV in the real case is quite different from the SWV simulated in the idealized flow and is generally associated with much deeper circulation and stronger vertical motion. The SWV reported by Kuo et al. [1986], which develops further through merger with the eastward-moving vortex, shows strong vertical vorticity and velocity from the surface up to 250 hPa. Two important mechanisms can potentially promote further development of a preexisting shallow, low-level SWV. One is the coupling of upper-level weather disturbances, as the interaction with upper-level disturbances could trigger strong vertical development of the low-level shallow vortex in certain weather conditions [e.g., Yasunari and Miwa, 2006; Fu et al., 2010], such as the upper-level vortex mentioned above. The other is related to the moist processes that are not included in the experiments in this paper. Moist processes, such as the latent heat release associated with moist convection, are important for the vertical development and long-term maintenance of the SWV [e.g., Wang et al., 1993].

4. Dynamics of SWV Formation

4.1. Pathways for Creating SWV Vorticity

To investigate whether the vorticity streams identified in section 3.1 actively contribute to the SWV vorticity, backward trajectory analyses are performed for parcels initiated within the vorticity center of the quasi-stationary SWV at 24 h (Figure 5). Note that the boundary layer (hereafter BL) is stable (the potential temperature increases with height; Figures 4c–4d), and the height of the stable BL is about 500–1000 m above the ground (Figures 4c–4d), as defined by the height of the low-level wind maximum discussed by Mahrt et al. [1979]. The main body of the vorticity volume (vorticity greater than $25 \times 10^{-5} \text{s}^{-1}$) extends vertically up to about 1 km above the ground (~1.5 km above mean seal level; Figures 4c and 4d), which is roughly the height of the BL. The initial parcels selected for backward trajectory analysis in Figure 5 are vertically centered within the vorticity volume of the vortex at low, middle, and upper levels of the BL (about 50, 500, and 1000 m above ground, respectively).
The trajectories perform well in representing the air parcels with high vorticity that contribute most to the vorticity of the SWV, which mainly come from outside of the dashed box that covers the Sichuan Basin and the SWV formed within it (Figures 5b–5d). The important air parcels originate from the south and west and are associated with the HVS and TVS, respectively. As shown in Figure 3h, two regions of intense vorticity generation are evident on the border between the Hengduan Cordillera and Sichuan Basin, the area common to the three topographic features. The two regions of intense vorticity generation are directly on the path of trajectories following the HVS and TVS. The directions of the trajectories tracing the vorticity streams are also consistent with the evolution of the vorticity streams (Figures 5 and 3h). When parcels following the trajectories enter one of the two regions of intense vorticity generation, their vertical vorticity increases rapidly. Parcels with increased vorticity will then be advected following the HVS and TVS and finally converge within the SWV circulation to form the enhanced vorticity volume of the SWV (Figure 5).

Figure 5. Backward trajectory analysis from 24 h for 36 parcels sampled along circle within the vorticity core of SWV shown in Figure 5a on (b) 50 m, (c) 500 m, and (d) 1000 m above ground level. The vorticity (shaded, $\times 10^5$ s$^{-1}$) and horizontal winds (full barb represents 5 m s$^{-1}$, half barb 2.5 m s$^{-1}$) shown in Figure 5a are on grid level 6 of the model, which is approximately 500 m above ground and through the vorticity volume core of SWV in vertical. The backward trajectories shown in blue in Figures 5b–5d are marked with small dots at 1 h interval and labeled in red with height above mean sea level at 2 h interval. The dashed box covers the main part of SWV and Sichuan Basin. The parcels that flow into the dashed box are found from west related to TVS and south related to HVS. The trajectories of the parcels from west are basically confined at the lower boundary layer (TVS-L), and the trajectories of the parcels from south represent HVS at the lower (HVS-L), middle (HVS-M), and upper boundary layer (HVS-U), respectively. Dynamic analyses along each of these trajectories are separately averaged to represent the characteristics of the vorticity streams at the corresponding levels, which are shown in Figure 6. The horizontal wind fields in Figure 5a is also overlaid in Figures 5b–5d for comparison. The terrain is outlined in each of the plots as that in Figure 3.
More trajectories follow the HVS than the TVS, indicating the more important contribution from the HVS to the SWV vorticity. Backward trajectory analyses from air parcels near the surface within the SWV vorticity show that both HVS and TVS feed into the low level in the BL (HVS-L and TVS-L in Figure 5b), while the parcels initialized within the SWV vorticity in the middle and upper BL only trace back along the HVS (HVS-M in Figure 5c and HVS-U in Figure 5d). The parcels tracing back through the HVS or TVS at different levels experience different flow conditions and terrain effects and are associated with different dynamics of vorticity generation. In the next subsection, the trajectories at each level along the HVS or TVS are averaged to represent the vorticity stream trajectory at the corresponding level, and the results of dynamic analyses along each of the trajectories are also averaged accordingly. The averaged vorticity stream trajectories and dynamic analyses are then used to analyze the dynamics of the HVS and TVS.

### 4.2. Dynamics of the Vorticity Streams Contributing to SWV Formation

The mechanisms of vertical vorticity generation along the HVS and TVS are diagnosed using the absolute vorticity equation (equation (1)) in a Lagrangian framework. Although steady state Bernoulli analysis associated with potential vorticity dynamics, as proposed by Schär [1993], is useful to diagnose the dissipative processes of orographic effects, the method does not address in detail the dynamics of vorticity and potential vorticity generation and cannot explain how the individual air parcels in the lee vortex or wake acquire vorticity or potential vorticity [Epifanio, 2003]. In equation (1), \( u, v, w \) and \( \zeta, \eta, \zeta \) are the wind speed components and relative vorticity in the \( x, y, z \) directions, respectively; \( p, \alpha \) are pressure and specific volume, respectively; \( F_x, F_y \) are the friction forces in the \( x, y \) directions, respectively; and \( f \) is the planetary vertical vorticity (Coriolis parameter).

\[
\frac{d}{dt} (\zeta + f) = - (\zeta + f) \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + \zeta \left( \frac{\partial w}{\partial x} + \eta \frac{\partial w}{\partial y} \right) + \left( \frac{\partial p}{\partial x} - \frac{\partial p}{\partial y} \right) + \frac{\partial F_x}{\partial x} - \frac{\partial F_y}{\partial y}
\]

Following an air parcel, the change of absolute vertical vorticity in equation (1) is due to stretching of the air column, tilting of horizontal vorticity into the vertical, the baroclinic effect, and friction. In equation (1), the terms apart from the friction term are calculated using the model output, and then the friction term is diagnosed from equation (1). The terms are calculated or diagnosed on the model grid and are then interpolated to each parcel location along each parcel trajectory. The dynamic analyses are carried out trajectory-by-trajectory, and then the results are separately averaged for trajectory groups associated with the vorticity streams at the different levels shown in Figures 5b–5d. The averaged trajectories of TVS-L, HVS-L, HVS-M, and HVS-U are shown in Figures 6a–6d, respectively, and the dynamics associated with the averaged trajectories are also shown in Figure 6 accordingly. The averaged transient vorticity generation rates are shown in Figures 6e–6h, while the importance of the dynamic processes can be more sensibly evaluated from their accumulative contributions to the vorticity generation in Figures 6i–6l. Furthermore, the vorticity generation due to stretching and tilting is shown in detail in Figures 6m–6p and Figures 6q–6t, respectively.

The dynamic analyses shown in Figures 6e–6t are averaged results, and averaging may introduce some errors. The trajectories in each of the trajectory groups are slightly different in position, and this implies that the parcels following different trajectories will experience different airflow environments and orographic effects; as a result, the dynamics of vorticity generation will be slightly different. The differences in the dynamics with respect to the averages are shown as error bars in Figures 6e–6h. The values of the error bars are greater at around 5 h when the parcels enter regions of very steep terrain (Figures 6a–6d) and then quickly decrease to small errors in the next few hours (Figures 6e–6h). Generally, the errors do not change the relative importance of the dynamic processes represented by the averages of the transient vorticity generation rate.

It should be noted that the simulation of CNTL in the first few hours includes a weak initial response to the idealized background flow. The initial response occurs within about the first 4 h, during which time the
Figure 6. Vorticity budget analyses of the terms in equation (1) for TVS and HVS. The trajectories in Figures 6a–6d are averaged from the trajectory groups of TVS-L, HVS-L, HVS-M, and HVS-U shown in Figures 5b–5d. Correspondingly, the vorticity budget analyses associated with the averaged trajectories are averaged from the individual analyses for each of the trajectory groups. The averaged transient and accumulative generation of vertical vorticity are shown in Figures 6e–6h and 6i–6l. And the associated stretching effect and tilting effect are analyzed in Figures 6m–6p and 6q–6t, respectively. The transient generation means vertical vorticity generation within a short time span of half an hour, and the accumulative generation is the time integration of the transient generation. The numbers labeled along the averaged trajectories in Figures 6a–6d denote the local trajectory height above ground. Error bars associated with the average of transient vorticity generation for each of the trajectory groups are shown in Figures 6e–6h. See context for the detail.
low-level initial background winds quickly adjust to a state of slow evolution associated with the orographic effect (not shown). The vorticity budget analyses within the initial 4 h may not be representative of the vorticity generation associated with the orographic effect but should not alter the general results discussed below that are based mainly on the dynamic analyses after the initial 4 h.

### 4.2.1. Development of the TVS

The TVS is mostly confined within low levels near the surface (Figure 6a). Generally, the positive vorticity contributions of stretching and tilting slightly outweigh the negative vorticity input due to friction, and the stretching effect is greater than the tilting effect (Figure 6i). The baroclinic effect is weak along the TVS (Figure 6i), possibly because the initial background flow in summer in the Tibetan Plateau region is associated with weak baroclinicity.

The stretching effect is strong along the TVS (Figure 6i). Referring to equation (1), the change of vertical vorticity due to the stretching depends on horizontal convergence or divergence. Air parcels travelling along the TVS are associated with larger negative vertical velocity and a stronger convergent environment when they pass over the steep terrain (Figures 6a and 6m). Downslope winds are found on the path and near the level of the TVS (Figures 3j–3l). The downslope winds contribute to the larger negative vertical velocity and also to the stronger convergent environment because they converge with the north wind along the steep terrain on the leeside of the Tibetan Plateau and with the SWV circulation as discussed in section 3.2. The stronger convergent environment leads to stronger stretching vorticity along the TVS (Figure 6m).

The horizontal vorticities that feed the tilting effect along the TVS are of comparable value in the x and y directions, but the tilting of x component of the horizontal vorticity dominates the tilting effect (Figure 6q). This is because the TVS is oriented roughly east-west, and the terrain along the TVS is steep and can induce a larger horizontal difference of vertical velocity and force more tilting of horizontal vorticity in the x direction.

### 4.2.2. Development of the HVS

The HVS is deeper than the TVS. The vertical scale of the HVS that eventually extends into the SWV is comparable to that of the vorticity volume of the SWV, around 1 km, lying directly above ground level as discussed earlier. Tracking back along the averaged trajectories, the HVS becomes shallower, and the top of the HVS near its beginning may be less than 200 m above ground level (Figures 6b–6d). Since the HVS near its beginning is concentrated within such a shallow layer, some trajectories from different trajectory groups that sample the different levels of the HVS track backward to similar heights. For example, near the 2000 m terrain contour in Figures 5b–5d, the trajectories start at about 2.0–2.1, 2.1, and 2.2 km above mean sea level, respectively. The different trajectory groups near the beginning of the HVS differ slightly in position and density but evolve in very different ways downstream in the HVS in the lower, middle, and upper BL (Figure 5).

Within approximately the initial 6 h when the HVS is confined more closely to the surface, BL friction plays a dominant role in the positive vorticity generation (Figures 6j–6l). Later on, the positive vorticity generated by stretching and tilting gradually dominates, and vorticity generation due to friction turns negative (Figures 6j–6l). During the formation of the SWV, the baroclinic effect along the HVS is also weak (Figures 6j–6l).

The stretching effect is important along the HVS at the upper level, especially through stretching of the planetary vorticity. From near the surface to the mid-level of the HVS, from 0 h the parcels experience a divergent environment when they descend down the steep terrain and move away from the upstream parcels (from about 0 to 6 h in Figures 6n and 6o; c.f., Figure 3j); later (after about 6 h in Figures 6n and 6o), the parcels encounter a convergent environment as the descending airflow converges with the air mass previously filling the Sichuan Basin (c.f., Figure 3k). This means that from near the surface to the mid-level of the HVS the stretching term is generally negative earlier and positive later (Figures 6n and 6o). The stretching term near the surface increases faster than that at the mid-level of the HVS later on (Figures 6n and 6o), because the near-surface trajectory follows a steeper incline, as indicated by the height of the trajectory above ground level (Figures 6b and 6c). Only later (after ~12 h) does the stretching make the largest contribution to the vorticity generation along the HVS from near the surface up to the mid-level (Figures 6j and 6k). At upper levels of the HVS (Figure 6p), the parcels experience stronger convergence shortly after weaker divergence, and stretching generates strong vorticity, which is the dominant contribution to
vorticity generation (Figure 6l). Stretching of the planetary vorticity plays an important role in the generation of the dominant stretching-induced vorticity along the upper levels of the HVS. The planetary vorticity where the SWV forms is positive with a value of about $7 \times 10^{-5}$ s$^{-1}$ (gray line in Figures 6m–6p). In this study, the relative vorticity is initially almost zero, as shown in Figures 6i–6l. The planetary vorticity initially and continuously feeds the stretching effect that makes the dominant contribution to the vorticity along the HVS at the upper level.

The dynamics of the upper-level HVS confirm that stretching of the planetary vorticity is an important mechanism of vorticity generation contributing to SWV formation, as reported in case studies [e.g., Kuo et al., 1988]. This mechanism may explain the climatologically favorable location for the formation of the SWV in the Sichuan Basin, since cyclonic relative vorticity is often created by the descending airflow from the Hengduan Cordillera into the Sichuan Basin through stretching of the planetary vorticity. Kuo et al. [1988] analyzed a backward trajectory initiated at 700 hPa within the vorticity center of a real SWV, revealing that the trajectory is somewhat similar to the trajectory of HVS in the upper BL in this study (Figure 6d), which starts from the SWV vorticity center at 1 km above ground (~1.5 km above mean sea level, 850 hPa). The parcel following the trajectory in Kuo et al. [1988] gains vorticity of $-20 \times 10^{-5}$ s$^{-1}$ within a 15 h period, while stretching of the planetary vorticity could make a contribution of $5 \times 10^{-5}$ s$^{-1}$ even if only a relatively weak stretching effect is assumed associated with a convergence of $1 \times 10^{-5}$ s$^{-1}$. In this study, the stretching effect is most active before 12 h (Figure 6h), while the associated convergence or negative divergence is strong with a maximum up to $18 \times 10^{-5}$ s$^{-1}$ (Figure 6p). The vorticity generation due to stretching of the planetary vorticity includes direct stretching of the planetary vorticity and indirect transformation of the previously accumulated relative vorticity due to earlier stretching of the planetary vorticity. By 12 h, the vorticity generation through stretching of the planetary vorticity reaches $24 \times 10^{-5}$ s$^{-1}$ (not shown), which accounts for $\sim60\%$ of the total stretching vorticity (Figure 6p, $-40 \times 10^{-5}$ s$^{-1}$ at 12 h) and even greater than the total vorticity of the parcel (Figure 6l, $-16 \times 10^{-5}$ s$^{-1}$ at 12 h).

The tilting also plays an important role along the HVS (Figures 6r–6t). From near the surface to the mid-level of the HVS (Figures 6r and 6s), negative horizontal vorticity in the $x$ direction and positive horizontal vorticity in the $y$ direction are generated due to surface friction that decelerates the southwest airflow. The HVS is oriented roughly north-south, along the steep terrain between the Hengduan Cordillera and the Sichuan Basin (Figures 6b and 6c). Tilting of the $y$ component of the horizontal vorticity dominates the total tilting term (Figures 6r and 6s). This confirms that tilting is more effective in converting horizontal vorticity along steep terrain, as discussed for the TVS. The generation of vorticity by tilting at the HVS mid-level is similar to that near the surface, and the tilting term is slightly larger than the vorticity tendencies due to other effects in both cases from about 6 to 12 h (Figures 6j and 6k). In the upper-level HVS (Figure 6t), both components of the horizontal vorticity decrease since the trajectory is higher and the surface frictional effect weakens, so the vorticity generated by tilting is also reduced and is found to be of minor importance in building the vorticity of the upper-level HVS (Figure 6l).

4.2.3. The Role of Friction

Friction plays an important role in vorticity generation along the HVS and TVS (Figures 6i–6l). Surface friction can induce regions of vertical wind shear near the surface (e.g., regions of vertical differences of horizontal winds near the surface in Figures 4c and 4d) and plays a role as a vertical vorticity source or sink when the vorticity stream trajectory passes through the regions of vertical shear. The frictional vertical shear induces a vorticity vector approximately parallel to the local terrain surface, and the vorticity vector will have a positive (negative) vertical component when the terrain surface is higher on the left (right) side of the vorticity stream trajectory (looking down the vorticity stream trajectory in Figures 6a–6d and keeping in mind that the winds generally blow along the trajectory to transport the parcels).

The frictional effect has been traditionally emphasized in SWV formation [e.g., Lu, 1986]. To further investigate the role of the friction associated with the main topographic features in the Tibetan Plateau region, we design an experiment without surface friction, the CNTL_NF. Without friction, the SWV forms earlier with some characteristics similar to those in the CNTL; for example, the vorticity stream and regions of intense generation of vorticity linked with the SWV formation can still be identified (Figure 7). Vorticity generation near the surface in the absence of surface friction (Figure 7a) is associated with a downward extension of the stretching or tilting effect at the mid-level to upper BL discussed earlier to the low-level BL. These
results suggest that the frictional effect is not necessary for the formation of the SWV, as found by Kuo et al. [1988]. However, the frictional effect does exist and can induce strong vorticity generation in the low-level BL, as well as combine with the stretching or tilting effects to generate the vorticity of the SWV (Figure 6).

4.3. Topographic Control of SWV Formation

As discussed above, the steep terrain associated with the Tibetan Plateau, the Hengduan Cordillera, and the Sichuan Basin can induce regions of intense vorticity generation and two vorticity streams. In this section, results from sensitivity experiments with different combinations of the Tibetan Plateau/Hengduan Cordillera/Sichuan Basin, as listed in Table 1, are analyzed, focusing on the individual role of each of the main topographic features in SWV formation.

The experiment IT_ALL produces a SWV with similar low pressure, circulation, vorticity structure, regions of intense vorticity generation, and vorticity streams to that in the CNTL (comparing Figures 3l and 8a, Figures 3i and 8b). This implies that the scales of the Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin used in the Appendix A capture well the real scales of these three main topographic features. Using the idealized topography, it is easy to design the experiments IT_TH and IT_TP to investigate the effect of the Sichuan Basin, Hengduan Cordillera, and Tibetan Plateau on SWV formation by comparing with the experiment IT_ALL (see Table 1).

If the Sichuan Basin is removed (Figures 8c and 8d), the depth and steepness of the terrain among the Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin will decrease, and the vorticity generation in this region is reduced (comparing Figures 8a and 8c, Figures 8b and 8d). As a result, the associated TVS will contribute less to the creation of the vorticity of the SWV. The Sichuan Basin can help enhance the low pressure associated with the SWV; the 850 hPa geopotential height near the vortex center at 24 h in IT_ALL is found 10 geopotential meters less than that in IT_TH (Figures 8b and 8d). The vortex forms over the Sichuan Basin with better organized circulation and vorticity, and the SWV vorticity is concentrated nearer the center of the vortex with stronger intensity (comparing Figures 8a and 8c, Figures 8b and 8d). In addition, when the vortex evolves within the Sichuan Basin, the basin slows its outward movement and favors a quasi-stationary state of the vortex. In the IT_TH, the SWV also takes longer to form (Figure 9), while the vortex tends to move away from the Tibetan Plateau and Hengduan Cordillera (not shown). In fact, the Sichuan Basin provides a natural region of dynamic convergence of the surrounding airflow associated with the HVS and TVS, and maintains the circulation of the SWV that is favorable for its further development.

If the Hengduan Cordillera is also removed (Figures 8e and 8f), only a weak cyclonic circulation forms over the southeast periphery of the Tibetan Plateau; the cyclonic circulation is associated with weak low...
Figure 8. Same as Figure 7 but for the idealized terrain experiments at 24 h. (a, b) IT_ALL, (c, d) IT_TH, and (e, f) IT_TP.
geopotential height at 850 hPa and weak low pressure near the surface. Instead of the HVS and TVS, a longer vorticity stream attached to the southeast side of the Tibetan Plateau is found, extending farther into the cyclonic circulation (Figures 8e and 8f). The cyclonic circulation is similar to the edge cyclone simulated by Murakami and Nakamura [1983]. It appears that the cyclonic circulation cannot capture the important features of the SWV, such as the position, the scale, and the associated vorticity streams, which are closely linked to the local meso-scale topography of the Hengduan Cordillera and the Sichuan Basin integrated with the Tibetan Plateau.

The obvious effect of the Hengduan Cordillera is to modify the airflow around the southeast side of the Tibetan Plateau (Figures 8c–8f). The southwest flow is blocked on the upstream side of the Hengduan Cordillera at low levels (Figures 8c and 8d) and then turns around the southeast side of the Hengduan Cordillera, leading directly to the generation of a lee vortex with a closed circulation, namely the SWV (Figure 8d). The vorticity associated with the flow around the Hengduan Cordillera (Figures 8c and 8d) extends into the lee vortex, corresponding to the HVS that contributes to the formation of the SWV vorticity. The SWV simulated in the IT_ALL (Figure 8b) is comparable with the SWV that forms later in the IT_TH (Figure 9), especially in terms of scale and location. This result indicates that the combination of the Tibetan Plateau and the Hengduan Cordillera is critical to the formation of the SWV, and the Sichuan Basin, as discussed above, plays a secondary role compared with the Hengduan Cordillera (Figures 8a–8d).

5. Summary and Conclusions

In this paper, the SWV induced by the topography in the Tibetan Plateau region was examined in an idealized background flow. The SWV has the characteristics of a shallow circulation system below the 3 km level with a horizontal scale of 400–500 km and ascending flow over the west-to-southwest side of the vortex. Two topographically induced vorticity streams are absorbed into the circulation of the SWV and reorganize to build the SWV vorticity. The first vorticity stream originates from the southeast Hengduan Cordillera (HVS), and the second extends from the east side of the Tibetan Plateau conjoint with the Hengduan Cordillera and Sichuan Basin (TVS). Surface friction, stretching, and tilting contribute differently to vorticity generation in the two vorticity streams. Friction is important at lower levels, as traditionally emphasized, and serves as a source or sink of vertical vorticity, as the low-level vorticity due to frictional shear is almost parallel to the slanting terrain surface and has a vertical component. The frictional vorticity plays a dominant role where the HVS begins within a thin layer near the surface over the southeastern Hengduan Cordillera. The HVS then passes over steep terrain between the Hengduan Cordillera and Sichuan Basin and thickens. First the
tilting and then the stretching make the major contributions to the vorticity of the HVS from the near surface to middle level; in the upper-level HVS, the dominant contribution comes from the vorticity associated with stretching of planetary vorticity. The frictional, stretching, and tilting effects associated with the TVS are stronger than for the HVS, since the TVS is confined within a thin layer near the surface and passes over steeper terrain than the HVS. For the TVS, the positive stretching vorticity is greater than the negative or positive tilting vorticity, and the sum of them generally exceeds the negative frictional vorticity that is strongly generated along the TVS.

SWV formation is controlled by the multi-scale topography in the Tibetan Plateau region in the idealized background flow. The sensitivity experiments with different topography combinations are designed to investigate the individual roles of the Tibetan Plateau, Hengduan Cordillera, and Sichuan Basin in SWV formation. The southwesterly flow over southwestern China determines the environment for SWV formation. The Hengduan Cordillera blocks the southwesterly flow at low level and forces the southwesterly flow to turn around the Hengduan Cordillera on its southeast side which directly induces the HVS. The role of the Sichuan Basin is to generally enhance the steepness of the terrain in the Tibetan Plateau region and thus strengthen the vorticity generation of the two vorticity streams associated with stretching and tilting effects. The Sichuan Basin appears to be a preferred region for merging of the surrounding airflow and the associated vorticity streams; it also naturally slows the migration of the vortex formed within it and thus favors the maintenance and further development of the SWV. The position and scale of the SWV are controlled by the Tibetan Plateau and Hengduan Cordillera, and the effect of the Sichuan Basin is secondary to that of the Hengduan Cordillera.

Noted that the SWV simulated in this study is associated with idealized or simplified conditions. The idealized terrains are only good approximation to the real topography in the Tibetan Plateau region, and the background flow used in this study is a long-term average of monthly mean climatic data, so upper-level weather disturbances are smoothed away and are not involved in the formation of the SWV. Furthermore, the moist processes that play important roles in SWV formation in a real atmosphere are not included in the simulations; they are still not well understood and need further study.

The formation of the shallow SWV at low level can be considered as the initial stage of lee cyclogenesis in the Tibetan Plateau region, which is characterized by the effects of different mountain complexes and regional atmospheric flows, and is not accounted for in the quasi-geostrophic model of Rocky Mountain lee cyclogenesis or the two phases of Alpine lee cyclogenesis. Additional studies are needed to investigate the necessary conditions and dynamic mechanisms in the development stage of lee cyclogenesis in this region after the formation of the SWV.

Appendix A: Idealization of the Three Main Topographic Features in the Tibetan Plateau Region

The Northern Lambert projection is used in the model, with two true latitudes of 30°N and 60°N and true longitude of 100°E. The model domain is centered on the conjoint point (100°E, 30°N) of the Tibetan Plateau and Hengduan Cordillera. The centers of the Tibetan Plateau and the Sichuan Basin are located at distances of (−750 km, −400 km) and (500 km, 50 km) from the conjoint point, respectively. The Tibetan Plateau is represented by an ellipse with semi-major axis $L_x \approx 1450$ km and semi-minor axis $L_y \approx 725$ km, while the Sichuan Basin is represented by a circle with radius $L_c \approx 275$ km. The Hengduan Cordillera extends toward the southeast from the conjoint point at an angle of 25° clockwise from south, and its width $L_{Hx}$ and length $L_{Hy}$ are 500 and 800 km, respectively. A surface reference height $H_0$ is assumed as 1000 m because the SWV develops over about 1000 m above sea level except within the Sichuan Basin. The mean height of the Tibetan Plateau $H_T$ and the maximum height of the Hengduan Cordillera $H_H$ are set to 5000 m, while the bottom height of the Sichuan Basin $H_S$ is chosen as 500 m. According to these scales, the three main topographic features, $h_T$, $h_H$, and $h_S$, can be defined as in (A1), where $D_T$ and $D_S$ are the distances from a point $(x, y)$ to the center of the Tibetan Plateau and the Sichuan Basin, respectively, and $D_{Hx}$ is the minimum distance between a point and the central ridge line of the Hengduan Cordillera, while $H_{Hy}$ is the minimum distance to the line perpendicular to the central ridge line of the Hengduan Cordillera and across the conjoint point. The idealized terrain of the Tibetan Plateau is shown in (Figure 2d). The idealized terrain of the Tibetan Plateau and the Hengduan Cordillera combined (Figure 2c) is obtained with the terrain height set
to the higher value of the two, \( \max(h_T, h_H) \). When the Sichuan Basin is added (Figure 2b), the height is set to change gradually according to (A2) in an overlap region of ±0.3\( \Delta_S \) near the boundary of the Sichuan Basin.

\[
h_T(x, y) = H_0 + (H_T - H_0) \left( 1 - \cos^2 \left( \frac{\pi}{2} \left( 1 - D_T \right) \right) \right)
\]

\[
h_H(x, y) = H_0 + (H_H - H_0) \left( 1 - \cos^2 \left( \frac{\pi}{2} \left( \frac{L_{xH} - D_H}{L_{xH}} \right) \right) \right) \cos^2 \left( \frac{\pi}{2} \left( \frac{D_H}{L_{xH}} \right) \right)
\]

\[
h_S(x, y) = H_0 + (H_S - H_0) \left( 1 - \cos^2 \left( \frac{\pi}{2} \left( \frac{L_s - D_S}{L_s} \right) \right) \right)
\]

\[
h_{\text{mod}}(x, y) = \max(h_T, h_H) \left( \frac{1}{2} \left( 1 + \sin \left( \frac{\pi}{2} \left( \frac{D_S - L_S}{0.3L_s} \right) \right) \right) + h_S \left( 1 - \frac{1}{2} \left( 1 + \sin \left( \frac{\pi}{2} \left( \frac{D_S - L_S}{0.3L_s} \right) \right) \right) \right)
\]

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