FLOW REGIMES FOR MAJOR TOPOGRAPHIC OBSTACLES OF CHINA

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Abstract  Major topographic obstacles in China are taken into account as a whole and approximate scales of these topographies are dynamically idealized according to the theoretical results of mountain flow dynamics. For the typical west-east and north-south upstream flow, the questions are focused on the different flow regimes, such as flow-over/flow-around and quasi-geostrophic balanced or not. The results show that main topographies in China can be classified as three types, one is over-flow dominated and quasi-geostrophic balanced, the second is over-flow dominated but quasi-geostrophic unbalanced, and the third is around-flow dominated and quasi-geostrophic unbalanced. In fact, the primary flow characteristics are determined by not only the scales of the topographies but also their shapes and the upstream flow direction. The rationality of the regimes is validated through qualitative analysis of the flow over the Dabie Mountains and Taiwan Mountains which are numerically simulated using a mesoscale model.

Key words  Major topographies of China, Flow over mountains, Flow regimes, Flow over, Flow around, Quasi-geostrophic dynamics

1 INTRODUCTION

In recent tens of years, the dynamics of topography-induced disturbance has been focused as an interesting scientific question in the atmospheric dynamics[1~7]. When air stream passes through a mountain, the flow, especially the lower-level flow, will be mainly characterized by flow over or around the mountain. The other essential flow regimes are whether it satisfies quasi-geostrophic (hereafter QG) balance or not. The boundaries can be identified to distinguish the different regimes, which are very important to understand the dynamics of flow over mountains and useful to verify the simulations from numerical models. The factors influencing the flow characteristic mainly come from two aspects. One is the condition of the atmosphere, such as the strength, shear, and stability of airflow, the direction of airflow approaching the mountain; the other is associated with the topographic parameters, such as the length, width and height of the topography. The factors are so complex that how each of them influences the flow characteristics is still an open question till now.

Under the free-slip boundary condition, for the airflow over mountain with an upstream uniform wind $U$ and constant stability $N$ on $f$-plane, there are several non-dimensional dynamic parameters introduced to describe the characteristics of airflow over topography (Fig. 1): the Rossby number $Ro=U/Lf$, non-dimensional mountain height $H=Nh_m/U$ (reverse of Froude number $Fr=U/Nh_m$), where $L$ and $h_m$ are the half-width and maximum height of the mountain respectively. When the mountain shape is taken into account, the aspect ratio $A$ is identified as the half-width across the flow direction divided by that along the flow direction. In addition, there is upstream-effect scale, i.e. the radius of deformation $L_u=Nh_m/f$, within which the wind speed is obviously decelerated. When $L_u$ is compared with the mountain scale across the flow direction, another parameter can be defined as $\varepsilon=L_u/L_y=RoH/A$ to denote the strength of the upstream effect[6,8].

For typical condition in the mid-latitudes ($U=10\text{m}\cdot\text{s}^{-1}$, $N=10^{-2}\text{s}^{-1}$, $f=10^{-4}\text{s}^{-1}$), Rotunno and Ferretti[9] simply reviewed the dynamics of flow over mountains in dry atmosphere. Considering the scales of the topography, there are two horizontal scales, $U/N$ and $U/f$, to express the two dividing lines which denote the importance of stratification and rotation respectively. There is a critical height $U/N$ deciding the linear or nonlinear character of topographic disturbance in the vertical direction. Therefore, the three scale-lines sep-
arate the flow characters into several regimes, but the QG and non-QG regimes, especially the flow-over and flow-around regimes are not clear enough there.

Fig. 1  Control nondimensional parameters when ideal airflow ($f$-plane, dry-adiabatic, uniform stratified $N$ and constant flow $U$) passes over an isolated topography with height $h_m$ and half breadth $L$, the nondimensional height $H$, the Rossby number $Ro$, the aspect ratio $A$, the scale $L_u$ and the strength parameter $\varepsilon$ of the upstream effect (see text for detail)

Without rotation, some theoretical studies show that the non-dimensional height $H$ is the only parameter controlling the flow regimes. The critical height $H_c$ is about $1.2^{[2,3,5,10]}$. When $H > H_c$ ($H < H_c$), the around-mountain (over-mountain) flow will dominate. When the influence of Coriolis force is included, the concept of critical height is still useful by combining it with Rossby number, that is $H_c = H_c(Ro)$. For a rotating system, the Coriolis force will restrain the upstream effect by adjusting the flow toward QG balance. If the mountain is high enough, the lower-level flow will be totally blocked, and the flow within the deformational radius will be hypo-geostrophic. The lower-level airflow will be concentrated mostly on the left (with back to the flow direction) and be driven around along the mountain ridge$^{[4]}$. Comparing with the case without rotation, the flow feels the mountain becoming lower than it really is, so the critical height for rotational case will be greater than 1.2.

For the three-dimensional unsymmetrical topography, the critical height will also be dependent on the aspect ratio $A$, that is $H_c = H_c(Ro, A)$. For the barotropic stratified flow over mountains on $f$-plane, if the mountain horizontal scale along the flow direction is fixed ($L_x$=const.), larger (small) $A$, namely larger (small) $L_y$, will lead more (less) airflow over the mountain. The similar results are larger $\varepsilon$ ($RoH > A$) tends to favor the flow-around regime while smaller $\varepsilon$ ($RoH < A$) tends to flow-over regime$^{[8]}$.

For the dynamics of flow over mountain, it is important to understand the interaction between the balanced flow and unbalanced flow for a typical flow condition$^{[11]}$. Schär$^{[7]}$ summarized some theoretical studies of flow over mountains and gives a simple dividing line defined as $RoH=0.5$. When $RoH < 0.5$, the QG dynamics can be implemented which means the balanced dynamics dominates in the mountain flow.

There are very complex topographic obstacles in China. The weather and climate are significantly influenced by mountains. Larger scale mountains can not only have direct impacts locally, but also can affect the weather and climate far away, and even can obviously change the hemispherical and the global atmosphere. Otherwise, the mesoscale mountains mainly have particular influence on the local weather and climate$^{[12]}$. A lot of studies have been done to investigate the influence of topography on the regional weather and climate. In this paper, some theoretical results for mountain flow dynamics are applied to all the uppermost mountains in China to discuss the flow pattern as a whole. The emphases are on flow-over, flow-around and QG dynamic regimes. The regimes about whether flow-over or flow-around would occur and whether QG-balanced dynamics for the flow passing over these major obstacles in China is important to understand the regional weather.
This paper is organized as follows. Section 2 gives the qualitative analyses of flow regimes for major topographic obstacles in China. In Section 3, the flow over Dabie-Mountain-scale and Taiwan-Mountain-scale topography are numerically simulated using a mesoscale model to verify the qualitative results in Section 2. Conclusions are summarized in Section 4.

2 FLOW REGIMES FOR MAJOR TOPOGRAPHIC OBSTACLES OF CHINA

As a whole, the topography of China has a stepped feature from higher mountains at west to lower mountains at east. In the present work, 24 major mountains are selected and classified by the flow regimes, they are Tibetan Plateau (TP), Hengduan Cordillera (HD), Nei Monggol Plateau (NM), Huangtu Plateau (HT), Yungui Plateau (YG), Altay Shan (AS), Tian Shan (TN), Da Hinggan Ling (DX), Taihang Shan (TH), Qin Ling (QL), Daba Shan (DB), Xiao Hinggan Ling (XX), Changbai Shan (CB), Tai Shan (TS), Dabie Shan (DS), Mufu-Jiuling Mountainous Region (MJ), Wannan Mountainous Region (WN), Xuefeng Shan (XF), Nanling (NL), Luoxiao Shan (LX), Jiulian Shan (JL), Zhemin Mountainous Region (ZM), Wuzhi Shan (WZ), and Taiwan Central Mountains (TW). The two capital letters bracketed denote each of the mountains for short (Table 1).

Table 1 Layout-characters, scales and the associated non-dimensional parameters of major topographies in China

<table>
<thead>
<tr>
<th>No.</th>
<th>Mountain</th>
<th>Short Layout</th>
<th>Mean Length</th>
<th>Length</th>
<th>$H$</th>
<th>$R_{oWE}$</th>
<th>$R_{oNS}$</th>
<th>$A(WE/NS)$</th>
<th>$A(NS/WE)$</th>
<th>$R_{oWEH}$</th>
<th>$R_{oNSH}$</th>
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<td>HD</td>
<td>NS</td>
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<td>1.67</td>
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<td>NM</td>
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<td>200</td>
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<td>150</td>
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<td>100</td>
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<td>2.00</td>
<td>4.00</td>
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<td>2.00</td>
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<td>NL</td>
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<td>200</td>
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<td>2.00</td>
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<td>NE-SW</td>
<td>1000</td>
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<td>100</td>
<td>1.00</td>
<td>1.60</td>
<td>4.00</td>
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<td>1000</td>
<td>750</td>
<td>300</td>
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<td>Q-NS</td>
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<td>100</td>
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<td>4.00</td>
<td>1.43</td>
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</table>

Table 1 shows the layout-characters, scales and the associated nondimensional parameters of major topographies in China. The layout-characters, mean height and length are from several data sources of Chi-
inese topography,[13–15] while the width of the mountains are estimated from two detailed maps of China terrain[16,17]. Because of the complexity and non-isolatedness of the mountains, it is difficult to give accurate scales of them. But for qualitative analysis in this paper, the values in Table 1 are veracious enough. Then, some non-dimensional parameters can be defined, such as the nondimensional height \( H \), the Rossby number for west-to-east flow \( Ro_{WE} \) and for south-to-north flow \( Ro_{NS} \), and the associated aspect ratio \( A(\text{NS/WE}) \) and \( A(\text{WE/NS}) \).

A bell-shaped topography as the approximation of real topography is needed to get the nondimensional parameters in a theoretical framework of dry mountain flow. Generally, a bell-shaped mountain formed as \( h(x,y)=h_m\left[\left(\frac{x^2+y^2}{L^2}+1\right)^{-3/2}\right] \) is often used in theoretical studies[3,6,7,10]. For quantitative analysis in this paper, the width at 0.1\( h_m \) of the bell-shaped mountain is chosen to compare with the real mountain width, because the non-isolated real topography makes the mountain profile not on the sea-level surface but above that at some height. Fig. 2 shows that the width at 0.1\( h_m \) is about 4\( L \), therefore, the half-width to calculate \( Ro \) in Table 1 is 1/4 of the width scale. Otherwise, most of the mountains lay basically from south to north or from west to south. Several mountains spreading to other directions are approximated to the two main types, such as CB, ZM and JL (from northeast to southwest) are looked as west-east ones while AT and DB (from northwest to southeast) are regarded as north-south ones. Errors in the approximation for these orographic scale parameters will certainly occur. For example, the influence of aspect ratio \( A \) is excluded and for some mountains the upstream wind direction is changed. These errors will be particularly discussed later.

Fig. 3 Rossby number map for major topographies of China

Typical values for \( U, N \) and \( f \) in mid-latitudes \((U=10\text{m·s}^{-1}, N=10^{-2}\text{s}^{-1}, f=10^{-4}\text{s}^{-1})\) are used to calculate the nondimensional parameters. Fig. 3 gives major topographies in China with different Rossby number. From Fig. 3, we can see that most of the mountains in China are located in the regions \( A_{\text{NS/WE}} < 1.0 \) which means that the west-east is the main layout-direction of major topographies in China. In general, for small mountains, the horizontal scale is about of 10km or less which has a Rossby number greater than 40 \( (Ro > 40) \). However, for typical mesoscale and large scale mountains, the horizontal scales are about of 100km and 1000km, respectively and the corresponding Rossby numbers are about of 4 and 0.4. The horizontal scale of mountains investigated here are mainly from mesoscale to large scale. If \( Ro=1 \) is chosen as the dividing line to distinguish the two scales, we can see that TP, HD, HT, YG and NM are large scale mountains while the other mountains are mesoscale in the width-direction at least. There are still mountains that are in the large scale and mesoscale at the same time, e.g. their length is in the large scale but width in the mesoscale, such as QL, DB, NL, TN, ZM, TH, DX and AS. For these mountains, the dynamic Rossby number can markedly vary between \( Ro_{NS} \) and \( Ro_{WE} \) when the upstream wind direction changes.
Figure 4 gives the major topographies in China within a \( Ro-H \) map for the different upstream flow. The topographies are represented as the circles, and the numbers up the circles are the mountain aspect ratios. The thick solid line shows the boundary of quasi-geostrophic approximation, under which the quasi-geostrophic balance can be applied and above that can not. The straight horizontal line is \( H = H_c \approx 1.2 \), the dash-dotted line denotes the division of flow over and flow around, under which the major flow characteristic is over the mountains while above that is around, there is still uncertainty about this line when \( Ro < 0.25 \) which is denoted as a question mark.

Comparison with Figs. 4a and 4b shows the dynamic characteristics of flow over these mountains are dependent on not only the horizontal scales of mountain, but also the direction of upstream flow. Three flow regimes for mountain flow in China can be classified by the two curves in Fig. 4. One is for the flow-over and QG-balanced, the second is for the flow-over but not QG-balanced, the third flow regime is for QG-unbalanced but flow-around.

For the west-east flow (Fig. 4a), the most large scale mountains in the west of China can be described by the QG theory, such as TP, NM, HT, YG and QL. But only TP is high enough to force the air flow around it. There are also lower mountains satisfying QG-dynamics with the over-flow, such as NL and ZM in the southeast of China and CB in the northeast of China. But many mesoscale mountains in the middle and lower reaches of Yangtze River and the south of China are unbalanced, such as WN, MJ, DB, XF and LX and some other mountains such as TS, WZ, DX and XX. The heights of these mountains are only on the order of 1000m which makes over-flow dominating. Mountains TW and TH basically lay from north to south, the lesser scale at west-east direction and the larger altitudes result in the regime with the unbalanced and flow-around flow. However, the prominent altitudes of AS, TN, HD and DB decide their locations in the QG-unbalanced and flow-around regime.

In the case of south-north flow (Fig. 4b), mountains NM, DX and XX are QG-balanced. TP, YG, and HT are not QG-balanced but the over-flow dominates. TN, QL and DB have west-east layout, the south-north scale is small while the nondimensional height is greater than the critical value, which lead to the regime of flow-around and QG-unbalanced. Most of the mountains over the middle and lower reaches of Yangtze River and the south have the same dynamic characters as the west-south flow case. The mountains AS, HD, TW and TH are in the regime of QG-unbalanced and flow-around as Fig. 4a.

The three regimes in Fig. 4 are not determined only by the non-dimensional height and Rossby number for a symmetrical mountains whose aspect ratio can change the flow pattern greatly. With the influence of \( A \) included, Fig. 5 shows the diagram in \( A-RoH \) map to classify these mountains. Figs. 5a and 5b are for west-east and north-south airflow respectively. \( \varepsilon \) is the nondimensional parameter denoting the upstream effects of topographies. More flow over mountain will be flow-around when \( \varepsilon \) is larger, while more will be flow-over when \( \varepsilon \) is smaller. For the west-east upstream flow, the flow rushing at TN and TW will be dominated by around the mountains whereas DX, XX etc. over the mountains. For the north-south upstream flow, the around-flow is
still the principal part for TW whereas the overflow for NM, QL etc. The tendency changing from flow-over to flow-around could be simply shown in Fig. 5, which includes consideration of the full characteristics of topography. There are notable differences between the regimes in Fig. 4 and Fig. 5, but till now, the theoretical dividing lines for the flow-over, flow-around and QG-balance are not clearly recognized in the \( A-RoH \) map yet.

The bias in Fig. 4 due to the approximation of real topographies as the circle isolated obstacles is shown in Fig. 6. There are two possible modifications of the aspect ratio \( A \) when such theoretical approximation is made, that is \( A \) is enlarged or reduced. For mountains \( A < 1 \) (dotted lines), the aspect ratios are magnified, and the real airstream will tend to the flow-around much more. However, for mountains \( A > 1 \) (dashed lines), the aspect ratios are reduced, and the real airstream will tend to the flow-over much more. These results are the same both for the east-west and north-south flow. Despite of the bias, the flow regimes of mountain flow shown in Fig. 4 are still approximately correct for most major topographies in China because of the indistinctive variations of \( A \) for most of the mountains.

![Fig. 5 Major topographies of China in \( A-RoH \) map](image)

(a) East-west airflow; (b) North-south airflow.

More airstream will flow around (over) the mountains where \( \varepsilon \) is larger (smaller).

![Fig. 6 Effects of the changed aspect ratio \( A \) on the flow over mountains when real topographies are idealized as circle isolated obstacles](image)

3 VALIDATION OF THE FLOW REGIMES WITH NUMERICAL EXPERIMENTS

To validate the rationality of the simplification of mountains and the qualitative results in Section 2, the numerical simulations with the full dynamic processes are conducted to two representative mountains: the Dabie
A non-hydrostatic and storm scale numerical model system, named ARPS (Advanced Regional Prediction System) is incorporated to the simulation of the real flow over DS and TM within an ideal atmospheric condition, which has been fully developed at CAPS (the Center for Analysis and Prediction of Storms) of the University of Oklahoma\textsuperscript{[18,19]}. The ARPS is a three-dimensional, non-hydrostatic compressible model formulated in generalized terrain-following coordinates. A lot of state-of-the-art physics processes and parameterization schemes are included in ARPS to perform explicit prediction of atmospheric flows from small-scale to large scale. And especially, the model includes options for a free slip boundary condition and several ideal atmosphere backgrounds and is very convenient for preparing idealized simulations.

The grid numbers are designed as $101 \times 101$ with 4km grid space in horizontal direction. Vertically, 35 levels are defined with a vertical grid stretching applied which gives vertical grid spaces growing with height with a minimal value of 100m near surface. The vertical grid distribution favors the better description of low-level flow. The initialized field is hydrostatic and QG-balanced with a constant-stability atmosphere designed using the typical values of $U$, $N$ and $f$ as in Section 2. To make the simulations comparable with theoretical results, the ideal conditions using a free-slip boundary surface are set up with land-surface, boundary layer and moist physics being neglected in the present simulations.

### 3.1 Dabie Mountains

The Dabie mountains located at the middle and lower reaches of Yangtze river is selected here since it is very important for the initialization and development of mesoscale convective systems evolved there and the surroundings especially during Meiuy season in China. Fig. 7a presents the real profile while Fig. 7d is the

![Fig. 7 Typical mid-latitudes westerlies passing the Dabie-mountain-scale obstacle](image)

(a) Real Dabie mountain; (b) Streamline and potential vorticity near surface; (c) Vertical slice of potential temperature, potential vorticity and $U-W$ wind vector through the center of topography along the flow direction. (d), (e) and (f) are for idealized topography. (For each plot, down left corner are the variables and units, down right are their corresponding max/min or interval values, color bar on the right side is the interval value for the shaded plot. The same for Figs. 8~11).
idealized one for Dabie Shan with $Ro\approx 2.0$ and $H\approx 1.0$ contoured in 100, 500 and 1000m respectively. The shape and extension of the Dabie Shan contours are similar sufficiently, which makes the simplification of the mountains effective.

Only a typical mid-latitudes west wind passing the DS is simulated because the mountain flow is not sensitive to the wind direction for the almost circle-shape mountains. The flow pattern reaches a quasi-steady state after 12 hour integration of the model. Simulations at 24 hour are selected to analyze the dynamic structure of flow over DS. Figs. 7b and 7e show the streamline and potential vorticity (hereafter PV) near the surface, respectively, while Figs. 7c and 7f are the corresponding vertical cross-section of potential temperature, potential vorticity and $U-W$ wind vector through the center of DS along the flow direction for the real and the idealized topography respectively. For each plot, down left corner are the variables and units, down right are their corresponding maximum, minimum or interval values, color bar on the right side of each chart is the interval value for the shaded plot.

Figure 7b shows that the around-flow only occurs near several mountain peaks with the corresponding pairs of PV banners attached behind them. For the idealized topography (Fig. 7e), the real individual mountain peaks are smoothed to give a slight higher mountain profile as a whole (comparing Figs. 7c and 7f), but the over-flow structure is still the dominative flow pattern. Only one pair of PV banners forms at the position like the real topography case while the vertical structures of the PV for both cases are very similar. The perspective through PV makes the dynamic flow structure more clear. From Figs. 7c and 7f, we know that the main over-flow could be directly understood because there are no remarkable discontinuities of the potential temperature near the mountain surface which is the substance surface for dry air parcels to flow along.

Figures 11a and 11d give the distribution of low-level (on 950hPa, about 500m above surface) ageostrophic wind vector and PV respectively. There are obvious ageostrophic winds disturbed by the mountains and the value of $RoH$ for west-east flow (2.0) is greater than 0.5, a critical value for QG-balanced dynamics. Both of these imply that the QG-balanced dynamics can not be applied here. For Dabei-mountain-scale obstacle, the simulations put the flow dynamics to the flow-over and QG-unbalance regimes, which are consistent with the qualitative analysis of Section 2 (Fig. 4).

3.2 Taiwan Central Mountains

The Taiwan Central Mountains (hereafter TS) is a typical isolated mountain in China which has significant influence on the tropical weather systems, mid-latitudes ones from north and some locally-generated severe weather phenomena. Fig. 8a shows the real TS topography, and Fig. 8b gives the idealized one with width of 100km in west-east direction and length of 280km in south-north direction. According to the half-width of the mountain for west-east and north-south flow, which are 25km and 70km respectively, two kinds of idealized topographies in bell-shape can be gotten as Figs. 8c and 8d. The averaged maximum height of TS is about 3000m which gives an $H$ of 3.0.

The flow characteristics at 10 hour simulation are clear enough to perform the analysis. Fig. 9 shows the streamline and PV near the surface for typical mid-latitudes west and south winds passing the TS-like obstacle as Figs. 7b and 7e. Figs. 9a and 9d are the west and south upstream flow cases for the real TS, Figs. 9c and 9d are for the ideal TS-shaped terrain and that for bell-shape-idealized ones are illustrated in Figs. 9e and 9f respectively.

From Fig. 9 it is evident that, the over-flow structure is the dominative flow pattern both for the real and idealized TS. The upstream low-level flow is evidently deflected by the TS under Coriolis force. A stagnant point can be found where the flow are distorted most distinctly which denotes there is obvious flow-splitting occurring. On the leeside of the mountain, a couple of severe lee-vortexes clearly going with a positive and a negative PV centers form there due to the dominative flow around the mountain.

Figure 10 shows the corresponding vertical cross-section of Fig. 9 for potential temperature, PV and $U-W$ wind vector through the center of each mountain along the upstream flow direction. As shown in Fig. 10, the mountain flow has the obvious nonlinear patterns. The non-dimensional mountain height of TS is about 3.0,
Fig. 8  Taiwan-mountain-scale topography
(a) Real, (b) idealized, and dynamically approximated topography for (c) east-west and (d) north-south airflow.

Fig. 9  Streamline and potential vorticity near surface for typical mid-latitudes west (a,b,c) and south (d,e,f) winds passing the Taiwan-mountain-scale obstacle
(a,d) Real topography; (b,e) Idealized topography; (c,f) Dynamically approximated topography.
Fig. 10 The same as Fig. 9, but for vertical slice of potential temperature, potential vorticity and U-W wind vector through the center of the mountain along the flow direction.

Fig. 11 Low level ageostrophic wind vector and potential vorticity for typical mid-latitudes airflows passing the Dabie- and Taiwan-mountain-scale obstacles.

Dabie mountain case: (a) real and (d) idealized topography; Taiwan mountain case for west flow: (b) real and (e) dynamically approximated topography; Taiwan mountain case for south flow: (c) real and (f) dynamically approximated topography.
which is more than 1.0, therefore a nonlinear mountain flow will occur over TS same as the theoretical analysis in Section 2. Obviously the wave-breaking occurs over leeside and on the lee-slope of the mountain. As shown in Schneider et al. [20], the PV will be generated heavily where the potential temperature surface intersects with the mountain on the leeside. The low-level flow over mountain is apparently blocked upstream, and backflow also could be found at low-level downstream which is to compensate the divergence there due to upstream flow-splitting.

For the TS, the aspect ratio has a large variation from $A(\text{NS}/\text{WE})=2.8$ to $A(\text{WE}/\text{NS})=0.36$ (Table 1). Therefore, there is an evident difference between the real and idealized topography cases. More air parcels will flow over the mountain for large $A$ as shown in Figs. 9b ($A=2.8$) and 9c ($A=1.0$). The same results will be got if Figs. 9e and 9f are matched each other. This is identical to the analysis at the end of Section 2.

Figure 11 gives the distribution of low-level ageostrophic wind vector and PV for real and idealized TS with the different upstream flow. The ageostrophic winds are more prominent comparing with the DS case. The low-level flow in TS is deflected and blocked much more, and the PV is more greatly generated where the ageostrophic wind is also stronger. The value of $RoH$ for west-east upstream flow is about 12.0, and for north-south upstream flow is about 4.29, which are both greater than the critical value of 0.5 for QG-balanced dynamics. Therefore the typical mesoscale and higher mountain finally leads to a flow regime which is the flow-over and QG-unbalanced. The feature is also consistent with the qualitative analysis in Section 2.

4 CONCLUSIONS

In this paper, the major mountains in China are dynamically classified according to theoretical studies of flow over topography. For the horizontal scale of mountain, the scale analysis shows that the huge mountains in the west of China, such as TP, HD, YG, HT and NM, are in large scale; the second kinds of mountains with very large or small aspect ratios are in the large scale along the length direction, but in the mesoscale along the width direction, for examples, QL, DB, NL, TN, ZM, TH, DX and AT; while the rest, DB, TS, MJ, WN, XF, LX, WZ, TW and so on, are the mesoscale mountains in both directions.

There are three different flow regimes based on the nondimensional mountain height and Rossby number. One is the flow-over and QG-balanced, the second is the flow-over but not QG-balanced, the third regime is QG-unbalance but flow-around. The obvious difference between west-east and north-south upstream flow cases shows that the dynamic characteristics of flow are evidently influenced by the upstream flow direction.

For the case of west-east upstream flow, TP, QL, HT, YG, ZM, NL, NM and CB are about in the regime of QG-balance but flow-around. Most of the mesoscale mountains over the middle and lower reaches of Yangtse River and the south, such as WN, MJ, DB, XF and LX, and some other isolated mountains as TS and WZ are in the regime of flow-over and QG-unbalance. Mountains DB, TH and the mountains with prominent altitudes, TW, HD and AS locate in the QG-unbalanced and flow-around regime.

In the case of south-to-north upstream flow, mountains NM, DX and XX are QG-balanced and flow-over. Mountains TP, HD, AS, TN, QL, DB, YG, HT and TH are about in the regime of flow-around and QG-unbalance. Over the middle and lower reaches of Yangtse River and the south, most of the mountains have the same dynamic characters as the west-east flow case.

When the influence of $A$ included in a diagram of $A$-$RoH$ map, the flow-over and flow-around can be connected to the parameter $\varepsilon$. More airstream will flow around mountain when $\varepsilon$ is larger, while more will flow over when $\varepsilon$ is smaller.

The rationality of the regimes is also validated through detailed analysis of the flow over Dabie Mountains and Taiwan Central Mountains, which are simulated using a mesoscale numerical model with ideal atmospheric conditions. Results of the simulations are consistent with the qualitative regimes according to simple theoretical studies.

The classification in this paper will give a conceptual basis to understand the flow structure of dynamics of the major mountains in China. Moreover, it is also helpful to interpret the studies of theoretical researches
and numerical simulations on flow-topography interactions from mesoscale to large scale.

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REFERENCES