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Numerical experiments on the genesis of vortices over the Qinghai-Tibet plateau

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ABSTRACT

The formation of a vortex and shear line over the Qinghai-Tibet Plateau (QTP) was investigated with numerical experiments using the ECMWF grid point model. The case chosen occurred between 24 and 26 July, 1982, when the south-west monsoon invaded the QTP and a vortex developed.

The correct simulation of the vortex in the model shows that it is possible to predict the atmospheric circulation over the QTP and the consequent weather over China. When the simulation was rerun with a dry model (i.e., without the release of latent heat), it was found that only a weak vortex formed. This shows that the release of latent heat is an extremely important factor in the development of the vortex over the QTP, and confirms earlier diagnostic and synoptic studies.

The surface sensible heat fluxes, large near the northern and southern flanks of the QTP, appear to have a damping effect on the formation of the vortex; i.e., the vortex was greatly intensified in their absence. It was also found that the intensity of the vortex was dependent upon the height of the QTP: when the mountain height was reduced, the westerly trough invaded the QTP and no vortex formed at 500 mb; when it was increased, the south-west monsoon travelled along the southern boundary of the QTP and intensified the low-level jet south of the vortex area.

The results of a 48-h integration with a fine-mesh model (resolution 0.5° of latitude and longitude) showed an improvement in forecasting the location of the vortex with respect to the coarse-mesh model (1.875° of latitude and longitude). However, when compared with the coarse-mesh analysis, the intensity of the vortex was overpredicted. This may be due to mesoscale orographic forcing and exaggerated latent heating.

1. Introduction

The Qinghai-Tibet plateau (hereafter referred to as QTP), is the largest plateau in the world. Because of its size (the mean height almost reaches the 500 mb level) it influences the large scale atmospheric flow through both dynamic and thermal forcing. In this section we summarize some of the characteristics of the circulation over the QTP and the investigations that have been carried out. One of the main features of the circulation over Asia in winter is a quasi-stationary trough near 140° E, east of the QTP, which can be partly explained by the conservation of potential vorticity in the westerly flow over the mountains (Charney and Eliassen, 1949). However, the thermally induced circulation appears to be the most interesting effect of this large Plateau. It seems that the semi-permanent sub-tropical high pressure system in the upper troposphere over the QTP and the easterly jet-stream over southern Asia in summer are partly maintained by diabatic heating from the QTP.

In summer, when the south-west monsoon is sufficiently strong to travel over the Himalayas and invade the middle of the QTP, it not only causes a dynamic perturbation of the flow but also transports heat and moisture to the QTP, which appears to be a source of vortices (Lhasa Workshop, 1981—hereafter LW). From June to September the average surface sensible heat flux is about

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97 W m^{-2} and the mean temperature lapse rate is super-moist adiabatic below 400 mb; therefore the stratification is very similar to that found over the tropical oceans (Yeh and Y. X. Gao, 1979).

All the factors described above produce favourable conditions for convective development. An estimate of cloud amount from satellite pictures shows that over the QTP region there are 20 to 50 well-developed cumulonimbus per 10^5 km^2 per day—that is nearly 300 cumulonimbus over the QTP per day (Flohn, 1968). Such abundant convective activity, similar to that over tropical oceans, is accompanied by two kinds of α-mesoscale circulations (as defined by Orlansky (1975)): shear-lines and vortices. The shear-line is a line of confluence with cyclonic wind shear and a horizontal gradient of temperature (though small it is sufficient to create a warm belt). Some precipitation can be produced south of the shear-line when the south-west monsoon prevails. The vortex, with a scale of 500–1000 km and a vertical extent of 2–3 km (i.e., up to 300 mb), is located in the moist convergence zone and has a warm structure; above 300 mb there is an anticyclone. The organized cumulus convection in the vortex is thought to be an important mechanism for the vertical transport of vorticity, moisture and sensible heat which maintains the mean circulation. The vortex usually starts on the shear line and moves eastwards off the QTP, causing heavy precipitation over south-east China. In some cases it can move further east and influence the Japanese weather (Tao and Ding, 1981).

In this article, some numerical simulations with real data are presented in order to derive information about the possibility of numerically forecasting the circulation systems over the QTP. The ECMWF limited area model was used with the same version of the global model (Burridge and Haseler, 1977). It is in the σ coordinate system with 15 level in the vertical. The physics includes the large-scale condensation; a modified Kuo (1974) convective parameterization scheme; radiation and boundary layer physics (Tiedtke et. al., 1979). The data were taken from the global analysis which was initialized by using diabatic nonlinear normal mode initialization. The integration area extended from 0° N to 70° N and from 40° E to 160° E. The lateral boundary values were updated every time step (15 min) from a linear interpolation of the analyses taken at 12-h interval. The smoothed orographic representation used in the control experiment (Fig. 7a) was derived from the US Navy data set. A grid point filter was passed over grid points using a bi-dimensional Gaussian weighing function with a radius of influence 100 km.

Firstly, we tried to simulate the main features of shear lines and vortices with a coarse mesh version of the model (resolution 1.875° of latitude and longitude), even though no great detail should be expected for the representation of phenomena with a scale of 1000 km. Secondly, the thermal and dynamic effects of the QTP are examined by changing the model physics and the height of the Plateau. Finally, a fine-mesh version of the model (resolution 0.5° of latitude and longitude, i.e. ~37 km at 45° N) was used to investigate these phenomena in greater detail.

2. Description of the event of 24–26 July 1982 and the control experiment

Vortex generation over the QTP occurred during the period 24–26 July 1982 and subsequently a large amount of precipitation was recorded over the southern part of the QTP and south-west China when it moved eastward off the plateau. Fig. 1 shows the 500 mb wind field analyses obtained from the ECMWF objective analyses and corrected with observations and subjective analyses carried out in the Qinghai Meteorological Office, China (the 500 mb height is about 1 km above the mean height of the QTP, so it is considered as the gradient wind level over the QTP region).

At 12 GMT 24 July (Fig. 1a), the 500 mb flow was characterized by an active south-west (SW) monsoon over India, with the monsoon trough located near 25 °N, 60°–90° E, which is further north than normal. The SW monsoon travelled northwards and was intensified by the development of the subtropical high over Burma (24° N, 94° E). When the monsoon reached the southern slope of the QTP (Mt. Himalaya) the flow split with part flowing westward along the southern flank of the QTP, while the other part ascended the plateau, acquired anticyclonic vorticity and formed a westerly wind belt along 32° N. Since the monsoon extended to 35° N, the southern part of the QTP was occupied by moist and potentially unstable air; north of the QTP, a westerly trough located along 75° E approached the QTP. Normally the vortex

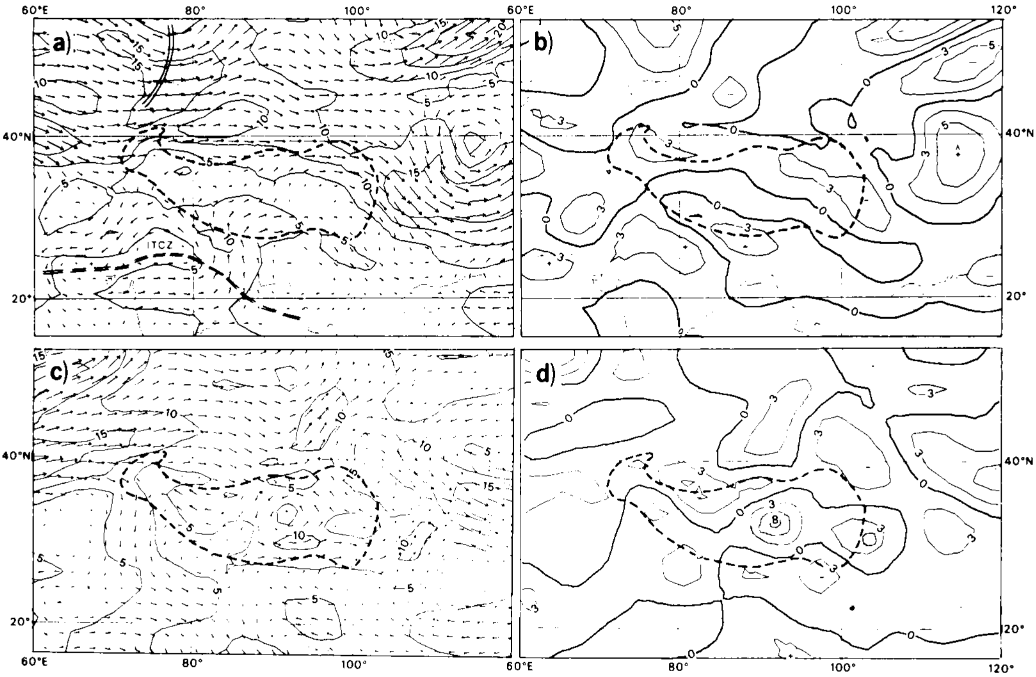

Fig. 1. Analysis of the 500 mb (a) wind (isotachs in m s^{-1}) and (b) vorticity (isopleths in 10^{-5} s^{-1}) for 12 GMT 24 July, 1982. (c) and (d) same as (a) and (b) but for 12 GMT 26 July, 1982. (The dashed line represents the 3000 m height contour.)

forms 8° of longitude downstream of the trough (LW, 1981) and it seems that the upper divergence ahead of the trough can have a triggering effect on the generation of the QTP vortex. Part of the westerlies travelled towards the QTP, climbed the northern slope of the mountain and merged with the SW monsoon: the confluence line was located near 35° N over the QTP. The feature of large-scale flow is typical for the vortex generated over the Plateau. In the associated vorticity field (Fig. 1b), two negative centres (-3×10^{-5} s^{-1}) were present on the northern and southern flanks of the Plateau. The former was associated with the anticyclonic shear south of the westerly jet and the latter with the SW monsoon current; slightly positive vorticity existed over the middle of the QTP.

24 h later (figure not shown), a shear line formed across the middle of the QTP from 75° E to 100° E. By 12 GMT 26 July (Fig. 1c), the vortices had developed over the shear line—the main one over the middle of the QTP (33° N, 92° E) and the other on its eastern flank (32° N, 100° E). These two vortices caused precipitation of 20 mm of water per day over the middle southern QTP. Three days later, when they moved eastward off the Plateau, torrential rain with a maximum of 160 mm day^{-1} was observed over the Sichuan province (105° E, 32° N) east of the QTP. South of the vortices, a low level jet (LLJ) was created with maximum wind over 10 m s^{-1}; it travelled eastwards and merged with the south-easterly current from the South China Sea. The westerlies north of the QTP travelled to the south and formed an anticyclonic vortex (37° N, 82° E) over the north-west QTP. It seems evident that these mesoscale systems were generated by the interaction of the westerlies and the monsoon, and the forcing of the Plateau. Two large areas of positive vorticity, associated with two vortices, were generated over the QTP during the 48 h period (Fig. 1d), one with the value of 8×10^{-5} s^{-1} (32° N, 92° E) and the other with 5×10^{-5} s^{-1} (31° N, 102° E).

Fig. 2a shows, in the vertical cross-section along 92° E, the structure of the QTP vortex. The axis of

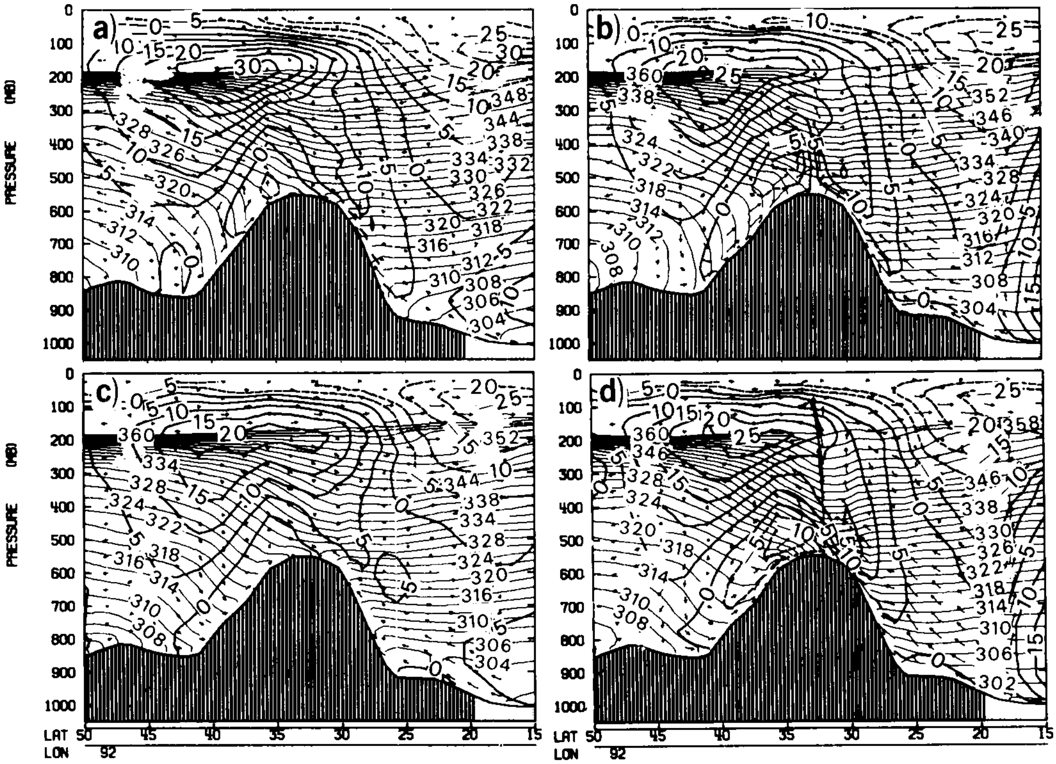

Fig. 2. Vertical cross-sections from (a) analysis at 12 GMT, 26 July, 1982 and from the 48 h forecast from (b) control, (c) dry and (d) no surface sensible heat flux experiments. Thin lines are isentropes every 2 K, thick and dashed isolines are lines of equal wind speed with direction perpendicular to the plane (every 5 m s^{-1}, positive into the plane), and arrows are proportional to the wind speed parallel to the plane. The bottom contour represents surface pressure.

the vortex defined by the zero isotach, with easterlies on the north and westerlies on the south, appears to be slightly tilted towards the north. The potential temperature, higher in the vortex centre than in the surroundings, shows the warm structure of the vortex which is different from that found in extra-tropical frontal cyclones. A westerly LLJ was present south of the vortex with wind speed 10 m s^{-1}. The vortex extended up to 400 mb, and above this at 200 mb a strong westerly subtropical jet stream to the north of the vortex and strong easterly flow on the south are visible. This anticyclonic circulation is the well known large scale subtropical high over the QTP which has the QTP vortex beneath it.

An experiment with the model containing all the physics and the smoothed orographic representation is used as the control experiment. Fig. 3a shows that the 48 h simulated 500 mb wind field has a well predicted shear line over the plateau (along 32° N from 85° E to 105° E). Due to the coarse resolution, the location of the vortex cannot be clearly identified from the wind field, but from the vorticity distribution (Fig. 3b) two large positive centres with values 8 × 10^{-5} s^{-1} are visible near 32° N, 92° E and 32° N, 100° E; these are almost identical to those analysed (Fig. 1d). The westerly LLJ south of the vortex is well simulated but the wind speed appears higher than the observed, especially on the east of the QTP. From the vertical cross-section of the 48 h forecast (Fig. 2b), the vortex appears to have a warm structure similar to that in the analysis (Fig. 2a). The axis of the vortex is nearly vertical and extends up to 400 mb; also both the LLJ south of the vortex and the low level easterlies to the north appear slightly stronger than in the analysis, which is consistent with the 500 mb wind and vorticity fields. Besides this, the ascent

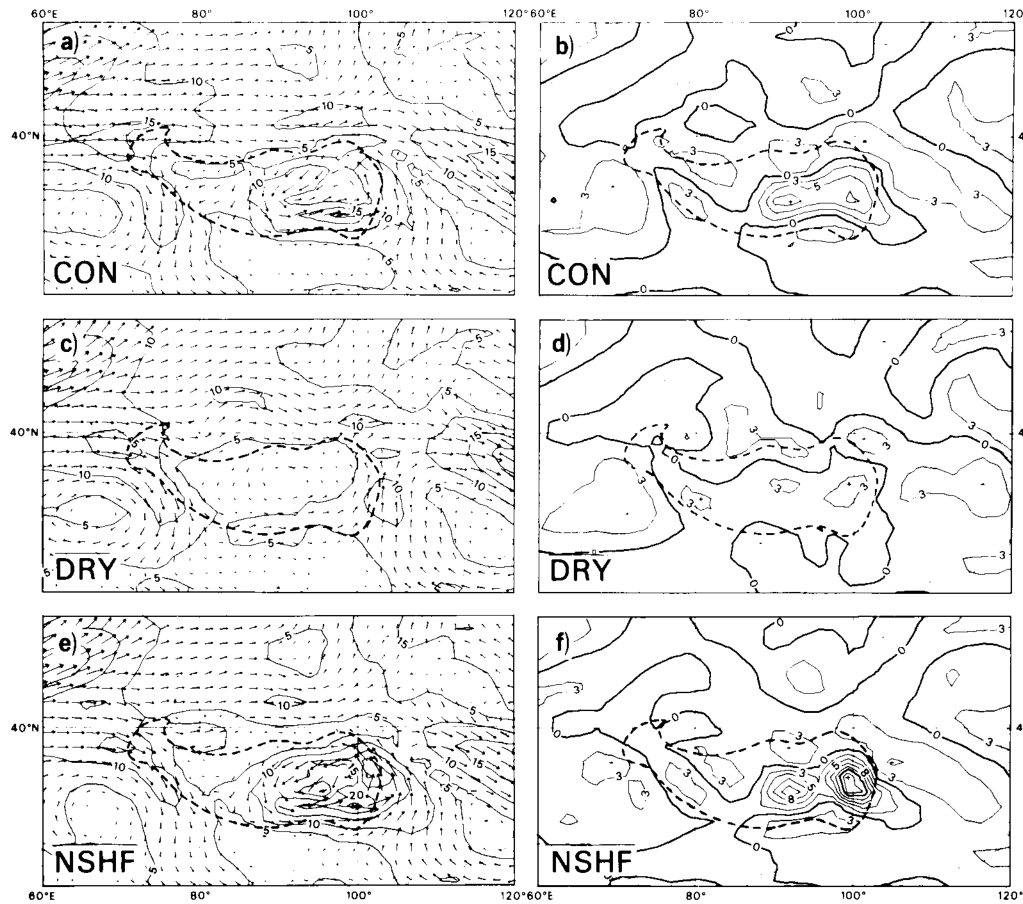

Fig. 3. 48-h forecast for the wind (left) and vorticity (right) at 500 mb from (a) and (b) control (c) and (d) dry, (e) and (f) no surface sensible heat flux experiments. (Units and isolines as in Fig. 1.) Verified with analysis; 12 GMT 26 July 1982 (Fig. 1c and 1d).

south of the vortex is also stronger in the control experiment than in the analysis. Despite these problems, the model captured the main features of the vortex generation over the QTP, and so it can be used to examine the various mechanisms which generated the vortex.

The accumulated precipitation between 24 h and 48 h of the control forecast was 20 mm in the vicinity of the vortex over the QTP (Fig. 4a). The belt of precipitation along the southern flank of the Plateau was caused by the monsoon flow being lifted by the orography in the Himalayan region. Unfortunately the observations of precipitation over this region and the Western Plateau (west of 90° E) were not available. However, over the eastern part of the Plateau, two centres of precipitation of 20 mm day were analysed (Fig. 4b), and a band of bright clouds, 300 km wide along 30° N from 85° E to 100° E, was observed from a satellite picture (figure not shown); this indicates that the simulated precipitation in the control experiment is reasonable.

To examine the influence of the convective parameterization scheme on the vortex generated over the plateau in the model the Arakawa–Schubert scheme (Arakawa and Schubert, 1974) was tested. The generated vortices were similar to that in the model with Kuo's scheme both in the location and intensity; no pronounced difference was found.

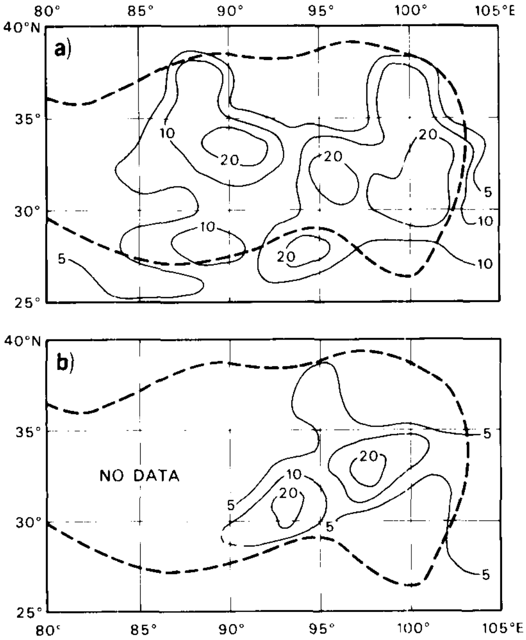

Fig. 4. (a) Simulated 24 h–48 h accumulated precipitation from the control experiment and (b) observed 24 h precipitation for 12 GMT 25–12 GMT 26 July, 1982. (Units in mm day^{-1}.) There is no data west of 90° E.

3. Thermal forcing over the Qinghai-Tibet plateau in the vortex generation

Two types of thermal forcing seem important for vortex generation over the QTP: latent heat release due to large scale condensation and convection, and surface sensible heat flux. To investigate these processes two experiments were performed: a 'dry' experiment in which the release of latent heat was excluded in the model, and another experiment without surface fluxes of sensible heat.

3.1. The effect of the latent heat release

Fig. 3c shows the 48 h simulated wind field at 500 mb in the dry model. The main features are quite different from those in the control experiment (Fig. 3a). There is a cyclonic circulation over the QTP, but the wind speed is below 5 m s^{-1}; also the SW monsoon current over the southern QTP only reaches 5 m s^{-1} and the LLJ is nearly absent. The associated vorticity field over the plateau (Fig. 3d) is positive but the values, with maximum 3×10^{-5} s^{-1}, are less than half those in the control experiment, with maximum 8×10^{-5} s^{-1} (Fig. 3b). Another difference is that in the dry experiment the positive vorticity occupies quite a large area instead of being concentrated in a narrow band. The vertical cross-section along 92° E for the dry experiment is shown in Fig. 2c; the corresponding analysis and control are given in Figs. 2a and 2b. Clearly the dry experiment has a weaker cyclonic circulation below 500 mb than the others. In the upper troposphere, both the subtropical westerly jet north of the plateau and the southern Asian easterly jet are weaker.

Early synoptic and diagnostic studies about the QTP vortex suggested that its development is due to the latent heat release (Yeh and Y. X. Gao, 1979). From our experiments, it can be inferred that the mechanical forcing by the QTP and baroclinic processes trigger the vortex. That is, in the dry simulation, only a weak vortex occurred. The concentration of the positive vorticity is mainly due to the dynamic response of the released latent heat. However, it must be noted that the vortex appears slightly more intense in the control simulation than in the analysis, which suggests that a more appropriate parameterization of the release of latent heat may be necessary in order to improve our ability to forecast this phenomenon.

3.2. Effect of the surface sensible heat forcing

Fig. 5a gives the distribution of the 48 h mean surface sensible heat flux in the control experiment; clearly the sensible heat flux is not uniform over the Plateau. Two belts of large values appear; over the southern boundary (along Mt. Himalaya 32° N, 80°–90° E), with a maximum value 114 W m^{-2}, and the other over the northern boundary (Mt. Altyn 38° N, 90° E and M. Chilien 37° N, 100° E). Over the middle of the QTP, the mean heat flux is still positive but small. Thus in the model the flux of sensible heat into the atmosphere occurs along the northern and southern boundaries rather than over the whole plateau.

During the period of the meteorological experiments over the QTP, July 1979, many more data were obtained in the western region of the plateau. Chen and Weng (1984) studied in detail the sensible heat processes by using these data. They showed that two large values of SH are positioned, one over Mt. Himalaya (south-west flank of the QTP) with a maximum value of 112 W

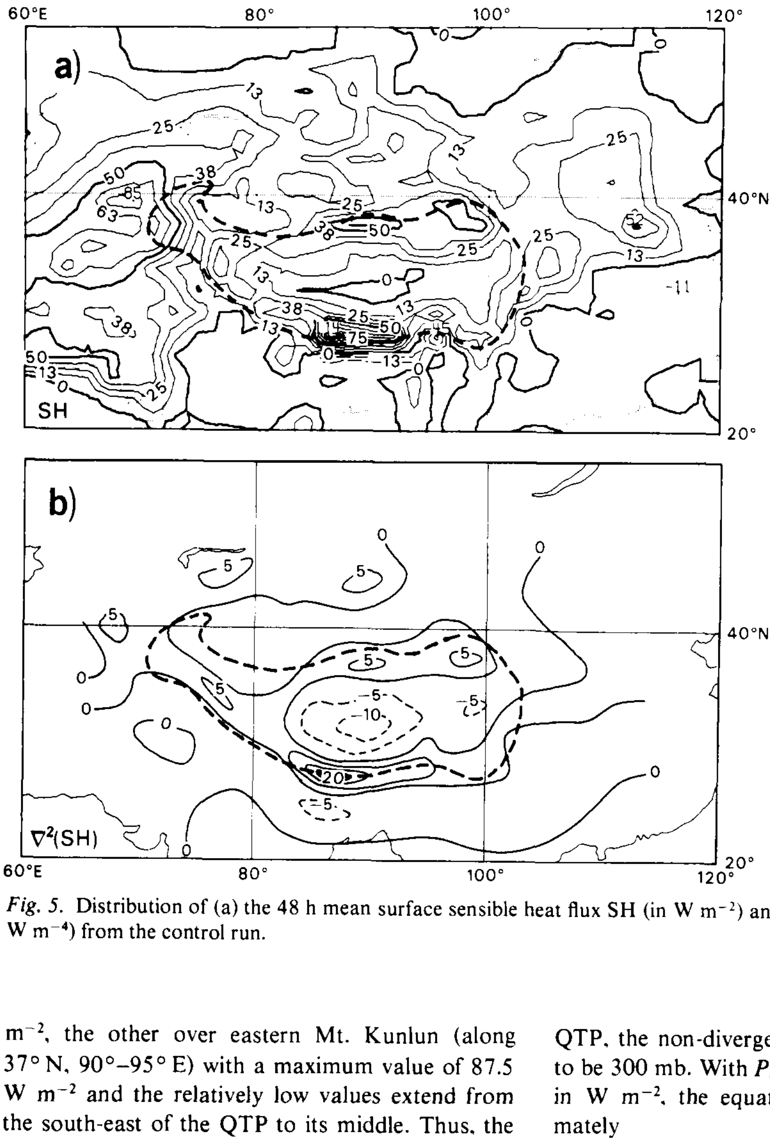

Fig. 5. Distribution of (a) the 48 h mean surface sensible heat flux SH (in W m^{-2}) and (b) smoothed $-\nabla^2$SH (in 10^{-10} W m^{-4}) from the control run.

m^{-2}, the other over eastern Mt. Kunlun (along 37° N, 90°–95° E) with a maximum value of 87.5 W m^{-2} and the relatively low values extend from the south-east of the QTP to its middle. Thus, the distribution of surface sensible heat flux in the control experiment seems reasonable.

From the quasi-geostrophic theory, the effect of diabatic heating on the development of vorticity ζ_0 near the ground can be described by (Petterssen, 1956):

$$\frac{\partial \zeta_0}{\partial t} = \frac{-Rg}{C_p f(P_0 - P)} \int_P^{P_0} \nabla^2(\mathrm{SH}) \frac{dp}{p}$$

where P_0 is the surface pressure over the plateau; P is the pressure value of the level of non-divergence and SH is the surface sensible heat flux. Over the QTP, the non-divergence level P may be assumed to be 300 mb. With $P_0 = 500$ mb and SH expressed in W m^{-2}, the equation can be written approximately

$$\frac{\partial \zeta_0}{\partial t} = -0.48\ \nabla^2(\mathrm{SH}),$$

where the vorticity tendency is expressed in s^{-2} and ∇^2(SH) in W m^{-4}; i.e., a value of $\nabla^2(\mathrm{SH}) = -2.4 \times 10^{-10}$ W m^{-4} gives a vorticity tendency of 10^{-5} s^{-1} day. The equation shows that the genesis of the surface vorticity is proportional to $-\nabla^2$(SH), i.e. a cooling [heating] relative to the environment yields $-\nabla^2(\mathrm{SH}) < 0 [-\nabla^2(\mathrm{SH}) > 0]$ causing the damping [amplifying] of the vorticity system. In order to obtain a synoptic feature of ∇^2SH, a nine grid-point filter was first used for the SH field. Then ∇^2SH was calculated, at last, ∇^2SH was again smoothed with the same filter for SH. Fig. 5b shows the distribution of smoothed ∇^2(SH) in the model—it is negative over the middle of the QTP, suggesting that the surface sensible flux has a damping effect on the vortex over the central plateau.

Fig. 3e shows the 500 mb wind field from the 48 h forecast without surface sensible heat fluxes. The QTP vortex is well predicted but it is more intense than in the analysis and control (Fig. 1c and Fig. 3a). Also the LLJ south of the vortex increases and attains a maximum speed of about 20 m s^{-1}. The associated vorticity field (Fig. 3f) shows that the two positive centres of vorticity increases to 10^{-4} s^{-1} and 1.5×10^{-4} s^{-1} which are about twice the values found in the control. From the vertical cross-section (Fig. 2d) the enhancement of the vortex can be clearly seen—both the westerlies south of the vortex and the easterlies to the north have increased. This shows that the surface sensible heat flux has a damping effect to the vortex development.

In a numerical model, the differential thermal forcings are not independent. Taking out one heating source from the model modifies the others. For instance if the sensible heat flux is excluded in the model, the latent heat is affected and it appears possible that the difference between results of experiments with and without surface sensible heat flux may be partly due to the different latent heat release; this in turn is closely related to the precipitation. Therefore an indication of the effects of the latent heat release can be shown by the precipitation.

Fig. 6 shows the difference between the forecast total precipitation from the experiment without surface sensible heat flux and the control for the period between T + 24 to T + 48. Positive values mean that the precipitation in the experiment without sensible heat is larger (more latent heat release) than that in the control. The location of two simulated vorticity centres are marked as C1 and C2 in the figure. Over the central plateau, where the main vortex C1 is located, the difference in precipitation is quite small, about 5 mm day^{-1}.

Therefore, we can deduce that the strengthening of this vortex in the experiment without sensible heat flux is not related to the change of latent heat release, but to the effect described previously. A belt of positive values of precipitation difference

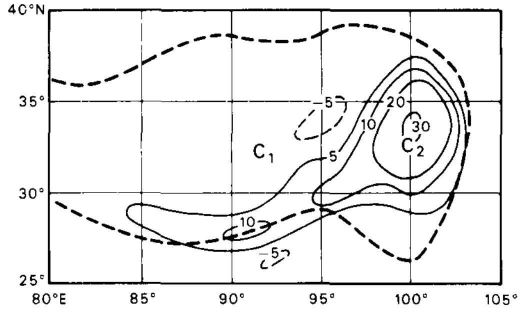

Fig. 6. Difference of predicted precipitation for 24 h–48 h between the experiment with no sensible heat flux and the control. (Units in mm day^{-1}.)

occurs along the southern flank of the QTP, close to the LLJ south of vortex. Earlier numerical experiments showed that the released latent heat can enhance the LLJ over the Asian monsoon area (Chen and Dell'Osso, 1984). Therefore it can be inferred that the stronger LLJ simulated in the experiment without sensible heat (Fig. 3c) is partly due to this extra latent heat release. Another positive value of precipitation difference exceeding 30 mm day^{-1} occurs over eastern plateau close to the vorticity maximum C2. Thus, unlike C1, the intensity of this vorticity centre is partly due to the extra latent heating.

In previous synoptic studies, it has been suggested that the sensible heat gives a positive contribution to the genesis of the vortex (LW, 1981). However this was not found in our numerical experiments; on the contrary, the sensible heat appears to have a damping effect. Further detailed diagnostic and numerical studies to investigate the role of the sensible heat forcing in the vortex development are needed in order to confirm this results.

4. Dynamic forcing by the Qinghai-Tibet plateau

Two experiments were carried out to examine the dynamical forcing exerted by the QTP: one with the height of the mountains reduced and the other with them increased. In the first case the smoothed topographic height in a grid-square (h) is replaced by half this value. In the second case h is increased by a value which is a proportion (e) of the standard

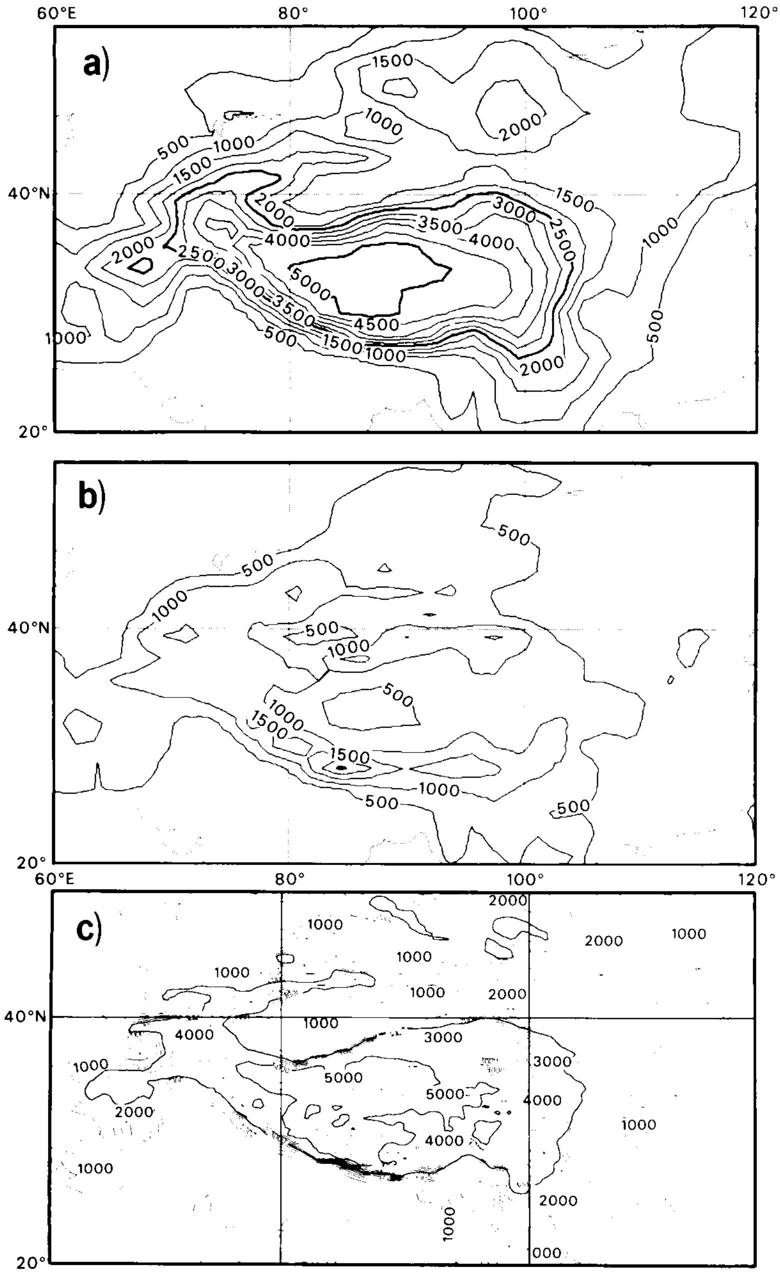

Fig. 7. (a) Height of the smoothed QTP. (b) Difference in height between enveloped and smoothed QTP. (c) Orographic representation at resolution 0.46875° latitude/longitude.

deviation (σ) of the sub-grid scale orography in the same grid square; the orographic height is then given by $h + e\sigma$. This type of orographic representation is referred to as an envelope orography (Wallace et al., 1983). The difference of the height envelope orography with $e = \sqrt{2}$ and smoothed orography is shown in Fig. 7b. The envelope orography can be significantly higher

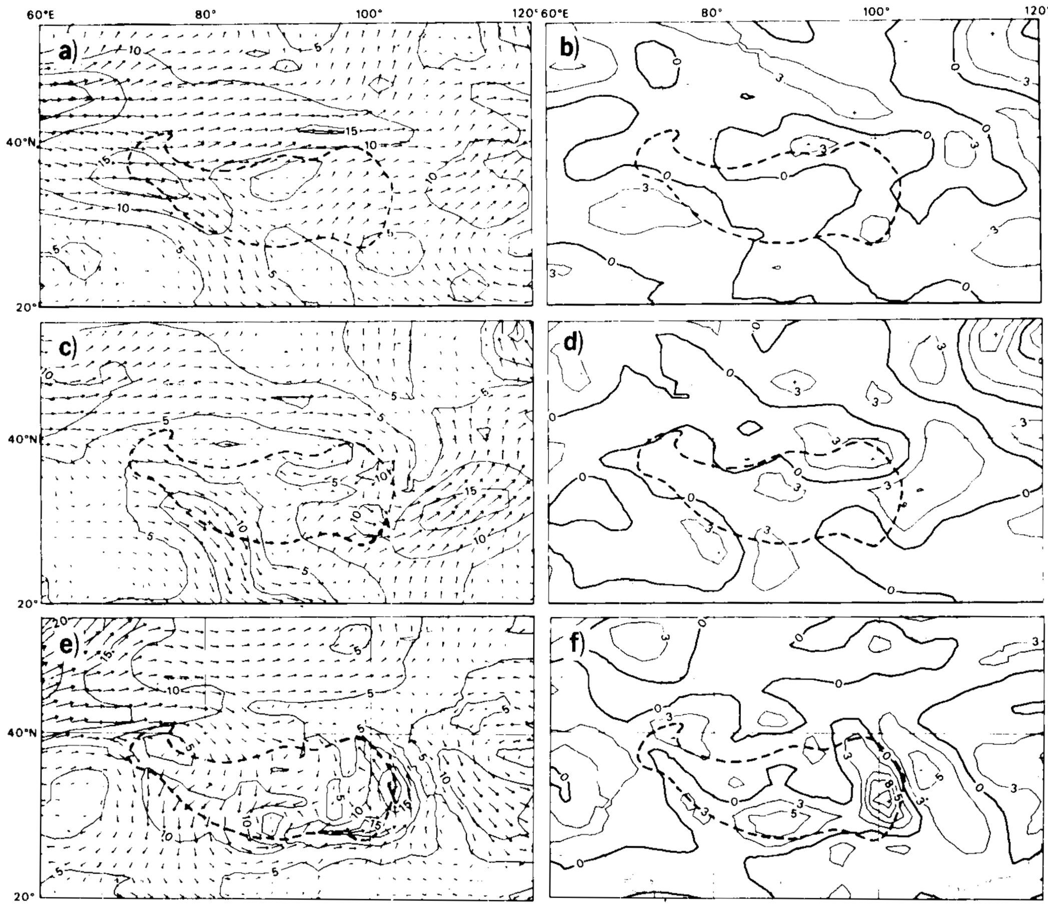

Fig. 8. 48-h forecasts of (a) 500 mb wind and (b) associated vorticity for the experiment with reduced QTP height; (c) and (d) as (a) and (b) but for 700 mb; (e) and (f) as (a) and (b) but for the envelope orography experiment. (Units as in Fig. 1.)

than the smoothed type, especially on the northern and southern flanks of the QTP, where σ is large.

The model was initialized by changing the orographic height steadily in the first 12 h of integration to adjust the fields to the new orography.

4.1. The experiment with reduced orography

Fig. 8a shows the 48-h forecast of the 500 mb wind field when the reduced QTP is used. The main features of the circulation over the Plateau are very different from those in the control (see Fig. 3a). The reduction in the orographic height allows the westerlies, which are initially north of the QTP, to spread southwards and travel over the plateau. Also the westerlies upstream of the Plateau moved southwards with the maximum wind in excess of 15 m s^{-1} now being located at 37° N, 70° E instead of 3° further north. Over the middle of the plateau a north–south orientated trough forms along 90° E, whereas in the control experiment and the verifying analysis there is a vortex. The other main effects of the reduced orography are found to the south of the Plateau. Here the monsoon current incorrectly retrogresses and merges with the westerlies, and the 500 mb LLJ along the southern boundary of the QTP found in the analysis and the control run (Figs. 1c and 3a) is absent. Fig. 8b

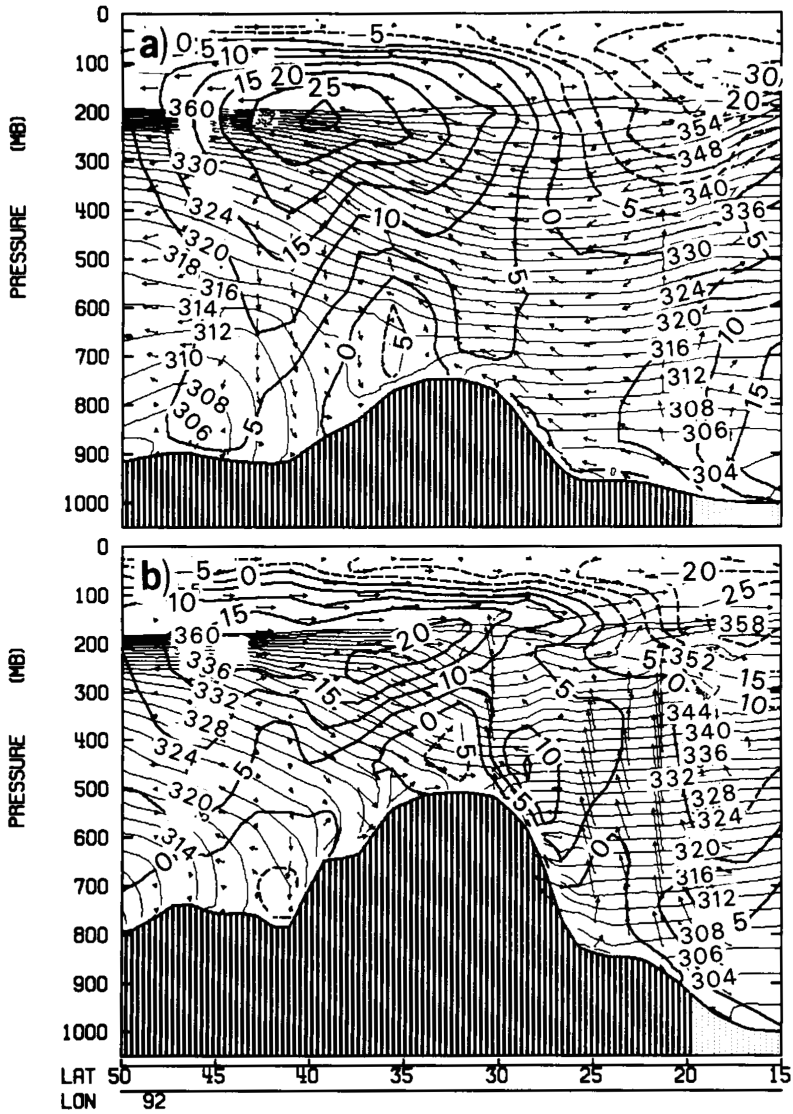

Fig. 9. Vertical cross-sections from the 48 h forecast from (a) reduced orography and (b) envelope orography experiments. (Units as in Fig. 2.) Verified with Fig. 2a and 2b.

shows the 500 mb vorticity field which correspond to the wind field given in Fig. 8a. Comparison of the vorticity field with that in the control (Fig. 3b) shows that there is no positive concentration of vorticity over the Plateau: this suggests that the dynamical forcing cannot extend up to 500 mb when the height of the plateau is reduced. At 700 mb (Fig. 8c) a relatively weak vortex occurs over the middle of the plateau near 34° N, 88° E. However, compared with the control it is too small and does not extend far enough to the east. The associated vorticity field (Fig. 8d) also appears rather weak and has a similar intensity to the 500 mb vorticity field from the dry run (Fig. 3d).

Comparison of the cross-sections along 92° E for this experiment (Fig. 9a) and the control (Fig. 2b) shows that for the reduced orography the QTP vortex has a considerably smaller vertical extent (confined below 600 mb) and is much weaker.

As mentioned in Section 3, the release of latent heat is important for the development of the QTP vortex provided there is a favourable background circulation brought about by the SW monsoon and the westerlies interacting over the QTP. As the height of the Plateau is reduced, the blocking effect is also reduced. When the height of the orography decreases to about 2 km, it seems more efficient for the westerlies to flow over the mountain rather than being deflected (Wu, 1983). Consequently in these circumstances the 500 mb westerlies spread southwards and occupy the whole of the plateau; this causes the SW monsoon to be limited to south of 30° N and below 500 mb. As a result of these changes the interaction between these two currents does not occur at 500 mb and so the vortex does not develop at this level. However at 700 mb where the blocking effect is still pronounced, the currents interact to produce a vortex (though it is rather weak). These effects are illustrated in Fig. 9a—the weak vortex only extends up to 600 mb, the westerlies south of the vortex are rather weak (speeds only up to 5 m s^{-1}) and there is no clear LLJ as in the analysis. Therefore it appears that dynamical forcing is also important in the QTP vortex generation.

To confirm this conclusion, the model was run with the QTP omitted. It was found that the initial 500 mb trough along 70° E (Fig. 1a) develops at 80° E after 48 h, and the trough is more intense than in the reduced QTP experiment. Also the westerlies now extend to 25° N with the SW monsoon limited to the region south of this (figure not shown). In this experiment the vortex did not form in the lower troposphere and so we can infer that it is necessary for the height of the QTP to exceed 3 km in order for the model to simulate the vortex.

4.2. The experiment with the envelope orography

From Fig. 7b, it can be seen that the use of the envelope orography increases the height of the model QTP mainly on its northern and southern slopes. For example, the average height of Mt. Himalaya increases by up to 1500 m, while in the middle of the plateau the increase is only 500 m. On the northern boundary Mt. Altyn and Mt. Chilien increase by 1000 m as does Mt. Tain which is north of the plateau (located around 42° N from 78° E to 90° E). Consequently the northern slope of the Plateau is not increased as much as that in the south. On the other hand, the area of the QTP is unrealistically expanded and it is found that in many places the envelope height is greater than the actual height. For example at 40° N, 100° E the actual height is 1480 m whereas the average and envelope orographies have values of about 2000 m and 3000 m, respectively.

Using the envelope orography, we find that the deflection effect is much more pronounced, especially on the southern slope of the QTP. This can be seen in Fig. 8e which shows the simulated 500 mb wind field after 48 h. The SW monsoon from India travels eastward along the south periphery of the plateau and then turns northwards at 103° E around the eastern boundary. During the forecast, a LLJ is created and accelerates downstream to reach 20 m s^{-1} at 103° E—this is stronger than in both the control and the analysis. The blocking effect of the QTP is not so pronounced for the westerlies as compared to the monsoon current for two reasons. Firstly the northern slope is increased less than the southern one, and secondly the westerlies form a deep flow whereas the monsoon current is shallow. Consequently the westerlies can still flow over the Plateau.

Another feature of the experiment with the envelope orography is that the confluence zone moves southwards causing the vortices (located at 29° N, 87° E and 31° N, 100° E) to be further south than they should be. The eastern vortex appears to be stronger than in the control and this is partly due to the strengthening of the LLJ. This can also be seen in the 500 mb vorticity field shown in Fig. 8f.

From the vertical cross-section along 92° E (Fig. 9b), it is clear that with the envelope orography a much more well defined LLJ appears on the southern flank of the QTP with the core about 1 km above the surface. This should be compared with the LLJ in the control and reduced orography experiments (Fig. 2b and Fig. 9a). These experiments suggest that the formation of the LLJ is mainly due to orographic forcing. Therefore there are similarities with the East-African LLJ (Bannon, 1982) in the cross-equatorial flow which is forced by the east African Highlands. However, in the case considered here the LLJ is forced by the QTP acting on the SW monsoon current.

Previous studies about the QTP vortex have emphasized the thermal forcing by the plateau (LW, 1981). However, the results from these experiments indicate that mechanical forcing is as important as thermal forcing. It appears that the mechanical forcing by the Plateau creates a favourable background in which the thermal forcing mainly due to the release of latent heat, can take place.

5. Results of a fine-mesh model experiment

As discussed earlier, the coarse-mesh model can capture the main features of the QTP vortex genesis, but it appears to be unable to simulate the circulation with the same detail found in the analysis. Therefore it is worth examining the effect of increasing the horizontal resolution on the simulation of the circulation over the QTP.

A 48-h forecast experiment with resolution higher than in the previous experiment (i.e., one quarter of 1.875° in latitude and longitude, ~37 km at 45°) was carried out with the ECMWF limited area model. The initial data were interpolated directly from the coarse-mesh analysis to the high-resolution grid. The more detailed and better defined high-resolution orography with more realistic height and steepness is expected to give a better description of the circulation over the plateau (Dell'Osso, 1984). The high-resolution orography of Fig. 7c is an average of the US Navy data set over grid squares with an area one sixteenth of the coarse grid. As a consequence the average height of the plateau increases by 500 m and the slope of its southern flank becomes 1/50, about twice that in the coarse-mesh model. Furthermore, the mountain is more confined to its actual position instead of being spread over a larger area as in the coarse resolution.

Fig. 10a shows the wind field at 500 mb for the 48 h forecast. To verify the results, a high-resolution analysis is needed, but due to the sparse

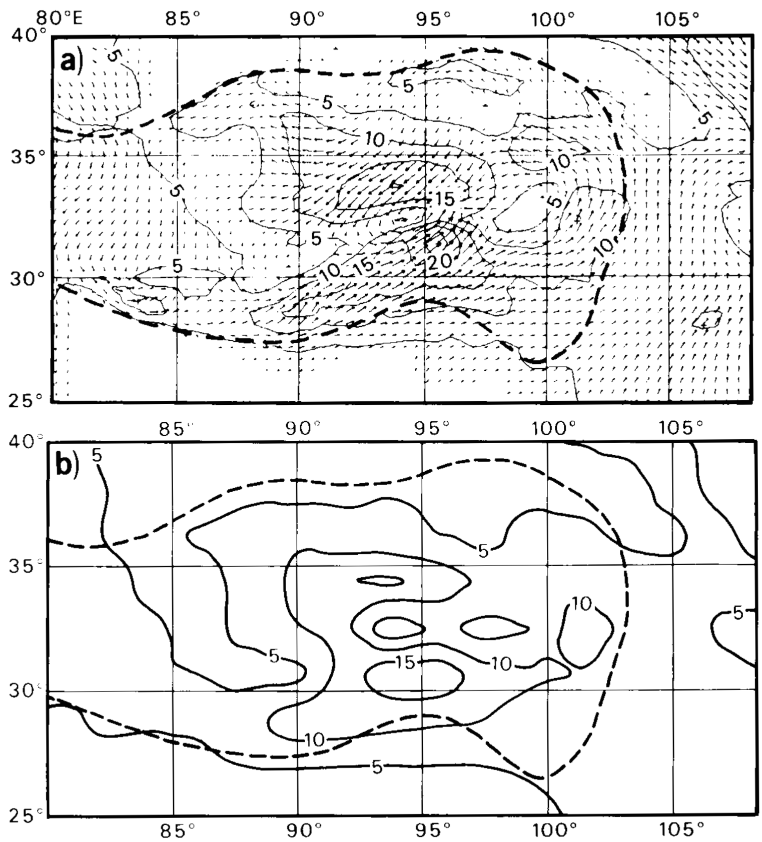

Fig. 10. 48-h forecast for the (a) 500 mb wind from the high resolution experiment; (b) average of (a) over grid squares with 4 × 4 points. (Isotachs in m s^{-1} and arrow length proportional to wind speed.)

data over the Plateau, such an analysis is not available. Therefore, we are obliged to compare the fine-mesh forecast with the coarse-mesh analysis (Fig. 1c). The model produces the interaction between the SW monsoon (that travels over Mt. Himalya) and the northerly wind (from Xin Jiang region) at the middle of the plateau, where the vortices formed. The two vortices are well simulated; the main one at 32.5° N, 94° E and the eastern one at 33° N, 99° E are in the same location as those in the analysis; in the coarse-mesh model no cyclonic circulation centre can be seen, and the vortex can only be identified by the positive vorticity centre. A LLJ streak south of the vortices attains a velocity of more than 25 m s^{-1}. With its horizontal scale of 200 km, it appears as a mesoscale structure; this structure is quite clear in the analysis, although the wind velocity is weaker than predicted. Unfortunately, the lack of data over the plateau does not permit a detailed discussion of the results; nevertheless, on the whole, the results do show an improvement in the forecasts of the QTP vortex when the model's resolution is increased.

A possible error in the high-resolution forecast appears to be the prediction of vortices stronger than those in the analysis: the associated relative vorticity is up to 30×10^{-5} s^{-1}, while the analysed value was 8×10^{-5} s^{-1}. Also in another high resolution experiment (Chen and Dell'Osso, 1984) a vortex and sheared-line appear over-intensified over the Plateau. The predicted total precipitation for the 24 h between the 24- and 48-h forecast increases to 80 mm day^{-1}, associated with the main vortex along 32.5° N, 94° E, which is about two to three times larger than that in the coarse-mesh forecast and in the analysis. The exaggerated latent heat release in the model may be one of the reason which cause the vortices to overdevelop. Obviously, the latent heat release is partly dependent on the orographic forcing, thus how to treat the large scale orography in order to improve the circulation forecast over the QTP in a fine-mesh model appears to be an important problem which needs further study.

However, when comparing data at various resolutions, one must consider what they represent. In the analysis, the sparse data over the plateau are (in some way) averaged over grid squares of about 200×200 km^2; similarly, in the coarse-mesh forecast, the results represent the average values over a grid of that size. The results of the fine-mesh forecast are values that represent the average over much smaller squares of 50×50 km^2. At this point it is worth considering an average of the fine-mesh results over boxes of sixteen grid points. Fig. 10b shows that the effect of averaging is a reduction in the strength of the wind everywhere: the maximum value of more than 25 m s^{-1} is reduced to less than 20 m s^{-1}. Now the strength of the wind is not so different from the analysis. Therefore, while a complete evaluation of the detail of the fine-mesh experiment is left to when a denser data coverage permits a more reliable comparison, it is likely that the use of a fine-mesh model will simulate vortices and shear lines which a coarse-mesh forecast can only suggest.

6. Concluding remarks

During the summer the QTP acts as a source of vortices, and many α-mesoscale systems which originate over the plateau give rise to rain-bearing synoptic scale systems when they move out over eastern China. In this report, a numerical study of the genesis of vortices and a shear line over the plateau is carried out in order to obtain a better understanding of the physical mechanism of the genesis of vortices over the QTP as well as to show the potential of the numerical weather prediction over this region.

The ECMWF grid point model, even with a coarse resolution (1.875° of latitude and longitude), is capable of capturing the main features of the vortex/shear line genesis over the QTP up to 48 h ahead. This shows that the numerical prediction over the Plateau is possible.

A series of experiments were performed to investigate the effect of thermal and dynamical forcing in the vortex genesis. The latent heat release is the main thermal forcing causing the development of the vortex over the plateau. If the latent heat is excluded from the model, the vortex becomes weak and no subsequent development takes place. The energy supply for the vortex is due to the release of latent heat just as in tropical cyclones, although the process is weaker.

The surface sensible heating is mainly produced over the northern and southern flanks of the QTP during the vortex generation, and from the model results it seems that the relatively small fluxes of sensible heat over the middle of the QTP have a damping effect on the vortex. Previous synoptic studies inferred that the sensible heating gives a positive contribution to the vortex, but no direct proof was given (LW, 1981). Due to difficulties in the sensible heat calculation this problem is not yet solved; further investigation of the impact of the sensible heat on the genesis of these vortices should be carried out with more diagnostic studies and numerical experiments.

The dynamic forcing of the QTP provides a favourable circulation background for the latent heat release to take place. If the height of the QTP is reduced to below 2.5 km, only a weak cyclonic circulation develops at 700 mb, and this circulation does not extend up to 500 mb although the latent heat is included in the model. When using the mean orographic representation the maximum height of the Plateau reaches almost 5000 m and the vortex is reproduced, although not as well defined as in the analysis. However, when representing the orography in a model it is important to reproduce the correct shape. If a $\sqrt{2}$ *envelope* orography is used the height of the mountain increases in proportion to its standard deviation from the mean. Therefore it increases in a non-uniform way and the blocking effect of the QTP on the SW monsoon is enhanced.

An experiment with a fine-mesh model shows that the horizontal resolution plays an important role in forecasting the vortices circulation centres with great detail. The mean orography in this case preserves not only the height and shape of the QTP, but also its geographical position; the plateau is not spread out as in the previous experiment but is confined to its actual boundaries. The simulated vortices are well defined and correctly located although they appear to be too strong, but lack of data prevents a verification of such a detailed forecast.

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