A STUDY OF NUMERICAL MODELLING ON THE DEVELOPMENT OF DEPRESSIONS IN THE SOUTH CHINA SEA

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ABSTRACT

The comparison analyses between two tropical depressions in the South China Sea are completed by numerical experiments with a limited area model developed in Guangzhou Institute of Tropical and Oceanic Meteorology. One of the depressions develops and finally becomes a typhoon within 24 hours of the analyzing period (defined as DVD hereafter), and the other not (defined as UNDVD). The analyses show that their initial structures of temperature, humidity, pressure, wind and stability are obviously different from each other. There are a very deep wet layer and a clear warm–cored structure in the mid–lower troposphere in the depression area in the DVD case, but with the warm core in the upper rather than lower troposphere and a very shallow wet layer in the lower troposphere in the depression area in the UNDVD case. The developing and non–developing processes are successfully simulated by the model, showing that the CISK mechanism plays the most important role in the development of SCSDs (Tropical Depressions in the South China Sea). Several numerical experiments show that the structures of humidity and temperature in the depression area have important effect on the development of SCSDs. It is favourable to the development of SCSDs when a very deep wet layer exists in the mid–lower troposphere or a warm–cored structure exists in the mid–lower troposphere instead of in upper troposphere, and conversely, it is unfavourable to the development of SCSDs when the wet layer is very shallow in the lower troposphere or the warm–cored structure is in the upper troposphere rather than in mid–lower troposphere. The structures of stability for each case are also analysed, which shows evident differences between the two cases, with a deeper instability layer in the DVD case and a shallower one in the UNDVD case. Finally, the sensitivity of the development of the SCSDs to the vertical structures of humidity and temperature in the depression area is discussed.

Key words: numerical modelling, deppressions in the South China Sea, stability, structures of temperature and humidity

I. INTRODUCTION

Tropical depressions occur frequently in South China Sea (about 10 every year), some of them develop into typhoons and some not. They have intensive impacts on the weather in coastal South China, and closely related to the weather prediction in this area. So, it is necessary to study the processes and mechanisms governing the development of the SCSDs. Zhang (1978), McBride and Raymond (1981) and Liang and Zhang (1989) made comparison between developing and non–developing tropical cyclones by means of synoptic analysis or composition, and Liu and Liang (1988) diagnosed the physical factors at four developing stages of the life cycle for the SCSD. Some dynamical and thermodynamical features have been revealed by them, and the importance of the CISK and the existence of differences in the structures of temperature and humidity between developing and non–developing SCSDs have also been emphasized.

However, no numerical modelling study has been found in this area, but it is very necessary. With the numerical modelling, we can check the role of a single factor (e.g., its value or distribution) or process (e.g., convective heating) according to our purposes. In addition, numerical simulation gives a continuous time series of a process, with which we can do more detailed analysis. This takes advantage of that in synoptic analysis, which is based on rather discrete data. Therefore, we try to study the process and mechanisms of the development of SCSDs by means of numerical experiments.

II. DATA AND MODEL

The 7–level grid data ($2.5^\circ \times 2.5^\circ$) analyzed by ECMWF are used to get the model grid values through linear spatial interpolation. The 6–level limited area primitive equation model (commonly known as "TL6") developed in Guangzhou Institute of Tropical and Oceanic Meteorology in 1987 is used, which consists of two parts, one is the large mesh model which uses fixed lateral boundary conditions, with grid length of about 3° latitudes and extent of 50°E to 170°E and 30°S to 45°N, and the other the fine mesh model which gets the lateral conditions from the large mesh model by one way nesting, with grid length of about 1.5° latitudes and extent of about 3500km in the side length. Most of the basic physical processes are included in the model, and a detailed description and the corresponding prediction tests of the model can be seen in Xue et al.(1988).

III. CASES AND SYNOPTIC ANALYSIS

1. *Brief Description of the Processes*

Two tropical cyclone processes in the South China Sea are selected at random, between which one develops and becomes a typhoon and the other not.

The first process (Aug. 2—10, 1981) originates in the disturbances of summer monsoon flow in South China Sea(13°N, 112°E), moves slowly northeastwards and strengthens, then

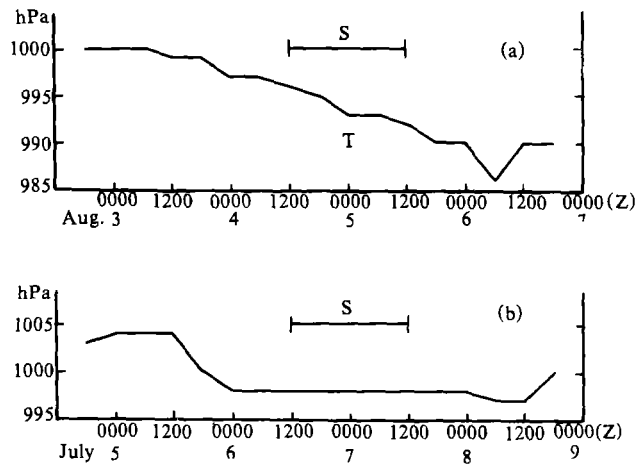

Fig. 1. Time variation of sea level pressure in the depression center. The bar under "s" denotes the period for study, "T" shows the time it develops into a typhoon. (a) the case for Aug.3—7, 1981; (b) the case for July 5—9, 1985.

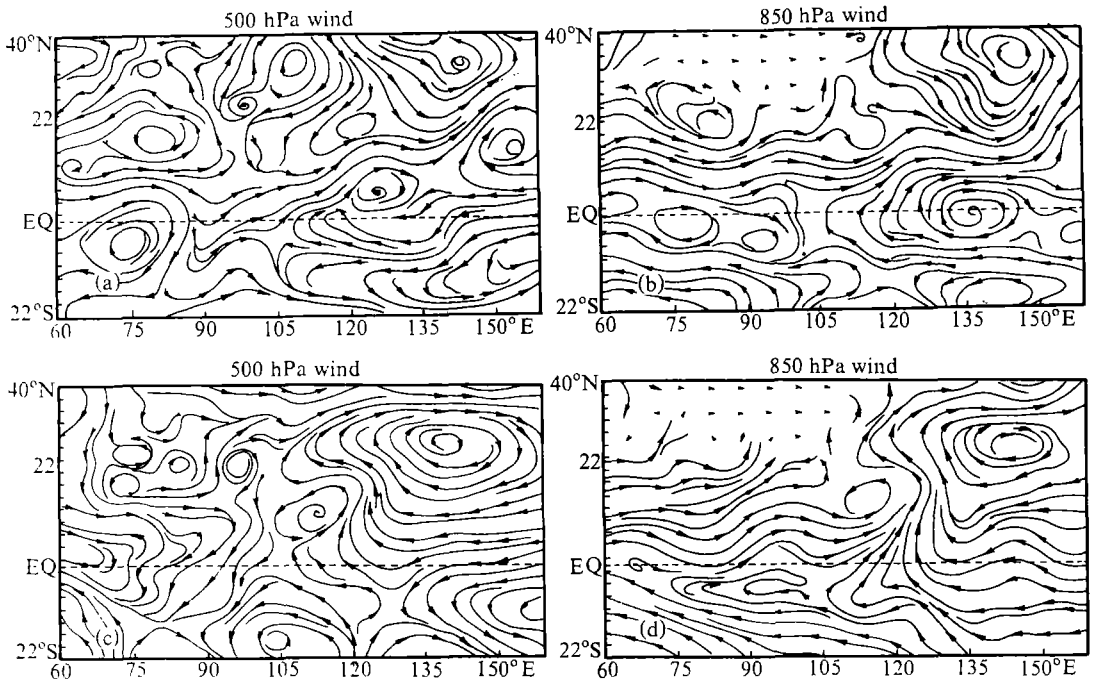

Fig. 2. Initial stream fields on 500hPa and 850 hPa: (a) and (b) at 1200 August 4, 1981, (c) and (d) at 1200 July 6, 1985.

develops into a typhoon (Typhoon No. 8111, Roy) at 00Z 5 August, with the maximum wind of 20m / s, and strengthens further afterwards. Fig. 1a shows the time variation of the SLP (sea–level pressure) in the cyclone center for this case.

The second process (July 2–9, 1985) originates in tropical western Pacific (8°N, 136°E), moves northwestward fast and gradually strengthens at the early stage. On July 6, it enters into the South China Sea, with the SLP near the center going down to 998 hPa sharply. But instead of developing further into typhoon, it remains steady for about two days and finally weakens, with the maximum wind of only 15 m / s in this process. Fig. 1b gives the time variation of the SLP for this case.

To make the comparison study of the two different SCSDs (one develops into typhoon and the other not), we choose 12Z Aug.4, 1981 and 12Z July 6, 1985 as the initial times for each case respectively, and make 24–h predictions. We can see from Fig. 1 that, during the above selected periods, the DVD develops and becomes a typhoon at 00Z, Aug. 5 (i.e. it is developing), and the UNDVD shows undevelopment, but keeps steady instead (i.e., it is non–developing).

2. *Comparison Analysis between Initial Fields of the Two Cases*

Figs. 2a and 2b give out the initial 500hPa and 850 hPa stream fields for the DVD and UNDVD respectively.

In Fig. 2, it can be seen that obvious differences exist in the circulation features of the two cases. In the DVD case, the summer monsoon flow and the deep equatorial westerlies stretching eastward to 160°E are very strong, with remarkable westerlies in 500hPa in the monsoon area. A monsoon trough pattern dominates from Indian Ocean to the South China Sea, and the western

Pacific subtropical high is weak and withdraws eastwards, accompanied by the Typhoon No.8110 near Japan. And there are strong anticyclonic flows at 500 hPa over China and westerlies to the south of the South China Sea, which forms a strong shear trough in the DVD area.Meanwhile the cyclonic circulation is weaker, with closed cyclonic stream lines at 850 hPa and unclosed at 500 hPa, where it is dominated by sharp shear trough. However, in the UNDVD case, it shows entirely different features, with strong western Pacific subtropical high and trade wind, which stretches westwards to about 130°E, and shallower monsoon westerlies, which can not stretch to 500hPa. The depression locating between the trade winds and the monsoon westerlies is very deep, with closed stream lines at both 850 hPa and 500hPa, but the circulation center is not overlapping.

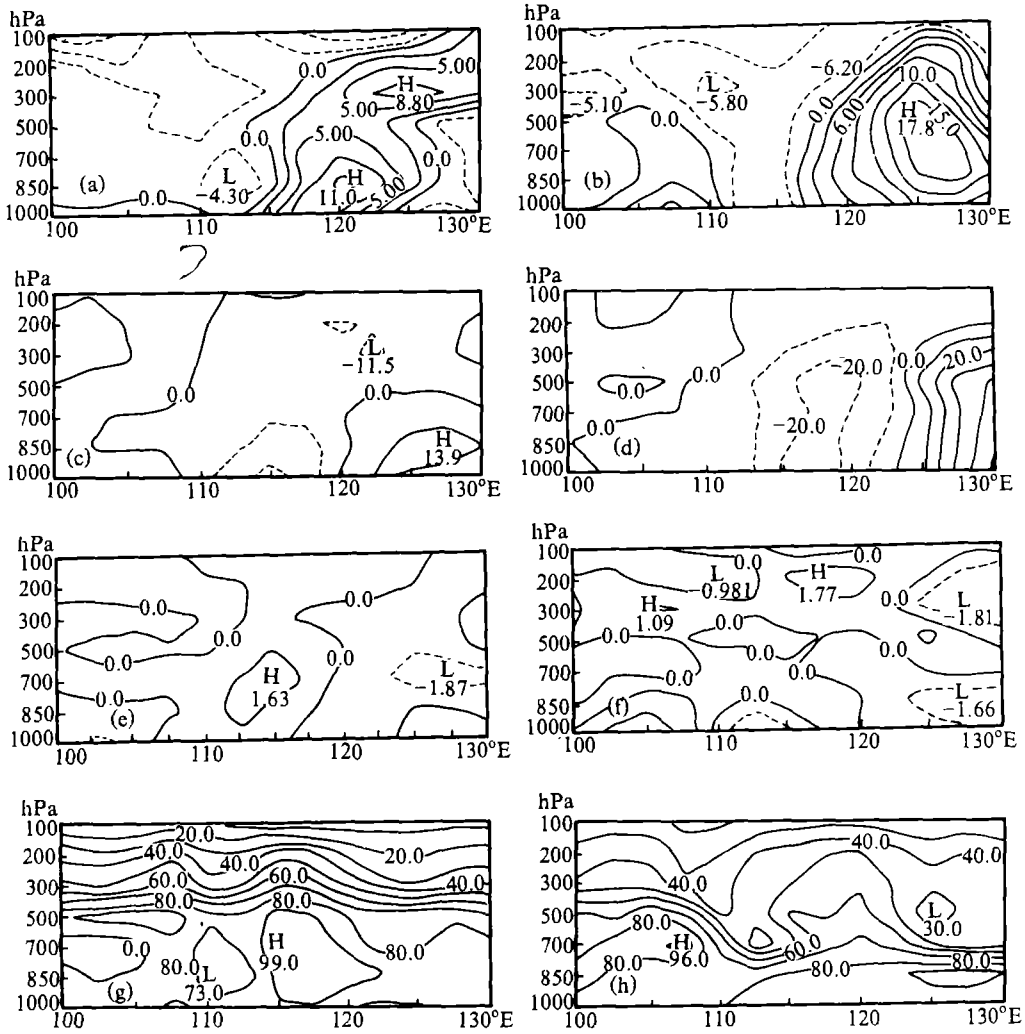

Fig. 3. Longitude–height cross sections of meridional wind v (a) and (b),geopotential height H (c) and (d), temperature T (e) and (f) and relative humidity RH (g) and (h), where H and T are the deviations from their longitudinal means and the contour intervals for v, H, T and RH are 2.5m / s, 10gpm, 1°C and 10%, respectively. Figs.3a, 3c, 3e and 3g for Aug. 4, 1981 and Figs. 3b, 3d, 3f and 3h for July 6, 1985.

To study the more detailed features and differences in the structures of temperature, humidity, pressure and wind between the two depressions, Fig.3 gives the longitudinal–vertical cross–sections of the above factors across the centers of the two depressions respectively. From Fig. 3 we see that, (a) in the DVD case, the cyclonic flow is weak and shallow, and is only stronger at 850 hPa; but in the UNDVD case, the circulation is stronger and deeper, with the strongest flow occurring at 500hPa instead of at 850 hPa; (b) the DVD has a smaller horizontal scale of about 7.5°latitudes (where the horizontal scale defined as the distance between the maximum southerlies and the maximum northerlies in the depression area); while the UNDVD has a larger horizontal scale of about 10—12.5°latitudes. The latitudinal–vertical sections of wind u (not shown) also show the similar results. As to the height (or pressure) structure, it is found that in the DVD case, the low is remarkable (with negative deviations greater than 10 m)only below 700 hPa , and is almost absent above it; but in the UNDVD case, the remarkable low pressure can stretch up to 300 hPa. This again implies that the DVD is shallower and the UNDVD is deeper at their initial times. While the temperature sections show that, in the DVD case, there is a warm–cored structure (with deviations greater than +1°C) at lower levels of the

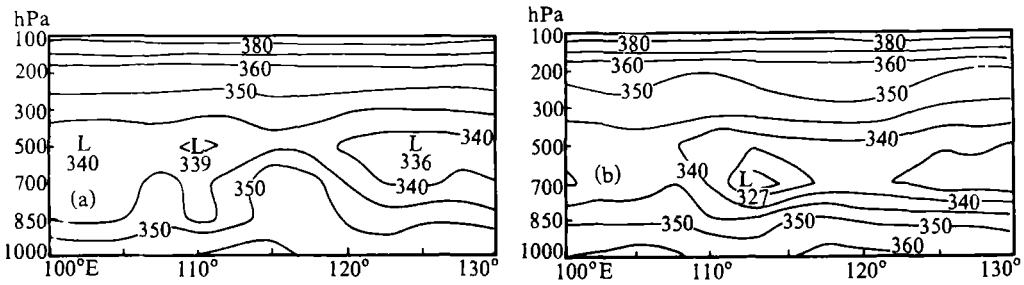

Fig. 4. Same as Fig. 3, but for θ_{se}.

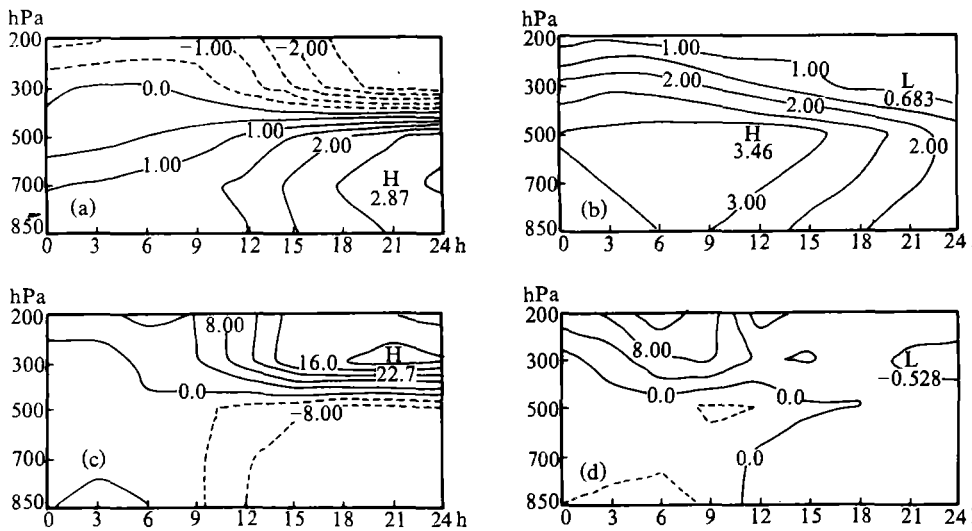

Fig. 5. The height–time section of vorticity (VOR)(a) and (b) and divergence (DIV) (c) and (d) in the depression area in numerical predictions. The contour intervals for VOR and DIV are $0.5\times10^{-5}s^{-1}$ and $4\times10^{-6}s^{-1}$ respectively.

troposphere from 850 hPa to 500hPa, with the maximum positive deviation value at 700 hPa, and no warm core exists in upper levels; but inversely, in the UNDVD case, the warm–cored structure exists in the upper levels (about 200—300 hPa) rather than in lower levels. Finally, the humidity sections show that, in the DVD case, there is a very deep wet layer in the mid–lower levels, with relative humidity greater than 90% below 500hPa, but in the UNDVD case, the wet layer is very shallow, which concentrates on the lowest levels, with the humidity of less than 90% even below 850 hPa.

From the above analyses we can see that, remarkable differences exist in the structures of wind, pressure, temperature and humidity between the two depressions.

The existence of defferences between the two cases in the structures of temperature and humidity inevitably results in the defference in the structure of stability. Fig. 4 shows the longitudinal–vertical sections of θ_{se} across the two depressions respectively, from which we see that, in the DVD case, the minimum value of θ_{se} is at 500hPa, below which it is conditional unstable and above which it is stable; while the minimum value of θ_{se} is at 700 hPa in the UNDVD case. This implies that the DVD has a deeper conditional instability layer (up to 500hPa), and the UNDVD only a shallower instability layer (below 700 hPa).

IV. NUMERICAL MODELLING OF THE PROCESSES

We now at first make 24–h predictions for the two cases respectively (known as the control runs of the two cases respectively in the later analyses). From the predicted evolution of the stream fields for the two cases (not shown) we can see that, the evolution processes of the depressions can be well predicted by the model , in which the DVD develops into a typical typhoon pattern at the 18th hour of the prediction, and the UNDVD does not develop into a typhoon but weakens instead. All these are basically consistent with the actual processes, meaning that the two processes could be simulated well by the model.

Next, we make comparison analyses of the two processes with the model outputs.

Fig. 5 shows the evolution processes of vorticity and divergence for the two depressions, respectively. It is indicated that, in the DVD case, the convergence and positive vorticity increase gradually under 400hPa level and the divergence and negative vorticity increase above that, which are especially fast after the 12th hour, and the level with maximum vorticity goes up gradually from 850 hPa to 700 hPa, in the UNDVD case, the lower–level convergence, the upper level divergence and the mid–lower level positive vorticity increase slightly at the first 6 hours, but in the later hours, the lower level convergence and upper level divergence reduce or even vanish, and correspondingly, the positive vorticity decreases gradually, with the maximum vorticity value remaining at 500hPa. These results are consistent with those in the stream predictions mentioned before, and again show that the processes, one develops and the other not, have been well predicted in our experiment.

Liang and Zhang (1989) pointed out that the maintenance and development of positive vorticity in SCSDs are basically driven by the generation term of vorticity, where the lower level convergence causes the generation of positive vorticity, and the vertical advection of vorticity transports the positive vorticity upwards. The results in Fig.5 are consistent with the above analyses, where in the DVD case, the mid–lower level positive vorticity increases with the increase of low level convergence and in the UNDVD case, the lower level convergence changes gradually into devergence, and naturally the vorticity generation term changes into negative values.

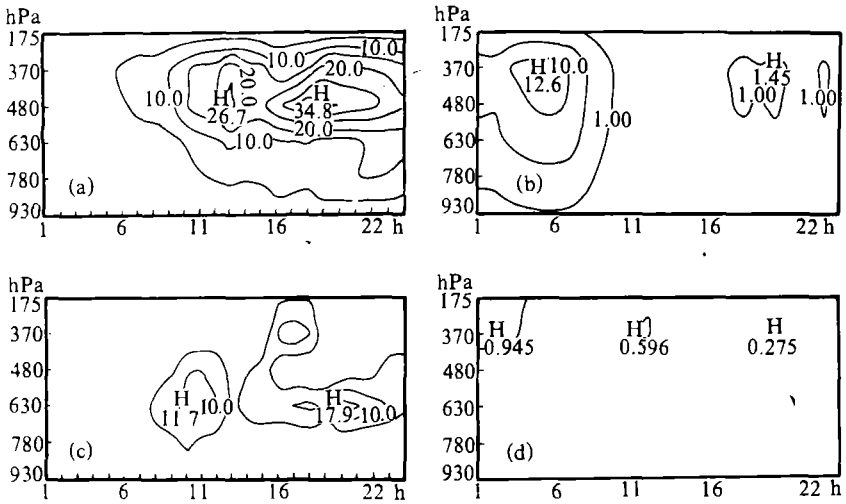

Fig. 6. Time–height sections of the convective heating rate Q_c (a) and (b) and the large scale latent heating rate Q_l (c) and (d) for the control runs. Contour interval 5°C / d, and additional lines of 1°C / d for (b) and 0.5°C / d for (d) are drawn.

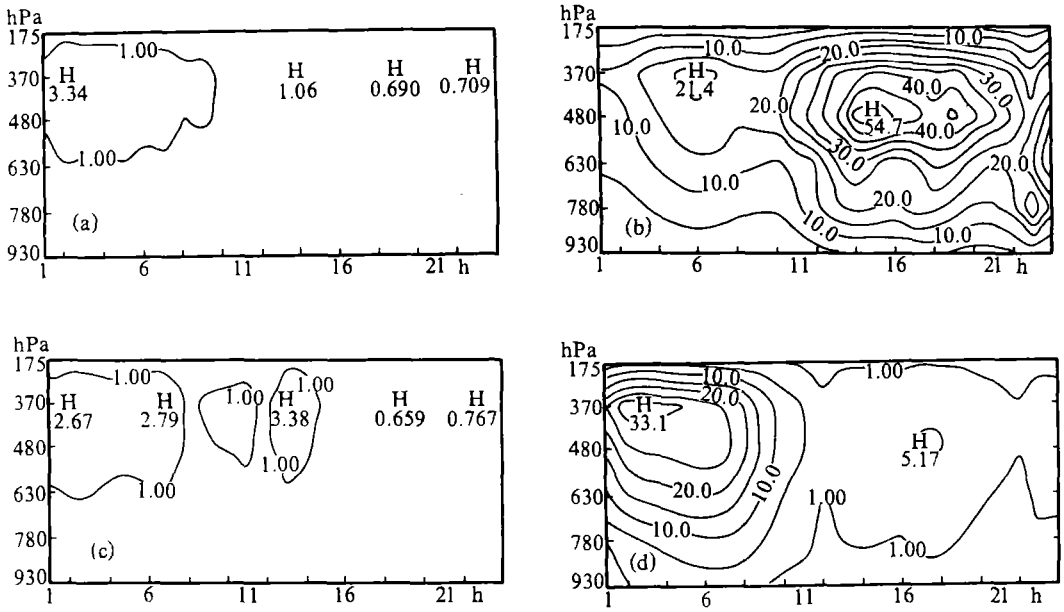

Fig. 7. Time–height sections of convective heatings in each experiment. (a) Ex. I; (b) Ex. II; (c) Ex. III; (d) Ex. IV. Contour interval is 5°C / d, and the additional 1°C / d contour is drawn.

then the positive vorticity decreases.

To make further analysis of the mechanisms governing the development of SCSDs, we turn to look at the heating features in the two cases.

Fig. 6 gives out the time–height sections of the Q_c (convective heating rate) and the Q_l (large scale latent heating rate) in the depression area for the two cases, respectively. Obvious differences can be found between the two cases, where as for the DVD case, the Q_c increases

with time and reaches the value of 10°C / d at the 9th hour of the integration, meanwhile the lower level convergence and positive vorticity increase gradually to -4×10^{-6} s^{-1} and $1.4\times 10^{-5}s^{-1}$ respectively (see Fig.5). And continuously, the Q_c increases further , reaching the maximum value of 34°C / d at the 18th hour, and correspondingly the lower level convergence and positive vorticity increase further (Fig. 5), with the time phases basically same as that of the Q_c. This reflects that the CISK develops sufficiently, driving the depression to develop. Meanwhile the Q_l in this case is about 3 times smaller than the Q_c, with the maximum value of 10°C / d near 630 hPa, which shows that the Q_l also has certain importance on the development of the DVD. But as for the UNDVD case, the Q_c is greater than 5°C / d only before the 8th hour, and after that, it decreases rapidly to be very weak (about 1°C / d), which is consistent with the change of lower level convergence into devergence and the decreases of positive vorticity (see Fig. 5). This means that in this case, the CISK can not develop sufficiently like that in the DVD case, and the importance of CISK is stressed again in the development of SCSDs. While the Q_l in this case is very small (less than 1°C / d) throughout the integration.

The analyses in the previous paragraph show that the CISK (or the Q_c) plays the key role in the development of SCSDs, and determines whether the SCSDs develop or not, meanwhile, the Q_l make positive contributions to the development of SCSDs to some extent, which would be an amplifier of the CISK.

V. CONTROL EXPERIMENTS

To seek why the Q_c increases in the DVD case and decreases in the UNDVD case, we naturally consider the differences between the two cases in their initial fields (see Fig. 3), where obvious differences in the vertical structures of humidity and temperature exist. This results in the defference in the structures of stability between the two cases (see Fig. 4). And the depth of the instability layer would influence the development of the CISK. According to the above considerations, we make a number of control numerical experiments, by modifying the initial vertical structures of humidity and temperature of the two cases in the depression area, respectively, to investigate the impacts of the structure of humidity and temperature on its development. The vertical structure of humidity or temperature of one case is modified, so that the modified structure of this case is consistent with the unmodified structure of the other case, respectively. Then the numerical integration is completed with modified data. In this way, we can easily understand the importance and the sensitivity of vertical structures of humidity and temperature in the development of SCSDs. According to Fig.3, the following four experiments are made.

Experiment I: for the DVD case, the humidity reduces at lower level (i.e., $\sigma=4$, 5, 6 levels corresponding to about $p=630$, 780,930 hPa levels respectively) with the increments of -0.9, -1.5, -2.0 g / kg at each level equivalent to a decrease of 10% in relative humidity at each level in the depression area. Then make prediction for 24 hours.

Experiment II: same as experiment I, but for the UNDVD case, and the increments are negative to those in Experiment I.

Experiment III: for the DVD case, to raise temperature at upper levels and to drop down temperature at lower levels, with the increments of +0.5, +0.5, −0.5, −1.0,−1.5,−0.5°C at each σ level (corresponding to about $P=175$, 370, 480, 630, 780, 930hPa levels). Then do prediction.

Experiment IV: same as experiment III, but for the UNDVD case and reducing temperature at upper levels while raising it at lower levels.

Very obvious differences emerge in the predicted evolution precesses of the two depressions from their control runs, in the above four experiments (not shown). The result is that, in experiment I, the depression does not develop, but gradually weakens instead; and in experiment II, the depression strengthens gradually and becomes a typical typhoon within 24 hours; while in experiment III, the cyclonic circulation weakens rather than strengthens; and finally in experiment IV, the depression circulation shows slowly weakening after the 12h integration. Table 1 gives a brief description of the development of the depression in each experiment.

Table 1. Brief Description of the Depression Development in Each Experiment

Case	Scheme	Brief description of the depressions
DVA	CTRL	Develops and becomes a typhoon within 24 hours
UNDVD	CTRL	Weakens gradually
DVD	Ex.I	Weakens rapidly
UNDVD	Ex.II	Develops and becomes a typohoon within 24 hours
DVD	Ex.III	Weakens graually
UNDVD	Ex.IV	Weakens slowly after the 12th forcast hour

The above analyses show that essential changes take place in the predictions after the modification of the initial structures of humidity or temperature, in which the depression does not develop (experiments I and III) in the DVD case, and develops (experiment II) or the depression weakening is reduced (experiment IV) in the UNDVD case. Why these changes take place? Let us see the convective heating (Q_c) in each experiment (Fig. 7). It shows that the Q_c is very small (less than 4°C / d) in experiments I and III, but it is much larger and increases gradually with time (with the values of 20—50°C / d) in experiment II, and in experiment IV, the Q_c remains larger (about 10—30°C / d) before the 10th hour, and decreases to the values of 1—5°C / d after that. It is very clear that the time variations of Q_c in Fig.7 are basically in phase with those of depression circulations in each experiment. This means that the convective heating plays a key role in the development of SCSDs, and again proves that the CISK is the essential mechanism of the development of the SCSDs.

VI. DISCUSSION AND CONCLUSION

It is complicated and necessary to study the development of SCSDs, which usually occurs in the data sparse area and could rapidly influence coastal South China. It is shown that each of the structures of wind, pressure, humidity and temperature may have important effects on the development of the SCSDs. But only the effects of humidity and temperature are numerically analyzed here, showing that the development of SCSDs is very sensitive to the change in the initial fields of humidity and temperature, that is, a change of lower level temperature by about 1.5°C, or of lower level humidity by about 10%(1—2g / kg), may cause a change of the tendency of the development of a SCSD. This raises another problem about the numerical prediction of SCSDs——data collection and analysis, which remains to be the most important problem in the numerical weather prediction. And just as the above description, the effects of structures of wind and pressure on the development of SCSDs also need to be included in the numerical studies. Furthermore, a more complicated numerical model with more sufficient physical processes including the air–sea interactions is needed to make more detailed studies about the SCSDs. All

the above should be paid attention urgently in the future.

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