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FEATURES OF WATER VAPOR TRANSPORT OF TYPHOON DAN (9914)

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ABSTRACT: The 2.5˚×2.5˚ gridded ECMWF reanalysis data are used to diagnose the genesis, development and dissipation of typhoon Dan by calculated stream function, velocity potential and vapor budget. It is shown in the result that when typhoon Dan moved westwards, water vapor mainly came from the eastern and western boundaries, with most of it was transferred by the easterly flow south of the western North Pacific subtropical high; after Dan swerved northwards, water vapor mainly came from western boundary of the typhoon, and the vapor came from the South China Sea and the Indian Ocean. The transfer of water vapor was mainly concentrated on the mid-lower troposphere, especially the level of 925hPa, at which the most intensive transfer belt was located. During the different period of typhoon Dan, there was great water vapor change as indicated by stream function, velocity potential and vapor budget, which suggest the importance of water vapor in the development of typhoon Dan.

Key words: typhoons; water vapor; transport

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1 INTRODUCTION

Water vapor is one of the most essential conditions for rainfall. The maintenance of typhoon and rainstorm need uninterrupted vapor supply through vapor convergence. The conditional instability of second kind (CISK) derived from scale interaction is an important mechanism to explain the growth of typhoon. Boundary layer air convergence and upward transport of vapor will enhance the disturbance: by water vapor condensation, latent heat is released to warm higher tropospheric air, then mass flows out to lower surface air pressure, so lower tropospheric air convergence is strengthened. The cycle goes on and on[1]. Ding and Liu[2] calculated the vertical transport of heat and moisture by cumulus convection in Typhoon No.7507 (unnamed) utilizing the denser upper-air observations, and the results show consistent distribution of apparent heat source, moisture sink cloud mass flux and main type of clouds. Gao et al.[3] and Gao et al.[4] took into account net waste of moist air caused by large precipitation in a rainstorm system, and applied moisture potential vorticity to diagnose rainstorm system. According to the simulated results from a typhoon numerical model, Kurihara[5] studied the relationship between latent heat of vapor condensation and vapor convergence in the boundary layer, and the correlation coefficient is 0.75 between inflow of vapor through a cylindroid surface at the radius of 100 km at the height of 1.2 km and mean precipitation rate over an area within 100 km. Gamache et al.[6] computed the vapor budget of Hurricane Norbert by means of two different retrieval techniques of microphysics and revealed the importance of asymmetric vapor budget in Hurricane Norbert, which explained nearly half of the net condensation. The most of the coagulations and maximum rainfall took place to the left of the hurricane track, while evaporation mainly occurs at the rear of the track. Ding and Chen[7] simulated the environmental vapor field of Typhoon No.8407 (Ed) and proposed that water content in the passage to the

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right of the storm's core is critical to the precipitation. Ding and Liu[8] analyzed the vapor budget of typhoons over the ocean and concluded that mass convergence related to divergent winds is the largest contributed component to the precipitation. Vertical transport shifts the lower tropospheric vapor up to mid-upper troposphere and cumulates in larger amount there. Evaporation is also important and accounts for 13% of the precipitation and 23% of the vapor convergence. In order to retrieve the rain rate of tropical cyclone in one hour using GMS5 multispectral data, Ding and Lin[9] divided South China to several parts and explored the relationship between the GMS5 multispectral data and the rain rate from TRMM satellite for a tropical cyclone; Lin et al.[10] used satellite data to generally investigate 48 cases, and studied the relation between precipitation distribution and tropical cyclones making landfall in South China during 1990 – 1999; Lan et al.[11] researched the interannual relation of atmospheric heat source and vapor sink over the tropical Pacific to the SSTA. Chen and Ding[12] summarized the former research and considered that the vapor lateral inflows from the moist boundary layer, instead of evaporating directly from the ocean, provide most of the energy for typhoons within a small sea area (150 km to the typhoon core); ocean evaporation will become the main vapor source when the typhoon radius is larger than 500 km. The above studies associated with typhoon vapor mentioned above have achieved a lot in the synoptic and dynamic aspects of typhoon rainstorm, but few analyses of vapor process effects on typhoons are made. The discussion on the genesis and maintenance of typhoon should take vapor into account as an important factor. Vapor transport and convergence at large scales are needed for typhoon genesis, in other words, insufficient vapor transport and supply would not generate and maintain typhoons. So, the large-scale vapor condition should be analyzed during the whole process of genesis, development, movement and dissipation of Typhoon Dan before studying its detailed thermal and dynamic structure, to understand the vapor transport and convergence during its different stages.

2 INTRODUCTION TO TYPHOON DAN (NO.9914) AND WEATHER SITUATION

2.1 Introduction

Typhoon Dan (coded 9914 in China) generated as a tropical cyclone on the ocean east off the Philippines October 3, 1999 (UTC is used all over the paper), and then it moved nearly westwards and was strengthened step by step. On October 4, the tropical cyclone had been enhanced into a typhoon and the strength persisted for 114 hours. On October 6, it turned to move northwards at 00:00 UTC and almost directly northwards after 18:00 UTC. The typhoon made landfall at town Gangwei, Longhai county nearly south of Xiamen about 30 km at 02:00 UTC in the morning of 9th with maximum velocity 35 m/s and Level-12 wind force. The typhoon core had stayed there for about 5 – 6 hours and the maximum wind force exceeding Level 12. It met a major astronomical tide on September 1 of Chinese traditional calendar, and had the highest observed tidal level of 7.32 m, 0.32 m over the alert level, at Xiamen oceanic station. After landfall, the typhoon moved northwards slowly and passed through Xiamen and Quanzhou, and then gradually filled up inland (Fig.1). Dan is the strongest typhoon landing Fujian for the past 30 years, and it affected Fujian and Zhejiang with wind force at Levels 8 – 10 and maximum at Level 11 – 12 in coastal areas. It was accompanied by heavy rain or storm almost all over eastern Guangdong, Fujian and Zhejiang, and there was very heavy rainstorm in the part of Fujian (There are 200 – 300 mm of total precipitation in the parts of Putian and Jinjiang, Fujian, and 519 mm precipitation was poured into Chongwu, Fujian.). The total precipitation reached 50 – 200 mm in eastern Zhejiang. Extremely strong gale, storm and storm tides caused casualties and great economic loss in southern Fujian, and direct economic loss was as high as 8.1 billion yuan. Direct economic loss in stricken Zhejiang, Fujian, Guangdong, jiangsu and Shanghai amounted to 19.619 billion yuan[13].

2.2 Surface weather situation

A strong cold air invaded the East Asian continent before 00:00 UTC October 3. The surface temperature decreased substantially. Cyclonic waves developed over the lower reaches of Yantze River and a cold high controlled the continent of East Asian (Fig.2). The situation persisted to October 7. At 00:00 UTC 8th, the cold high strengthened slightly and moved fast eastwards. A weak frontal rainfall area formed along Japan to coastal areas of East China at 06:00 UTC 8th, and the front met with Dan. The encounter didn't change the structure of Dan but increased its cyclonic curvature and pressure gradient force instead to strengthen the typhoon in the evening of 8th. As it made landfall, the continental cold high moved eastwards over the sea, and the continental weather was mainly influenced by the inverted trough of Dan.

2.3 Upper weather situation

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Fig.1 Track of the Typhoon Dan.

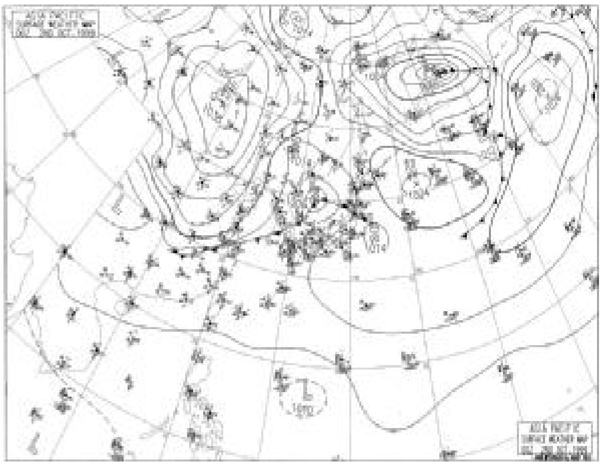

Fig.2 Surface weather situation at 00:00UTC Oct.

Before October 6, the ridge of a strong 500-hPa subtropical high was aligned east to west and steadily was at 27˚N (Fig.3). Being in the easterly south of the subtropical high, Dan moved westwards along its periphery. A deep trough east to the Tibet Plateau moved eastwards and extended southwards, and the subtropical high divided into eastern and western parts at 27°N, 121°E under the influences of both the trough and the typhoon at 00:00 UTC 6th. The western part centered on the Indo-China Peninsula, and the eastern center dominated the ocean south to Japan and east to Taiwan. The divided subtropical high coupled with the north trough, which was very favorable for the turning of the typhoon. Then, the typhoon was over the western part of the oceanic subtropical high, where the southwesterly guided it to move northeastwards slightly. From 12:00 UTC 6th to 00:00 UTC 7th, the high splitting from the subtropical high withdrew from the Indo-China Peninsula, so Dan was led to the north by the southerly west of the eastern part of the subtropical high. The isoline of 588-geopotential-height west of 140˚E extended southwestwards, as the subtropical high enlarged, and the west-east ridge changed into southwest-northeast one (Fig.4). At 04:00 UTC 8th, strengthened western Pacific subtropical high accelerated the southerly in western periphery, with the strongest wind at 20 m/s. The enhanced steering flows caused the strengthening and stagnating Dan to move northwards at greater speed. At the same time, the strengthened southerly prevented Dan from filling up rapidly after landfall and maintained it at Level-12 wind for 8 hours and lowest pressure for 3 hours. The analysis above indicates that the evolution of subtropical high (e.g. weakening, enhancing, division, and so on) influences the typhoon track, especially its turning clearly.

3 ANALYSES OF VAPOR TRANSPORT STREAM FUNCTION AND VELOCITY POTENTIAL DURING TYPHOON DAN EVOLUTION

Besides the favorable ambient field, the formation, evolution, movement and decaying of typhoon were also related to large-scale condition of vapor transport. This section focuses on the analyzing of the vapor transport features during every stage using stream function and velocity potential of vapor flux to understand the vapor variation and influence. Hereafter the 2.5°×2.5° gridded ECMWF reanalysis data are used, which have 11 levels at 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100 hPa.

3.1 Computing vapor transport stream function and velocity potential

We computed the stream function and velocity potential of vapor transport to obtain its rotating and convergent components. Thereby, they can be used to analyze the detailed characteristics of vapor transport. If

$$\vec{Q} = \vec{k} \wedge \nabla y + (-\nabla c) = \vec{Q}_y + \vec{Q}_c \qquad (1)$$

Then,

$$\nabla^2 y = \vec{k} \bullet \nabla \times \vec{Q}_y \,, \quad -\nabla^2 c = \nabla \bullet \vec{Q}_c \qquad (2)$$

$$\vec{Q}_y = \vec{k} \times \nabla y \,, \quad \vec{Q}_c = -\nabla c \qquad (3)$$

The detailed calculation comprise of the following steps of

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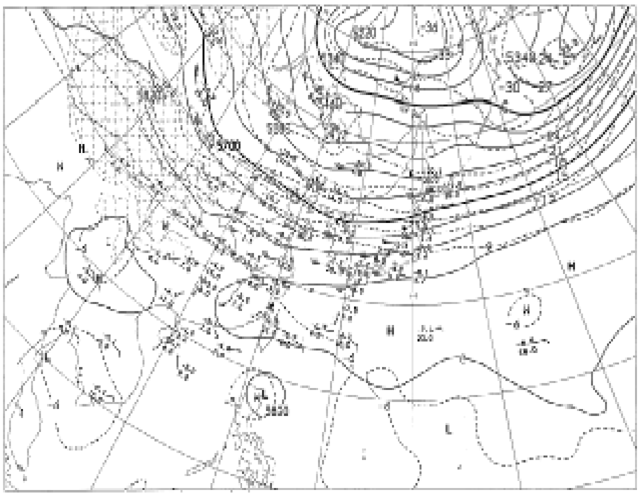

Fig.3 Geopotential height at 500 hPa at 00:00 UTC October 5th .

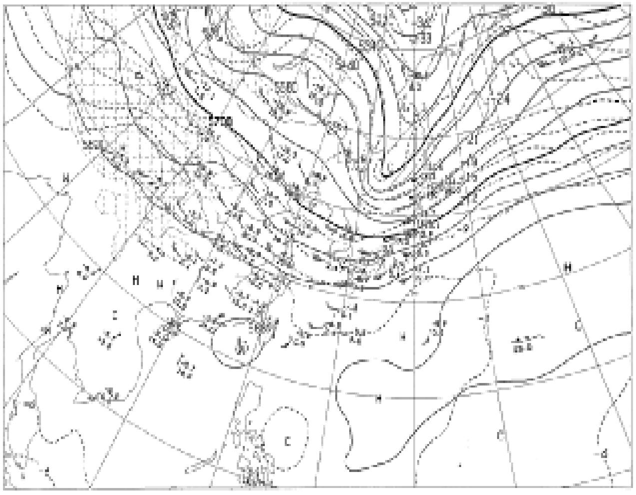

Fig.4 Geopotential height at 500 hPa at 00:00 UTC October 8th.

i. Computing $\vec{Q}$ and its convergence and vorticity by gridded q, u and v;

ii. Solving Poisson Equation and Eq.(1) to obtain the numerical solutions of stream function and velocity potential by the method of exceeding relaxation;

iii. Getting the convergent and rotating components of vapor transport from Eq.(2); and

iv. Integrating Eqs.(1) and (2) vertically to get the potential and stream functions for unit area of air column and the convergent and rotating components of vapor transport[14].

Here $\vec{Q}$ is the vapor transport flux, $\vec{Q}_y$ its convergent component and $\vec{Q}_c$ its rotating component. y is the stream function vapor transport and c the velocity potential. q is the relative humidity, u and v are the zonal and meridional wind, respectively.

3.2 Analyses of vapor transport stream function, velocity potential and vapor flux components during Typhoon Dan's evolution

Dan was analyzed from vapor conditions, including stream function, velocity potential, rotating and convergent components of vapor flux. The rotating vapor stream function, namely rotating vapor flux, reflects the vapor flux component transported along isobars, which is the main part in the global vapor transport. The convergent component describes the isobar cross of vapor flux, which plays an important role in water vapor sources and sinks despite small contribution to global vapor transport. Now, corresponding analysis of Dan will be done for different stages.

The daily stream function and rotating component of vapor flux (Fig.5.1a – 4a) show that the vapor was mainly transported from the western Pacific by the easterly south of the subtropical high during Dan's evolution. The calculation results indicate that high value centers of vapor flux stream function in the western Pacific and mainland of China are associated with a channel of vapor transport from east to west along the equator and another channel in the southern edge of the subtropical high, as noted from the stream function and velocity potential of the column vapor flux and corresponding rotating and convergent components (Fig.5.1a), during the initial stage of Dan genesis (October 2 – 3). The vapor convergence centered in the Indian Ocean, the west parts of China and Japan, whereas the divergence center was in the east of China. Since October 3, a close center of vapor flux stream function come to appear over the ocean east to Philippines, and the stream function over the mainland had higher value center than the day before. Vapor flux velocity potential and divergence component (Fig.5.1b) show that while the column convergence centers were still in the Indian Ocean and Japan, the vapor over the ocean east of the Philippines (near 17°N, 129°E) came into a convergence that reflects the vapor characteristic during the first stage of Dan genesis. After that, the stream function center over the ocean east of the Philippines, where Dan came into being, maintained and moved with the typhoon. And the high value center of velocity potential became larger and larger day by day. The velocity potential was 0 – 50 unit at 00:00 UTC 3rd, the center value reached 250 unit (Fig.5.2b) and maintained and concentrated more around the Dan core after 5th (Fig.5.2b – 4b). That is an important condition for Dan to keep and develop. The high vapor center over the Indian Ocean was a huge water vapor

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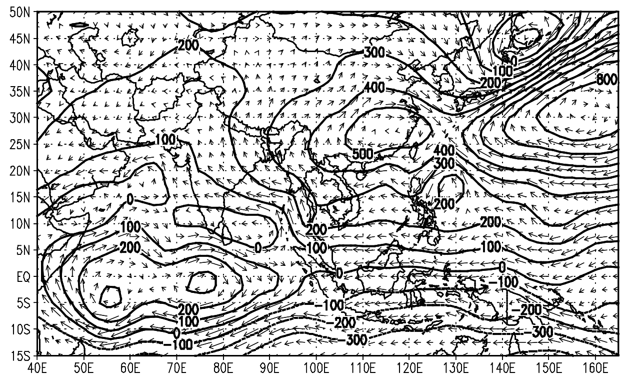

Fig.5.1a 03rd 00:00 UTC stream function.

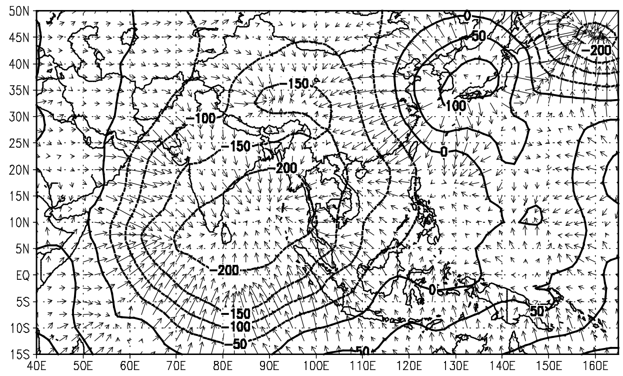

Fig.5.1b 03rd 00:00 UTC velocity potential.

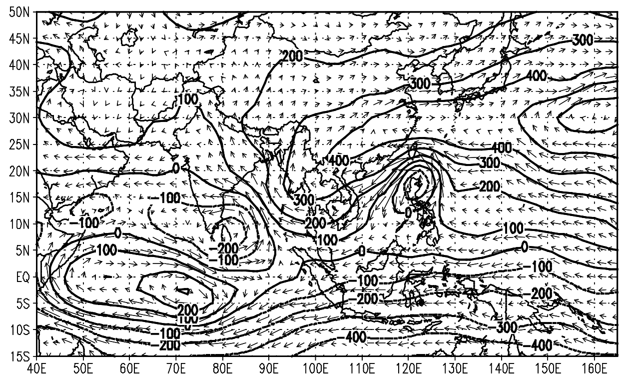

Fig.5.2a 05th 00:00 UTC stream function.

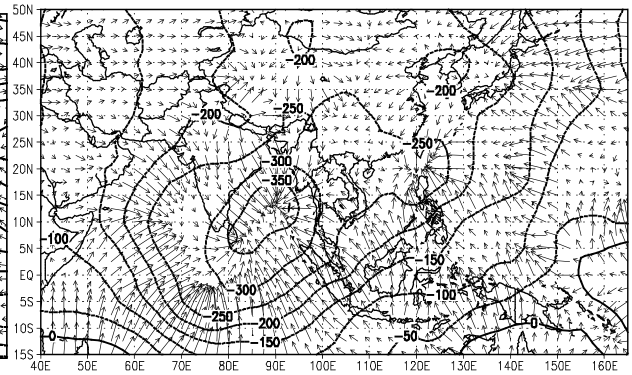

Fig.5.2b 05th 00:00 UTC velocity potential.

sink until 5th, and reached the highest value of –350 unit; after 6th, the center value decreased gradually (Fig.5.3b—4b). In addition, during the days when Dan was moving, the stream function center over the western Pacific associated with the subtropical high and the center over the east mainland of China converged to one center from 3rd. Dan moved along the southern edge of the large center. After turning on 6th, Dan moved northwards along the western edge of the stream function center related to the subtropical high (Fig.5.4a). During the course of Dan moving, it is clear that the stream function center over the western Pacific extended southwestwards, to the south of Dan (Fig.5.4a). Although abundant vapor was still transported from the west boundary at that time, water vapor coming from the east and south boundary, to maintain Dan, became less. The stream function associated with the western Pacific subtropical high completely controlled the South China Sea and littorals at 00:00 UTC 10th, and meanwhile the vapor disturbances of Dan disappeared, indicating the dying-out of Dan. Noted from the weather situation after turning of Dan at 00:00 UTC 7th, the typhoon divided the subtropical high into west and east parts. The west part was a little independent high maintaining over Indo-China Peninsula; the main body of the subtropical high extended southwestwards as soon as it had withdrawn eastwards and weakened, which cut off vapor transport into the typhoon system. So Dan was hard to be maintained and developed for decreased water vapor supply from the south and east.

It is seen from the analysis above that Dan mainly collected water vapor from the western Pacific. The motion of Dan was related closely to the western Pacific subtropical high along whose outside isobars Dan moved westwards first and northwards afterwards. As one of the causes, the dissipation of Dan may be due to the block of vapor channel associated with the isolation of the southwest-extended subtropical high. The distribution and movement of vapor flux associated with the subtropical high and of subtropical high mentioned in weather situation from this and last section respectively, had dynamical consistence. The simple analysis of weather situation and vapor flux showed the interaction between Dan and subtropical high. This is a case in which the typhoon motion was influenced greatly by the western Pacific subtropical high.

4. LARGE-SCALE VAPOR TRANSPORT AND BUDGETS OF DAN

The 3rd section has revealed the large-scale features of vapor transport and its convergence during every stage of Dan evolution, and this section focuses on the vapor transport and budgets of Dan. Vapor flux

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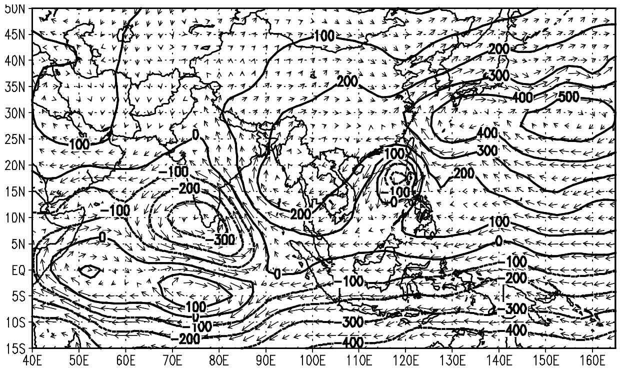

Fig.5.3a 06th 00:00 UTC stream function.

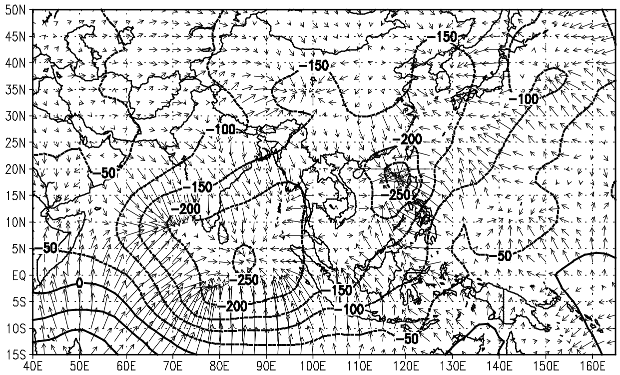

Fig.5.3b 06th 00:00 UTC velocity potential.

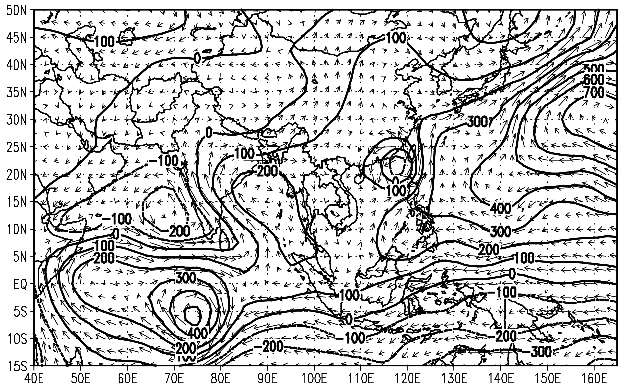

Fig.5.4a 08th 00:00 UTC stream function.

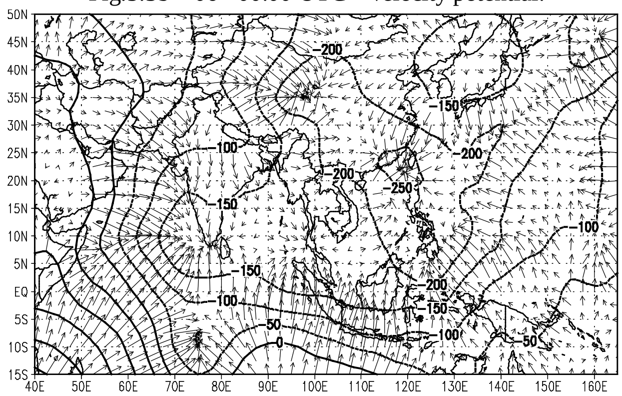

Fig.5.4b 08th 00:00 UTC velocity potential.

$\frac{1}{g}\left|\vec{v}q\right|$ and its divergence $\frac{1}{g}\nabla\cdot\left(\vec{v}q\right)$ are used in calculation, then integration is undertaken for the entire column $\frac{1}{g}\int_{p_s}^{p_t}\nabla\cdot\left(\vec{v}q\right)dp$. In this paper, the 'vapor budget' represents the sum of vapor flowing in and out of the region of typhoon. 'Vapor inflow' denotes that water vapor enters into the typhoon region and the typhoon acquires vapor, and 'vapor outflow' is an opposite process to 'vapor inflow'. Specifically, the equation of vapor budget is defined as

$$P-E_s=-\frac{1}{s\,g}\int_{p_s}^{p_t}\int_s\left(\frac{\partial q}{\partial t}+\nabla\cdot q\vec{v}+\frac{\partial wq}{\partial p}\right)dpds \quad (4)$$

where P is the precipitation, E_s the evaporation, s a selected region, and g the acceleration of gravity. p_s is the surface pressure, and p_t the pressure at the top layer. They are assumed to be 1000 hPa and 100 hPa respectively. $\frac{\partial q}{\partial t}$ is the local variation of water vapor, $\nabla\cdot q\vec{v}$ the vapor divergence, and $\frac{\partial wq}{\partial p}$ the vertical transport of vapor. Divergence of vapor flux is computed with

$$\nabla\cdot q\vec{v}=\frac{1}{s}\oint v_n q dl=\frac{1}{s}\left(\sum_{i=1}^{m}-\bar{v}_i\bar{q}_i\cdot\Delta l_s+\sum_{j=1}^{n}\bar{u}_j\bar{q}_j\cdot\Delta l_e+\sum_{i=1}^{m}\bar{v}_i\bar{q}_i\cdot\Delta l_n+\sum_{j=1}^{n}-\bar{u}_j\bar{q}_j\cdot\Delta l_w\right) \quad (5)$$

The four terms on the right hand of Eq.(5) represent water vapor entering the selected area from different boundary. $v_n q$ denotes normal components of vapor flux, m and n are meridional and zonal grid number for the specified area respectively, and '-' is the spatial mean. Δl_s, Δl_e, Δl_n and Δl_w are grid distance for different boundary. The total budget of vapor can be obtained by adding inflow and outflow at the four boundaries, and they are shown in Fig.6.

Most of Dan's water vapor mainly came from the western Pacific in all its lifetime (Fig.6) while some from the South China Sea as Dan evolved and moved westward. The vertical profiles of vapor budgets were calculated for different time at the north, south, east and west boundaries about 1200 km away from Dan, the center, and the results indicate that vapor flowing in Dan concentrated on the middle and lower troposphere at 500h Pa and below, with especially high values under the level of 925 hPa. More exactly speaking,

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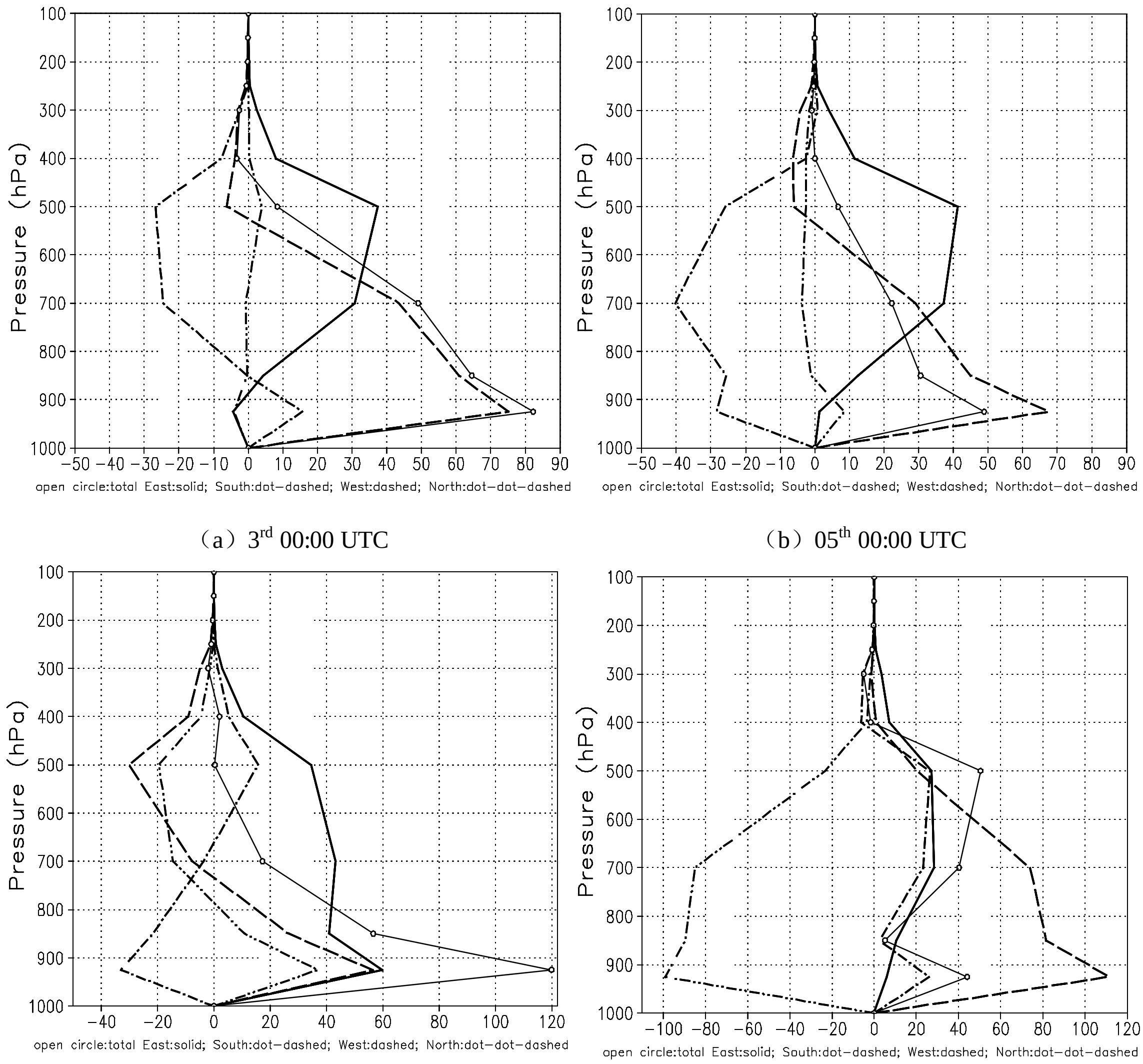

(a) 3rd 00:00 UTC (b) 05th 00:00 UTC

(c) 06th 00:00 UTC (d) 09th 00:00 UTC

Fig.6 Vapor budgets of Typhoon Dan (unit: 10^9g/s), with the *x* axis represent the vapor budgets, and *y* axis the pressure. Open circles: total budgets; solid lines: eastern boundary; dots and dashes: southern one; dashed: western boundary; dots and dashes: northern boundary.

vapor flowing in Dan increases with with enhanced typhoon (one of the causes is sufficient vapor supply that maintains and enhances the typhoon). During the first stage of Dan (Fig.6a), it was most remarkable that vapor pouring into Dan from the western boundary under the 925-hPa level, and the magnitude reached 75 $\times 10^9$g/s; it is clear that vapor also came from the eastern boundary in middle troposphere at 850 – 500 hPa, and the value at 500-hPa level reached 37×10^9g/s; little vapor flowed in and out of the northern boundary, whereas contribution of vapor flowing out of Dan was mostly on the southern boundary. The net budget of vapor in the typhoon area was vapor transported in, and main transport was in the mid-lower troposphere at 500 – 925 hPa, with the maximum at 925 hPa. At 00:00 UTC 4th, the transport is similar to that of 3rd. At 12:00 UTC 4th, except for the northern boundary from which water vapor is exported, vapor was flowing in on the other three boundaries, and the total vapor budget increased to 90×10^9g/s approximately.

Dominating inflow vapor was still at the eastern and western boundaries on 5th (Fig.6b), but total inflow vapor became less than that at 12:00 UTC 4th, with the maximum at 925 hPa was under 50 $\times10^9$g/s. A rapid increase occurred at 12:00 UTC 5th and the maximum exceeded 90×10^9g/s. Except for the southern boundary where the outflow of vapor is decreased, there is vapor inflow at the other three boundaries in the lower troposphere, making the net vapor budget stay above 110×0^9 g/s on 6th when Dan started turning (Fig.6c). By 12:00 UTC 6th, there is main vapor output at the northern boundary but vapor inflow at the other three

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boundaries, with the largest vapor flux at the western boundary. This pattern persisted until the landfall of Dan. At 00:00 and 12:00 7th after the complete turn of Dan, net vapor budget in the entire typhoon area was over 150×10^9g/s, which was the largest in Dan's lifetime. Since 8th, total vapor budgets had begun to decrease, and especially after 12:00 UTC 8th, inflow and outflow vapor mainly passed through the western and northern boundaries respectively. At 00:00 UTC 9th when Dan made landfall, the total vapor inflow was below 50×10^9g/s.

As a whole, during the first stage and westward moving of Dan (Fig.6a, 6b), its vapor mainly came from the western and eastern boundaries and went from the southern boundary; after turning, most of the vapor was supplied from the west and flows out from the north (Fig.6d), whereas there were small amount of inflow vapor from the other two boundaries at middle and lower levels. It is noted from vapor transport on large scale (Fig.4) that earlier vapor input from the western and eastern boundaries into Dan was mainly supported by a westward vapor transporting channel over the subtropical Pacific (20 – 25°N) supported. When the channel passed the typhoon circulation, it was greatly cyclonic as it rotated into the typhoon system. The westward channel was on the south of the subtropical high and was very strong from 3rd to 6th before Dan's turning (Fig.6a-c), On 7th and 8th after its turning, the channel disappeared and only the easterly near the equator maintained a small amount of vapor supply. During the latter stage, vapor passing through the western boundary into Dan mostly came from the South China Sea, including some from the Indian Ocean via the Bay of Bengal and the other with the easterly flow near the equator. Moreover, it can be seen from the total vapor budget (as indicated by open circles in Fig.6) that the inflow of vapor is always more than the outflow below 500 hPa and tended to be zero above 400 hPa either before or after Dan turned. It indicates that the main transport and convergence of Dan's vapor occurred in the mid-lower troposphere.

It can also be seen from Fig.6 that during both before and after the turning of Dan, rather high transport of vapor was maintained at the western boundary. After the turning, there was much vapor flowing into Dan, but continual decreases of vapor input from the east and south, due to southwestward extension of the subtropical high, resulted in decreased total budget of vapor for the entire typhoon system. In particular, after Dan's landfall on 9th, a much strengthened easterly controlled the subtropical ocean from 0° to 15°N. Meanwhile, there were vapor fluxes via the northeasterly over the western North Pacific and a convergent area was over the ocean at about 20°N. So the flows of vapor into Dan were stopped by an anticyclone associated with the southwestwards extension of subtropical high over the western Pacific, it is one of causes that Dan weakened into a low system after landfall.

Vapor budgets were calculated with decomposed rotating and divergent wind components, and the results show that vapor transport by rotating wind, equivalent magnitude and the vapor transport and budgets are dominant in the total budget of Dan, comparable with the magnitude of those at full wind speed and having similar results. It indicates that vapor transport by rotating wind component is still a main feature in typhoon systems with very strong cyclonic circulation.

5 SUMMARY AND DISCUSSIONS

Typhoon Dan moved along the isobars on the periphery of the western Pacific subtropical high and vapor flux and convergence changed obviously during the genesis, enhancing and weakening of Dan. Dan was strengthened along with strengthened vapor convergence near the system, and vice versa. During the genesis and development of Dan, the westward vapor flux south of the subtropical high over the western Pacific and the vapor transport from the South China Sea supported most of the water vapor for Dan: during the period of westward moving of Dan, vapor, mainly coming from westward transport south of the subtropical high, flowed into the typhoon from its western and eastern boundaries, and the channel disappeared after Dan's turning; during the period of northward moving of Dan, the leading vapor transport into the typhoon came from the South China Sea through the western boundary. The vapor was transported mostly in the mid-lower troposphere during all its lifetime.

The results of weather situation and vapor variation analysis further identify the interactions between the typhoon and the subtropical high. Because of lower resolution, the data used in this paper cannot reveal Dan's detailed structure and associated vapor effects. In addition, during the active period of Dan, the vapor transport and convergence took a remarkable change, in which a strong vapor sink changed to a weak vapor source, over the Indian Ocean. To study the relationship and interactions between the change and Typhoon Dan, further simulation and analysis are needed.

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