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PREDICTION OF DUSTSTORM EVOLUTION BY VORTICITY THEORY

H. Choi and Doo Sun Choi

Kangnung National University, Department of Atmospheric Environmental Sciences, Kangnung, Kangwondo 210-702, Korea, du8392@hanmail.net

ABSTRACT

The relation of duststrom in Mongolia and in northern China with vorticity was investigated from March 19 through 31, 2001, using three-dimensional nonhydrostatic model-MM5. Outside area of the maximum negative geopotential height tendency ($\partial\Phi/\partial t$) at the 500 mb level, the area of maximum negative vorticity which induces the strong upward motion of air coincides the area of the duststorm generation in the inner Mongolia of the northern China under relative humidity less than 30 % and wind speed over 8 m/s. The transportation of dust arisen after the source region always follows the negative vorticty area in the downwind side. The region of duststorm generation is the area of maximum negative vorticity and it is the same region of the unstable atmospheric layer (negative potential vorticity layer (PV)) near the ground surface in the vertical distribution of baroclinic PV, which is a function of diabatic heating and frictional terms with respect to time.

Dust parcels during the day are uplifted to about 700 mb level (about 3 km), where potential temperature gradient with pressure ($\partial\theta/\partial p$) is zero, but its uplift motion is confined to 700 mb level, where stable upper atmosphere influenced by the stratosphere exists. Convective boundary layer (CBL; negative PV value) exists in less or more than 1 km and initially dust particle floats from the ground surface to the mixed layer (ML) of about 1.5 km above the CBL and it remains inside the ML. Westerly wind drives the particles to the downwind side. At night, a shallow stable boundary layer near the surface (inversion layer; big positive PV) is developed and the particles inside the stable layer merge to the ground surface and move downwind side. The dust particles in the ML still move downwind side and their dry deposition from the top of stable layer into the surface occurred.

Key Words : Duststorm, Vorticity, Potential vorticity, Convective boundary layer, Stable Layer

1. INTRODUCTION

Duststorm, called another name of sandstorm or Yellow Sand, KOSA is one of severe meteorological phenomena, where strong winds blow a great amount of sand and dust (even small rock) from desert or dried area into the lower atmosphere and the dusts to travel for long distances out to several thousand kilometers, resulting in the reduction of the visibility less than 1km. As the air turbidity increases with the occurrence of duststorm, the amount of solar radiation reaching to the ground surface

reduces and the reduction of solar radiation can cause a great influence upon climate in the Asian continent, partially other continent like northern America.
Asian dust mainly originated from elevated ground at 1500 m or above sea level in Taklamakan, Gobi and Ordos deserts and Loess plateau and have seasonal cycles as generally observed in the dry season, spring. The threshold value of wind velocity for the dust mobilization of dustorm in the Loess Plateau and Gobi desert is in a range of 10 m/s ~12 m/s from field observation and wind tunnel experiments (Qian and Hu, 1997). Xuan and Sokolik (2002) suggested that the threshold valve of friction velocity were in a range of 25 cm/s to 70 cm/s, depending upon particle size and soil type. Tegen and Fung (1994) and Zhang and Zhong (1985) investigated that regions of duststorm occur more than 30 days per year coincide with those regions with relative humidity of air less than 40%, which is the representation of the surface water content of the soil layer.
As previous mentioned, statistic method and numerical simulation for the estimation of the dust amount from the origin of duststorm have been done, but unfortunately, most of previous research papers have not given us detail explanation on the generation of duststorm from meteorological concern, even though synoptic scale meteorological explanation using mainly weather map on the strong wind field near the surface, including few kinds of additional maps has existed. Meteorological approach was usually focused on the beginning stage of the generation of duststorm and how weather was for the formation of the duststorm, considering synoptic weather situation (Austin and Midgley, 1994; Bates et al, 2003; Carmichael, 1997; Chung et al., 2003; Fuelberg et al., 2003; Reed, 1979; Reed and Albright, 1986) . For quantitatively estimation of the duststorm, most of papers have been focused on the evaluation of dust amount from the soil surface into the atmosphere, but unfortunately there have been not much explanation on the generation of duststorm from meteorological point of views such as what kinds of meteorological motion could influence on the generation of the duststorm, rather than simply calculation of generated amount of the dust.
Thus, the objective of this study is to suggest a prediction technique for the duststorm generation and authors would like to explain the generation mechanism on the formation of duststorm and the propagation area of the duststorm by vorticity theory, regarding the contribution of baroclinic potential vorticity to the development of atmospheric boundary layer and the vertical and horizontal dispersion of the dust in the vicinity of the source region.

2. NUMERICAL METHOD AND VORTICITY THEORY

2-1. Numerical model and input data

A three dimensional of non-hydrostatic meteorological called MM5, V3.5 with an isentropic coordinate vertically was used for investigating meteorological conditions for the generation of dust storm during the period of March 18 through 25, 2001. Three-dimensional NCEP date of a horizontal resolution of 2.5^0 x 2.5^0 including topography, vegetation, snow cover or water, meteorological element-wind temperature, moist content, heat budget, sea surface temperature in the surface layer and sounding data on meteorological elements from the surface to 100 mb upper level were used as initial data for the coarse domain. Then interpolated input data were set for next triple nesting processes with grid numbers of 125 x 105 with horizontal 27 km interval and vertical grid number of 23 in the first coarse domain and in the second domain, grid number of 82 x 82 with 9 km interval and in the third domain, grid number 61 x 61 with 3 km interval. 2.5^0 degree interval terrain date was used for the largest domain and then the 0.9km interval data was used for fine mesh domain. MRF method was adopted as boundary layer process in the planetary boundary layer, simple ice method for the prediction was also considered. After the nesting process from a large domain to a small domain, authors made a straight cutting line from the west toward east, which was major transportation root of dust from the dust storm generation area, China toward Japan, in order to investigate vertical structure of meteorological distribution of wind, temperature, relative humidity, total cloud mixing ratio for moisture contents of the atmosphere and vertical velocity. In the first large domain, a straight cutting line lay in the line of Mogolia-Beijing-Seoul-Kyoto-Pacific Ocean like; (10, 90), (130, 40), respectively

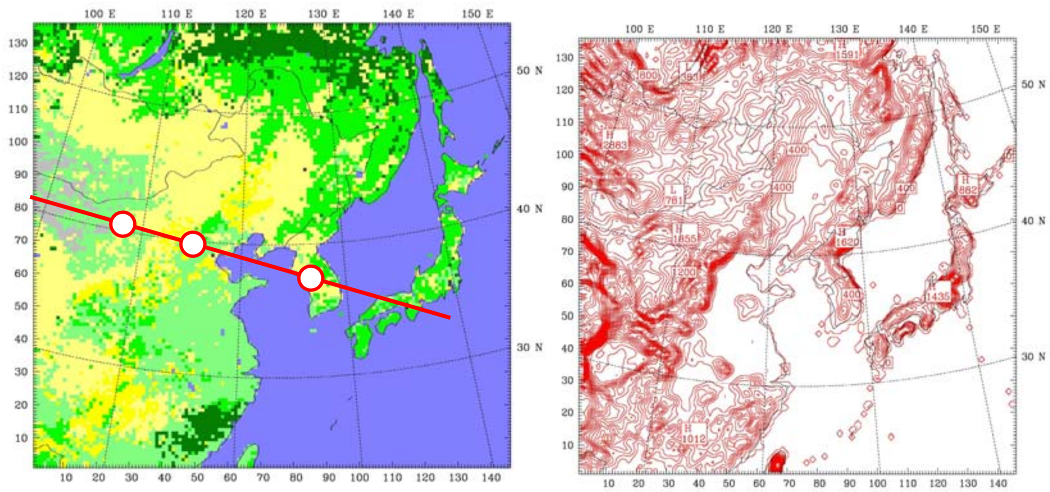


Figure 1. Land-use data and topography for a coarse domain of a horizontal grid size 27 km for
MM5 model. Circles denote Neimongo, Beijing (China) and Seoul (Korea).

2-2. Vorticity theory

Rossy (1937, 1940) insisted that potential vorticity on the isentropic surfaces was conserved for frictionless and adiabatic flow. Reed and Sanders (1953) used potential vorticity as a tracer and explained that air in middle and upper tropospheric fronts originated in the stratosphere. Chen et al (1991), Reed (1979), Reed and Albright (1986) and Sanders and Gyakum (1980) explained cyclogenesis and the development of frontal zone using vorticity theory in detail. Later, on the figures produced from the results of numerical simulation on potential vorticity using MM5 model in this research, a large value of potential vorticity is shown in the upper tropospheric atmosphere and sometimes is folded into the lower atmosphere. Haynes and McIntrye (1987) showed that potential vorticity could be diluted or concentrated

only by flow across isentropes: it cannot be created or destroyed within a layer bounded by isentropic surfaces.
However, if diabatic heating or frictional torques are present, potential vorticity is no longer conserved. It means that potential vorticity can be create or destroy and be away from the isentropes. So, if we consider frictional term with the diabatic vertical and horizontal advection terms on the horizontal momentum equation in isentropic coordinates, total derivative isentropic potential vorticity equation can be given by

$$\frac{\tilde{D}P}{Dt}=\frac{\partial P}{\partial t}+\mathbf{V}\cdot\nabla_{\theta}P=\frac{P}{\sigma}\frac{\partial}{\partial\theta}(\sigma\dot{\theta})+\sigma^{-1}\mathbf{k}\cdot\nabla_{\theta}\times\left(\dot{\mathbf{F}}_{r}-\dot{\theta}\frac{\partial\mathbf{V}}{\partial\theta}\right)$$

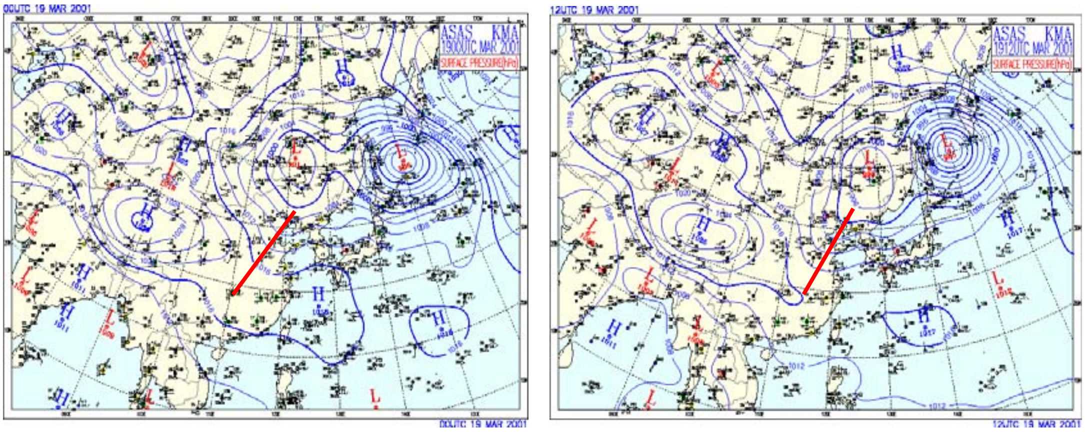
Here the density in (x, y, θ) space is defined as $\sigma \equiv -g^{-1}\partial P/\partial\theta$ and $P \equiv (\zeta_{\theta}. + f) / \sigma$ is Ertel potential vorticity, considering diabatic term in the first of right hand side and frictional term in the second. If the diabatic and frictional terms can be evaluated, it is possible to determine the evolution of the P following the horizontal motion on an isentropic surface. When the diabatic and frictional terms are small, potential vorticity approximately conserved following the motion on isentropic surfaces. However weather disturbances that have sharp gradients in dynamical fields, such as jets and fronts, even the generation of duststorm are associated with large anomalies in the Ertel potential vorticity (baroclinic potential vorticity) in the nonhydrostatic atmosphere.
At 500 mb contours and 1000 mb contours, there is strong vertical motion in the right hand side of trough of geopotential height at 500 mb above the warm sector in the right hand side of cold front at the surface, owing to differential relative vorticity advection and temperature advection. Ertel's potential vorticity theory have usually been focused on the relatively large scale motion of air regarding its small scale disturbance less than few thousand kilometers, but this theory is adopted to the atmospheric boundary layer with comparatively much smaller scale than general meteorological phenomena. In this case, the value of PVU is not necessary to be positive, but it can be negative or positive in the atmospheric boundary layer.

3. RESULT AND DISCUSSION

3.1 Vorticity effect on the duststorm generation

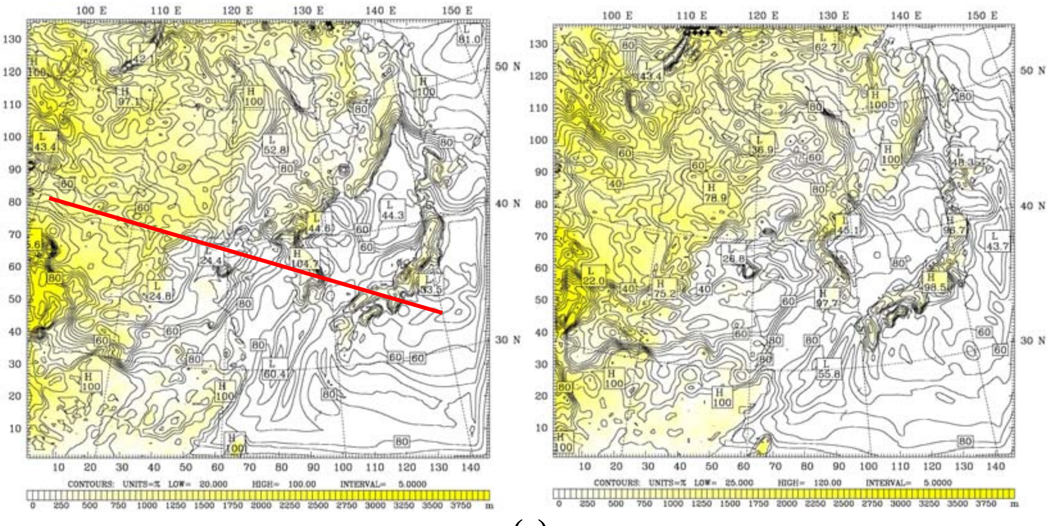
At 0000 UTC (0800 in China; 0900 LST in Korea), March 19, 2001, at the beginning stage of duststorm in Nei-Mongo, if relative humidity (RH) presenting the moisture content of air attached soil layer on the surface layer is over than 40%, under strong surface wind more than 6 m/s, wind can not generate dust from the surface, but it can blow the dust off soil layer under RH less than 30% (Yamamoto et al., 2003). As Zhong' research (1985) indicates that the regions of duststorm occurred more than 30 days per year coincide with those regions with relative humidity of air less than 40%, which is the representation of the surface water content of the soil layer.
In Neimongo, RH was 30% less or more, as shown in weather map and in the vertical distribution of RH simulated by MM5 meteorological model (Figure 2 and 3). A narrow zone of isobaric contours lay from the southern part of Mongolia (NW)

toward Zheongzhou (SE) in China and produced strong northwesterly wind higher than 10 m/s and that area was in a good condition for the generation of the dust (Chung, et al., 2003). However at 500mb, positive relative vorticity advection is a maximum above the surface low, while negative relative vorticity advection is strongest above the surface high.

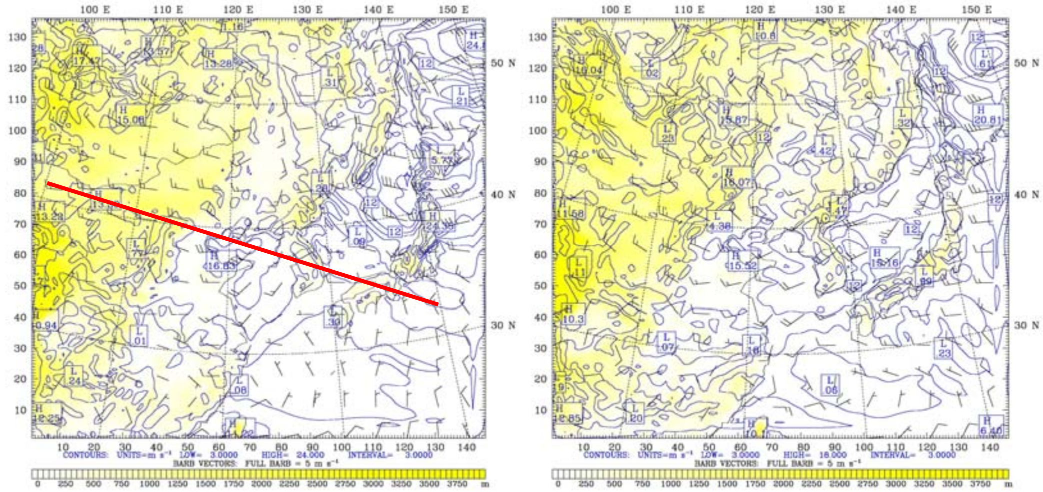


(a) (b)

Figure 2. Surface weather map (a) 00 UTC (09 LST) and (b) 12 UTC, March 19, 2001.



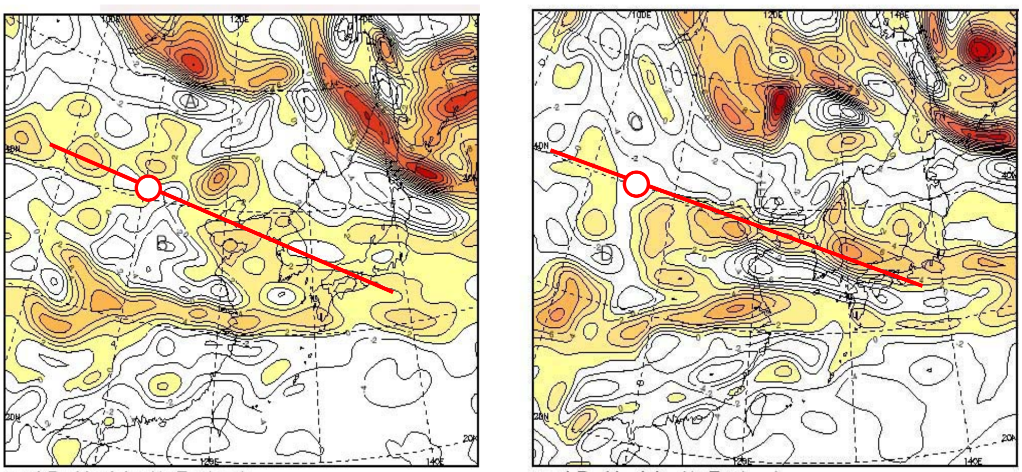
(a)



(b)

Figure 3. (a) Relative humidity (%) and (b) wind seed (m/s) at 00 UTC and 12UTC, March 19, 2001, from MM5 model simulations. Red line indicates a strait cutting line from the NW to the SE direction passing through Beijing, Seoul, Kyoto cities.

Next figures indicated that negative vorticity area (white color area) is found beside the maximum negative geopotential tendency, that is, in the left hand side of upper trough of cold low in Figure 4. Through the comparison of vorticity field with GMS (DCD-IRI-2) satellite picture provided by Japan Meteorological Agency, the area of negative vorticity, A and B (white color) at 0000 UTC, on March 19 directly coincide with the generation area of the duststorm and the transportation area of the dust follow the negative vorticity area stretched westward to Xinjiang province and eastward to Manchulia.



500hPa Vorticity (10E-5/sec) (a)

500hPa Vorticity (10E-5/sec) (b)

Figure 4. (a) and (b) Vorticity (10^{-5} sec^{-1}) at 500mb level at 1200 UTC on March 19, 2001. White area (negative relative vorticity area; red circle) on red line above B indicates the generation area of duststrom. In Figure (b), the duststorm area was

more extended on a line of west (Gansu province) and the dust was transported toward further west (C), south (D) and east (E) area.

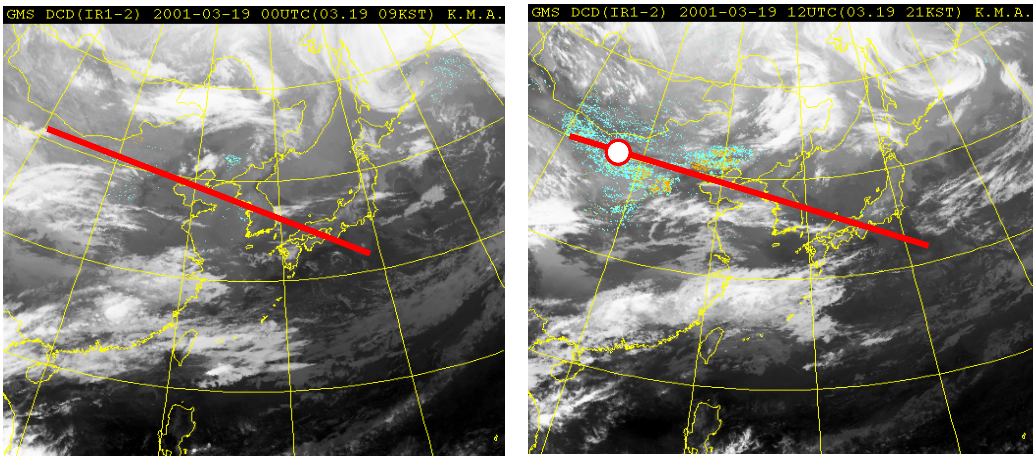
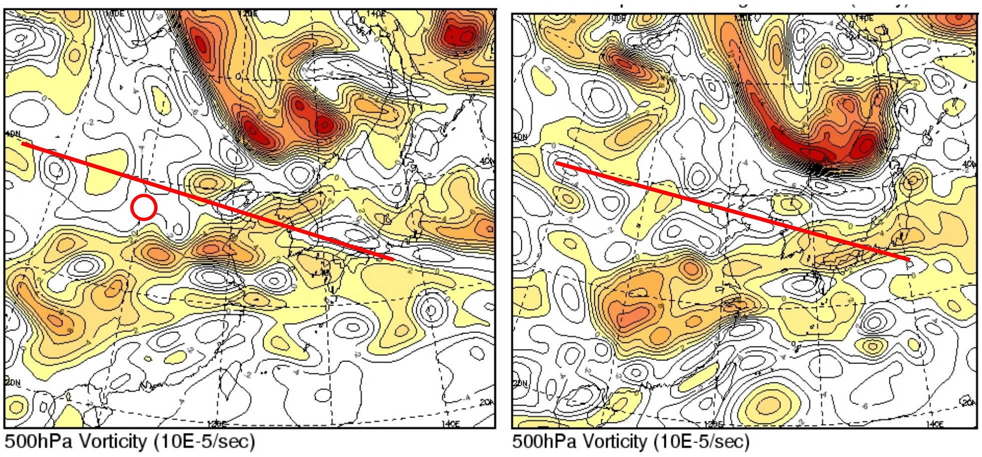
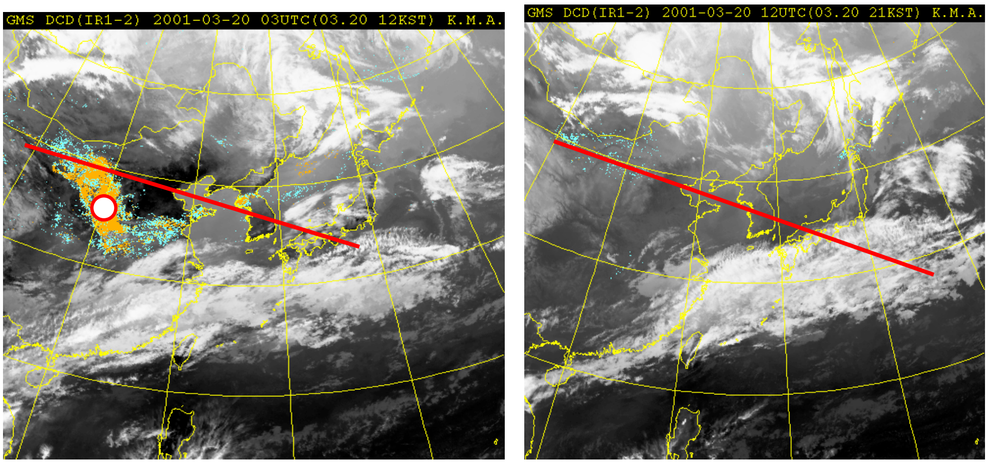


Figure 5. GMS (DCD-IRI-2) satellite pictures at 0300 UTC and 1200 UTC on March 19, 2001. Duststorm area coincides negative relative vorticity area. Even 0000 UTC picture was in bad resolution with cloud, it is possible to detect dust area, comparing with 1200 UTC one.



(a) (b)

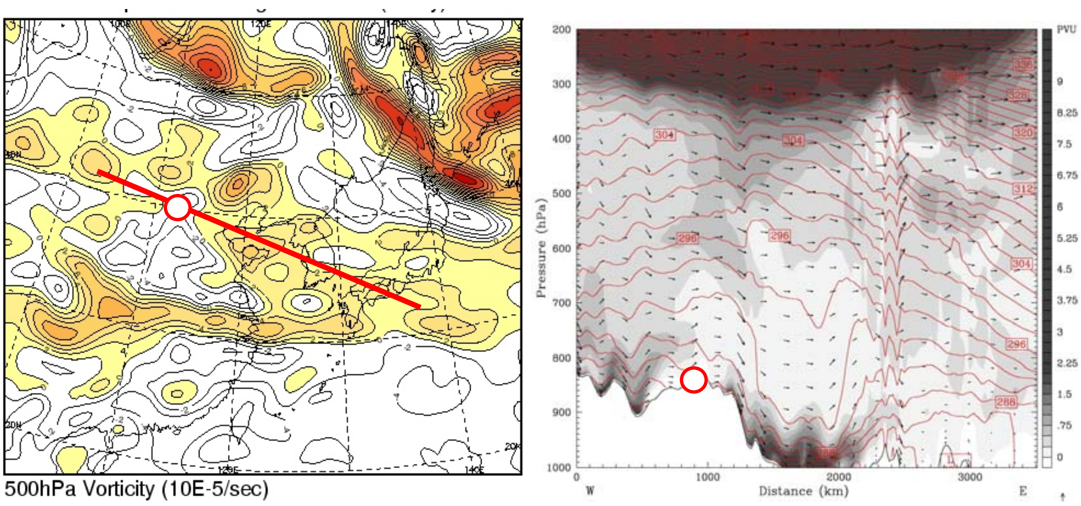
Figure 6. (a) Vorticity at 500 mb level 0000 UTC and (b) 1200 UTC on March 20, 2001.



(a) (b)

Figure 7. GMS (DCD-IRI-2) satellite picture at 0300 UTC and 1200 UTC on March 20, 2001. As the picture at 0000 UTC was in bad resolution, 0300 UTC picture is given by replacing 0000 UTC picture. Red circules indicate dust area.

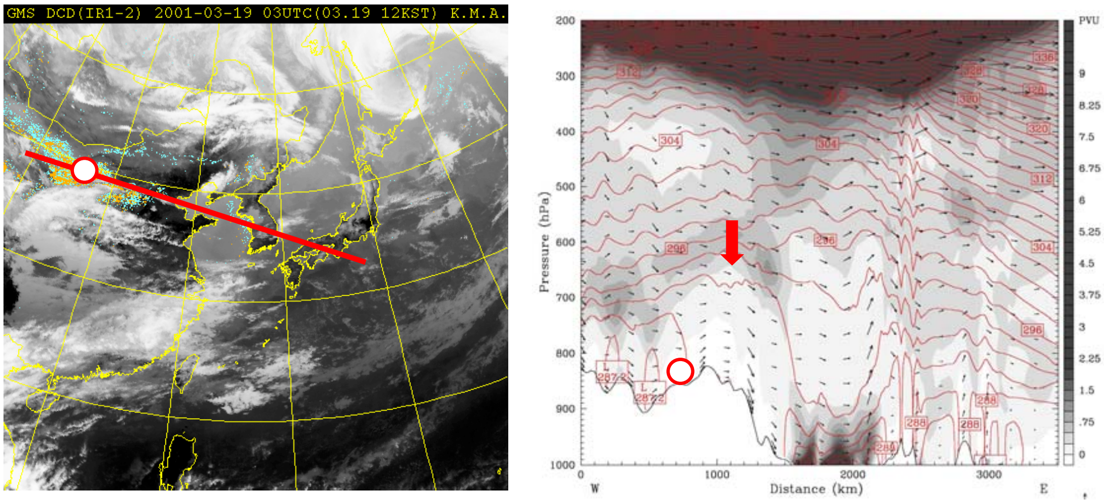
At 0000 UTC (0900 LST), March 19, on the strait cutting line of our figures (Figure 8a) simulated by MM5 model, which is on the high plain in the left hand side of model figure near sothern Mongolia and Nei-Mongo in the west-northern China, the layer of negative potential vorticty (here, less than zero in the unit) in its vertical distribution is found over the highest mountain region in the horizontal distance of about 1000 km away from the western boundary of the model domain (Figure 8 and 9). This negative potential vorticity (less than zero; white color layer) indicates unstable layer (convective boundary layer; CBL) of about 200 m with a mixed layer of about 1 km depth above the CBL, while positive potential vorticity layer (more than 1.5 PVU; black color layer) is also found in the surface boundary layer and upper atmosphere near 400 mb level



(a) (b)

Figure 8. (a) Relative vorticity and (b) potential vorticity fields at 0000 UTC (0900 LST), March 19, 2001 at the beginning stage of the duststorm. Red line is a straight

cutting line from southern Mongolia-Beijing, China-Seoul, Korea-Japan. White color, gray color and dark color area in (b) indicate convective boundary layer of about 200m with mixed layer of 1 km in Nei-Mongo and stable layer of 200 m ~ 700 m in the other area. Red circle denotes duststorm area, where unstable convective boundary layer occurred.



(a) (b)

Figure 9. (a) GMS satellite picture at 0300 UTC (1200 LST) and (b) potential vorticity. March 19, 2001. Red line in (b) is potential temperature. The 0300 UTC picture with partially cloud was used due to its bad resolution of 0000 UTC picture. Duststrom area in the satellite on the cutting line coincides the convective boundary layer-white color in the mountain sites in (b). Red arrow indicates the line (level) of $\partial\theta/\partial p = 0$, between dark and gray layers and the level limits the uplift of dust.particles.

In the upper atmosphere, positive potential vorticity indicates the air coming from the stratosphere into the middle troposphere. Our main concern is confined to the atmospheric boundary layer for the dust generation. Positive potential vorticity layer near the surface, which indicates stable atmospheric boundary layer during the day or nocturnal surface inversion layer at night reaches about 400 m in the southern Mongolia of upwind side and about 500 m in the downwind side. A shallow unstable layer (CBL) of about 200 m exists over the highest mountain in the inner Mongolia, but relatively big mixed layer of about 1 km (the height of $\partial\theta/\partial p = 0$) exists above the CBL (Figure 9b).

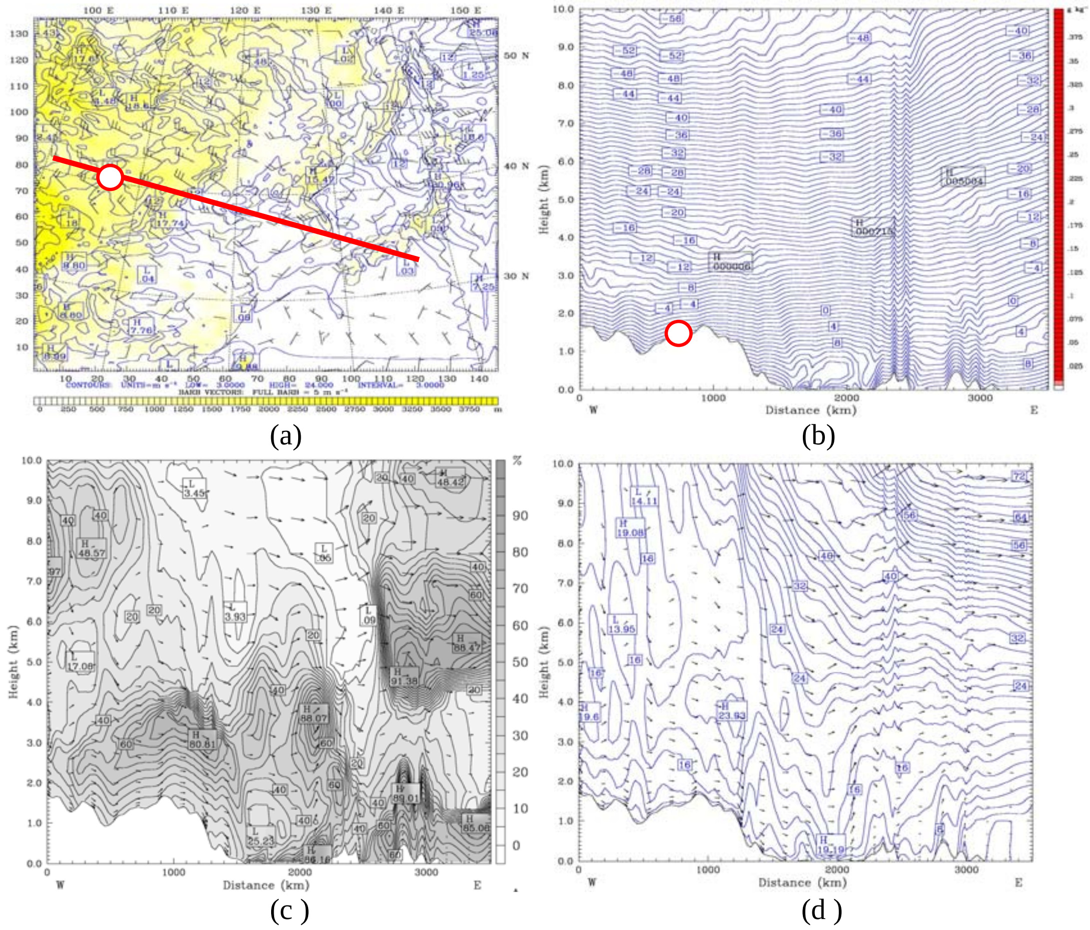
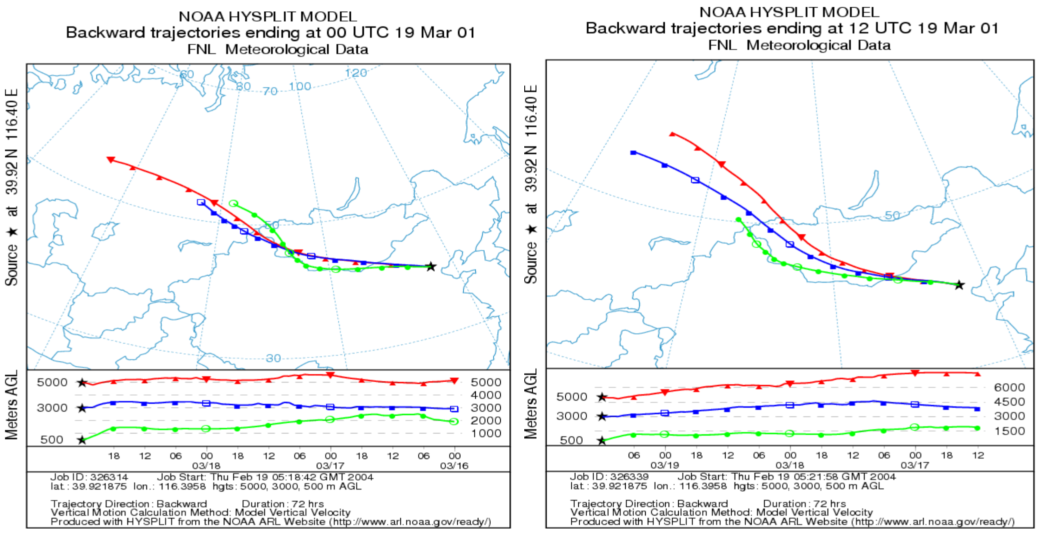


Figure 10. (a) Horizontal wind vector (m/s), (b) vertical distribution of air temperature, RH(%) wind speed(m/s) and horizontal wind speed(m/s) at 1200 LST, March 19, 2001

Above 700 mb level, there is stable upper atmosphere influenced by the stratosphere. Within 3km height, convective boundary layer (CBL; negative potential vorticity value-PVU < 0) exists with a depth of less or more than 1 km and initially dust particle in the CBL floats from the ground surface toward the atmosphere, reaching the mixed layer (ML) of about 1.5 km above the CBL, with its remaining inside the ML and then, westerly wind drive the particles to the downwind side. The reason why the mixed layer is much bigger than the CBL may be due to the daytime thermal induced vertical mixing process under less than 40% of RH (Figure 10c) and mechanical mixing process by strong wind (Figure 10a, 10d) below the 700 mb level. Since baroclinic potential vorticity equation contains both thermal and mechanical process with respect to time, one can easily catch up the evolution of potential vorticity such as the vertical and horizontal movement of air parcels. Especially, negative vorticity area at the 500 mb level, inducing upward motion of air parcel from the ground (duststorm generation area) is well matched with dust distributed area on GMS satellite (Figure 8 and 9).

3.2 Origin of air masses during duststorm

In order to investigate the root of dust transportation from its generation area in ther southern Mongolia and west-northern China (Gansu province) toward Beijing city, China, back trajectories of air masses at ever 6 hour were given for duststorm period from March 19 (its beginning stage) to 20, 2001 (Figure 11). Three levels through the surface to 10km height such as 500m ~ 1500m (showing roughly atmospheric boundary layer), 3km ~ 4500m (middle atmosphere) and 5000m ~ 6000m (high atmosphere including the effect of stratosphere) were considered.



(a) (b)

Figure 11. Back trajectory at every 6 hour on 3 levels-5000m (high level; red), 3000m (middle
level; blue) and 500m (low level; green) over the ground at Beijing, at 0000 UTC, March 19 and 0000 UTC, March 20, 2001.

Air trajectories on the beginning stage of DS in China on from 0000 UTC and 1200 UTC, March 19 gave us that air masses in the upper and middle atmospheres of 5 km and 3km heights passed through southern part of Mongolia and partially, through its middle part, while the masses in the lower atmosphere (atmospheric boundary layer) always passesed through southern part of Mongolia. Since back trajectory does not directly reflect all directions of moving parcels and only their major direction, it is a good qualitative method for the transport of dust to the interested area and .

4. CONCLUSION

the area of maximum negative vorticity which induces the strong upward motion of air coincides the area of the duststorm generation in the inner Mongolia under the relative humidity less than 30% and wind speed more than 7 ~ 8 m/s and the dust transportation always follows the negative vorticty area in the downwind side. The source region of the duststorm (maximum negative vorticity area) is the same region of the unstable atmospheric layer (negative potential vorticity value), near the ground

surface in the vertical distribution of baroclinic potential vorticity, which is a function of daibatic heating and frictional terms with respect to time.
From isentropic potential vorticity (IVP), during the day, the air parcels (dust) are uplifted to about 700 mb level (about 3 km height), where potential temperature gradient with pressure ($\partial\theta/\partial p$) is zero. Above 700 mb level, there is stable upper atmosphere influenced by the stratosphere. Within 3km height, convective boundary layer (CBL; negative potential vorticity value-PVU < 0) exists with a depth of less or more than 1 km and initially dust particle in the CBL floats from the ground surface toward the atmosphere, reaching the mixed layer (ML) of about 1.5 km above the CBL, with its remaining inside the ML and then, westerly wind drive the particles to the downwind side. The depth of the CBL decreases early in the morning and late afternoon, but the ML doses not much change all day long. At night, a shallow stable atmospheric boundary layer (or nocturnal surface inversion layer; big positive potential vorticity value) due to the cooling of the ground surface and the particle inside the stable layer merge to the ground surface and moves downwind side by the wind. The dust particles in the ML still move downwind side by wind and their dry deposition near the top of stable layer into the surface may occur.

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