Wind Storm Generated by Meso-scale Cyclogenesis in the Korean Eastern Mountainous Coast

Hyo Choi[1], Mi Sook Lee[2] and Soo Min Choi[3]
1.Dept. of Atmospheric Environmental Sciences, Gangneung-Wonju National University,Gangneung, 210-702, Korea
2.Dept. of Health Environment. Graduate Schoolal Energy, Hoseo University, Asan, Chungnam,336-795, Korea
3.Konkuk University High School, 265 Guiro, Kwangjin-Gu, Seoul 143-853, Korea
*du8392@hanmail.net

Abstract

Using a three-dimensional non-hydrostatic numerical model, WRF version 2.2, the evolution of windstorm was investigated in the eastern mountainous coastal region of Korea, Gangneung city from October 22 through October 23, 2006. From 2100 LST, October 22 until 0600 LST, October 23, no windstorm was detected and moderate southeasterly wind weaker than 2.8 m/s prevailed in the study area. On the other hand, from 07 LST, October 23, wind speed increases from 9.2 m/s to 15.5 m/s. Positive relative vorticity at 500 hPa level induced downward motion of cold air from the upper level toward the ground surface, showing a decreasing rate of air temperature of - 4 ^{0}C/day at 850 hPa level, and simultaneously, negative geopotential tendency of -140 m/day lay on the study area caused the atmospheric depth of 500 hPa level to the ground surface be much shrunken vertically. These kinds of downward motion of cold air and compression of atmospheric depth resulted in merging of streamlines with higher speed more than 25 kts of isotach at 850 hPa level and produced the formation of strong surface wind speeds. As synoptic northwesterly wind blew over the mountain terrain with steep dropoff in elevation (orography) toward the downwind side, coastal city was associated with mountain-land breeze by both nocturnal cooling of the ground surface and steep mountain terrain, it could be an intensified strong downslope wind like Katabatic wind. In addition, a strong northwesterly wind passed over the steep mountain barrier, the wind depicted a cyclonic flow, resulting in intensification of low pressure system, that is, cyclogenesis in the downwind coastal sea. Furthermore, when this wind storm passes by the coastal basin, much shallower nocturnal surface inversion layer than daytime convective atmospheric boundary layer could also make a contribution of the increase of surface wind speed. As air flew under shrunken nocturnal surface inversion could be fast, the shrunken of atmospheric boundary depth could be significant to induce the formation of windstorm and the maintenance of shrunken atmospheric boundary layer due to weak development of convective boundary layer under cloudy weather caused a maximum wind speed of 15.5 m/s near noon.

Keywords: Windstrom, Katabatic wind, Relative vorticity, Geopotential tendency, Cyclogensis, Mountain-land breeze, Convective boundary layer, Nocturnal surface inversion layer

Introduction

In the mountain and coastal regions, the occurrences of severe windstorms have been frequently reported by TV and newspapers in recent years. Since last few decades, many a meteorologists, even oceanographers have investigated the reason of wind storm generation, but unsolved questions have been proposed so far. By numerical simulation, Jackson and Steyn[1], Jangl[2-3] and Jangl, et al[4] explained the development of stratified flow over a mountain with a gap produced windstorm and orographuc gravity waves close to the nonhydrostatic limit of vertical propoagation. Hunt and Simpson[5] and Arya[6] depicted the formation of internal gravity waves with a hydraulic jump in the lee side of the mountain in cases of different Froude numbers.

. Choi[7-8] also explained the formation of a downslope windstorm with internal gravity waves, depicting a hydraulic jump motion bounding up and down in the lee side of the mountainous coast of Korea by a three-dimensional numerical simulation and he considered a windstorm to be a string wind over than 10 m/s.

Thermal contrast between mountain and basin surfaces or land and sea surfaces can also induce thermal circulations. Anderson[9] revealed katabatic wind field reponding to nocturnal inversions in valleys, using a two-dimensional model and Whiteman[10] explained observed thermally developed wind system in mountainous terrain. Pielke[11] also explained that windstorm in the mountain is generated by an intensified strong downslope wind like katabatic wind combined with synoptic scale wind and mountain-land breeze in the downwind side of a steep mountain.

Wind storm is generated under the occurrence of lee cyclogenesis associated with mesoscale convection[12-14]. Reed[15], Reed[16] and Albright and Durram[17] insisted that lee cyclogenesis accompanying windstorm in the mountain range or in the coast is generally detected, when downslope motion of air is organized into jetlike motion or the downslope motion exists over a steep terrain. Oscillation of mountain waves near the mountain barrier depicts a cyclonic flow pattern, resulting in cyclogenesis in the mountainous coastal surface[18]. In this study, the generation mechanism of windstorm in the mountainous coast was investigated by a three-dimensional WRF (Weather Research and Forecasting) Model-2.2, especially considering the effects of shrunken atmospheric depth and downward motion of up-cold air masses into the lower atmosphere and to predict the precursor of windstorm occurrence in advance[20].

Topographical feature of study area

The study area around Gangneung city ($37^0$45N, $128^0$54E) consisting of high mountainous in the west, basin in the middle and sea in the east (a smallest box as a fine-mesh domain in Fig. 1) covers an eastern part of Korean peninsula. In general, its daily weather and climate are strongly affected by steep mountains and the East Korea Warm Current (EKWC) bounding for north, which is a branch current of Kuroshio Warm Current. Due to steep mountains and relatively warm sea waters, the city is strongly heated during the day, upslope wind combined with valley wind from inland basin to the mountain top and sea breeze from the coast to the inland is generally developed, while nocturnal downslope wind combined with mountain-land breeze is dominant over the inland and coastal sea.

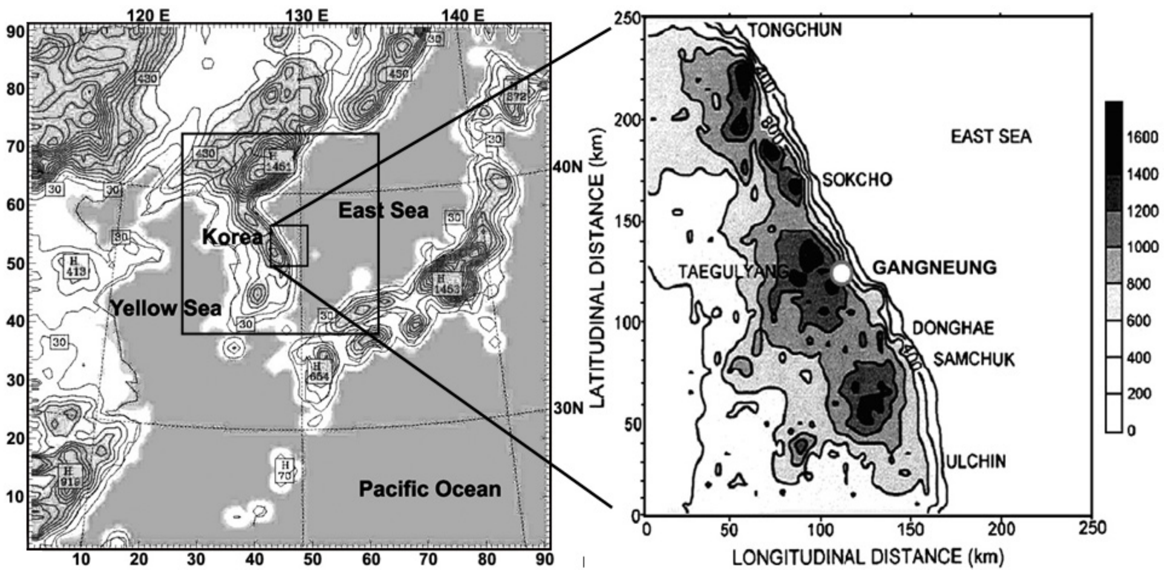

Fig. 1. Topographical features in the vicinity of Korean peninsula in three different domains (horizontal resolutions of 27 km, 9 km and 3 km, respectively) for numerical simulation using WRF-2.2 model (left) and the mountainous coastal region surrounding Gangneung city ($37^0$45N, $128^0$54E; 20 m above mean sea level) and Mt. Taegulyang (860 m) in a fine-mesh domain (horizontal resolution of 3km) (right).

Numerical Method and Input Data

For the generation of windstorm around Gangneung city in the mountainous coast, a three-dimensional Weather Research & Forecasting Model (WRF)-2.2 model with a terrain following coordinate system was adopted for 48 hours numerical simulation from 0000 UTC (Local Standard Time (LST) = 9h + UTC; 0900 LST), October 22 through 0000 UTC, October 24, 2006. During the numerical simulation using the model, wind, temperature, potential temperature, relative humidity, relative vorticity, potential vorticity, streamline and 500 hPa height change for 24 hours (i.e., geopotential tendency ($\partial\Phi/\partial t$); m/day) were evaluated in northeastern Asia (first domain), Korean peninsula (second domain) and near Gangneung city in the eastern coastal region of Korea (third domain). During the numerical process of calculating meteorological elements from a coarse domain toward a fin-mesh domain, one way, triple nesting technique was adopted using a horizontal grid spacing of 27 km, 9km and 3 km covering a 91 x 91 grid square in each domain. NCEP/NCAR reanalysis FNL (1.0^0 x 1.0^0) data was used as meteorological input data to the model and was vertically interpolated onto 36 levels with sequentially larger intervals increasing with height from the surface to the upper boundary level of 100 hPa.

In the atmospheric boundary layer, the WSM 6 scheme was used for heat and moist budgets and microphysical processes and for the planetary boundary layer., the YSU PBL scheme was adopted. The Kain-Fritsch (new Eta) for cumulus parameterization, the five thermal diffusion model for land surface, and the RRTM long wave radiation scheme and dudhia short wave radiation schemes were also used. Hourly archived wind, air temperature, relative humidity, cloud and geopotential tendency by Gangwon Regional Meteorological Administration in Gangneung city were used for the verification of numerical results of the meteorological elements.

Results and Discussion

Synoptic situation: Prior to windstorm event in the eastern coast of Korean peninsula at 2100 LST, October 22, low pressure system with central pressure 1010 hPa was located near western coast of Korean peninsula and 12 hours later (0900 LST, October 13, the low pressure centre moved to the eastern coast of Korea and more intensified to 1006 hPa (Fig. 2). At 2100 LST, whole Korean peninsula is underneath low pressure system, which directly affected weather situation over the Korean peninsula. This low pressure produced north-westerly in the inland and south-easterly in the sea near Gangneung area and supplied relatively warm and wet air from the eastern sea into the inland basin. As isobaric interval along the coast is much narrower in the northern sea from Gangneung city than the southern sea, wind speed is much higher from the coast toward offshore area in the northern sea (Figs. 3 and 4), because narrow displaced isobaric contours induced higher geostrophic wind speeds.

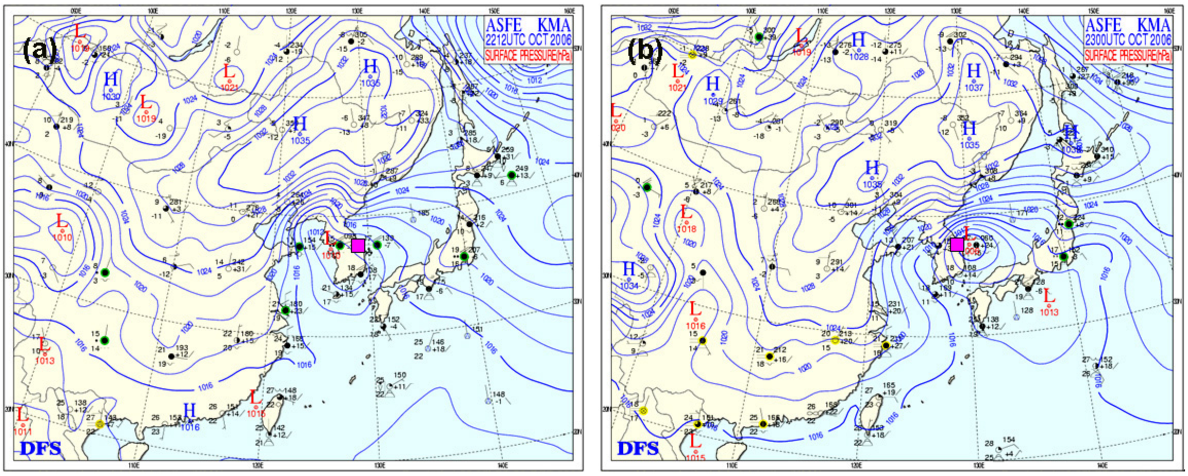

Fig. 2: Surface weather maps at (a) 2100 LST, October 22, 2006 and (b) 0900 LST, October 23 (three hours before windstorm occurrence at Gangneung city in Korea). A small box near the centre of weather map denotes Gangneung city and the low pressure centre moved from west coast toward east coast of Korean peninsula, enhancing isobaric displacement near Gangneung city and resulting in easterly wind storm.

After 0900 LST, October 23, the low pressure centre slowly moved the south-eastern coast of Korean peninsula. When wind storm was detected near Gangneung city at 1200 LST, the low pressure centre just passed by Gangneung city, showing denser isobar and causing strong surface wind. After 2100 LST, it stayed in the southern Honshu of Japan, the city was entirely out of the strength of low pressure system. As the low pressure system passed by the eastern mountainous coast, the low pressure system was developed, decreasing 4 hPa and surface wind was intensified, that is, cyclogenesis. Driving mechanism for the formation of cyclogenesis will be discussed in detail, in later section.

Wind field: As shown in Figs. 3a and 3b, before windstorm was not detected in the eastern mountainous coast of Korean peninsula at 2100 LST, October 22, the low pressure induced north-westerly wind in the land side from the coast near Gangneung city and observed winds at Gangwon Meteorological Administration in the downtown of the city was 0.4 m/s with a 300^0. On the other hand, wind in the coastal sea was still week with south-easterly wind. In the inland, these kinds of wind tendency continued to be under slightly changes of wind speeds of 0.4 ~ 1.8 m/s and directions of 250^0 ~ 360^0 until 0300 LST, October 23 (Figs. 3c and 3d). Numerically simulated surface winds at the city were also north-westerly wind and south-easterly wind in the coastal sea and offshore. Wind speeds at K were south-easterly wind of 0.4m/s in Fig. 4b and north-westerly alongshore wind of 1.1 m/s in Fig. 4d, showing the increase of wind speed by extension of strong wind band along the coast southward under wind shift, respectively.

As the low pressure system was intensified in the East Sea at 1200 LST, October 23, narrow displaced isobaric contours appeared on a surface weather map and produced a strong wind in the mountain and coastal region (Fig. 2b). Since the low pressure centre had already passed trough the study area toward the south-eastern coast of Korean peninsula at this time, the previous south-easterly wind in the coastal sea changed into north-westerly wind along the coast and the wind much strengthened to more than 15.5 m/s at the city (K) by more extension of strong wind band along the coast southward (Figs. 4a and 4b).

The strong wind band southward along the coast at 1200 LST was much bigger than previously its southward extension at 2100 LST, October 22. Six hours later, at 1800 LST, October 23 in Fig. 4c and d, the extension of strong north-westerly wind band toward south along the coast was prohibited by the wind shift from north-westerly wind into north-easterly wind, resulting in the decrease of wind speed. At that time, observed wind speed at the city was 7.6 m/s as same as numerically simulated speed in the fine-mesh domain as shown in Fig. 4d.

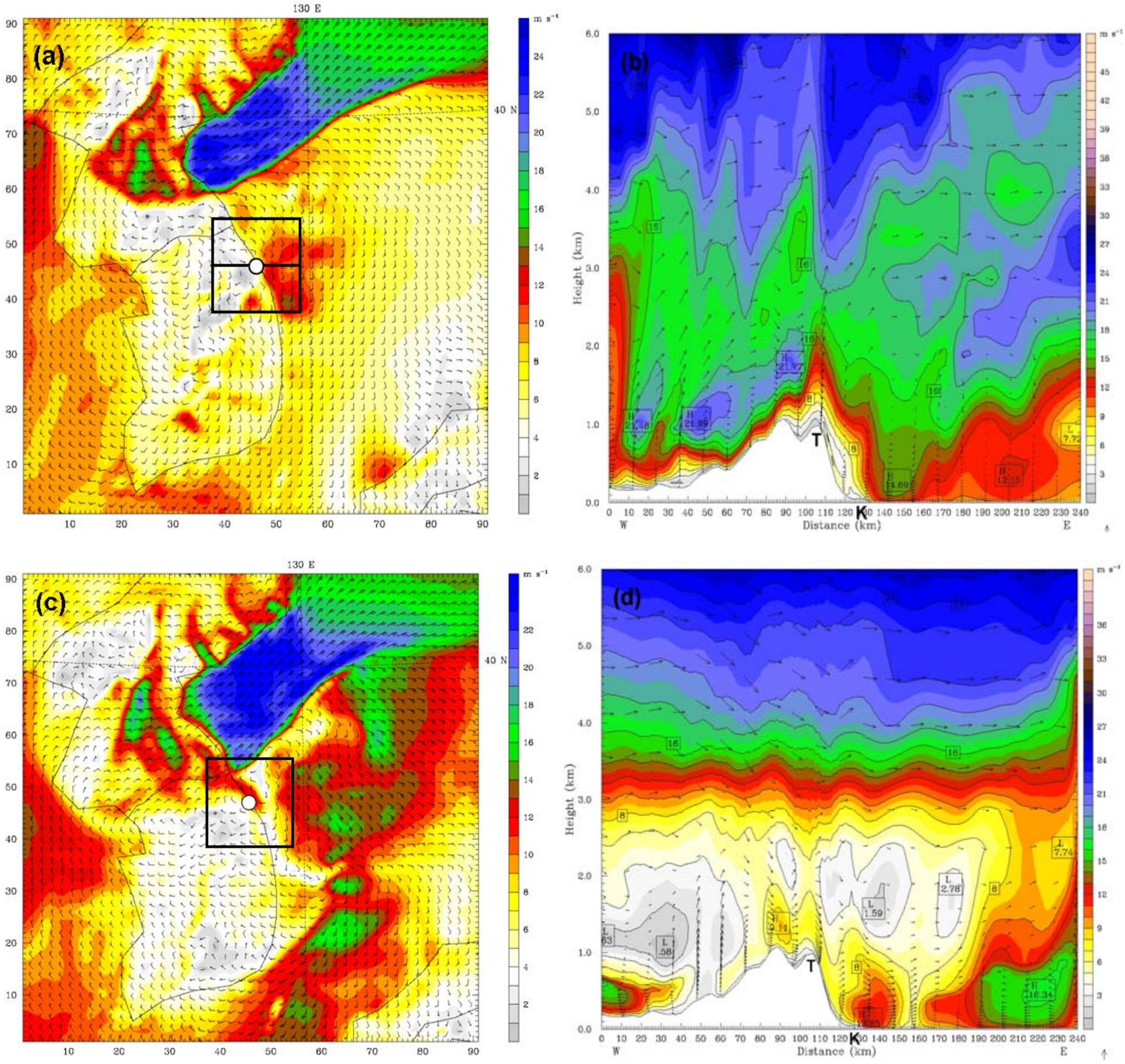

Fig. 3: (a) Surface wind (m/s; full bar-5m/s) in the second coarse-mesh domain with a 9 km horizontal resolution and (b) vertical profile of horizontal wind in a box of (a) (fine-mesh domain with a 3 km horizontal resolution) at 2100 LST, October 22. (c) and (d) are as shown in (a) and (b), except for 0300 LST, October 23. In (a), a small circle denotes Gangneung city, and T and K in (b) denote Mt. Taegulyang (865 m) and Gangneung city (20 m). Wind speeds at K were south-easterly wind of 0.4m/s in (b) and north-westerly alongshore wind of 1.1 m/s in (d), showing the increase of wind speed by extension of strong wind band along the coast southward under wind shift, respectively.

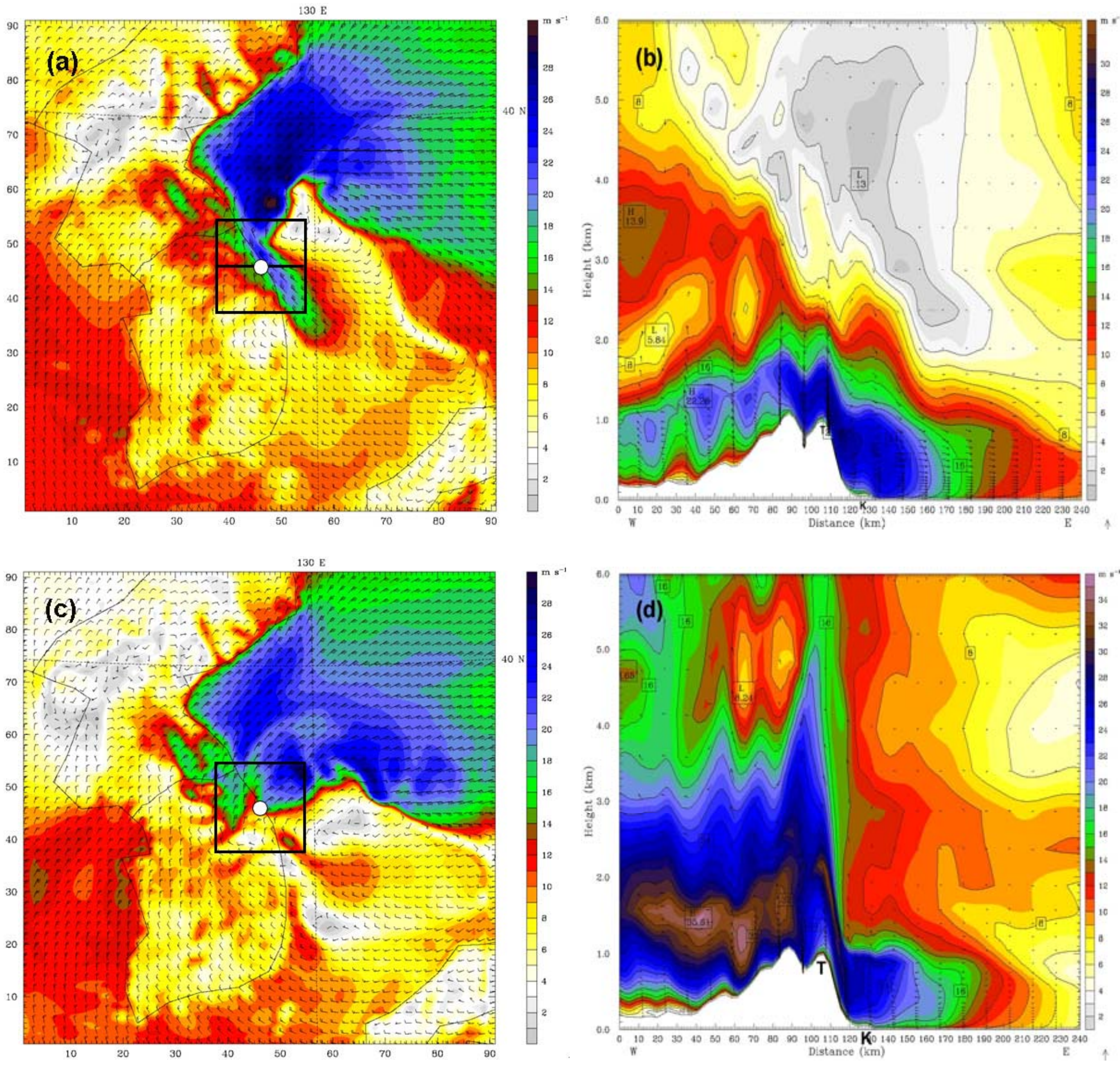

Fig. 4: As shown in Fig. 3, except for (a) and (b) at 1200 LST, October 23 and (c) and (d) at 1800 LST, respectively. T and K denote Mt. Taegulyang and Gangneung city. Wind speeds at K were north-westerly wind (alongshore wind) of 15.5 m/s in (b), showing the increase of wind speed by extension of strong wind band along the coast southward under wind shift, but north-easterly wind of 7.6 m/s in (d), showing weakness of wind speed by prohibiting strong wind band southward, respectively.

In order to investigate the effect of strong wind in the upper level on the formation of wind storm near the ground surface, streamline at 850 hPa level (approximately 1.5 km height above the ground surface) was analyzed. The streamline at 2100 LST, October 22 was located in the western coast of the Korean peninsula, major streamline band at 850 hPa level depicted a circle in the Korean peninsula (Fig. 5a). Gangneung city was under the influence of a small streamline circle, which passed by the Yellow Sea and southern inland of the Korean peninsula, showing cyclonic circulation like north-westerly, southerly and north-easterly flows. Colorful dark area with isotach greater than 25 kts was located in the northern Korean peninsula and Gangneung city was deviated from strong wind sector, which implied the wind speed at the city was less than 25 kts, resulting in no occurrence of windstorm expected in the study area. However, at 0900 LST, October 23, the city was located in both major streamline band in Fig. 5b and colorful dark area of strong wind sector. Thus, as wind speed at the city was greater than 25 kts, momentum transport from the upper level toward the ground surface could result in the occurrence of windstorm near the ground surface around 1200 LST.

Thus, after 2100 LST, October 22 until 0600 LST on October 23, synoptic south-easterly wind changed into north-westerly in the mountainous coastal region. Simultaneously, as synoptic north-westerly westerly wind blew over the mountain terrain with steep dropoff in elevation (orography) and began to move down along the eastern slope of the mountain, it was associated with mountain-land breeze generated by both nocturnal cooling of the ground surface and steep mountain terrain, resulting in an intensified strong downslope wind like Katabatic wind or windstorm. Thus, this downslope windstrom produced the propagation of internal gravity waves with a hydraulic jump motions bounding up and down over the coastal basin and sea (Figs. 4a and 4b). Calculated Froude numbers were in the range of 0.9 ~ 1.2 near the mountain top and 1.6 ~ 1.8 in the downwind side (Gangneung coastal city), respectively.

Furthermore, when this wind storm passes by the coastal basin, much shallower nocturnal surface inversion layer than daytime convective atmospheric boundary layer could also make a contribution of the increase of surface wind speed. As air flew under the shrunken nocturnal surface inversion could be fast, the shrunken layer could be significant to induce the formation of windstorm. In general, after 0600 LST, easterly sea breeze starts from the offshore side toward the coastal inland due to air temperature contrast over between the ground and sea surfaces, under clear sunshine state and in the study area, convective atmospheric boundary layer is developed up to 800 m ~ 1.5 km depth in the land and thermal internal boundary layer is up to 200m ~ 300 m depth in the coastal inland. However, the coast region was under thick clouds, of which base was lower than 600m height from 2100 LST, October 22 to whole day of October 23. Under this situation, it was very difficult to expect the occurrence of easterly sea breeze, and the north-westerly downslope wind could not be prohibited by easterly sea breeze, resulting in the consistency of strong westerly wind storm. Under cloudy condition, the expansion of atmospheric boundary layer could not occur, showing still shallow atmospheric boundary layer and inducing a strong channel flow and finally resulting in a strong wind storm until 1200 LST in Figs 4a and 4b.

As shown in Fig. 4c and 4d, as wind along the eastern coast region near Gangneung city after 1200 LST until 1800 LST, October 23 was shifted from north-westerly wind into north-easterly wind, the increase of wind speed by extension of strong wind band along the coast southward was prohibited, resulting in weakness of wind speed and showing wind speed of 7.6 m/s in Fig. 4d, respectively.

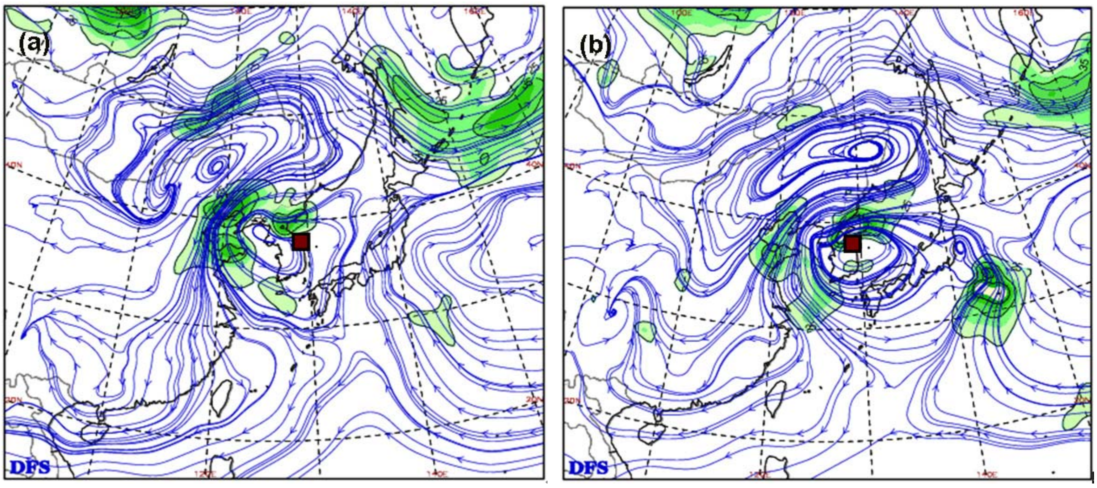

Fig. 5. (a) Streamline and isotach at 850 hPa level at 2100 LST October 22, 2006 and (b) 0900 LST October 23 (three hours before windstorm occurrence at Gangneung city in Korea). Thin line and colorful dark area denote streamline and isotach greater than 25 kts. A small box denotes Gangneung city. Wind speed near Gangneung city in (a) was less than 25 kts (no occurrence of windstorm), while the speed in (b) was greater than 25kts (occurrence of windstorm).

Response of vorticity, 500 hPa height change, and 850 hPa temperature change to wind field: The investigation on the effect of relative vorticity at 500 hPa level (about 5.5 km height) on the development or the decay of wind storm in the eastern coastal region of Korea had been performed for the study period. It has been known that positive relative vorticity (ζ; 10^{-5}/sec) advection at 500 hPa level is a maximum above the surface low, while negative relative vorticity advection is strongest above the surface high[18]. Convergence of air parcels occurs in the region of positive relative vorticity depicting a cyclonic flow by cold low at 500 hPa level and the merged cold air parcels moved toward the ground surface, resulting in their merging into the ground surface. On the other hand, divergence of air parcels occurs in the region of negative relative vorticity at 500 hPa and the air parcels from the ground surface moved upward to 500 hPa level.

At 2100 LST, October 22 (12 hours before the occurrence of wind storm at Gangneung city), the centre of maximum positive vorticity with a downward motion from 500 hPa level toward the ground surface was located in the Bohai Sea in the northern Yellow Sea. This time, Gangneung city was in the positive vorticity state area of 4.5 x10^{-5}/sec, which caused strong downward motion of air parcels from the 500 hPa level toward the ground surface, resulted in the shrunken of atmospheric depth and surface wind speed increased in the city. On the other hand, at 0900 LST, October 23, three hours early than the occurrence time of wind storm at Gangneung city, maximum positive vorticity with a value of 12 x 10^{-5}/sec could strongly induce the strong downward motion of cold air from 500 hPa level toward the ground surface. Thus, the downward motion of cold air caused cooling of air parcels at 850 hPa level (about 1.5 km height) and resulted in a decreasing rate of air temperature with - 5^0C/day. The cold air further moved to the ground surface and resulted in the shrunken atmospheric depth.

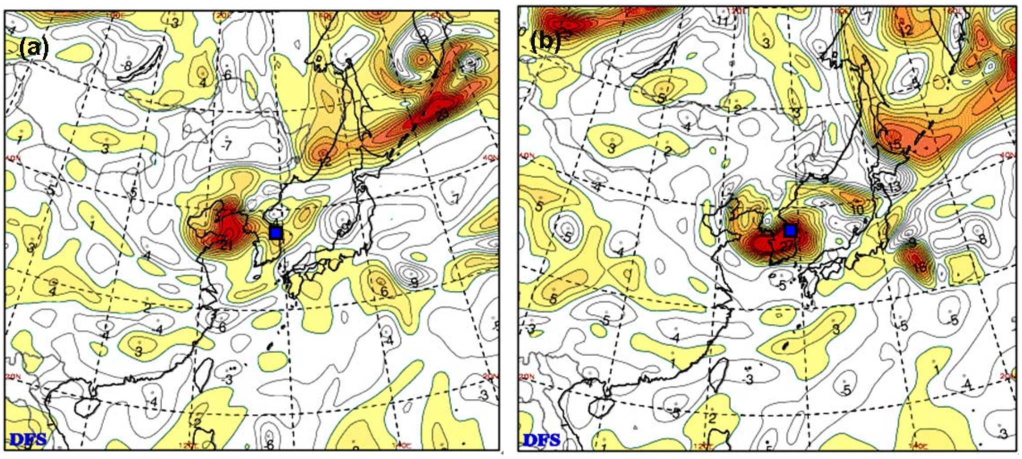

Fig. 6: Relative vorticity (10-5/sec) at 500 hPa at (a) 21 LST, October 22, 2006 and (b) 09 LST, October 23 (three hours before windstorm occurrence at Gangneung city in Korea). White area denotes negative vorticity (upward motion) and yellow-red area, vice verse. A small box denotes Gangneung city. As the centers of maximum positive vorticity inducing downward motion from 500 hPa (about 6 km height toward the ground surface and maximum negative geopotential tendency at 500 hPa level) inducing the shrunken atmospheric depth approached from Bohai in the left of Korean peninsula toward Gangneung city in the eastern coast of Korea near noon, October 23, surface wind should be more intensified, due to the downward of cold air toward the ground surface and the compressed lower atmospheric depth.

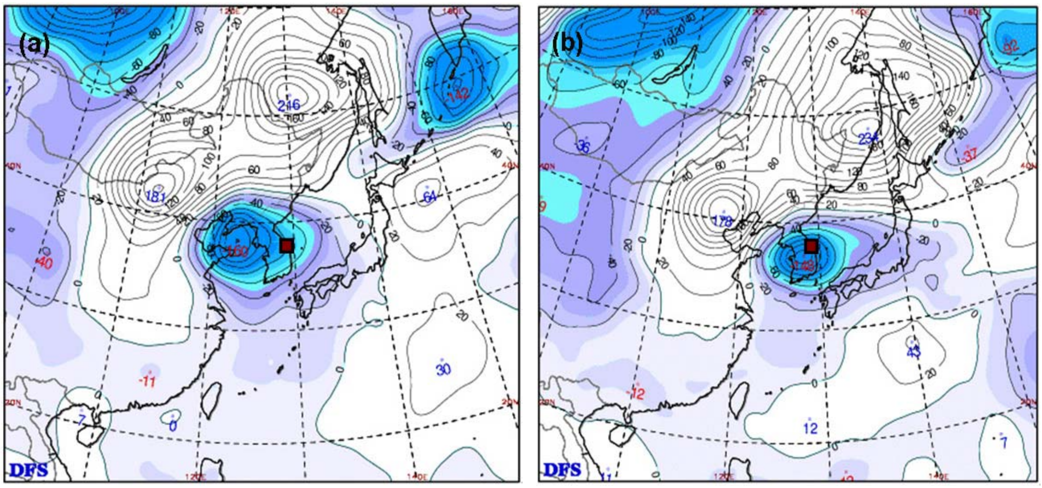

Fig. 7: 500hPa height change for 24 hours (m/day) called Geopotential height tendency (∂Φ/∂t; m/day) at (a) 2100 LST, October 27, 2003 in the expansion (+ 50m/day) and (b) 0900 LST, October 28 in the shrunken (-160m/day). Shade area denotes the decrease of geopotential height tendency, which implies shrunken of atmosphere and white one, vice verse. A small circle indicates Gangneung city.

Another driving mechanism was applied to explain on the formation wind storm. Temporal variation of geopotential height at 500 hPa level for 24 hours, called geopotential tendency (∂Φ/∂t; m/day) indicates atmospheric depth at 500 hPa to the ground surface to be vertically shrunken or expanded. The region of negative geopotential tendency implies the area of vertically shrunken atmospheric depth from 500 hPa to the ground surface, while the region of positive geopotential tendency produces the expansion of atmospheric depth. According to Bernoulli theory[22], fluid velocity in a channel is inversely proportional to vertical cross sectional area. Thus, much shrunken atmosphere in a certain area produces a strong channel flow, resulting in increasing a possibility of wind storm formation and vice versa.

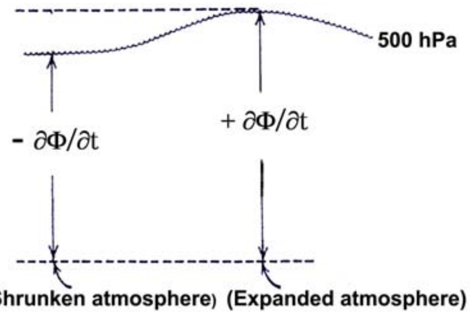

Fig. 8. Schematic profile of 500 hPa height change for 24 hours (i.e. geopotential tendency (∂Φ/∂t; m/day)).

At 2100 LST, October 22, before we had wind storm at Gangneung city, negative geopotential tendency of – 80 m/day was detected in the study area, where the atmospheric depth between two levels should be shrunken vertically and the narrow depth of atmosphere could induce surface wind to be intensified in the coastal region (Figs. 3a, 3b and 7a). This situation continued to be until 0300 LST, October 23. As time went on, the magnitude of negative geopotential tendency at 1200 LST, October 23 (occurrence time of wind storm) decreased up to – 140 m/day in the study area, where the atmospheric depth should be vertically much shrunken and more narrow depth of atmosphere than one at 2100 LST, October 22 could produce more intensification of surface winds in the coastal region (Figs. 4a, 4b and 7b). Thus, these kinds of atmospheric processes of downward motion by strong positive vortcity at 500 hPa level, much cooling of air parcels at 850 hPa level, merging of streamlines with higher speed more than 25 kts of isotach at 850 hPa level and negative geopotential tendency for 24 hours at 500 hPa level near the study area could generate a strong channel flow and induce the formation of strong surface wind speeds more than 25 m/s in Mt. Taegulyang and 15.5 m/s at the downwind side, Gangneung city, resulting in wind storm (Figs. 4a and 4b, 5b, 6b, 7b, 8b).

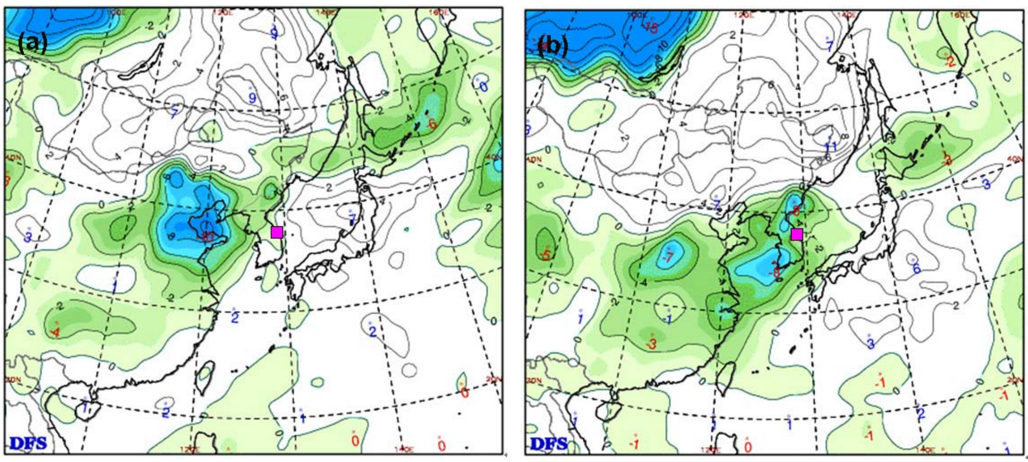

Fig. 9. 850 hPa temperature change for 24 hours (∂C/∂t; C^0/day) at (a) 2100 LST, October 22, 2006 before the occurrence of windstorm in the Gangneung city and (b) 0900 LST, October 23, around the occurrence of windstorm. A small box denotes Gangneung city and dark colorful and white areas denote cooling and warming areas, respectively.

At 1800 LST, October 23, north-westerly wind was shifted into north-easterly wind in the coastal region and became weak (Figs. 4c and 4d). At the same time, Gangneung city was under negative vortcity at 500 hPa level, which induced upward motion of air parcels from the ground surface into the upper level (500 hPa level). Strong wind band with higher than 25 kts on streamline was also away from the city and surface wind speed at the city became moderate wind. The city was under positive geopotential tendency, which induced the expansion of atmospheric depth at 500 hPa level and air temperature variation for 24 hours at 850 hPa level for 24 hours had also positive value. Thus, these kinds of atmospheric circumstance induced the surface wind in the city to weaken.

In addition, when the air parcel has passed over the mountain barrier, the air column has returned to its original depth and the air parcel in the south of its original latitude. Thus, as Coriolis parameter, f with a function of latitude will be smaller, the relative vorticity from potential vorticity conservation equation must be positive, resulting in the air trajectory to have cyclonic curvature. Thus, steady westerly wind blowing over a mountain barrier can produce a cyclonic flow pattern to the east of the barrier, following by a trough and a ridge downstream like a wavelike trajectory in the x, y plane, As soon as synoptic westerly wind begins to pass over Mt. Taegulyang barrier, the strong westerly downslope wind enforced by combining with mountain-land breeze depicts a cyclonic flow pattern, resulting in cyclogenesis in the coastal sea and a good condition for the formation of a wind storm.

Comparison of observed and calculated winds: After 48 hours of numerical simulation with FNL meteorological data sets, results of calculated winds were compared with observed ones at Gangwon Regional Meteorological Administration in Gangneung city, Korea. The general tendency of calculated winds well matches with those of the observed, without much discrepancy of each other (Table 1).

Table 1. Comparison of calculated wind (m/s) and direction (^{0}; ( )) to observed one at (a) Gangneung city from October 22-23, 2006.

Date	Comparison	1500	1800	2100	0000	0300	0600	0900	1200	1500	1800	2100
(a) 10/27	Observed	1.5	0.1	0.4	0.6	1.1	1.2	9.6	15.5	8.4	7.6	6.8
		(180)	(360)	(360)	(250)	(320)	(230)	(360)	(340)	(340)	(360)	(340)
~10/28	Calculated	0.5	4.5	0.6	1.3	1.6	5.2	10.8	16.5	9.0	8.2	7.2
		(180)	(350)	(360)	(250)	(320)	(230)	(360)	(340)	(340)	(360)	(346)

Conclusion

The generation of windstorm was investigated in the eastern mountainous coastal region of Korea, Gangneung city for two days. Before wind storm existed in the study area, positive relative vorticity of 4.5 x 10^{-5}/sec at 500 hPa level induced downward motion of cold air from the upper level toward the ground surface, showing a decreasing rate of air temperature of - 1 ^{0}C/day at 850 hPa level. Simultaneously, negative geopotential tendency of - 80 m/day lay on the study area caused the atmospheric depth of 500 hPa level to the ground surface be much shrunken vertically, resulting in the increase of a channel flow, that is, the increase of wind speed. .

When wind storm occurred, the magnitude of positive relative vorticity at 500 hPa level increased to 12 x 10^{-5}/sec at 500 hPa level induced much strong downward motion of cold air from the upper level toward the ground and caused a decreasing rate of air temperature of - 4 ^{0}C/day at 850 hPa level. Negative geopotential tendency also reached -140 m/day, which caused the atmospheric depth of 500 hPa to be much shrunken vertically, resulting in stronger surface wind speed up to 15.5 m/s. As synoptic northwesterly wind blew over the mountain terrain with steep orography toward the downwind coastal city was associated with mountain-land breeze by both nocturnal cooling of the ground surface and steep mountain terrain, it could be an intensified strong Katabatic wind. In addition, a strong northwesterly wind passed over the steep mountain barrier, the wind depicted a cyclonic flow, resulting in intensification of low pressure system, that is, cyclogenesis in the downwind coastal sea. Furthermore, when this wind storm passes by the coastal basin, much shallower nocturnal surface inversion layer than daytime convective atmospheric boundary layer could also make a contribution of the increase of surface wind speed. As air flew under shrunken nocturnal surface inversion could be fast, the shrunken of atmospheric boundary depth could be significant to induce the formation of windstorm. Under cloudy weather condition during the day, the maintenance of shrunken atmospheric boundary layer existed due to weak development of convective boundary layer under thick clouds, resulting in the formation of wind storm of 25 m/s at the top of the mountain in the west of the coastal city and 15.5 m/s in the coast near noon.

Acknowledgement

This work was funded by the Korea Meteorological Administration Research and Development Program under Grant CATER 2006-2308-"Generation mechanism and prediction of wind storm in the mountainous coast" in 2010 ~ 2011.

References

1. Jackson, P.L. and Steyn, D.G., Gap winds in a fjord, Part II: Hydraulic analog, *Monthly Weather Review*, 122, 2666-2676 **(1994)**.

2. Zangl, G., Stratified flow over a mountain with a gap, Linear theory and numerical simulations, *Quarterly Jpurnal of Royal Meteorological Society*, 128, 927-949 **(2002a)**.

3. Zangl, G., Orographic gravity waves close to the nonhydrostatic limit of vertical propagation, *Journal of Atmospheric Sciences*, 60, 2045-2063 **(2003)**.

4. Zangl, G., Gohn, A. and Geier, G., South foehn in the Wipp Valley – Innsbruck region: Numerical simulations of the 24, October 1999 case (MAP-IOP 10), *Meteorology and Atmospheric Physics*, 86, 213-243 **(2004)**.

5. Hunt, J.C. and Simpson, J.E., Atmospheric boundary layer over nonhomogeneous terrain, In Engineering Meteorology (Plate, E.J., ed.), 269-318, Elsevier, Amstrerdam **(1982)**.

6. Arya, S.P., Introduction to micrometeorology, Academic Press, 307 pp **(1988)**.

7. Choi, H., Persistent high concentration of ozone during windstorm conditions in southern Korea, *Meteorology & Atmospheric Physics*, 87, 93-107 **(2004)**.

8. Choi, H., Extreme cold sea outbreak near Cheju Island, Korea by strong wind and atmospheric pressure change under typhoon Rusa, *Disaster Advances*, under print **(2009)**.

9. Anderson, O.J., The katabatic wind field and nocturnal inversions in valleys: A 2-dimensional model (Report No. 1),

Department of Meteorology, University of Bergen, Norway **(1981)**.

10. Whiteman, C.D., Observations of thermally developed wind system in mountainous terrain. Atmospheric Processes over complex terrain, Meteorological Monograph, No. 40, American Meteorological Society, 5-42 **(1990)**.

11. Pielke, R.A., Mesoscale meteorological modeling, Academic Press, 612 pp **(1984)**.

12. Eom J., Analysis of the internal gravity wave occurrences of April 19, 1970 in the Midwest, *Monthly Weather Review*, 103, 217-226 **(1975)**.

13. Anthes, R.A., Kuo, Y.H., Benjamin, S.G. and Li, Y.F., The evolvation of the meso-scale environment of severe local storms: Preliminary modeling results, *Monthly Weather Review*, 110, 1187-1213 **(1982)**.

14. Bosart, L.F. and Seimon A., A case study of an unusually intense atmopsheric gravity wave, *Monthly Weather Review*, 116, 1857-1886 **(1988)**.

15. Reed, R.J., Cyclogenesis in polar air stream, *Monthly Weather Review*, 107, 38-52 **(1979)**.

16. Reed, R.J. and Albright, M.D, A case study of explosive cyclogenesis in the Eastern Pacific, *Monthly Weather Review*, 114, 2297-2319 **(1986)**.

17. Durran, D.R., Another look at downslope windstorms, Part I: On the development of supercritical flow in an infinitely deep, continuously stratified fluid, *Journal of Atmospheric Sciences*, 43, 2527-2543 **(1986)**.

18. Holton, J.R., An introduction to dynamic meteorology, fourth edition, Academic Press, 535 pp **(2004)**.

19. Cheung, T.C. and Chan, P.W., Improving wind and rain simulations for tropical cyclones with the assimilation of Doppler radar data, Reprint 835, 10th Annual WRF Users' Workshop, 23-26 June 2009, Boulder, CO, USA **(2009)**.

20. Choi, H., Choi, D.S. and Choi, M.S., Heavy snowfall by orography and wind shift in cold front crossing Korean eastern coast, *Disaster Advances*, 2(4), 48-60 **(2009)**.

21. Reed, R.J. and Albright, M.D, A case study of explosive cyclogensis in the Eastern Pacific, *Monthly Weather Review*, 114, 2297-2319 **(1986)**.

22. Roberson, J.A. and Crowe, C.T., 1976, Engineering fluid mechanics, second edition, Houghton Mifflin Company, 149-159 **(1976).**