Cold Sea Outbreak near Cheju Island under Strong Wind and Atmospheric Pressure Change by Typhoon Rusa

Choi Hyo *
Department of Atmospheric Environmental Sciences, Gangneung-Wonju National University, Gangneung 210-702, KOREA
du8392@hanmail.net

Abstract

Cold sea water outbreak after the passage of Typhoon Rusa across Cheju Island in the south sea of Korea was investigated using GMS-MCSST satellite image of sea surface temperature (SST) distribution and GMS-Infrared image of cloud and a three-dimensional non-hydrostatic numerical model - Weather Research & Forecasting Model (WRF) version 2.2 with FNL initial meteorological data from 0000 UTC, August 30 through 12 UTC, September 1, 2002. Before typhoon on August 29, northeasterly sea surface winds in the vicinity of Cheju Island were moderately less than 5 m/s and SST was 29^{0}C. After the typhoon passed across the island after 1500 LST on August 31, cyclonic surface winds were more than 12 m/s and the SST in the coastal sea of the island was remarkably changed into 17^{0}C, showing a 12^{0}C decrease. A cyclonic wind of typhoon and a fast movement of typhoon caused a divergence of ocean current by upwelling (Ekman pumping) process by which deep sea cold water was brought to the sea surface and outward spreading of cold water, resulting in colder water outbreak near the island, especially its observation behind the typhoon on its track. Simultaneously, on the typhoon track, negative minimum geo potential tendency of 500 hPa for 24 hours, was detected in typhoon eye and its vicinity where the shrunken of atmosphere existed in the negative area. On the other hand, a positive maximum value of geo potential tendency of 256 m/day was detected behind the moving typhoon, where the atmospheric depth should be maximum expanded and the expansion of the atmosphere induces ascending of sea surface, resulting in upwelling of deep sea cold water into the sea surface and extreme low temperature distribution in the southwestern coastal sea of Cheju Island.

Keywords: Cold sea water outbreak, Sea surface temperature, GMS-MCSST satellite images of SST, GMS-Infrared image of cloud, WRF model-2.2, Geo potential tendency of 500 hPa.

Introduction

During the movement of a typhoon from the origin of its occurrence, destructive hazards such as storm surges, strong wind, cold water outbreak due to sea surface temperature variation, torrential precipitation and flood by typhoons have been frequently reported in summer season in the north-eastern Asia. The term of typhoon is used in the north-western Pacific Ocean, while it is called hurricane in the North America, willy willy in Australia and severe tropical cyclone in the rest of the world[1]. It is also an intense vertical storm and an axisymmetric vortex about the vortex center that develop over the tropical oceans in regions of very warm surface water[2]. Typically typhoons or hurricanes have radical scales of several hundred kilometers and bring about hazardous weather including strong winds and heavy rain associated with the outer rain bands[3-6].

The term of typhoon is classified into three categories as tropical depressions with maximum sustained surface winds less than 17 m/s and tropical storm with ones reaching 17 m/s and typhoon with ones more than 33m/s respectively. As typhoon is basically a low pressure system without front systems, its development energy comes from evaporation of water particles from sea surface, condensation from convective clouds and deepening atmospheric pressure and it diminishes the deficit of supply of water vapor passing through the island or inland area.

Based on the cloud structure, a mature typhoon can roughly be divided into three regions such as the eye, the eye wall and the spiral rain bands[2]. The typhoon eye is roughly circular and is found at the centre of a typhoon. The air inside the eye is sinking. Its size varies from below 10 km to over 200 km across, but most are about 30 to 60 km in diameter. The eye is the region of lowest surface pressure and winds are comparatively light with the fair weather inside the eye. The eye is surrounded by the eye wall, a roughly circular ring of thick clouds. However, the eye wall has very deep convection and is the area of highest surface winds and heavy rain in the typhoon. Outside the eye wall, there are the spiral rain bands.

Crease[7] explained the response of the ocean to a moving hurricane using a delta function and Geisler[8] and Gill[9] clearly showed the hurricane-induced upwelling observed a few days after the passage of a hurricane across the Gulf of Mexico. Gill[9] explained that on the storm track, Ekman transport takes place away from the path of the storm center, resulting in horizontal displacements of particles in the surface layer which can amount to some tens of kilometers in the case of a hurricane. Consequently, water near the axis of the storm is up welled, possibly by some tens of meters vertically. Price[10, 11] and Greatbatch[12] had developed models on the effects of a hurricane that include both mechanical and thermal effects, which showed lee waves, upwelling behind the storm, removal of heat from the ocean and effects of mixed layer deepening due to stirring by the storm.

Regarding the presence of cold waters in the vicinity of a moving hurricane, Knauss[13] insisted that cyclonic surface winds of a hurricane resulted in upwelling of bottom colder waters into the sea surface, because the surface wind stress can results in surface divergence and upwelling in the open ocean by the changes in the wind speed or direction. The cyclonic wind of a hurricane resulted in upwelling and colder surface water has been observed in the wake of a hurricane. Upwelling is also an important process by which deep, cold, nutrient-laden water is brought to the sea surface, usually by the wind divergence or coastal winds along the coast pushing sea waters away from the coast toward the right hand side. Rotunno and Emanuel[14] also explained an air-sea interaction theory for tropical cyclones using a non-hydrostatic axisymmetric numerical model.

Since a typhoon Rusa (TY21W) with maximum sustained winds of 65 knots (gusting to 80 knots) had landfall at Goheung coastal city in the south of Korean peninsula, there were 113 fatalities and 71 missing in South Korea and a total of 88,625 people in all were evacuated, showing the most powerful typhoon to hit South Korea since 1959[15]. The main purpose of this study is to investigate cold water outbreak in the vicinity of Cheju Island in the south sea of Korea, after the passage of the typhoon across the island around August 31, 2002, using GMS-MCSST satellite image of sea surface temperature distribution and GMS-Infrared image of cloud and WRF version 2.2 model with FNL initial meteorological data, due to the occurrence of upwelling by a convergence of air flow at the sea surface and resultantly a divergence of ocean flow, resulting in upward vertical flow of colder sea water to the sea surface.

Study Area

The study area indicating a box in fig. 1 covers a part of the South Sea of Korea near Cheju Island and the southern part of Korean peninsula which are affected by the Yellow Sea Warm Current (YSWC) in the west of the study area and the East Korea Warm Current (EKWC) in the east. The YSWC and EKWC are branch currents of Kuroshio Warm Current, which is a strong western boundary current in the western north Pacific Ocean and Kuroshio current begins off the east coast of Taiwan and flows northeastward past Japan, merging with the easterly drift of the North Pacific Current. The adjacent sea of Cheju Island is sallow less than 100 m in the west, north and east of the box domain and relatively deep greater than 100 m to 300 m in the south. Cheju Island is the largest island with a bell shape topographical feature in Korea and the size of the island is 73 km from east to west, 41 Km from north to south in the shape of an oval. This island has an area of 1,845 km^2 with a circuit road of 182 km along the seashores and there is Mt. Halla in the center of the island, which was a volcano once rising 1,950 m above the sea level.

In summer, most of typhoons pass through this area reaching Korean peninsula. The island with a high mountain is strongly heated during the day favoring the development of upslope wind, which combines with valley wind from inland basin to the mountain top and sea breeze from the coast to the inland. On the other hand, during the night down slope wind combined with mountain wind and land breeze is dominant over the inland and coastal sea.

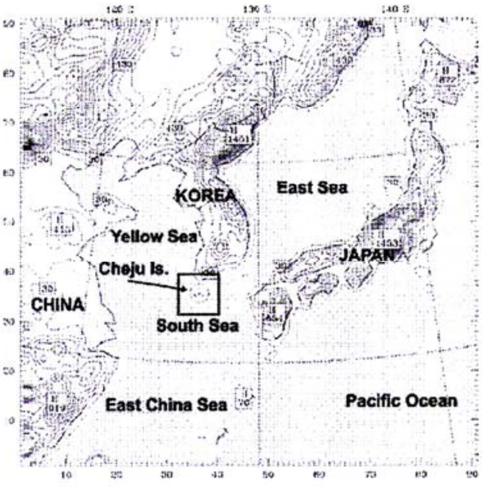

Figure 1: Location of study area near Cheju Island in the South Sea of Korea.

Numerical Method and Input Data

A three-dimensional, grid point Weather Research & Forecasting Model (WRF) version 2.2 model with a terrain following coordinate system was adopted for the generation of wind and 500 hPa height change for 24 hours near Cheju Island in the south sea of Korea. Numerical simulation using the model was carried out from 0000 UTC (Local Standard Time (LST) = 9h + UTC; 0900 LST), August 30 through 12 UTC, September 1, 2002. In the numerical simulation, one way, triple nesting process from a coarse-mesh domain to a fine-mesh domain was performed using a horizontal grid spacing of 27 km covering a 91 x 91 grid square in the coarse mesh domain and a 9 km interval also covering a 91 x 91 grid square in the second domain. The third domain through final nesting process consisted of a 3 km horizontal grid spacing again on a 91 x 91 grid square. NCEP/NCAR reanalysis FNL (1.0^0 x 1.0^0) data were used as meteorological input data to the model and were vertically interpolated onto 36 levels with sequentially larger intervals increasing with height from the surface to the upper boundary level of 100 hPa.

For the heat and moist budgets in the atmospheric boundary layer, the WSM 6 scheme was used for microphysical processes and the YSU PBL scheme for the planetary boundary layer. 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. For calculating 3 hours accumulated precipitation amount, a mixed phase of both ice and water was considered. Hourly archived wind, air temperature, relative humidity, cloud and geo potential tendency by Cheju Meteorological Office were used for the verification of numerical results of the meteorological elements. In addition, GMS-IR satellite images made by the Japan Meteorological Agency were used for chasing the track of Typhoon Rusa and obtaining cloud information.

Results and Discussion

Synoptic situation: Prior to the cold break outbreak event in the vicinity of Cheju Island, in the south sea of Korea in August 31, 2002, the precursor of a tropical depression (or tropical disturbance; later called typhoon TY21W, Rusa) with a central pressure of 950 hPa and maximum wind speed of 60m/s for one minute average and 40m/s for 10 minutes average was initially detected in the north-northeastern part at about 1,900 km away from Guam Island, the western Pacific Ocean 0230Z (0230 UTC; 1130 LST), August 22, 2002 (Fig. 2). Then the first warning on the tropical cyclone was given at 1200Z (2100 LST) August 22.

This tropical depression developed southwest of Wake Island at the eastern periphery of the monsoon trough. This tropical cyclone tracked northwest toward Okinawa for approximately 8 days before turning toward the Korean Peninsula. At 0600 UTC, August 31, it made a landfall near the Goheung city in the southwestern part of Korea (in the north of Cheju Island) with a maximum sustained wind speed of 32m/s and gusting to 40m/s. The typhoon was changed into extra-tropical cyclone as it passed by Korean east coast and entered the East Sea of Korea (or the Sea of Japan) on September 1. Typhoon Rusa passed by Cheju Island after 1700 LST on August 31. Synoptic scale southeasterly and easterly winds were detected before the typhoon passage across the island, while northwesterly and westerly winds were after the typhoon passage (Fig. 3).

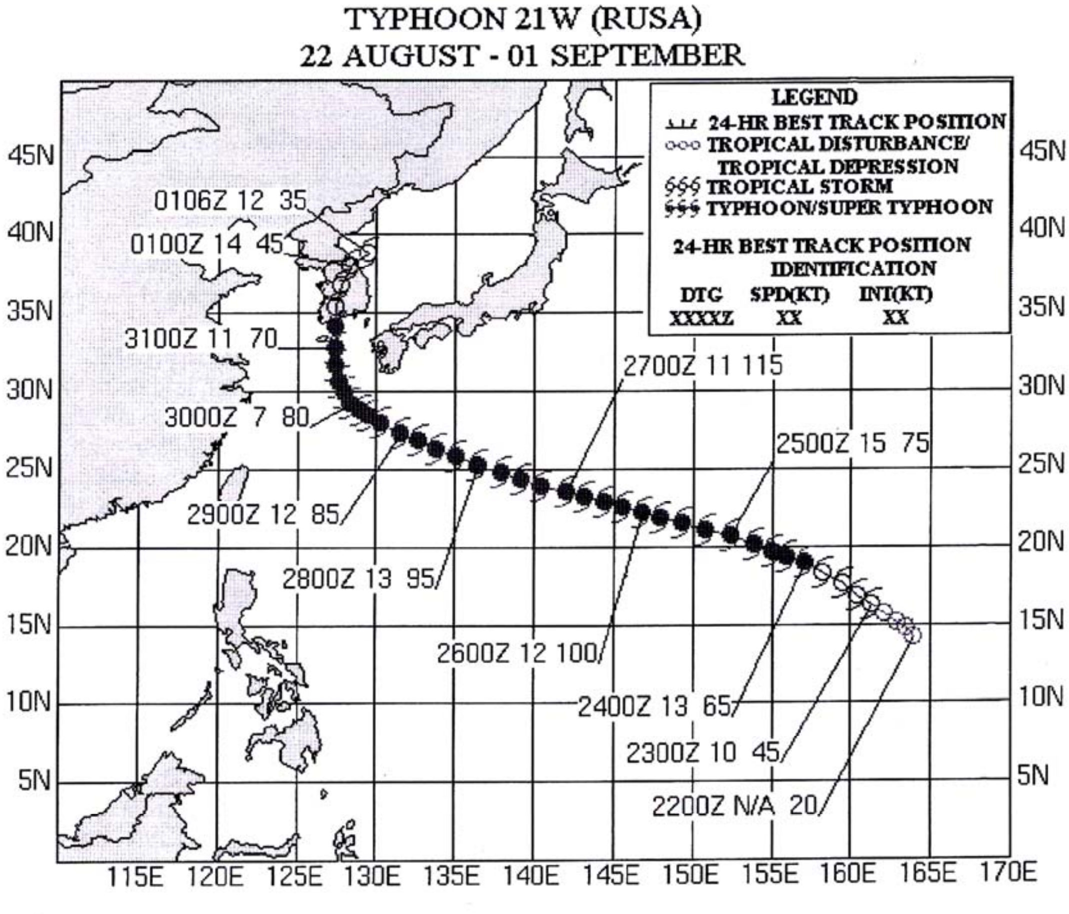

Figure 2: Track of typhoon Rusa (TY 21W) from August 22 through September 1, 2002

Cold sea water outbreak: On August 29, 2002, sea surface temperature was 29^0C, prior to cold water outbreak event in the vicinity of Cheju Island in the south sea of Korea and this area was not yet under the influence of typhoon Rusa (Fig. 4a). On the other hand, after the typhoon passage across Cheju Island on August 31, the sea surface temperature in the southwestern coastal sea reached 17^0C with a decrease of 11^0C than that on August 29 (Fig. 4b). The cold sea water outbreak near the sea of the island was mainly due to upwelling of deep sea colder water brought toward the sea surface by both strong marine surface winds generated by the typhoon and atmospheric expansion due to the increase of 500 hPa atmospheric pressure height change for 24 hours (i.e., positive geo potential tendency of 256 m/day) in the southern sea of the island behind the typhoon on the typhoon track (Figs. 5, 6, 7, 9) and its outward spreading in the vicinity of Cheju Island.

Upwelling of bottom colder water toward the sea surface can be generally produced by atmospheric forcing such as strong cyclonic wind and variation of atmospheric pressure influenced on the ascending of the sea surface in the open sea. Later, the response of the ocean to the atmospheric forcing is explained in sequence.

Wind field near Cheju Island under the influence of a moving typhoon: Sea is generally forced by the atmospheric disturbance like typhoon that moves across it and effects of variation of the Coriolis parameter with latitude are important in the deep sea. The response of the ocean to marine surface wind forcing is obtained by vertically averaging momentum equation. It is known that Ekman transport of sea waters causes away from the path of the tropical storm center, resulting in horizontal displacement of water particles in the sea surface layers that can amount to some tens of kilometers in the case of a hurricane or typhoon[9]. As a consequence, water near the axis of the storm is uplifted from the deep sea toward the sea surface, possibly by some tens of meters.

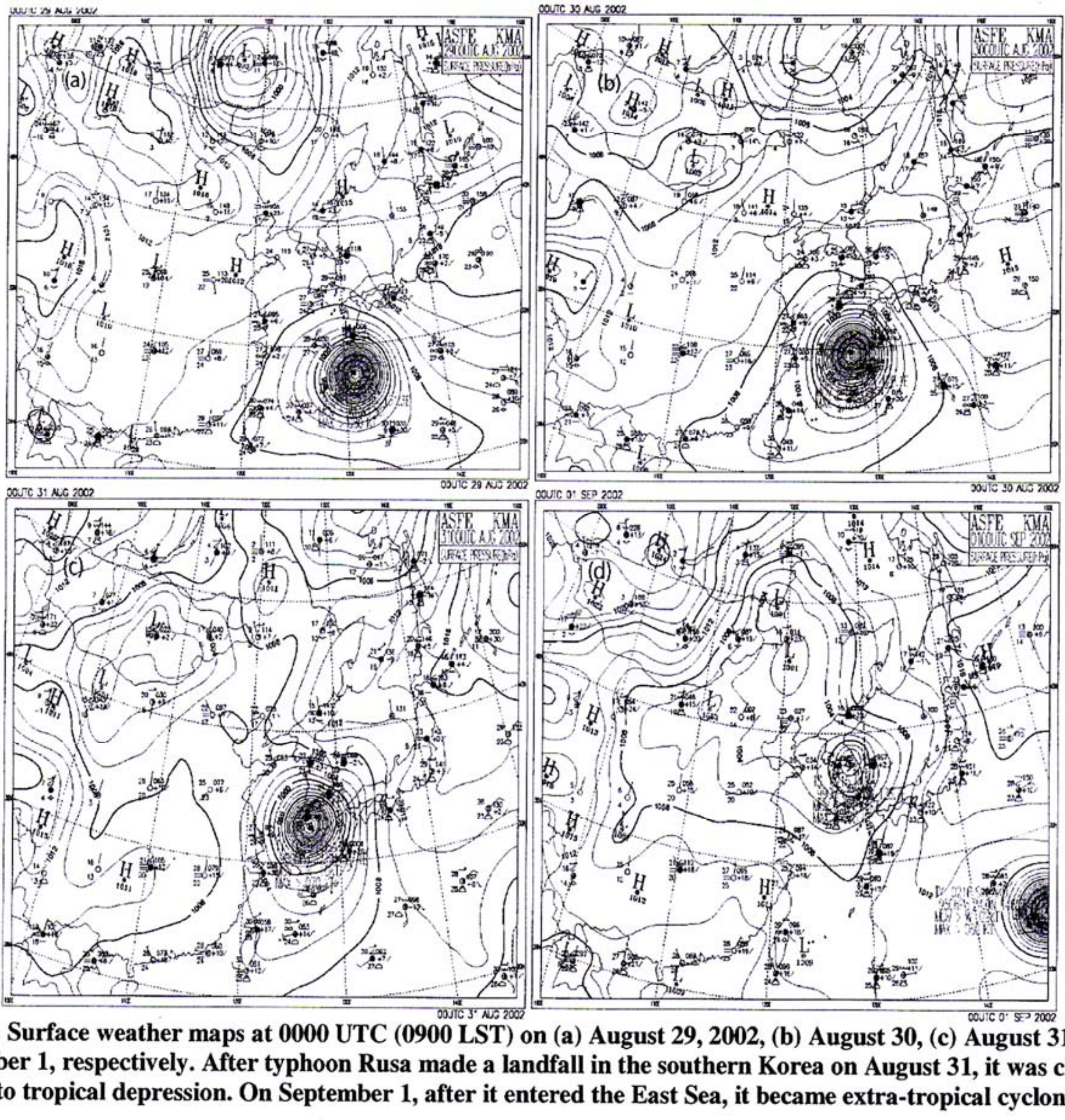

Figure 3: Surface weather maps at 0000 UTC (0900 LST) on (a) August 29, 2002, (b) August 30, (c) August 31 and (d) September 1, respectively. After typhoon Rusa made a landfall in the southern Korea on August 31, it was changed into tropical depression. On September 1, after it entered the East Sea, it became extra-tropical cyclone.

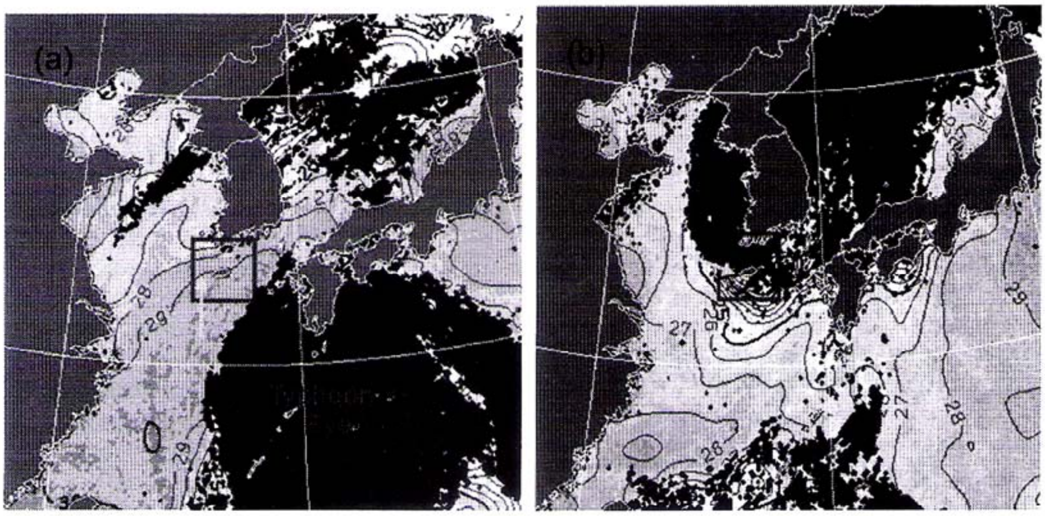

Figure 4: Daily mean of sea surface temperature by GMS-MCSST satellite images of Japan Meteorological Agency in (a) August 29, 2002 (29°C near Cheju Island before the typhoon passage) and (b) August 31 (17°C near Cheju Island shortly after the typhoon passage) respectively. Wide black area and red box denote cloud covered area and a fine-mesh domain of a 91 x 91 grid square with a 3 km horizontal grid near Cheju Island, Korea.

Using Ekman vertical displacement formula, Gill[9] and Leipper[16] calculated the hurricane-induced upwelling normal to the storm track under Coriolis parameter of 5 x 10^{-5} /s. Moving storm speed of 6 m/s, 40 m for the total upwelling during the passage of the hurricane was obtained and corresponding current speeds were strong around 0.5 m/s. Considering Gill's formula[9], moving speed of typhoon Rusa from August 30 before the typhoon passing by Cheju Island to August 31 shortly after its passage, in our case was 6.9 m/s ~ 7.2 m/s on the typhoon track and wind speed generated by typhoon was about 12m/s, it might be estimated for upwelling to be more than 50 m.

In general, as wind in a low pressure or outer band of typhoon shows a counter-clockwise motion (a cyclonic rotation) in the northern hemisphere due to the Coriolis force. Consequently the Ekmn transport in the atmospheric boundary layer is inward, bringing air masses in to fill the low and the associated vertical pumping velocity is therefore upward. The Ekman mass transport in the oceanic boundary layer is equal and opposite to that in the atmosphere. So there is an outward mass transport and upward pumping velocity in the ocean. In general, sea surface current direction is normal to wind direction and its speed is about 0.3 times of wind speed. Thus upwelling of colder water from the deep sea into the sea surface is brought usually by the wind convergence, because the wind convergence induces ascending of sea waters upward, resulting in this cold water to spread away from the wind convergence area outward showing divergence of current (Figs. 5 and 6).

In the coastal sea, coastal winds along the coast pushes sea waters away from the coast toward the right hand side. Price[10, 11] and Greatbatch[12] explained mechanical and thermal effects of hurricane by a model such as removing of heat from the ocean by hurricane and its redistribution within the ocean by the stirring action of the storm in addition to adjective effects and upwelling behind the storm, due to the fast movement of typhoon more than 6 m/s, wind speed more than 30 m/s generated by typhoon itself and latitudinal variation of Coriolis parameter and so on. According to upwelling of colder sea water to the sea surface, cold water is widely distributed and sea surface temperature behind a hurricane remains very low. Similar result of cold sea water outbreak behind the typhoon Rusa in the southwestern sea of Cheju Island, Korea was found on August 31 after the typhoon passage across the island in this study (Fig. 4b).

Before the typhoon passage across the island at 0900 LST, August 31, strong easterly winds of 13 m/s ~ 16 m/s prevailed in the northern coastal sea of the island in the fine-mesh domains (Fig. 5), while moderate easterly winds of 3 m/s ~ 8 m/s were detected in its southern sea of the island close to the typhoon center. After the typhoon passed across the island at 2100 LST, the strongest winds of 20 m/s were detected around 200 km away from the typhoon center.

In the fine-mesh domain, northwesterly strong winds more than 6 m/s from the coast to 12 m/s in the southwestern sea from the island could induce upwelling of deep sea colder waters to the sea surface spreading out from the coast toward the open sea in the southwest, resulting in cold sea water outbreak of 17°C in SST satellite image on August 31 in fig. 4b. Thus, this cold water outbreak on the sea surface behind a moving typhoon on its track is due to upwelling process by which deep sea colder water is brought to the sea surface and outward spreading of cold waters in the vicinity of Cheju Island, Korea.

Fig. 6 indicates vertical profiles of horizontal winds (m/s) in a fine-mesh domain with a horizontal grid spacing of 3 km covering a 91 x 91 grid square, in W-E axis crossing Cheju Island in fig. 5b. Before the typhoon passage across the island at 0900 LST, August 31, that is, in the frontal sea of the typhoon, strong surface winds more than 8 m/s with strong winds over 16 m/s in the elevated levels over the sea surface were detected in both the western and eastern seas of Cheju Island. On the other hand, shortly after the typhoon passage, moderate winds of 4 m/s in the coastal seas and relative strong wind of 6 m/s to 12 m/s in the open sea away from the island were observed.

By the Ekman relationship, a convergence of marine surface wind field can produce a divergence of surface currents and consequent upwelling of deep sea cold water with a cyclonic wind. Simultaneously, positive geo potential tendency (500 hPa height change for 24 hours from the sea surface to 500 hPa level) behind the typhoon on its track indicates the expansion of atmospheric layer from the surface to the 500 hPa level, which can induce ascending motion of sea surface and cause upwelling of deep sea colder water to the sea surface by spreading outward of cold water, resulting in cold water outbreak behind the typhoon on the typhoon track.

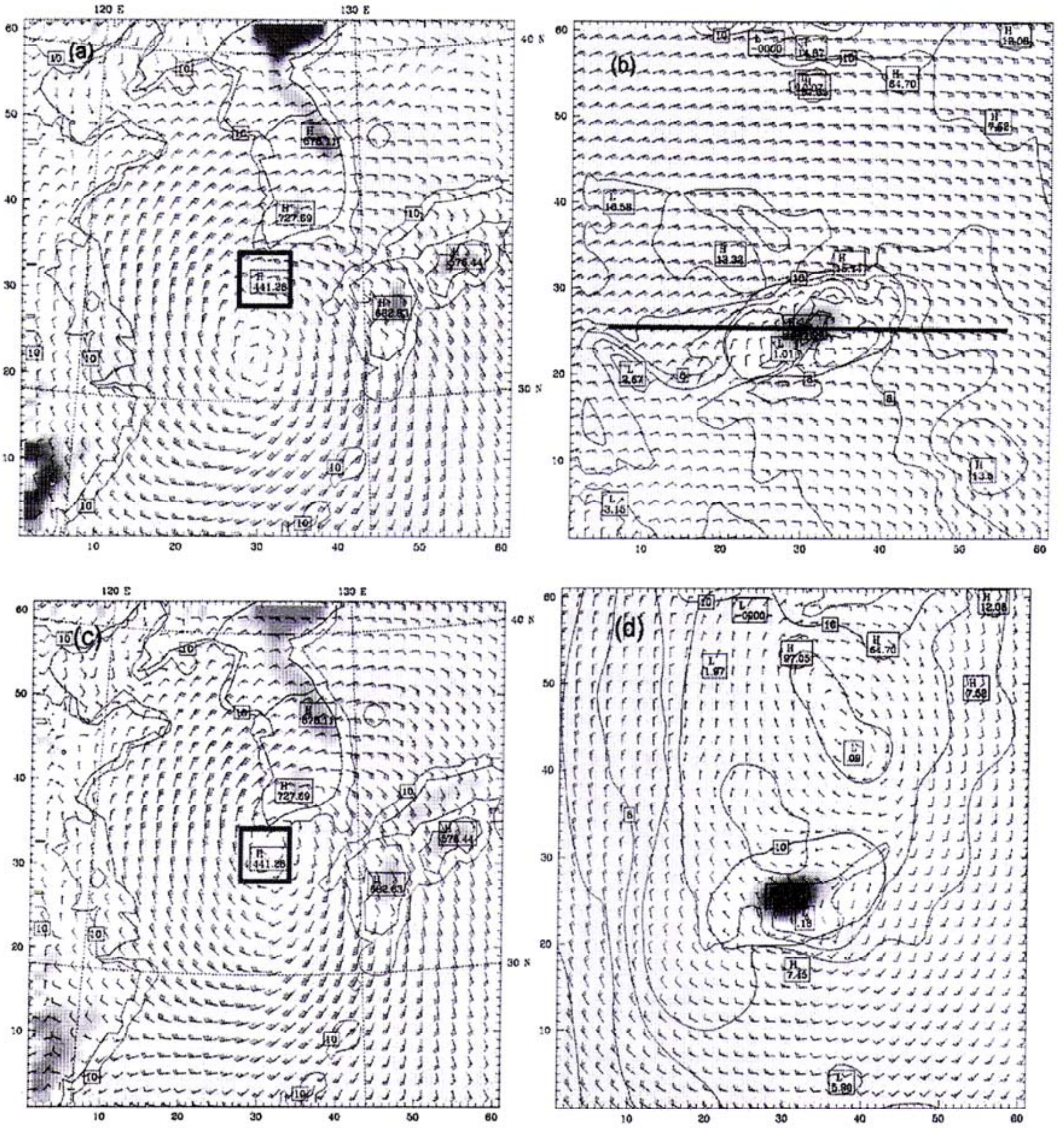

Figure 5: Surface winds (m/s) in (a) a coarse-mesh domain with a 9 km and (b) a fine-mesh domain with a 3 km horizontal intervals covering a 91 x 91 grid square in the model at 0900 LST, August 31, 2002 before the typhoon passage across Cheju Island and (c) and (d) at 2100 LST, after its passage, vice versa. Red box in a coarse-mesh domain denotes a fine-mesh domain. Full bar means 5 m/s. Very weak winds were detected in the center of the typhoon ("eye") in the coarse-mesh domains (Figs. 5a and 5c) and strong winds existed in the distance of about 200 km away from the center, but weak winds were detected again in the outside area, 200 km away from the center.

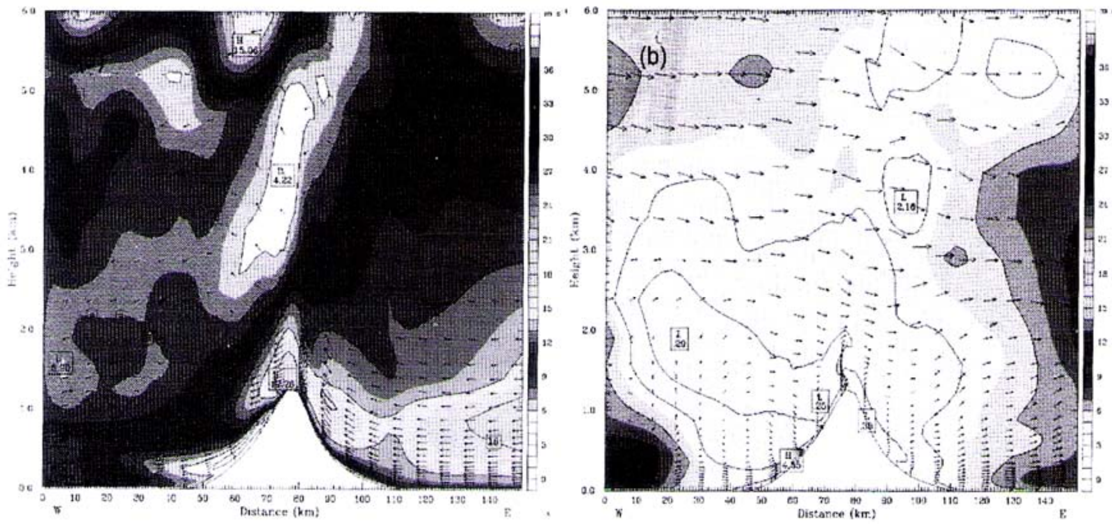

Figure 6: Vertical profiles of horizontal winds (m/s) in a fine-mesh domain with a horizontal grid spacing of 3 km covering a 91 x 91 grid square, in W-E axis crossing Cheju Island in Fig. 5b at (a) 0900 LST, August 31, 2002 and (b) 2100 LST. Strong winds over 8 m/s were detected in the western and eastern seas of the island, before the typhoon passage across the island in (a), while moderate winds of 4 m/s in the coastal seas and relative strong wind of 6 m/s to 12 m/s in the open sea away from the island were observed after the typhoon passage in (b).

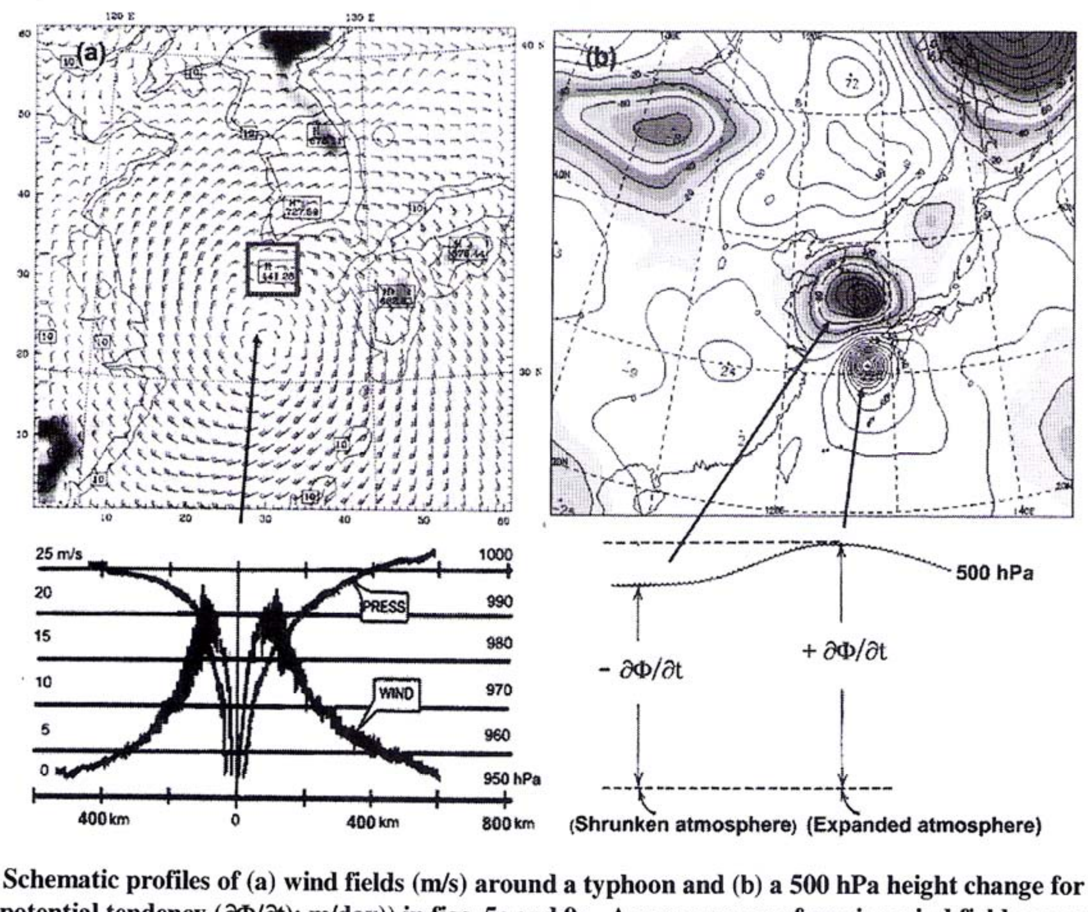

Figure 7: Schematic profiles of (a) wind fields (m/s) around a typhoon and (b) a 500 hPa height change for 24 hours (i.e. geo potential tendency ($\partial\Phi/\partial t$); m/day)) in figs. 5c and 9c. A convergence of marine wind field can produce a divergence of surface currents and consequent upwelling of deep sea cold water with a cyclonic wind. Simultaneously, the existence of positive geo potential tendency of 256 m/day behind the typhoon on its track implies the occurrence of atmospheric expansion between 500 hPa and sea surface, which can induce sea surface elevation and cause upwelling of deep sea cold water to the sea surface, resulting in cold water outbreak behind the typhoon on its track.

Responses of atmospheric pressure and ocean to a moving typhoon: Negative minimum geo potential tendency of 500 hPa, which implies 500 hPa height change for 24 hours (i.e. variation of atmospheric depth between the surface and 500 hPa level) near a typhoon track was detected in typhoon eye and its vicinity. It means that atmospheric depth between the surface and 500 hPa height should be shrunken in the negative area. On the other hand, positive maximum value of geo potential tendency is detected behind the moving typhoon. The atmospheric depth should be expanded in the negative area and the expansion of the atmospheric depth induces ascending of sea surface, resulting in upwelling of deep sea colder water brought to the sea surface and its outward spreading.

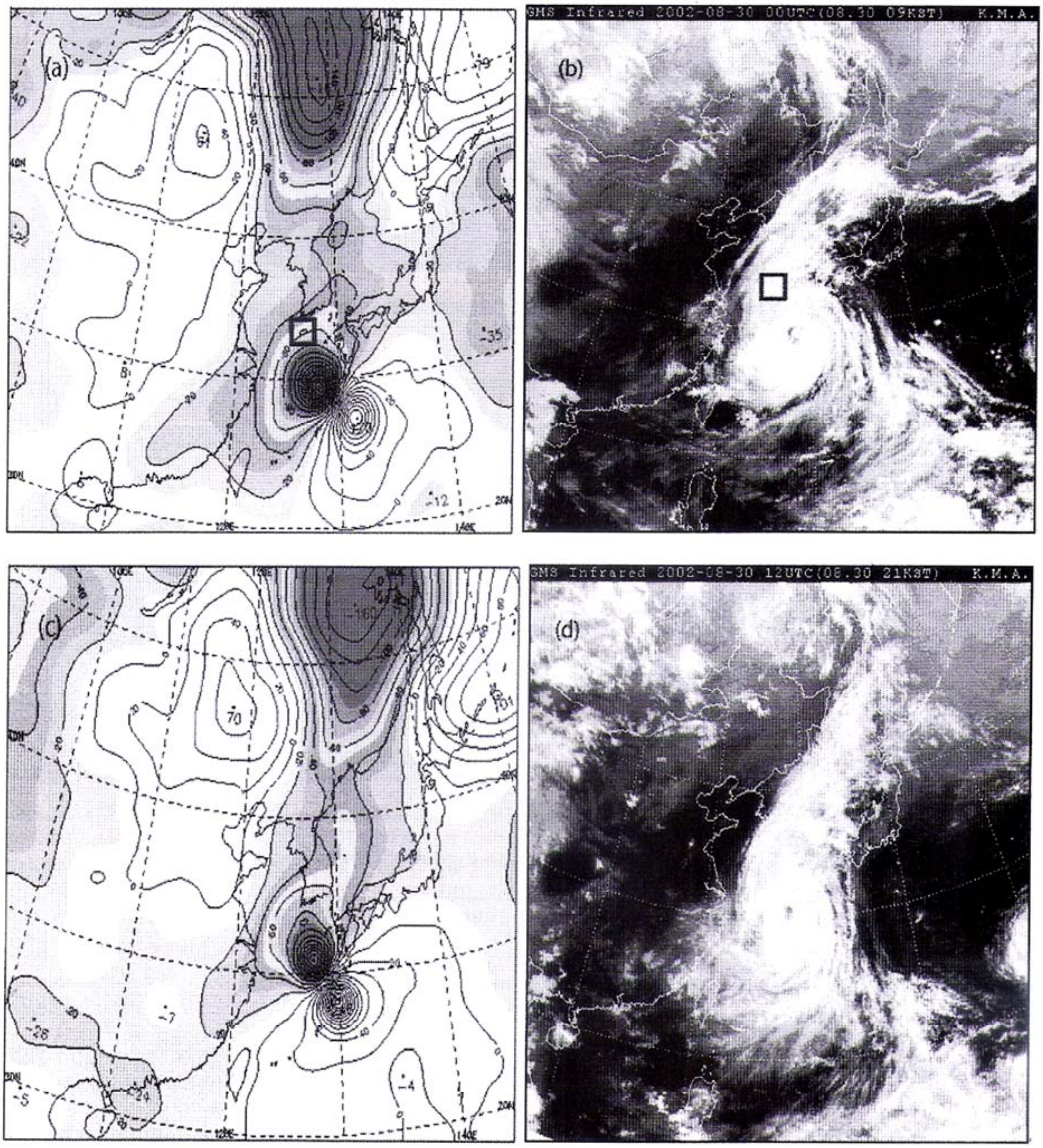

Figure 8: (a) 500 hPa height change for 24 hours (i.e. Geo potential tendency (∂Φ/∂t); m/day) over the sea and land surfaces and (b) satellite image of typhoon Rusa before typhoon passage through Cheju Island (inside box) at 0900 LST, August 30, 2002. (c) and (d) as shown in (a) and (b), except for 2100 LST, after its passage, vice versa. Behind the moving typhoon on its track, the maximum expansion of atmospheric layer with a maximum positive geopotential tendency may induce upwelling of cold sea water toward the sea surface, resulting in its spreading outward and cold water outbreak behind the moving typhoon near Cheju Island.

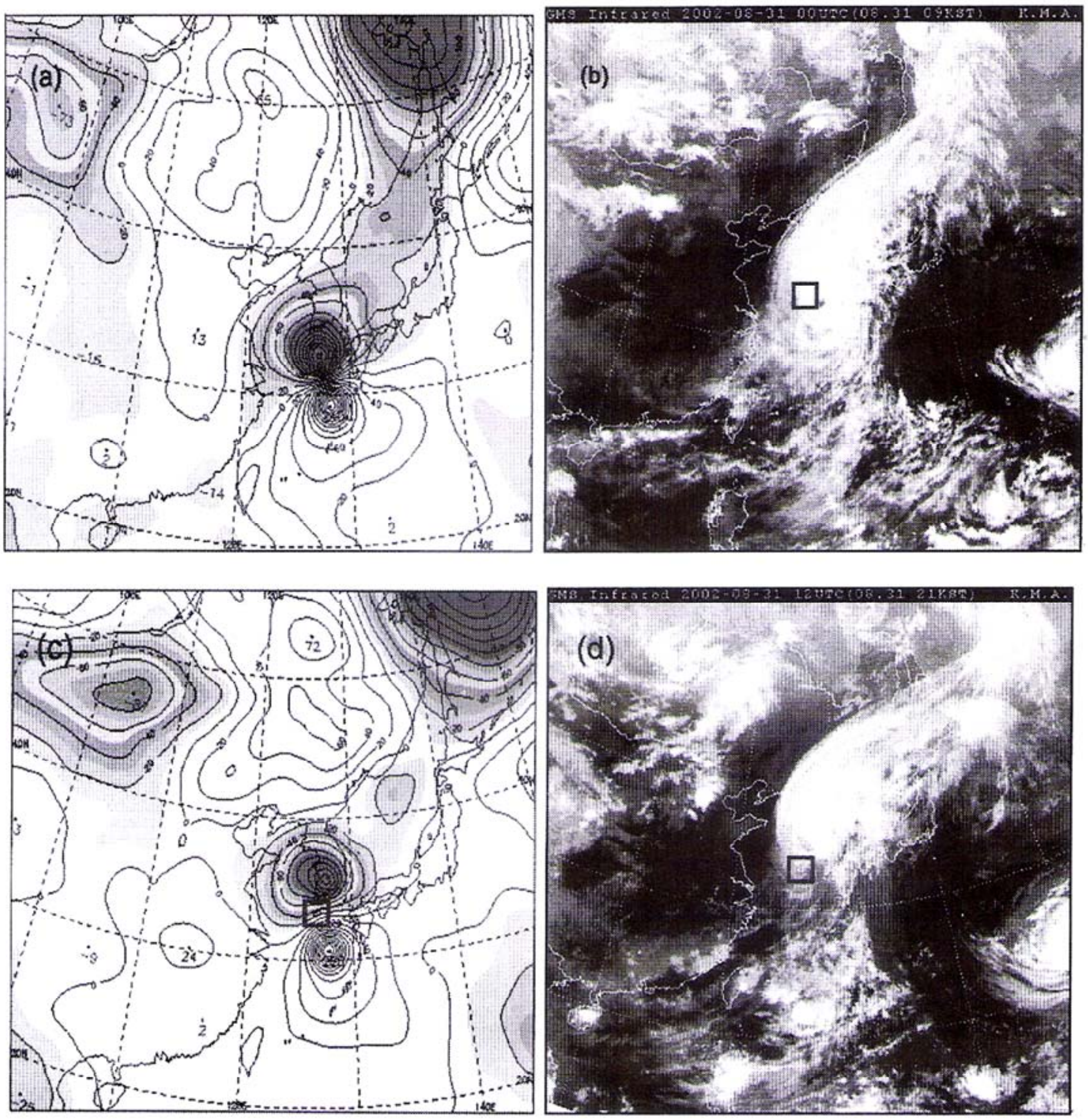

Figure 9: As shown in Fig. 8, except for (a) 0900 LST, August 31, 2002 and (b) 2100 LST. Box denotes the vicinity of Cheju Island in the south sea of Korea. After the typhoon passing through the island at 2100 LST, August 31, behind the typhoon on its track in the south of the island, there is the expansion of atmospheric layer (white color area) of a 256 m/day increase for 24 hours like in Fig. 9c, which induces upward motion of air currents, resulting in upwelling of deep cold waters to the sea surface and cold sea water outbreak of 17^0C in the southern sea of Cheju island.

In figs. 8 and 9, shrunken atmospheric layer between 500 hPa level and sea surface is detected in the center of typhoon Rusa, where air currents have downward motion in the center of typhoon such as typhoon eye. On the other hand, especially, at 2100 LST, August 31, the expansion of atmospheric layer is shown behind the typhoon on the typhoon track in the north-northwest and this expansion induces ascending of sea surface such as upward motion of air currents from sea surface toward upper atmosphere (here 500 hPa level), resulting in upwelling of deep sea colder waters toward the sea surface and the divergence of ocean currents outward by their sperading out and the occurrence of cold water outbreak in the vicinity of Cheju Island.

Conclusion

A cyclonic wind of typhoon and a fast movement of typhoon caused a divergence of ocean current by ascending of sea surface, where there was upwelling of deep sea colder water to be brought to the sea surface and outward spreading of cold water, resulting in colder water outbreak near the island, behind the typhoon. The reason why upwelling occurs is that there is a convergence of air flow at the sea surface, resulting in a divergence of ocean flow at the surface. This kind of process is due to the continuity by the Ekman relationship requiring upward vertical flow to replace the water lost by the surface divergence. Simultaneously, on the typhoon track, negative minimum geo potential tendency of 500 hPa for 24 hours was detected in the typhoon eye and its vicinity, where the atmospheric layer of 500 hPa should be shrunken. However, the expansion of the atmosphere in a positive maximum value of geo potential tendency was found behind the moving typhoon, which could induce ascending of the sea surface and divergence of ocean currents, resulting in upwelling of deep sea colder waters to the sea surface and outward spreading of cold waters behind the typhoon. Thus, cold sea water was widely distributed and extreme low sea surface temperature existed near Cheju Island.

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".

References

1. Palmieri S., Teodonio L., Siani A.M. and Casale G.R., Tropical strom impact in Central America, *Meteorological Applications*, **13**, 21-28 **(2006)**

2. Holton J.R., An introduction to dynamic meteorology, Fourth edition, 535 **(2004)**

3. Hellin J. and Haigh M. J., Rainfall characteristics of tropical storm Mitch in southern Honduras, *Weather*, **54 (11)**, 350-359 **(1999)**

4. Changnon S.A., Pielke R.A. Jr, Changnon, D., Sylves R.T. and Pulwarty R., Human factors explain increased losses from weather and climate extremes, *Bulletin American Meteorological Society*, **81**, 437-442 **(2000)**

5. Woo W.C., Tse S.M. and Lam H., Significant rain in Hong Kong associated with distant tropical cyclones over the South China Sea. Reprint 752, Guangdong-Hong Kong-Macau Seminar on Meteorological Science and Technology, Zhongshan, China, 21-23 January **(2008)**

6. 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, Boulder, CO, USA **(2009)**

7. Crease J., Propagation of long waves due to atmospheric disturbances in a rotating sea, Proceeding of Royal Society of London, Ser. A233, 556-569 **(1956)**

8. Geisler J.E., Linear theory of the response of a two-layer ocean to a moving hurricane, *Geophysical Fluid Dynamics*, **1**, 249-272 **(1970)**

9. Gill A.E., Atmosphere-Ocean Dynamics, Academic Press **(1982)**

10. Price J.F., Upper ocean response to a hurricane, *Journal of Physical Oceanography*, **11**, 153-175 **(1981)**

11. Price J.F., Internal wave wake of a moving storm, Part I: Scales, energy budget and observations, *Journal of Physical Oceanography*, **13**, 949-965 **(1983)**

12. Greatbatch R.J., On the response of the ocean to a moving storm, *Journal of Physical Oceanography*, **13**, 357-367 **(1982)**

13. Knauss J.A., Introduction to physical oceanography, Prentice Hall, Inc., 338 **(1978)**

14. Rotunno R. and Emanuel K.A., An air-sea interaction theory for tropical cyclones. Part II: Evolutionary study using a non-hydrostatic axisymmetric numerical model, *Journal of Atmospheric Sciences*, **44**, 542-561 **(1987)**

15. KMA, Report on typhoon Rusa, 1-50 **(2002)**

16. Leipper D.F., Observed ocean conditions and Hurricane Hilda, *Journal of Atmospheric Sciences*, **24**, 182-196 **(1967).**

(Received 15th November 2009, accepted 25th December 2009)