# Cold Sea Waters Induced by Cyclogenesis in the East Sea

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## Abstract

*The occurrence of cold sea waters induced by cyclogenesis along the eastern coastal sea of Korean peninsula was investigated from March 28 through 30, 2004, using NOAA MCSST sea surface temperature (SST) satellite pictures and a three-dimensional Weather Research and Forecasting Model (WRF)-version 3.3 with a one way-triple techniques. On March 28, westerly wind under a high pressure prevailed in the Gangneung coast and the open sea produced northeastward wind driven current, resulting in the northward intrusion of warm sea waters by the East Korea Warm Current toward the north along the Korean eastern coast. Under this situation, daily mean SST near Gangneung coastal sea and open seas of the East Sea were 10.5$^0$C. On March 29, low pressure with cold front in Bohai Sea between China and Korea produced a cyclonic air flow, which could cause strong southwesterly marine surface wind in the Korean eastern coastal sea near the study area and a strong southeastward wind driven current.*

*This current resulted in both upwelling of deep cold waters towards the sea surface and spreading outward in the coastal sea and the intrusion of cold waters of the North Korea Cold Current from the Korean northeastern coast toward Gangneung city along the coastline. On March 30, as the low pressure of 1013 hPa was more intensified with a decrease of 5 hPa to 1008 hPa in the East Sea (cyclogenesis) could cause the strong intrusion of cold waters from the northeastern coast into the southeastern and its cold front passed by the study area, both northwesterly wind along the coast and westerly wind in the offshore, resulting in a cold sea outbreak of 9$^0$C with a decrease of 1.5$^0$C than one on March 28.*

**Keywords:** Sea surface temperature, NOAA MCSST, WRF-3.3 model, Cyclonic air flow, Cyclogenesis.

## Introduction

When wind persistently blowing in the same direction over several hours changes its diection in the eastern coastal sea of Korean peninsula, the variation of sea surface temperature (SST) is frequently observed in the recent years. Reed [1] and Reed and Albright [2] insisted that wind storm is generated under the lee side cyclogenensis in the mountain or in the coastal sea. Strong wind in the coastal sea is generated by a narrow displacement between isobars, when a low pressure is intensified in the lee side of the mountain and produces a cyclonic flow [3].

Choi and Choi[4] and Choi et al[5] showed that coastal topography like steep high mountains and moisture and heat supplied from the sea surface causes the rapid development of a low pressure in the coastal sea and the intensification of cyclonic circulation (cyclogenesis). The momentum transport from jet stream in the upper level of atmosphere such as 500 hPa level toward the lower atmosphere also causes widely synoptic scale strong surface wind in the inland and sea.

The occurrence of cold sea surface temperature occurs under the passage of hurricane. Anthes and Chang [6] and Price [7] explained that response of the hurricane boundary layer to change in sea surface temperature by numerical simulations. Monaldo et al[8] showed sea surface temperature cooling in the wake of hurricane using satellite imagery and Cione and Uhlhorn [9] concluded that cyclonic surface winds in a hurricane cause surface divergence of sea surface water which induces upwelling of bottom colder waters to the sea surface and results in the occurrence of cold sea waters in the wake of the hurricane.

Vincent et al[10] also explained the characteristics of sea surface cooling induced by tropical cyclones. Similarly, Choi [11] also showed that for a few days for the passage of a typhoon accross the South Sea of Korea, typhoon-induced downwelling (or upwelling) before (or behind) its centre along its track causes the rapid change of sea surface temperature, especially showing cold sea outbreak in the wake of the typhoon track.

Gill [12] indicated that as the wind exerts a certain amount of force on the surface of the sea water, it causes the water to move at a right 90$^0$ angle in the northern hemisphere (anti-cyclonically), that is, wind-driven current. The strength and depth of the current are largely dependent on the wind speed and the current speed is evaluated by taking 0.03 of the wind speed. Knauss [13] showed that when the wind is parallel to the shore, upwelling of bottom cold waters occurs, resulting in the sea surface temperature to drop few degrees and cold sea outbreak in the surface layer. Especially, the surface temperature off Somalia drops even several degrees between April and July with the advent of the southwest monsoon.

In this study, Weather Research and Forecasting Model (WRF)-version 3.3 was used for the generation of wind fields and surface weather maps were used for the investigation on wind fields and the intensification of pressure systems such as a low and a high pressure. Daily mean sea surface temperature (SST) data of GOES-Multi-Channel Sea Surface Temperature (MCSST) were also used to assess the variation of SST responding to both atmospheric pressure change and surface wind in the East Sea of Korea.

## Study area

Fig. 1a indicates topographical features in the north-eastern Asia, which includes partial topography of China, Korean peninsula and Japan. The general topographical features in the Korean peninsula show low basins in the west and high mountains in the east and especially, high mountains lie from the south to the north, parallel to the coastline.

Gangneung city ($37^0$45N, $128^0$54E) in the study area (a smallest box as the third domain of WRF model domains in fig. 1a) is located in the eastern part of Korean peninsula and consists of high mountainous in the west, basin in the middle and sea in the east (Fig. 1b). Daily weather and climate near Gangneung city are strongly affected by synoptic pressure patterns like low and high pressure systems and cyclogenesis in the coastal sea and they are further modified by local topographical features of steep high mountains and sea-sea like sea-land breeze and valley-mountain winds[4].

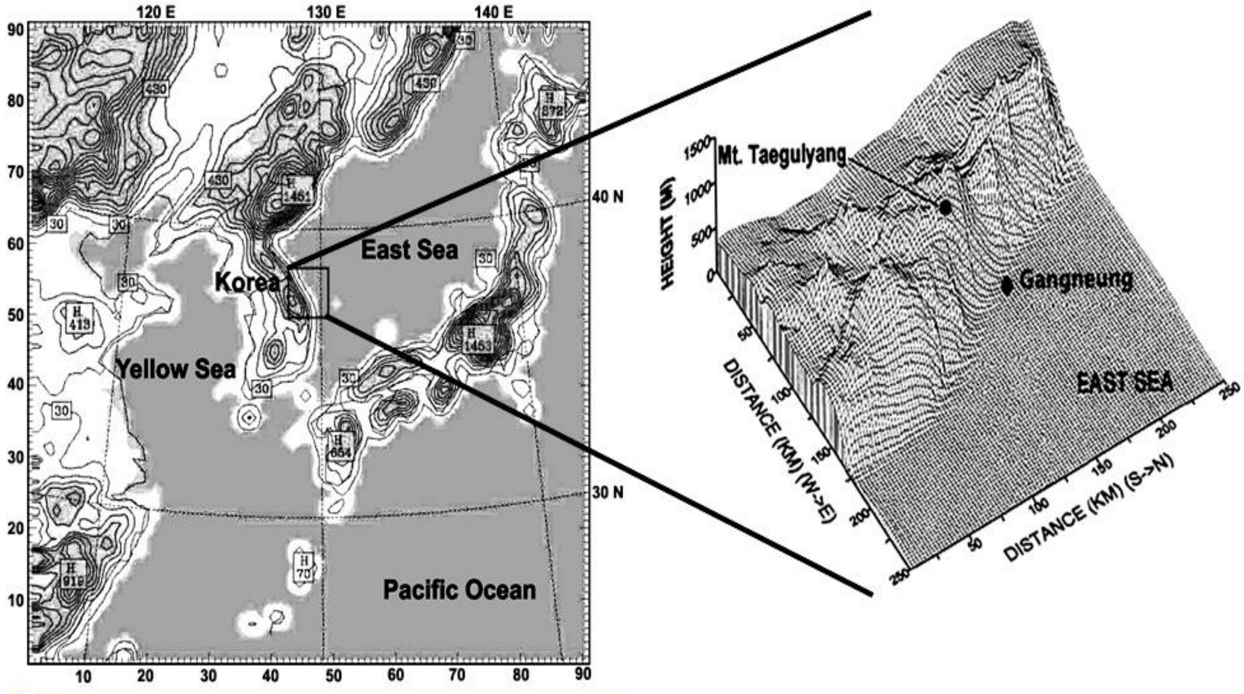
The weather and climate near Gangneung city are additionally affected by the passage of East Korea Warm Current (EKWC) along the coast, which is a surface oceanic current in the East Sea of Korea (the Sea of Japan) and flows from the Korea Strait toward the north along the coastline of the eastern Korean Peninsula to near Vladivostok, Russia[14].

In summer, the EKWC extends to the further north. The EKWC encounters the North Korea Cold Current (NKCC), which is a cold water oceanic current in the East Sea and flows southward from near Vladivostok along the coastline of the eastern Korean Peninsula to near Gangneung coast. The NKCC also extends to further south in winter. These currents parallel to each other turn to the central part of the East Sea. Thus, it is much warmer in Gangneung city than an inland city in winter and oppositely, much cooler than one in summer respectively.

## Numerical Method and Input Data

For the calculation of wind, a three dimensional Weather Research and Forecasting model-version 3.3 with a vertical terrain following coordinate system was adopted[15,16]. Numerical simulation by the model was carried out from 0000 UTC (Local Stand Time (LST) = 9h + UTC), March 28 through 2100 UTC, March 31, 2004.

In the numerical simulation, one way, triple nesting process from a coarse-mesh domain of a horizontal grid spacing of 27 km covering a 91 x 91 grid square to fine-mesh domains of horizontal grid squares of 91 x 91 with each 9 km and 3 km horizontal grid intervals was taken respectively. National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis-Final Analyses (FNL) $1.0^0$ x $1.0^0$ resolution 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 [17].




(a) (b)

**Figure 1: (a) Topographical features adjacent to Korean peninsula-the first domain of WRF-2.2 model simulation for March 28 trough 31, 2004 and (b) Gangneung city (small box) in the third domain**


**Figure 2: Oceanic currents in the vicinity of the Korean peninsula. NKCC, EKWC, TWC and a small circle in the eastern Korean peninsula denote North Korea Cold Current, East Korea Warm Current, Tsushima Warm Current and Gangneung city in the study area**

In the numerical simulation process using WRF-2-2 model, the WSM 6 scheme was used for heat and moist budgets and microphysical processes in the atmospheric boundary layer. In the planetary boundary layer, the YSU planetary boundary layer (PBL) scheme was adopted. The Kain-Fritsch (new Eta) for cumulus parameterization, the five thermal diffusion model for land surface, the RRTM long wave radiation scheme and dudhia short wave radiation schemes were also used. Hourly data sets of winds by Gangwon Meteorological Administration at Gangneung city were used for the verification of numerical results of meteorological elements.

## Results and Discussion

**Ocean currents around the Korean peninsula: N**ear Gangneung city, the East Korea Warm Current in the East Sea of Korea branches off from the Tsushima Current (a branch current of Kuroshio Current) at the eastern end of the Korea Strait and it flows north along the southeastern coastal line of the Korean peninsula. It further encounters the North Korea Cold Current between 36° and 40° N and veers east into the open sea, that is, the central part of the East Sea [18]. It is known that the current speed of the EKWC is about 0.5kt and it is faster in summer, but slower in winter. The current consists of higher water temperatures than $10^0$C in winter and $25^0$C in summer and high salinity of 34.4‰ and this current influences sea waters to the depth of vertically 50 ~ 150m.

On the other hand, the North Korea Cold Current is a cold water oceanic current in the East Sea of Korea. The NKCC is a branch of the Liman Cold Current from the Sea of Okhotsk and flows southward from near Vladivostok (the eastern Russia) along the coastline of the eastern Korean Peninsula to near Gangneung coast of about 38° latitude (even 36° latitude in winter) [19]. Then the current turns to the central part of the East Sea and circulates in the counterclockwise direction. It encounters the northward flowing East Korean Warm Current at latitude between 36° and 40°, depicting a clear ocean front at higher latitude in summer and lower latitude in winter. The current speed is about 0.2~0.5 knot and its flow pattern among ocean currents in the East Sea to be the most clear. Water temperature and salinity of the NKCC are about $0^0$C in winter and 34.0‰ in winter and they reach up to $16^0$C in the coastal sea in summer and 33.8‰, respectively.

**Surface atmospheric pressure and wind fields influenced on SST variations before cyclogenesis:** Cyclogenesis is defined as the intensification of cyclonic circulation under the rapid development of low pressure system [1, 2, 20]. At 2100LST, March 28, 2004, two days before the occurrence of cold sea waters in the coastal sea near Gangneung city in the eastern Korean peninsula, a low pressure with a central pressure of 997 hPa was located in the north-eastern China and its cold front extended south-westward near Beijing (Fig. 3a). The study area near Gangneung city was under a high pressure of 1020 hPa with a relative wide isobaric interval along the coast. However, south-westerly wind prevailed at the higher latitude than Gangneung city (a small circle in fig. 3c and 3d), southerly wind near the city and north-easterly wind at the lower latitude, depicting a clockwise motion from the south to the north with a speed range of 6 ~ 11m/s, respectively.

It means that by the association of synoptic-scale wind by a high pressure system with meso-scale mountain-land breeze, under the effects of high mountains and sea in the Gangneung coastal regions, observed anti-cyclonic surface winds in the inland coast were north-westerly (southeastward), westerly (eastward) and south-westerly (northeastward), while the winds in the sea were southerly (northward) and south-easterly (northwestward) as simulated surface winds by WRF model in figs. 3c and 3d.

Temporal variations of sea surface temperatures along the eastern coastal sea of Korean peninsula under strong wind filed were investigated from March 28 through 30, 2004, using NOAA MCSST sea surface temperature (SST) satellite. Knauss [13] insisted that if water currents were driven only by the transfer of momentum from the wind, surface current (wind-driven current) flows at a 45 degree angle to the wind due to a balance between the Coriolis force and the drags generated by the wind and the water. As the current direction also shifts slightly across each subsequent layer (right in the northern hemisphere), called the Ekman spiral, its speed decreases from a maximum at the surface until the downward momentum dissipates. If all waters flow over the Ekman layer, the net Ekman transportation of sea waters is at an angle of 90 degrees to the right (left) of the surface wind in the northern (southern) hemisphere.

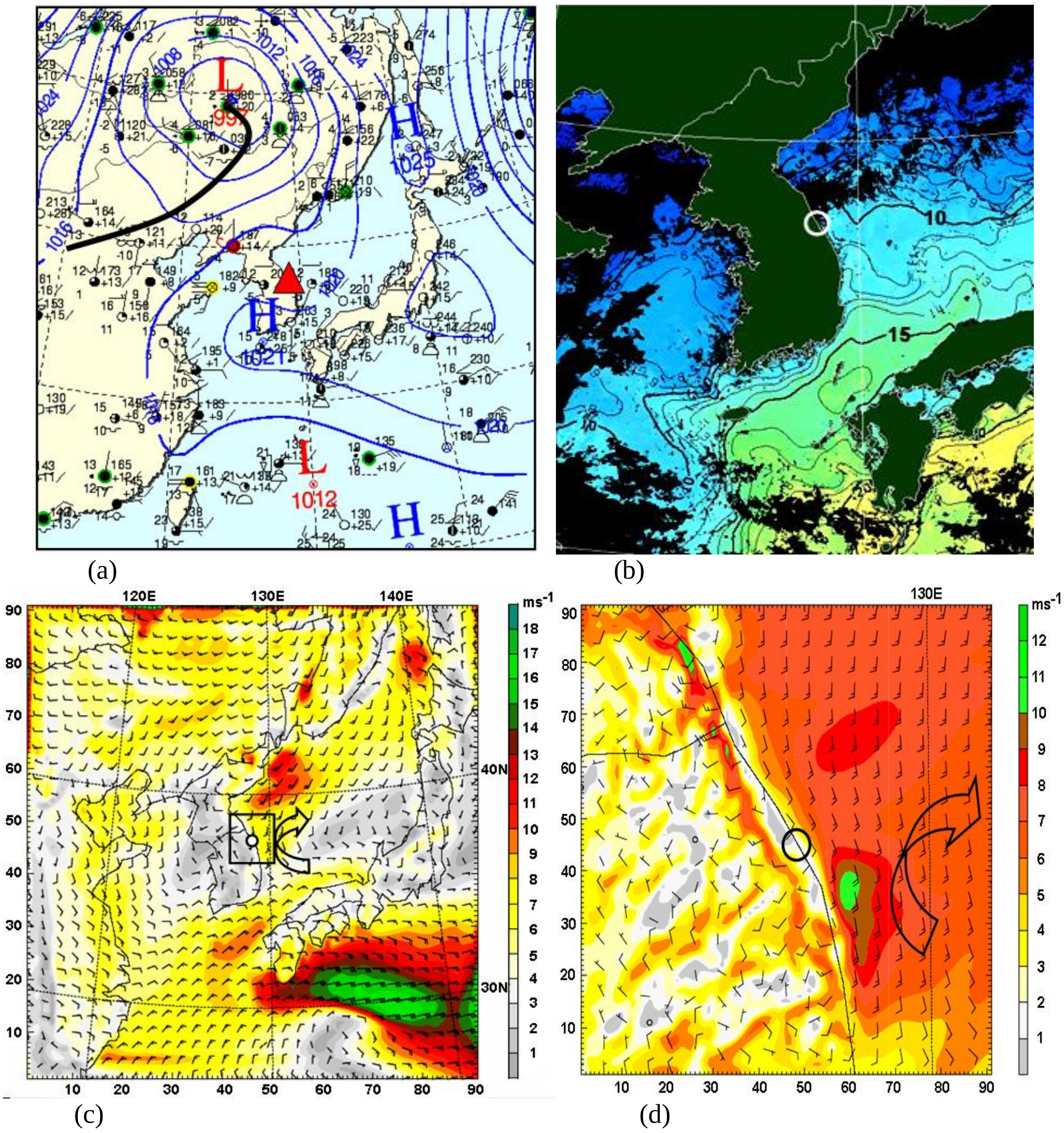



**Figure 3: (a) Daily mean sea surface temperature (NOAA MCSST) measured by NOAA satellite ($^{0}$C), (b) surface pressure (hPa), (c) surface wind at 10 m height in the first domain at 91 x 91 horizontal grids of a 21 km interval by WRF model at 2100LST, March 28, 2004 and (d) surface wind in the third domain of 3 km interval. SST in the Gangneung (a small circle) coastal sea was 10.5$^{0}$C in (b). Thick line in (a) and both circle and triangle denote cold front and Gangneung city**

On March 28, anti-cyclonic winds like clockwise winds under a high pressure prevailed in the Gangneung coast and especially southwesterly (northeastward), southerly (northward) and southeasterly (northwestward) winds in the open sea could produce northeastward wind driven current, resulting in the intrusion of warm waters of the East Korea Warm Current toward the north along the coast. Under this situation, SST near Gangneung coast and open seas were $10.5^0$C (Fig. 3b).

Gill [12] explained that if northward wind (southerly wind) blows parallel to the coast in the northern hemisphere like the Korean east coast, then Ekman transport produces a net movement of surface water 90 degrees to the right in the northern hemisphere, eastward wind-driven ocean current. This can result in coastal upwelling, which uplifts dense, cooler and usually nutrient-rich waters towards the ocean surface, replacing the surface warmer waters and then resulting in cooling of sea surface waters. Thus, as shown in figs. 3b, 3c and 3d, clockwise winds – south-westerly wind, southerly wind and south-easterly wind from the south toward the north in the Korean eastern coastal sea can induce south-eastward, eastward and north-eastward wind-driven current with a clockwise motion, which can cause the further intrusion of the East Korea Warm Current to the northern coast of the Korean peninsula, especially Gangneung coastal sea, resulting in $10.5^0$C in the Gangneung coastal sea and $10^0$C in the open sea, respectively.

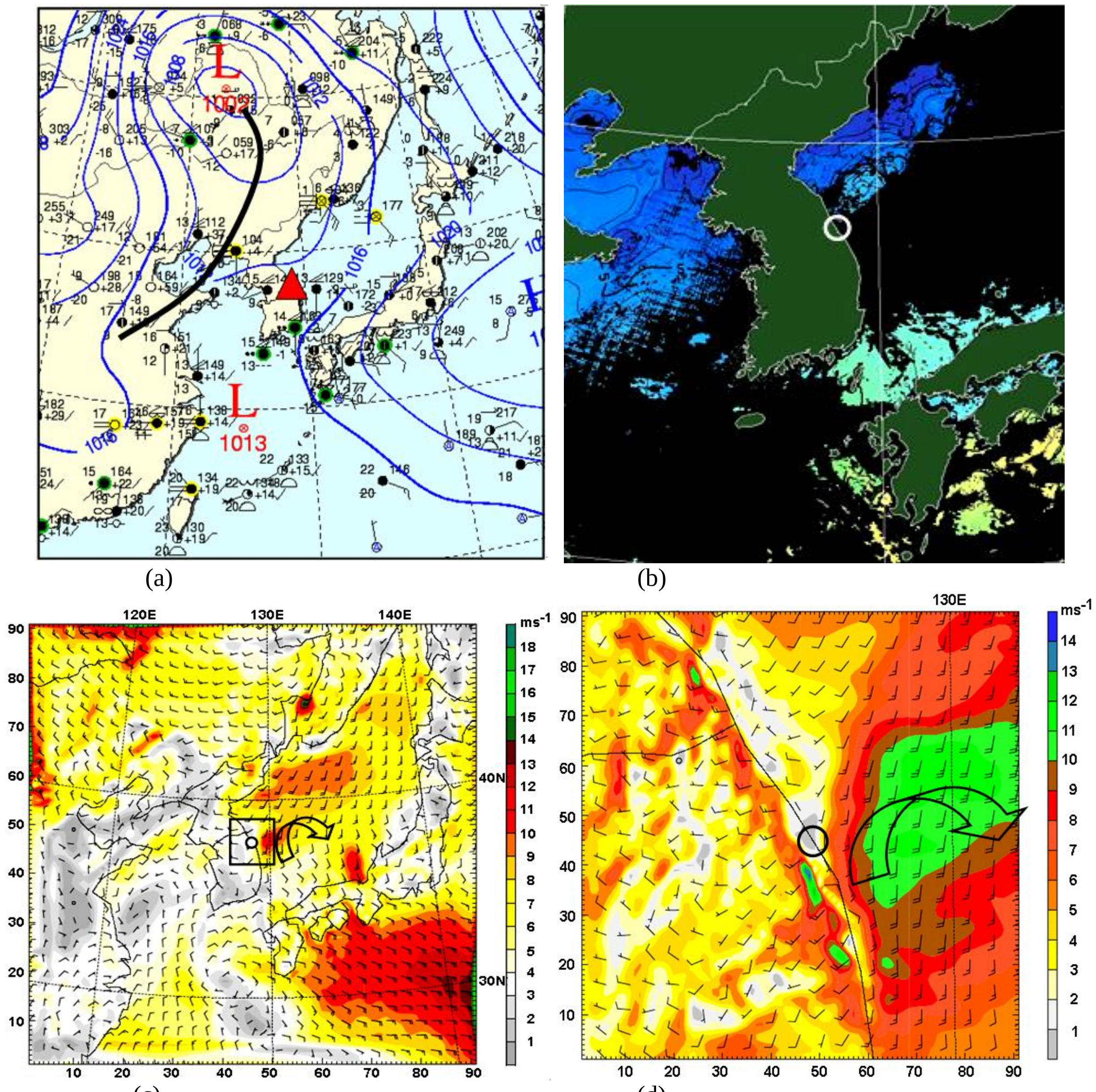


**Figure 4: As shown in fig. 3, except for 2100LST, March 29, 2004. SST in the Gangneung coastal sea was not seen in (b), due to cloud cover over sea, but it may be lower than $10^0$C**

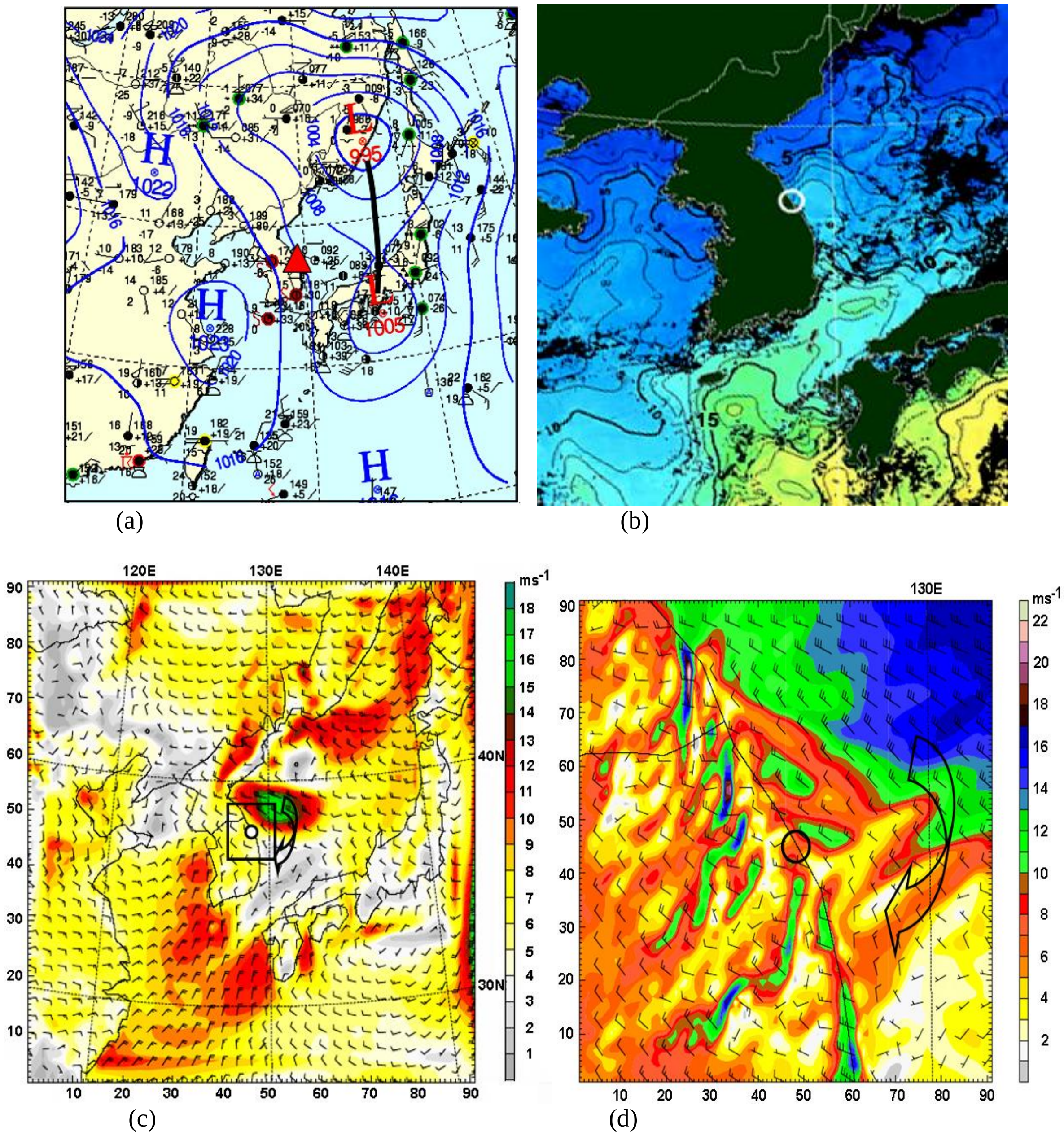



**Figure 5: As shown in fig. 3, except for 2100LST, March 30, 2004. As cold front under the more intensification of the low pressure like cyclogenesis in (a) just passed by the study area could produce both northwesterly wind along the coast and westerly wind in the offshore in (c) and (d) and cause the stronger intrusion of cold waters from the northeastern coast toward the south along the coastline, resulting in a cold sea outbreak of $9^0$C in (b)**

Simultaneously, in the northern coastal seas of higher latitudes of Gangneung city, southwesterly wind can produce southeastward wind-driven ocean current. This current can cause not only the intrusion of the North Korea Cold Current toward the south along the coastline, but also upwelling of deep cooler sea waters towards the sea surface in the coastal sea and spreading outward, resulting in prohibiting the northward warm waters of the East Korea Warm Current near the Gangneung coast.

Knauss [13] explained that as the wind exerts a certain amount of force on the surface of the sea water, it causes the wind-driven current and the current can get quite strong from the same persistent wind blowing in the same direction over several hours. The strength and depth of the current are largely dependent on the wind speed and the current speed is discovered by taking 0.03 of the wind speed. Wind-driven oceanic currents were estimated with about 12 ~ 33cm/s around this time using a calculating formula.

**Surface atmospheric pressure and wind fields influenced on SST variations during cyclogenesis:** At 2100LST, March 29, a low pressure centre of 1002 hPa located in the northeastern China slowly moved eastward and its accompanied cold front also slowly moved eastward and passed by the Bohai Sea in the left of the northwestern Korean peninsula and Sandong peninsula of the eastern China. The atmospheric pressure near the study area of the Korean east coast was more intensified to 1014 hPa (Fig. 4a) with a decrease of 6 hPa and produced strong southerly wind larger than 10m/s off coast of Gangneung city (Fig. 4c and 4d). As this low pressure induced south-westerly in the inland coast, more strong southerly or south-westerly wind in the sea intensified respectively.

Compared to winds on March 28, stronger southerly wind over 10m/s at 2100LST, March 29 is detected off coast of Gangneung city, which induces southeastward wind driven current, resulting in the upwelling of deep cooler waters from the bottom toward the sea surface and spreading outward in the coastal sea of the city and also further intensification of the southward North Korea Cold Current along the coastline. Under this situation, the SST near Gangneung coast and open seas might be lower than $10^0$C (not seen in the SST figure due to cloud cover over the sea) (Fig. 4b). As the more intensified low pressure moved eastward, passing by the East Sea, the cold waters intruded further southward along the eastern coastline of the Korean peninsula, showing lower sea surface temperature.

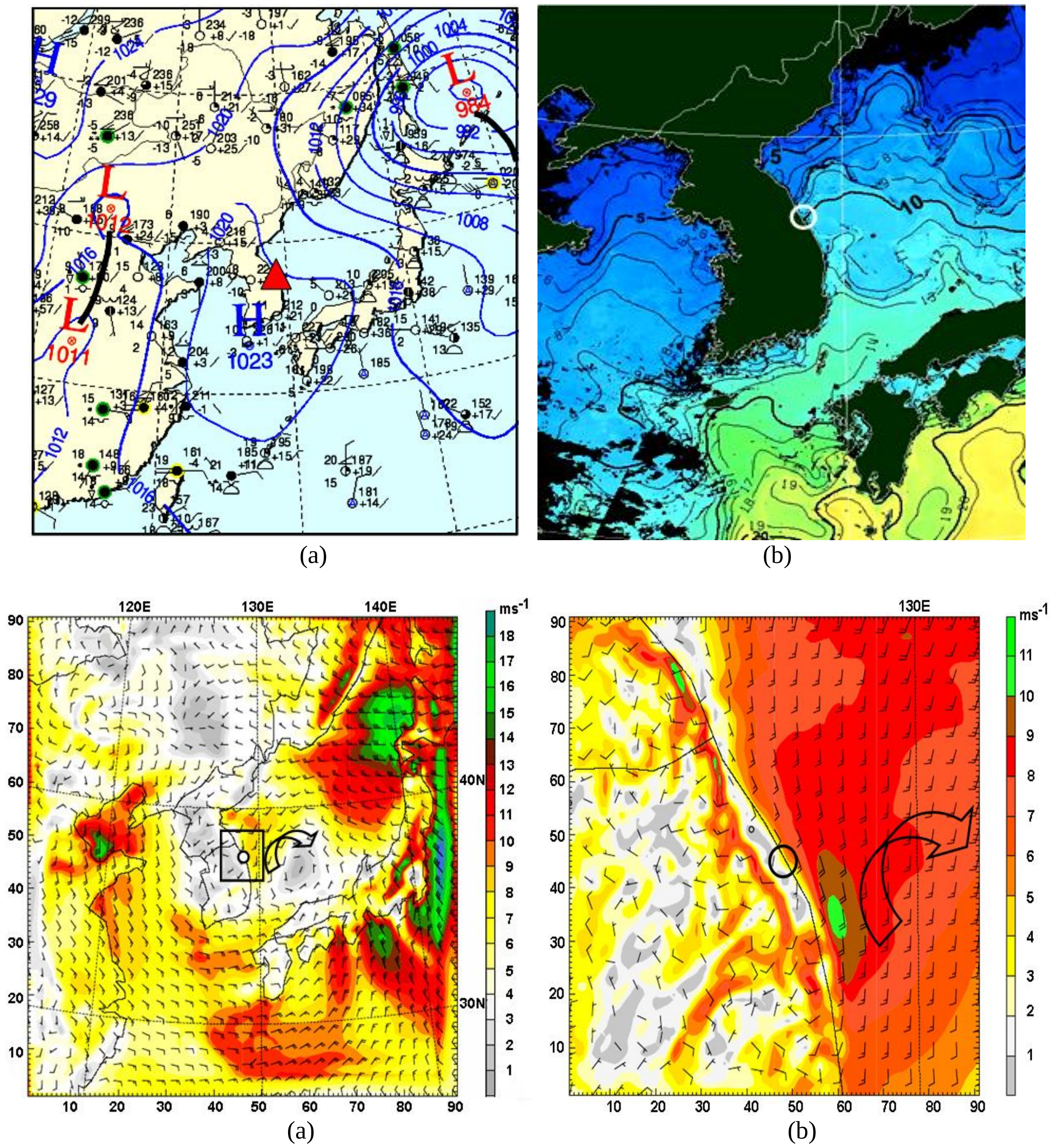



**Figure 6: As shown in fig. 3, except for 2100LST, March 31, 2004. SST in the Gangneung coastal sea was reduced to $10^0$C in (a) due to the southeastward intensification of the North Korea Cold Current along the eastern coastline of Korean peninsula by strong southwesterly wind. In (b), it was recovered into $10^0$C due to the intrusion of the East Korea Warm Current flowing northward along the coastline by relatively strong southeasterly wind**

At 0900LST, March 30, as the low pressure was more intensified from 1002 hPa into 995 hPa in its center with a decrease of 6 hPa and the cold front just passed by Gangneung city, strong northwesterly wind prevailed in the study area (Fig. 5a). At 2100LST, March 30, the low pressure at 2100LST, March 30 near the study area was more intensified with a decrease of 5 hPa from 1013 hPa at 2100LST, March 29 to 1008 hPa. The narrow displaced isobaric contour near Gangneung city and steep downslopes of the mountain barrier in the west of the city caused more intensified north-westerly or westerly wind speed than 4m/s to 22 m/s in the inland of the city and predominant north-westerly wind speed to 12m/s in the coastal sea and further being 17 m/s in the open sea (Figs. 5c and 5d). Especially, wind speeds in figs 5c and 5d got much higher from the coast toward offshore area in the sea.

Differently from south-westerly, southerly and southeasterly wind in the coastal sea in March 28 and 29, winds were shifted into strong northwesterly in the higher latitude of Gangneung city and southwesterly in the lower latitude, which could cause strongly southwestward and southeastward wind driven currents (Fig. 5b). These currents can cause the intrusion of cold waters of the North Korea Cold Current flowing south from the Korean northeastern coastal sea toward the Gangneung coastal sea, resulting in the cold sea outbreak of $9^0$C with a decrease of $1.5^0$C than one on March 28, 2004. Especially, strong northwesterly wind over 16m/s off coast of the city toward the open sea in the shown in figs. 5c and 5d could influence on the southward of cold waters in the open sea of the East Sea in fig. 5b.

**Surface atmospheric pressure and wind fields influenced on SST variations after cyclogenesis:** At 0900LST, March 31, the study area was underneath a high pressure of 1023 hPa and wind patterns were very similar to ones on March 28 (Fig. 6a). The high pressure system produced clockwise winds in the open sea of the East Sea (Fig. 6c and 6d). Winds in the higher latitude of Gangneung city were southwesterly (northeastward), while ones in its lower latitude were southerly and southeasterly winds. The surface wind patterns on March 31 were almost opposite to ones on March 30. In fig. 6d, anti-cyclonic circulation of air - southeasterly wind in the coastal sea, southwesterly wind in the open sea of both higher latitudes and near Gangneung city and southwesterly (northeastward) in the lower latitude could produce clockwise wind driven current - northeastward wind driven current in the coastal sea and southeastward wind driven current in the open sea, resulting in the intrusion of warm waters of the East Korea Warm Current toward the north along the coastline. Under this situation, the SST near Gangneung coast and open seas were $10^0$C (Fig. 6b), similar to one on March 28.

## Conclusion

When clockwise winds by a high pressure prevailed in the Gangneung coast and the open sea produced northeastward wind driven current, resulting in the northward intrusion of the East Korea Warm Current toward the north along the Korean eastern coastline, under this situation, a daily mean SST near Gangneung coastal sea and open seas was $10.5^0$C. However, a low pressure with cold front approaching the Korean peninsula produced a cyclonic air flow, which could cause strong southwesterly marine surface wind near the study area, resulting in a strong southeastward wind driven current. This wind driven current caused not only upwelling of deep cooler waters from the bottom toward the sea surface and spreading outward in the coastal sea, but also the intrusion of cold waters of the North Korea Cold Current from the Korean northeastern coast toward Gangneung city along the coastline.

As cold front just passed by the study area under the more intensification of the low pressure like cyclogenesis, it could produce both northwesterly wind along the coast and westerly wind in the offshore and cause the stronger intrusion of cold waters from the northeastern coast toward the south along the coastline, resulting in a cold sea outbreak of $9^0$C with a decrease of $1.5^0$C than under the high pressure, two days before.

As the study area was again underneath a high pressure, the high pressure system produced clockwise winds in the open sea of the East Sea such as southwesterly (northeastward) winds in the higher latitude of Gangneung city, while southerly and southeasterly winds in its lower latitude. These wind patterns could produce northeastward wind driven current in the coastal sea and southeastward wind driven current in the open sea, resulting in the northward intrusion of the East Korea Warm Current along the coastline and the SST near Gangneung coast and open seas to be $10^0$C back to the original state.

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