Sea Fog by Southerly Warm Air over Cool Sea Waters of the Southward North Korea Cold Current along the Korean East Coast under Cyclogenesis in the Yellow Sea

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Abstract

Sea fog in the southeastern coastal sea of Korea was investigated on February 21 ~ 23, 2005 by WRF 3.3 meteorological model, GOES-9 and NOAA-MCSST satellite images. On February 21, as a high pressure covers whole Korean peninsula, northwesterly in the Korean eastern coast caused moderate southwestward wind driven currents, resulting in southward littoral currents due to its coastal configuration. These currents caused further the intrusion of the North Korea Cold Current (NKCC) toward the south. Although air of 3 ~ 7^{0}C by cold northwesterly wind from the northern China moved over a cool pool area off the Pohang coast and it was in the easy condition of evaporation of water droplets from the sea and condensation of water vapour to form fogs under the air and sea surface temperature differences of - 3 ~ - 8^{0}C, strong marine surface dissipated fog droplet, resulting in 65% relative humidity (RH) with no formation of fog.

However, as low pressure showing an anti-clockwise wind pattern on February 22 became more intensified in the Korean northwestern coast (cyclogenesis), southwesterly wind in the Korea northern coastal sea could cause southeastward wind driven currents, which induce upwelling of deep cold waters toward the sea surface and simultaneously these currents caused further the intrusion of the NKCC toward the southeastern open sea in about 100km away from Pohang city (a cool pool of 7^{0}C cold waters).

As much warmer air of 7 ~ 9^{0}C by strong southwesterly wind of 6 ~ 11m/s moved over the cool pool in the open sea away from Pohang city, air and sea surface temperature difference was about 2^{0}C. So, the air over the cold sea must cool down to be saturated and water vapor in air to be condensed by salty condensation nuclei, resulting in the formation of sea fog or stratus cloud with 80% RH near the sea surface and vertically extended toward 1 km height.

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Keywords: Sea fog, WRF-3.3 model, GOES-9 satellite image, NOAA-MCSST satellite image, North Korea Cold Current, Cyclogenesis, Cool pool of sea waters.

Introduction

In the recent years, sea fog or coastal fog has been frequently detected in the vicinities of the East Sea and the Yellow Sea[1-5]. Fog reduces visibility to less than 1km, whereas mist reduces visibility to no less than 1 km. Under the influence of the coastal low accompanying fronts, synoptic scale fog is generated in the wide areas of inland coast, offshore and open sea along the frontal zones. Wang[6] insisted that sea fog is significant marine weather phenomenon occurring over oceanic or adjacent coastal sea with atmospheric visibility below 1km and Gao et al[7] presented that sea fog forms in response to relatively persistent southerly warm and moist wind over a cold sea surface and that turbulence mixing by wind shear is the primary mechanism for the cooling and moistening the marine layer.

Raynor et al[8] and Whiteman[9] presented that the accumulation or dissipation of heat flux over the sea and coastal complex terrain generates fogs. Ahrens[10] also showed that when warm moist air horizontally moves over a cold earth surface or a cold sea surface, the air becomes saturated and condensation occurs, resulting in advection fog. Its surface must be sufficiently cooler than the air above so that the transfer of heat from air to surface will cool the air to its dew point and produce fog.

Taylor[11] found that sea fog is formed when sea water is colder than the air in 80% of the observed 4 cases of sea fog. Sciocatti[12] explained that sea surface temperature influences on the formation or dispersal of advection fog with the passage of a coastal low and its formation can occur less than 80% of relative humidity, differently from inland fog with 100% of relative humidity. It means that the coastal low usually accompanies a frontal system generated by different air masses such as cold air in the left of the front and warm air in the right and vice versa. Ahrens[10] also insisted that condensation is a continuous process beginning when water vapour condenses onto hygroscopic nuclei at relative humidity as low as 75%.

Choi et al[13] explained that another significant fact on the formation of sea fog is salty nucleus in the marine atmosphere, which can easily make a droplet below 80% relative humidity, enhancing fog in the coastal region. In general, salt from the ocean serves very easily as the hygroscopic nucleus of fog droplets and a reduced droplet surface tension of salt allows fog to form under less than 100% relative humidity. For aviation purposes in the United

Kingdom, a visibility of less than 5 km but greater than 999 m is considered to be mist if the relative humidity is 70% or greater, while haze is reported when relative humidity is below 70%[14]. As relative humidity approaches 100% and the haze particles grow larger, both the increasing size of tiny water droplet and condensation of droplets further restrict visibility.

Tokinage and Xie[15] insisted that the cooling of air temperature by tide-induced cold patches over the Okhotsk Sea in summer can form a strong surface inversion layer and create favorable conditions for the formation of sea fog. Li et al[16] presented that in summer, most of sea fogs are advection fogs because warm air drifts over a cold sea surface and condensation takes place. In this case, wind speed over the sea surface is relatively strong up to 10m/s.

Different from the driving mechanism on the formation of inland fog like radiation fog produced over a land area, when radiational cooling reduces the air temperature to or below its dew point, the formation of sea fog in the open sea mainly depends upon humidity which is a function of temperature difference between air and sea surface. On the other hand, Tachibana et al[17] explained that in winter, evaporation fog (or steam fog) in the sea forms when very cold air passes across a warmer water surface and mixes with the warm moist air by the supply of moisture evaporated from the warm sea surface. For the formation of fog, there must be a large temperature difference between warm sea surface temperature and cold air temperature.

Lee[18] indicated that sea fog frequently occurred in the western coastal sea of the Korean peninsula in a period of spring tide due to a huge amount of inward and outward sea waters by flood and ebb tidal currents. Choi et al[13] and Choi and Speer[19] carried out a three-dimensional numerical prediction on the formation of coastal and sea fogs in the eastern and western coastal regions of the Korean peninsula, considering turbulent and sensible heat fluxes in the marine and coastal atmospheric boundary layers. Their researches indicated that radiation fog or upslope fog needs 100% relative humidity in the inland coast and further mountain area, but sea fog occurs at a larger than 80 ~ 85% relative humidity.

Gao et al[21] explained the formation of sea fog and stratus using a multi-functional transport satellite-IR, especially shortwave minus long wave brightness temperature difference in the Yellow Sea, but it was not still clear to distinguish to fog and stratus. In this study, the formation of sea fog in the Korean eastern coastal and open seas in the East Sea (the Sea of Japan) was investigated during the development of a low pressure (cyclogenesis) in the Korean peninsula. The effects of wind on the intrusion of cold sea waters of the North Korea Cold Current flowing from the northeastern coastal sea toward the south along the coastline and upwelling of deep cold sea waters toward the surface were explained by the numerical simulation using Weather Research and Forecasting Model-3.3 by the generation of wind, air temperature and relative humidity.

Study Area

The weather and climate along the eastern coast of Korea are strongly affected by the passage of two ocean currents such as the East Korea Warm Current (EKWC) and is the North Korea Cold Current (NKCC). The EKWC is a surface oceanic current in the East Sea of Korea (the Sea of Japan), which branches off from the Tsushima Current at the eastern end of the Korea Strait, as a branch current of Kuroshio Current[22]. It flows north along the southeastern coast of the Korean peninsula. It further encounters the NKCC between 36°N and 40°N and veers east into the open sea, that is, the central part of the East Sea[18].

The current speed of the EKWC is about 0.5 ~ 1.0kt, especially over 2kts in the Korea Strait and it is faster in summer, but slower in winter as the sea depth becomes lower and lower to about 300m. The current consists of higher water temperatures of about than 10^0C with 27^0C in the south and 20^0C in the north and high salinity of 34.4‰. This current influences sea waters to the depth of vertically 50 ~ 200m.

Simultaneously, the NKCC in the East Sea 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 the coast of about 38° latitude (Sokcho city) (even 36° latitude in winter; Gangneung city)[14, 23]. Then the current turns to the central part of the East Sea and circulates in the counterclockwise direction. It encounters the East Korean Warm Current at latitude flowing the northward between 36°N and 40°N, depicting a clear ocean front at higher latitude in summer and lower latitude in winter. The current speed is about 0.2 ~ 0.5kt and its flow pattern among ocean currents in the East Sea is the most clear. Water temperature and salinity of the NKCC are about 0^0C and 34.0‰ in winter and they reach up to 16^0C and 33.8‰ in summer respectively.

As shown in Fig. 1a, the study area on the formation of sea fog is located in the south-east of Korean peninsula, in the left of the East Sea. Two cities of Pohang and Ulsan in the south-east coast consist of low dune with height less than 30m widely spread out to 30 ~ 50km away from the coast and with low mountains extending to further on the inland side. In the further inland site, there are high mountains as shown in Fig. 1b in a fine-mesh domain.

Numerical Methods and Input Data

A three-dimension grid point model of Weather Research and Forecasting Model (WRF-3.3) in a terrain following coordinate system was adopted for the generation phenomena in the south-eastern coastal sea of Korea for 3 days from 0000 LST February 21 through 0000 LST, February 23, 2005 (Fig. 1). One way - triple grid nesting numerical process was made considering a horizontal interval of 27 km in a coarse domain, a 9 km interval in the second domain and a 3 km interval in the third domain (fine mesh domain) with grid numbers of 91 x 91 in each domain.

NCEP/NCAR reanalysis FNL (1.0^0 x 1.0^0) data was used for meteorological input data for the model and vertically was interpolated or extrapolated on 28 levels with sequentially larger intervals between levels with increasing altitude from surface to 100hPa height. Similar to Choi et al[22], in the atmospheric boundary processes of heat and moist budgets, WSM 6 scheme was used for microphysical process and YSU PBL scheme for planetary boundary layer, Kain-Fritsch (new eta) for cumulus parameterization, 5 thermal diffusion model for land surface, RRTM for long wave radiation scheme and Dudhia short wave radiation scheme.

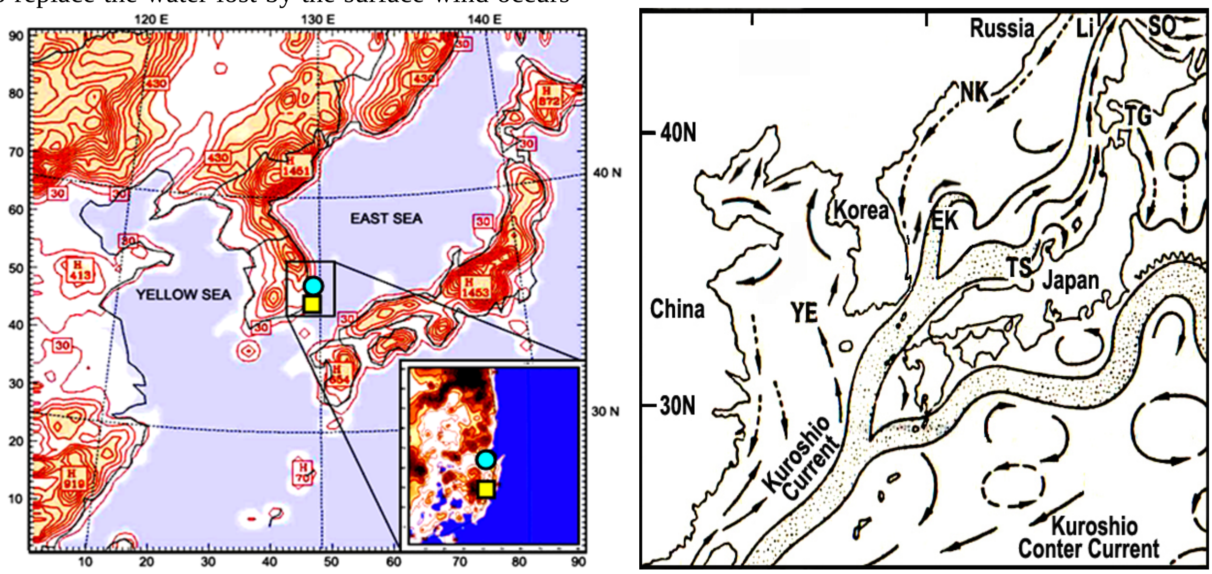
Results and Discussion

Before the formation of sea fog: At 0900LST, February 21, the center of a low pressure of 1025hPa was located near Tianjin (a small square) adjacent to Bohai Sea (at higher latitude than the Yellow Sea) in the eastern coast of China and a high pressure of 1032hPa was also located in the Shanghai in the mid-eastern coast (Fig. 2a). Wind near Pohang city (a small circle) in the southeastern coast of Korean peninsula was relatively strong northwesterly wind (that is, southeastward) (Fig. 2b).

According to Ekman theory, the effect of marine surface wind is to drive the water to the right of the wind in the Northern Hemisphere, that is, wind driven current[24]. Thus, maximum upwelling of deep sea water toward the sea surface to replace the water lost by the surface wind occurs when the surface wind is parallel to the shore. Especially, cyclonic winds generated by a low pressure produce divergence in the surface waters and upwelling of deep cold waters toward the sea surface and spread outward along the inclined surface offshore in the Korean eastern coast.

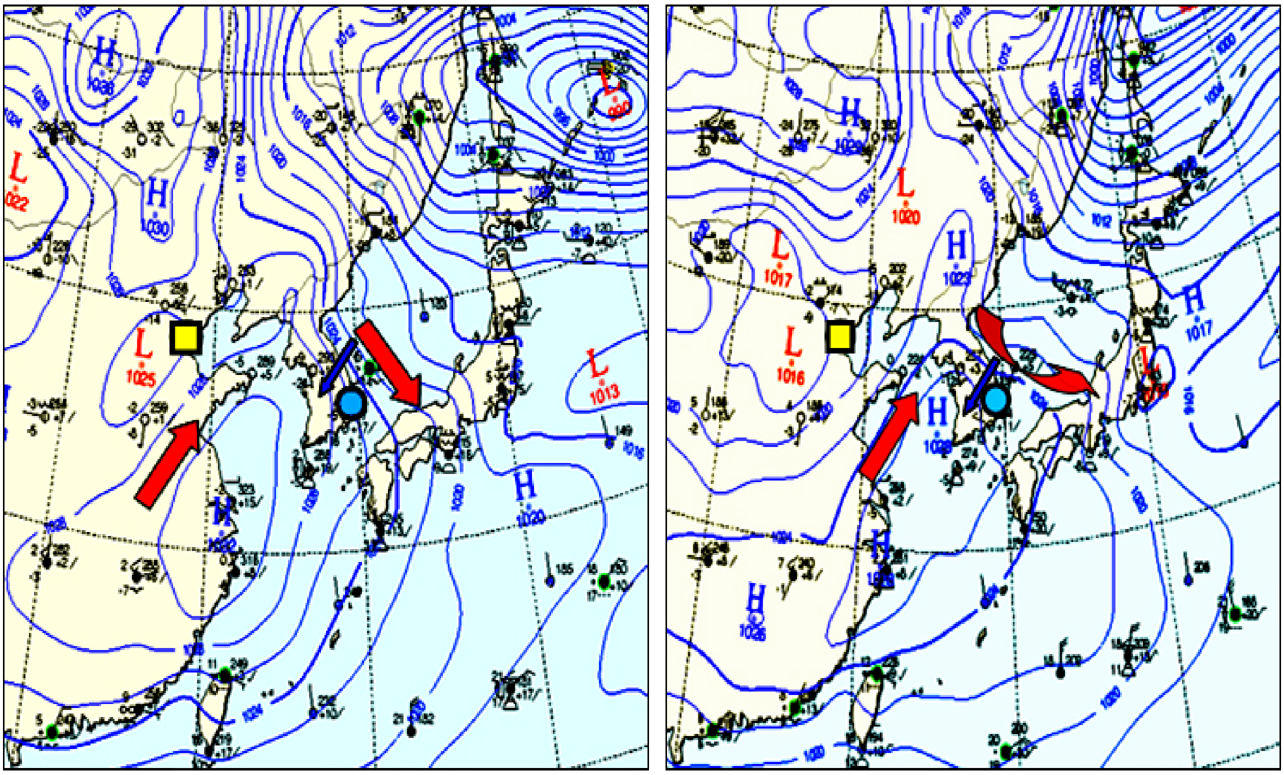
On the other hand, anti-cyclonic winds by a high pressure produce convergence and downwelling from the sea surface toward the deep sea. Under the influence of a high pressure over the Korean peninsula, northwesterly wind in the eastern coastal sea of Korea intrudes moderate south westward wind driven current, resulting in southward littoral current to the south and inducing cold waters of the North Korea Cold Current to the south along the coastline. As the low pressure at 2100LST moved toward the east, the low became slightly intensified from 1025hPa into 1016hPa with a decrease of 9hPa and a high pressure of 1032hPa near Shanghai in China also further extended to the southwestern coastal sea of Korean peninsula with its pressure of 1028hPa (Fig. 2b). Under the covering of high pressure over the whole Korean peninsula, marine surface winds depicted an anti-cyclonic wind pattern (clockwise) and weak north-westerly wind prevailed near Pohang city in the southeastern coastal city of Korea (Figs. 4a).

This clockwise wind pattern could cause inward wind driven currents in the coastal sea in the northern hemisphere as explained by Knauss[24]. It means that northwesterly wind in the eastern coast of Korea intrudes a moderate southwestward wind driven current which results in a southward littoral current (longshore current) moving roughly parallel to the shore toward the south, due to the coastal configuration of the Korean east coast and finally induces further the southward intrusion of the North Korea Cold Current to the south.



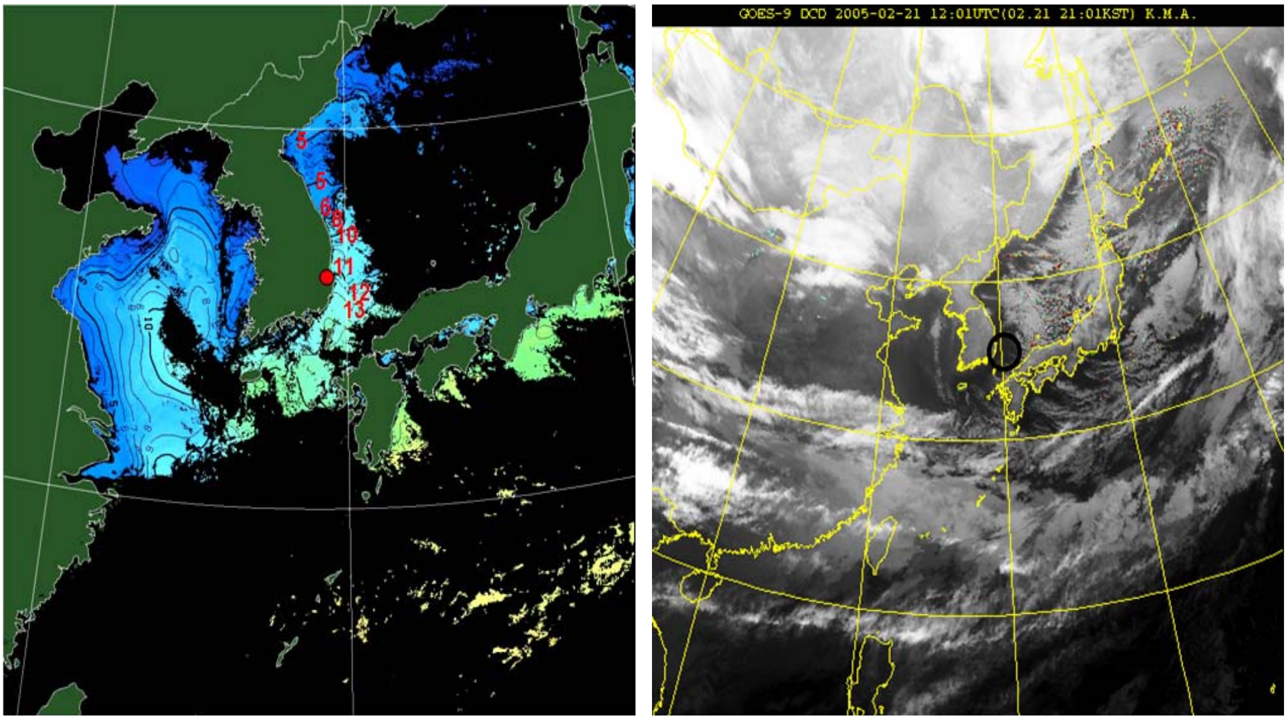
(a) (b)

Figure 1: (a) Topographical features in around Korean peninsula and the study area in a fine-mesh domain and (b) Ocean currents in the East Sea of the Korea (modified from Lee[18]). In (a), circle and square inside a small square denotes Pohang and Ulsan cities, Korea. In (b), YE, EK, NK, Li, TS, TG and SO denote Yellow Sea Warm Current, East Korea Warm Current, North Korea Cold Current, Liman Cold Current, Tsushima Warm Current, Tsugaru Warm Current and Soya Warm Current, respectively.



(a) (b)

Figure 2: Surface weather maps (a) 0900 LST (0000 UTC), February 21, 2005 and (b) 2100 LST (1200 UTC). Small square, circle, big and small arrows indict Tianjin (China) city, Pohang city (Korea), wind and wind driven current, respectively. As a low pressure around Tianjin city in (a) is developed from 1025hPa into 1016hPa in (b), a high pressure covers around Pohang city. Northwesterly wind in the eastern coast of Korea intrudes southwestward wind driven current, resulting in a southward littoral current and inducing cold waters of the NKCC to the south.



(a) (b)

Figure 3: (a) Daily mean sea surface temperature (SST; ^{0}C) of NOAA-MCSST on February 21, 2005 and (b) GOES-9 satellite images at 2100LST, February 21. SSTs in (a) were 11^{0}C in the coastal sea of Pohang city (a small circle) and 10^{0}C in the offshore of about 100 km away from the city. In (b), no cloud (no fog) was detected in the coastal and open seas in the vicinity of Pohang city (a big circle).

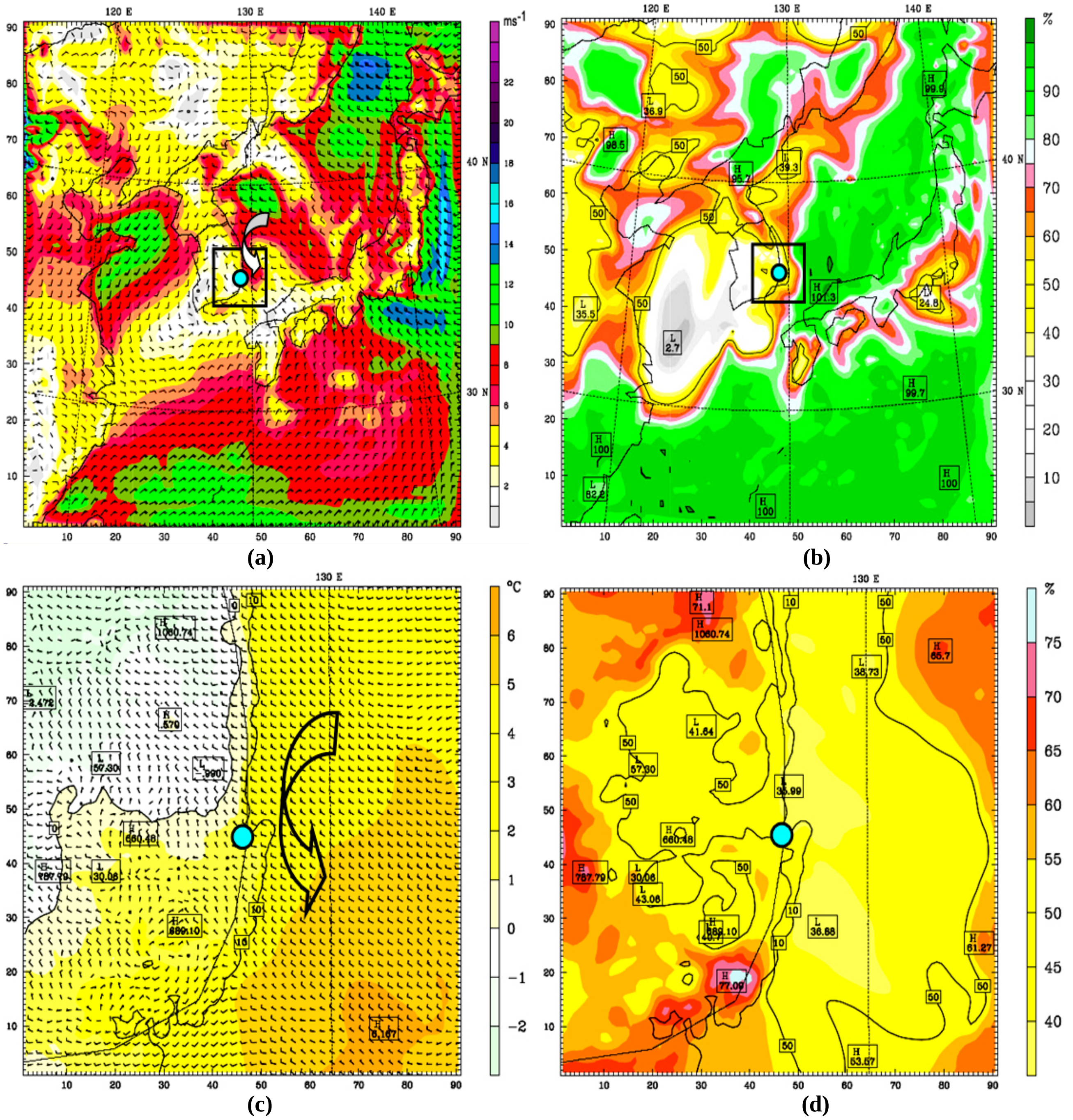


Figure 4: (a) Surface wind (m/s) at 10 m height and (b) relative humidity (%; RH) at 1km height in the first domain of a 27km horizontal grid at 2100LST, February 21, 2005. (c) Air temperature (^{0}C) with wind speed (m/s) and (d) relative humidity (%) at 10m height in the 3rd domain of a 3km horizontal grid, respectively. Small circles, small and big curved arrows in (a) and (c) denote Pohang city, wind and wind driven currents. Strong northwesterly winds greater than 5m/s prevailing in the southeastern coastal sea of Pohang city and the open sea far away from its coast intrudes southwestward wind driven currents, which results in a southward littoral current (longshore current) as well matching with the southward intrusion area of the NKCC on NOAA-MCSST images in Fig. 3a. In (b), RHs at 1km (10m) height were below 50% (55%) in the coast, but higher 95% (62%) in the 100km area away from the coast, showing the formation of clouds in Fig. 4b, but no fog in (d).

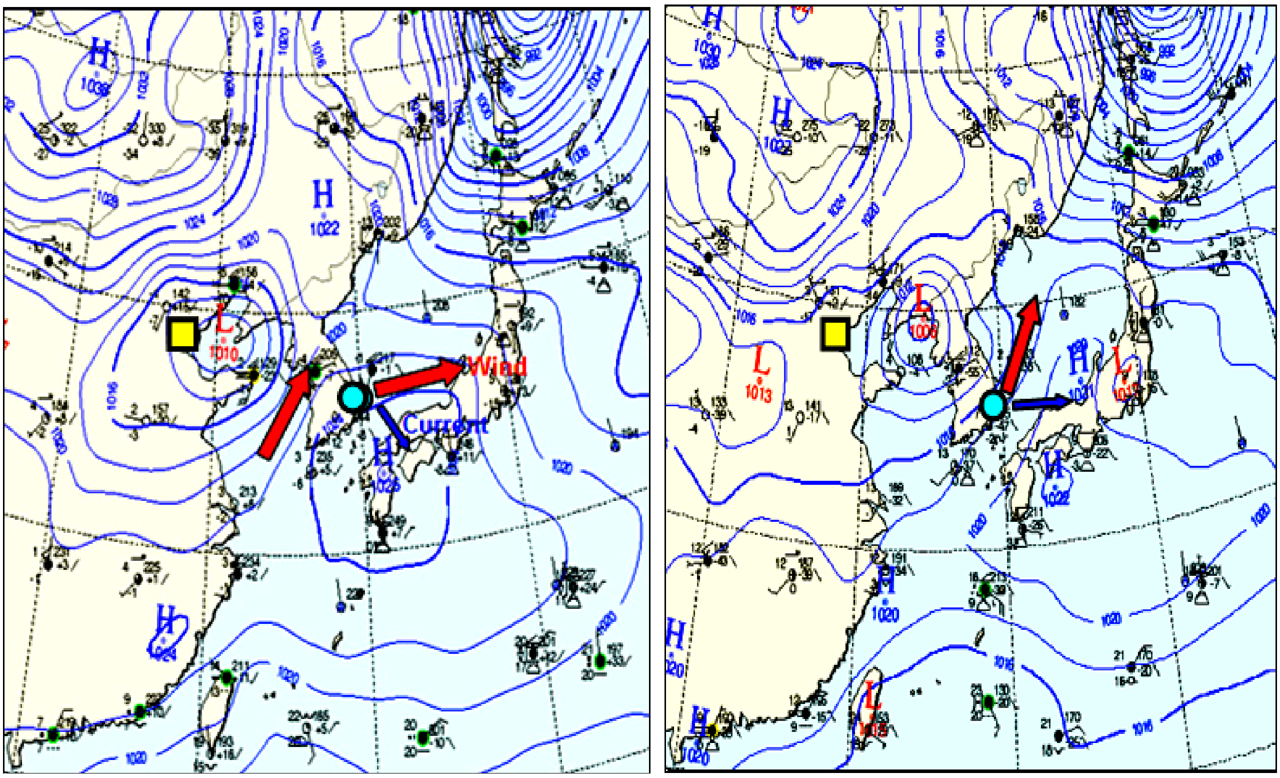
Thus, NOAA-MCSST daily mean sea surface temperature shown in Fig. 3a depicted 11^{0}C in the coastal sea near Pohang city and 10^{0}C in the open sea at about 100km off its coast. The SST was 12^{0}C in the coastal sea near Ulsan city at the lower latitude and 12^{0}C in the open sea. In Fig. 4a, as strong northwesterly winds greater than 5m/s prevailing in the southeastern coastal and open seas far away from the coast intruded south-westward wind driven currents, the regions of strong winds in the coast sea and the open sea far away from the coast were well matched with the regions of cold sea, that is, the southward intrusion area of the North Korea Cold Current on NOAA-MCSST images in Fig. 3a.

Further consideration was given to the formation of coastal and sea fogs in the study area. Fog is a type of a cloud like stratus and defined as a low-lying cloud near the surface typically distinguished from cloud with the same generation mechanism. Fog is known as a collection of water droplets suspended in the air at or near the ground or sea surfaces. When the air becomes saturated over ocean, fog can occur, even if the air is not at 100% relative humidity, because salt nuclei from the ocean serves very effectively as the hygroscopic nucleus of fog droplets[10, 13, 19]. This produces a solution of water and salt has a reduced droplet surface tension allowing fog to form when the relative humidity is well below 100%. Even as low as 97% in the presence of sufficient condensation, nuclei fog begins forming at 90 ~ 95% relative humidity.

There are two kinds of generation mechanisms on sea fog. When warm air blowing over a cold sea surface, it cools down to be saturated and condensation of moist air takes place, resulting in the formation of fog - advection fog. On the other hand, when cold air is supplied by moisture evaporated from the warm sea surface, the moist air near the surface is saturated until its humidity reaches 100% - evaporation fog (that is, steam fog).

In Figs. 4c and 4b, air temperature at 10m height over the cold sea surface in the coastal and open seas off the Pohang coast was 3 ~ 7^{0}C under the influence of cold northwesterly wind blowing from Manchuria of the northeastern China toward the study area. Although the difference between air temperature and sea surface temperature was - 8^{0}C in the coastal sea and - 3^{0}C in the open sea and it was in the easy condition of evaporation of water droplets over the sea surface, strong northwesterly surface wind accompanying cold and dry airs over 5m/s should dissipate fog droplets, resulting in very low relative humidity of 55% in the coastal sea and 65% in the open sea of about 100km offshore and causing no fog near the sea surface, except for the formation of clouds at 1km height.

During a period of sea fog formation: As the low pressure of 1015hPa in the left side of Tianjin at 2100LST, February 21 slowly moved into the Bohai Sea in the right at 0900LST, February 22, it was deepened into 1010hPa (Fig. 5a). The intensified low pressure produces strong southwesterly wind over 10m/s in the Yellow Sea and the East Sea in the northeastern coast of the Korean peninsula in Fig. 6a which should induce southeastward wind driven current along the coast of the northeastern Korea toward the south, resulting in the intrusion of the North Korea Cold Current to the south.



(a) (b)

Figure 5: As shown in Fig. 2, except for (a) 0900 LST (0000 UTC), February 22, 2005 and (b) 1500 LST (0600 UTC). A low pressure produces southwesterly wind prevailing in Pohang (small circle) coastal and open seas causes southeastward wind driven current in (a). In (b), a cyclonic air flow by the more intensified low pressure produced southwesterly wind near Pohang city to cause southeatward wind driven current, which induced upwelling of deep cold waters toward the sea surface and combining with the southward NKCC from the Korean northern coastal sea toward the Pohang coast, resulting in a cool pool in the southeast offshore in Fig. 7a.

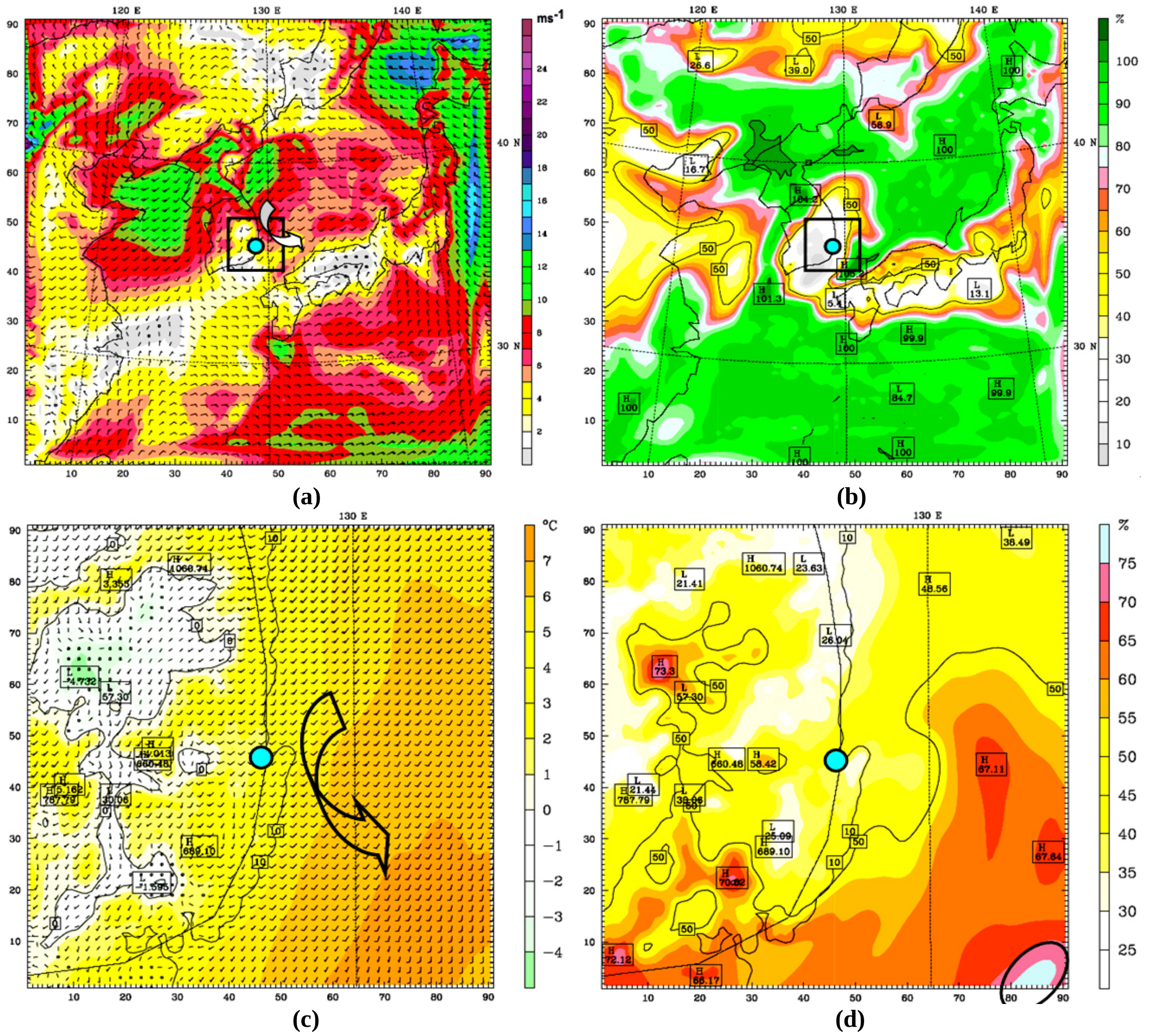
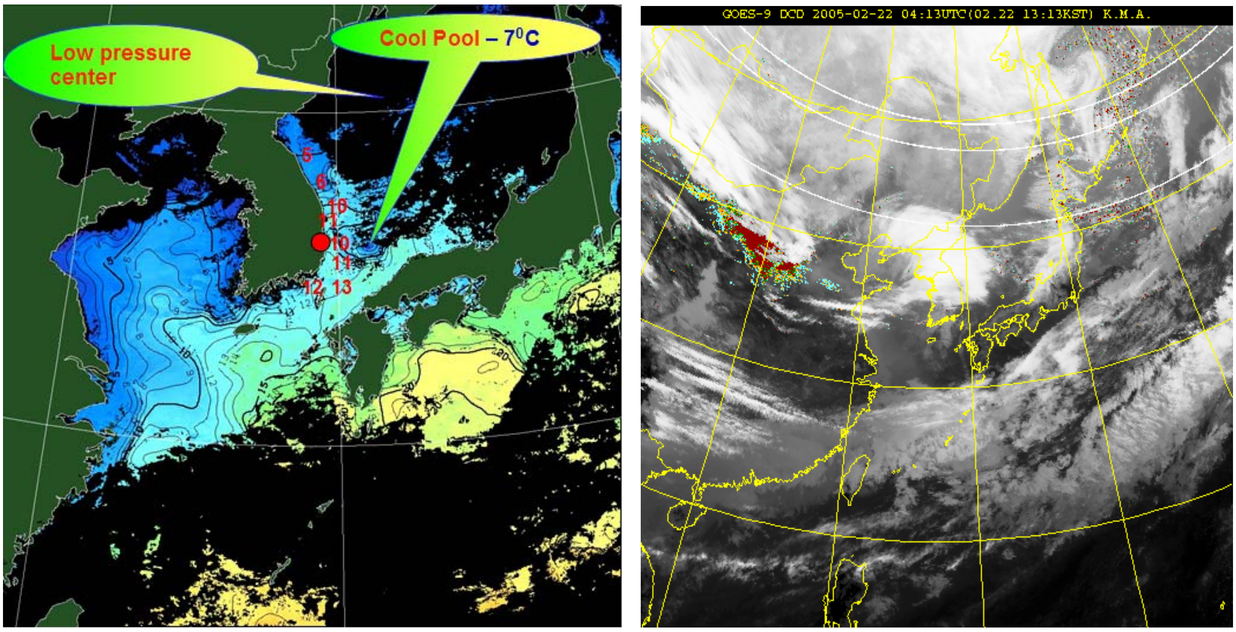


Figure 6: (a) Surface wind (m/s) at 10 m height and (b) relative humidity (%; RH) at 1km height in the first domain of a 27km horizontal grid at 0900LST, February 22, 2005. (c) Air temperature (^{0}C) with wind speed (m/s) and (d) relative humidity (%) at 10m height in the 3rd domain of a 3km horizontal grid, respectively. Small circles, small and big curved arrows in (a) and (c) denote Pohang city, wind and wind driven currents. In (a), southeastward wind driven currents by southwesterly wind over 5m/s in the eastern coastal seas caused further the intrusion of the NKCC to the south. As warm air by southwesterly wind moved over the cold sea in the southestern offshore from Pohang city in 6(a) and 6(c) should cool down to 75% RH (a circle in right) with no fog in (d).

At the same time, a high pressure still controlled the inland and sea in the southeastern Korean peninsula (the study area). This pressure system produced an anti-cyclonic flow of air (clockwise) such as southwesterly and easterly winds over 5m/s in the southeastern coast of the Korean peninsula caused the merging of surface sea water into the high pressure center and its downwelling into the bottom of the sea and further the intrusion of cool waters of the North Korea Cold Current along the coastline to the south shown in Fig. 1b. Thus, southwesterly winds produced south-eastward wind driven currents (Figs. 5a and 6a), which could further more intrude the cold waters of the North Korea Cold Current toward the coastal sea of Pohang city and the open sea offshore.

Thus, as strong southwesterly wind with warm airs of 5 ~ 8^{0}C at 10m height from Kyushu Island, Japan passing by the Korea Strait moved over cold seas of 7 ~ 12^{0}C in the coastal and open seas of Pohang city at 0900LST, February 22 (Figs. 6a and 6c), no fog formed at 10m height near the sea surface, due to insufficient saturation of water vapour with 50 ~ 75% relative humidity (Figs. 6b and 6d), but clouds occurred at 1 km height over the sea surface under relative humidity greater than 100% (Fig. 6b). We can postulate that there must be possibility of sea fog to occur near the sea surface, even though relative humidity was 75% in the southeastern sea from Pohang city.



(a) **(b)**

Figure 7: (a) Daily mean sea surface temperature (^{0}C) on February 22, 2005 and (b) GOES-9 satellite images at 1300LST, February 22.

After 0900LST, as southwesterly wind with warm airs of 5 ~ 8^{0}C continued to blow over the cold sea surface of the study area and relative humidity of 79% maintained before 1300LST, it may be possible to say that sea fog formed, because 80% relative humidity is not absolute condition to make the formation of fog as the previous research results by Sciocatti[12], Ahrens[10] and Wikipedia[14]. In this study, there is no observed evidence, but for the practical purpose of safe forecasting using a numerical model, it may be better to consider that sea fog forms, if relative humidity is below 80% but close to 80%. However, in the case greater than or equal to 80% relative humidity near the sea surface, it has been known that sea fog formed. From 1300LST, relative humidity became over 80%.

At 1300LST, February 22, as the low pressure slowly moved to the central part of the Bohai Sea and its pressure was more intensified into 1008hPa (Fig. 5b), where the pressure pattern caused strong southwesterly wind of 6 ~ 11m/s (Figs. 8a and 8c). Strong southwesterly wind in the eastern coastal and open seas caused southeastern wind driven currents which induced upwelling of deep cold waters toward the sea surface and became southward resultant littoral currents (i.e. longshore currents). These currents caused further the southward intrusion of the North Korea Cold Current toward the southeastern open sea in about 100 km away from Pohang city (a cool pool of cold waters seen in NOAA-MCSST images in Fig. 8a).

As much warmer air of 6 ~ 9^{0}C at 1300LST than 0900LST by strong southerly of 6 ~ 11m/s moved over the cold sea surface, especially the cool pool from Kyushu Island of Japan toward the southeastern sea of Pohang city, passing by the Korea Strait, the difference between air and sea surface temperature was about 2^{0}C, due to air temperature of 9^{0}C over the sea and sea surface temperature of 7^{0}C (Figs. 8a and 8c). So, the air must cool down to be saturated and water vapour in air to be condensed by salty condensation nuclei, resulting in the formation of sea fog with 80% of relative humidity at 10m height over sea of about 100km away from the Pohang coast (Figs. 8b and 8d) and stratus or stratocumulus clouds vertically extended to 1km height over the sea surface, similar to the research results by Taylor[11], Sciocatti[12], Choi et al[13] and Choi and Speer[19].

In our case, as warm air blew over the cool pool, the condensation of water vapour in the air could be achieved by dropping the ambient air temperature as typical advection fog (Fig. 8b and 8c). As the low pressure was still located in the northwestern coast of Korean peninsula, this fog near the cool pool area was not affected by cold front of the low pressure, that is, no frontal fog.

Choi et al[13] explained in the previous study that salty nucleus in the marine atmosphere can easily make a droplet below 80% relative humidity in the southeastern coastal sea of the Korean peninsula, enhancing fog in the coastal region, because salt from the ocean serves very easily as the hygroscopic nucleus of fog droplets and a reduced droplet surface tension of salt allows fog to form.

Differently from evaporation fog, sea fogs in our study area of the Korea southeastern coastal and open seas occurred under relatively strong wind, similar to the case by Li et al's research[16] in the Yellow Sea in the west of the Korean peninsula, when warm air blew over a cold sea surface and condensation takes place under wind speed strong up to 10m/s over the sea surface.

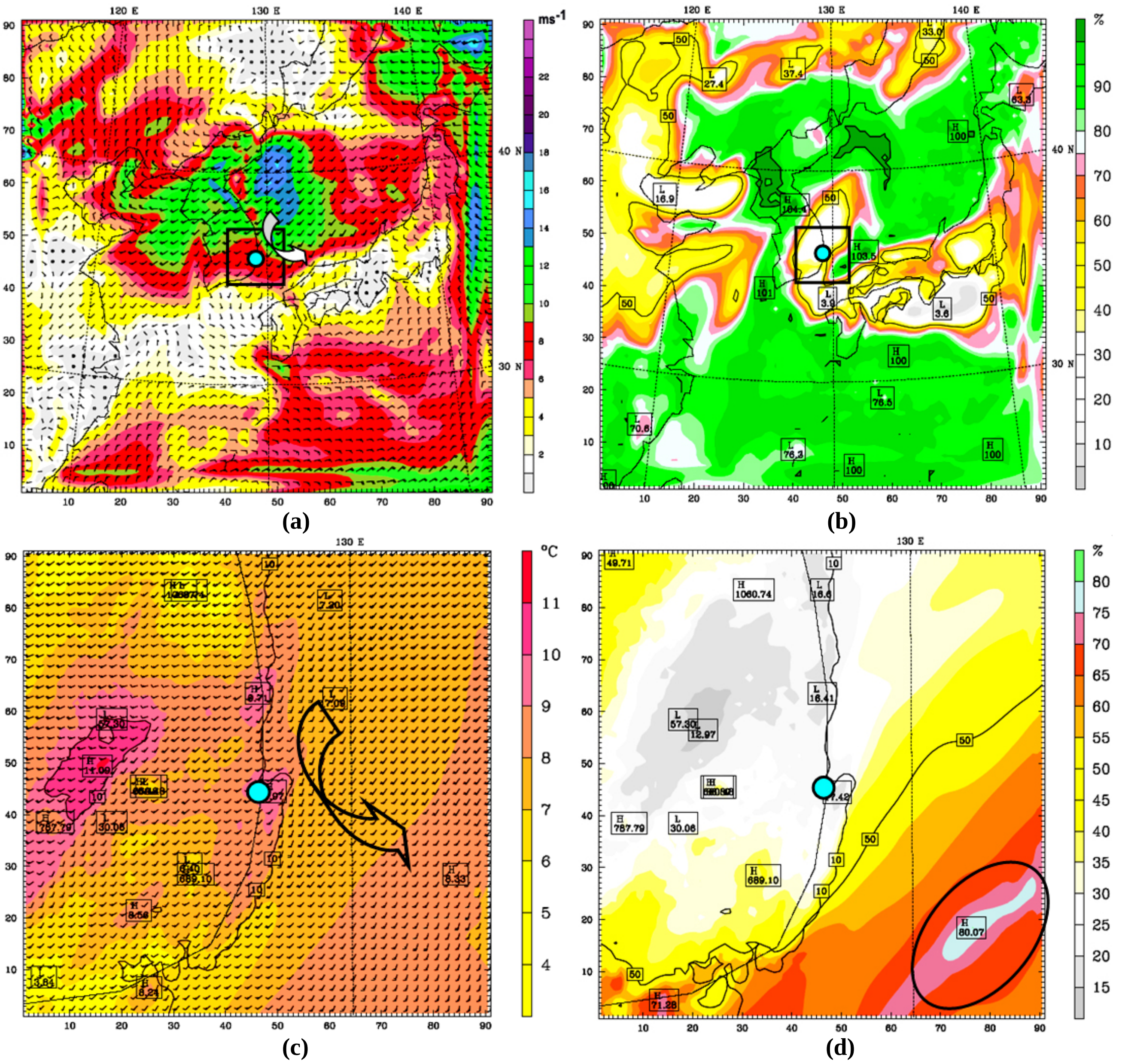


Figure 8: (a) Surface wind (m/s) at 10 m height and (b) relative humidity (%; RH) at 1km height in the first domain of a 27km horizontal grid at 1300LST, February 22, 2005. (c) Air temperature (^{0}C) with wind speed (m/s) and (d) relative humidity (%) at 10m height in the 3rd domain of a 3km horizontal grid. Small circles, small and big curved arrows in (a) and (c) denote Pohang city, wind and wind driven currents. Southeastward wind driven current in the Korean eastern sea caused further the southward intrusion of the NKCC into the 100km southeast away from Pohang city (a cool pool of 7^{0}C in Fig. 7a). As warm air of 6 ~ 9^{0}C by southerly of 6 ~ 11m/s moved over the cool pool in (a) and the difference between air and sea surface temperature there was about 2^{0}C, the air cooled down to be saturated at 80% RH, with sea fogs by salty condensation nuclei in (d) and clouds at 1km height in (b).

As shown in Figs. 8a and 8b, as strong northwesterly winds caused south-westward wind driven currents, the regions of strong winds in the coast sea and the open sea far away from the coast were well matched with the regions of cold sea, that is, the southward intrusion area of the North Korea Cold Current on NOAA-MCSST images in Fig. 7a and a cool pool area had about 100 km radius. As shown in GOES-9 satellite images at 1300LST (Fig. 7b), it is very difficult to distinguish fog from stratus and to find the heights of their formations, while a numerical simulation by the model gave us very detail information on the existence of fog or stratus.

As time went on, especially, the low pressure at 1500LST, February 22 reached the Korean northwestern coast (Fig. 6b) and southwesterly wind of 8 ~ 13m/s prevailed in the coastal and eastern open seas of Pohang city (Fig. 9a). Warmer air of 6 ~ 11^{0}C by southwesterly wind moved over the cold sea surface (especially air temperature of 8.4^{0}C over the cool pool of 7^{0}C cold waters), the difference between air temperature and sea surface temperature reached 1.47^{0}C (Figs. 7a and 9c). At this time, relative humidity was below 80% like 78% in the same area and it may be difficult for sea fog to form, as southwesterly wind became stronger, resulting in the dissipating fog droplets (Figs. 9b and 9d). Relative humidity of 78% continued to 1600LST.

From 1800LST, southwesterly wind under the more intensified low pressure passing by the northern Korean peninsula became much stronger and relative humidity in the study area was still less than 60%, resulting in no fog, although there was still formation of clouds at 1km height. Over all, from the practical point of view considering the previous researches on fog, if relative humidity is above 80% or close to 80%, it is possible to say that sea fog can form, even adopting a condition to form sea fog with relative humidity greater than or equal to 80% in this study.

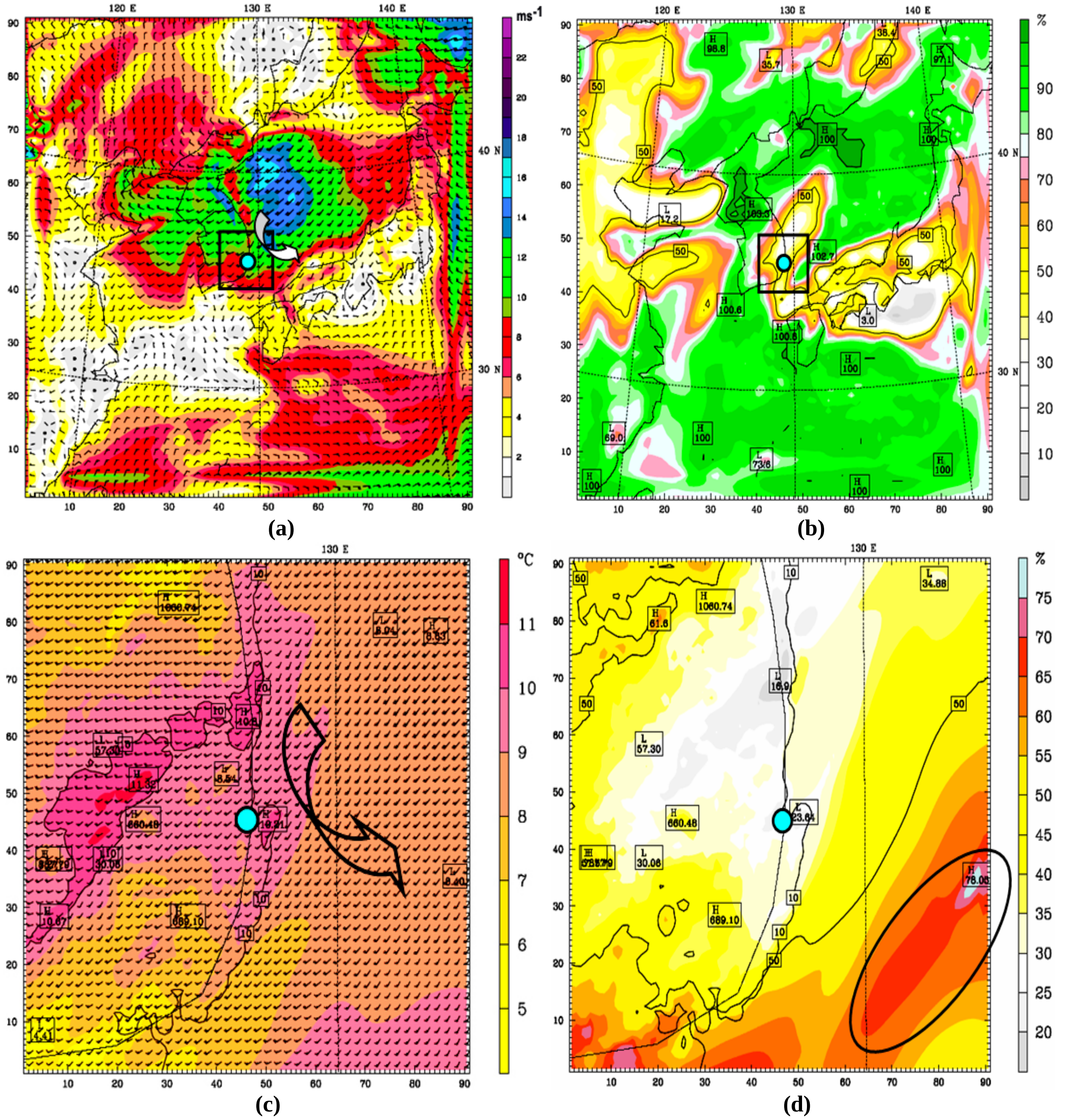


Figure 9: (a) Surface wind (m/s) at 10 m height and (b) relative humidity (%; RH) at 1km height in the first domain of a 27km horizontal grid at 1500LST, February 22, 2005. (c) Air temperature (^{0}C) with wind speed (m/s) and (d) relative humidity (%) at 10m height in the 3rd domain of a 3km horizontal grid. Strong southwesterly wind in the eastern coastal and open seas caused southeastward wind driven currents. As strong southwesterly winds of 8 ~ 13m/s with warm air of 6 ~ 9^{0}C from Kyushu Island blew over the cool pool in the open sea of Pohang city in (a) and (c), RH was 100% with clouds at 1km height in (b) and 78% with no sea fog at 10m height in (d).

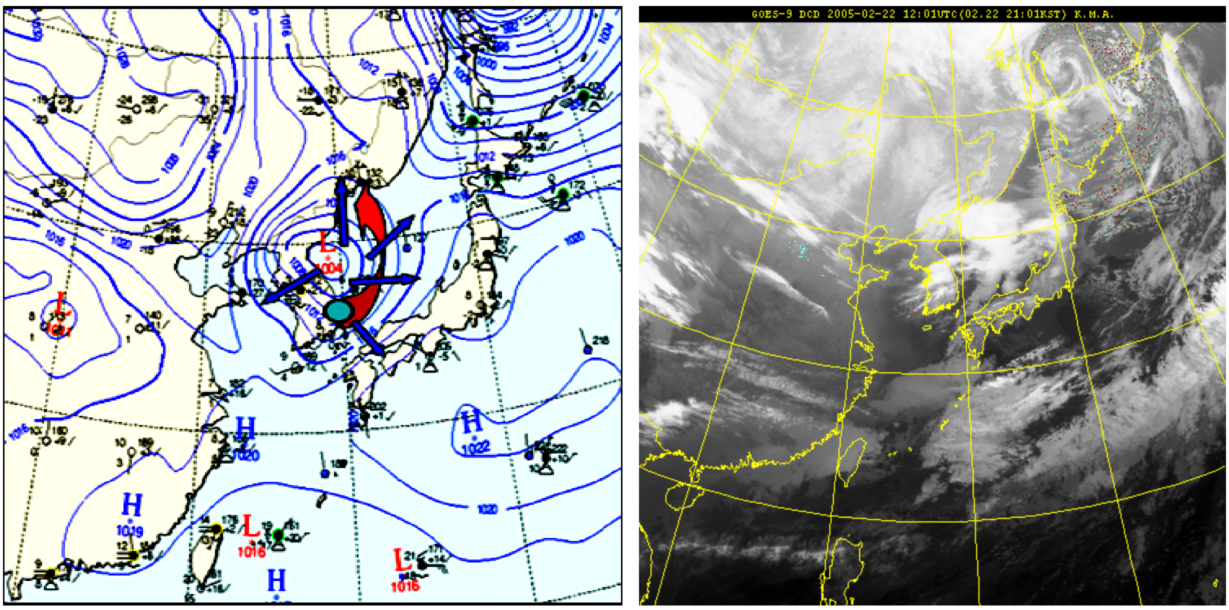
In Figs. 10a, 10b and 11a, as the low pressure at 2100LST, February 22 further moved into the northeastern coastal sea of the Korean peninsula, it became more intensified into 1004hPa and the low pressure produced a strong cyclonic flow of air (counterclockwise wind) called cyclogenesis. The counterclockwise wind pattern could cause an anti-cyclonic wind driven current which induces upwelling of cold bottom waters from the low pressure center and spreading out along the inclined sea surface from its center and further along the whole eastern coastal seas of Korea. The uplifted cold waters combined with cold waters of the existed North Korea Cold Current flowing to the south, parallel to the coastline and these waters should be transported by southeastward wind driven currents induced by strong southwesterly wind to the coastal seas of Pohang and Ulsan cities, depicting SST of 10 ~ 12^0C in the coastal sea and 7^0C of a cool pool of cold waters with a decrease of 5^0C in the open sea about 100 km away from their coasts toward the southeast (Figs. 7a, 11c and 11d).

As strong southwesterly wind of 10 ~ 15m/s accompanying warm air of 8 ~ 10^0C blew over the cold sea surface, especially a cool pool of sea waters in the southeastern coastal sea, the air should cool down to be saturated and water vapour in air might be condensed by condensation nuclei to form sea fog, under 2 ~ 3^0C differences between air and sea surface temperatures. However, relative humidity in the study area was below 70%, which could not make any fog, because southwesterly wind was too strong to make any fog, due to the dissipating fog droplets as such in Fig. 11d. As shown in Fig. 11b, there was no cloud at 1km height.

Differently from cold sea outbreak by strong wind under cyclogenensis in the coastal sea, Choi[25] explained that in the case of a typhoon Rusa, a cyclonic wind of the typhoon and its fast movement caused a divergence of ocean current behind the typhoon along its track by upwelling such as Ekman pumping process by which deep sea cold water was brought to the sea surface and outward spreading along the further inclined sea surface from the typhoon center generated by positive geopotential tendency at 500 hPa level, resulting in colder water outbreak of 17^0C with a great decrease of 12^0C near Cheju Island in the South of Korea. Thus, sea surface temperature induced by wind storm in the coastal sea did not much change than one by the typhoon.

Conclusion

The prevailing northwesterly wind in the Korean eastern coast under a high pressure in the whole Korean peninsula produced moderate southwestward wind driven currents which became southward littoral currents (that is, longshore currents) due to its coastal configuration from the north to the south. These littoral currents caused further the southward intrusion of the North Korea Cold Current toward the south, resulting in the extension of cold sea area (a cool pool) in the southeatern coastal sea near Pohang city of the Korean peninsula. As cold air by northwesterly wind blowing from the northern China moved over the cool pool area, it is possible for sea fog to form by evaporation of water droplets from the sea into the lower atmosphere and condensation of water vapour in air due to a relatively big difference between colder air and warmer sea surface temperatures, but there was no formation of fog by the dissipation of fog droplet by strong marine surface to 65% relative humidity.



(a) (b)

Figure 10: (a) Surface weather map (hPa) and (b) GOES-9 satellite images at 2100 LST (1200 UTC), February 22, 2005. Circle, big and small arrows denote Pohang city, cyclonic wind and wind driven current, respectively. Cold front existed in the left hand side of Pohang city. Even though no fog existed near the sea surface, nocturnal radiation fog near the inland surface and stratus cloud at 1km height still formed in Fig. 12.

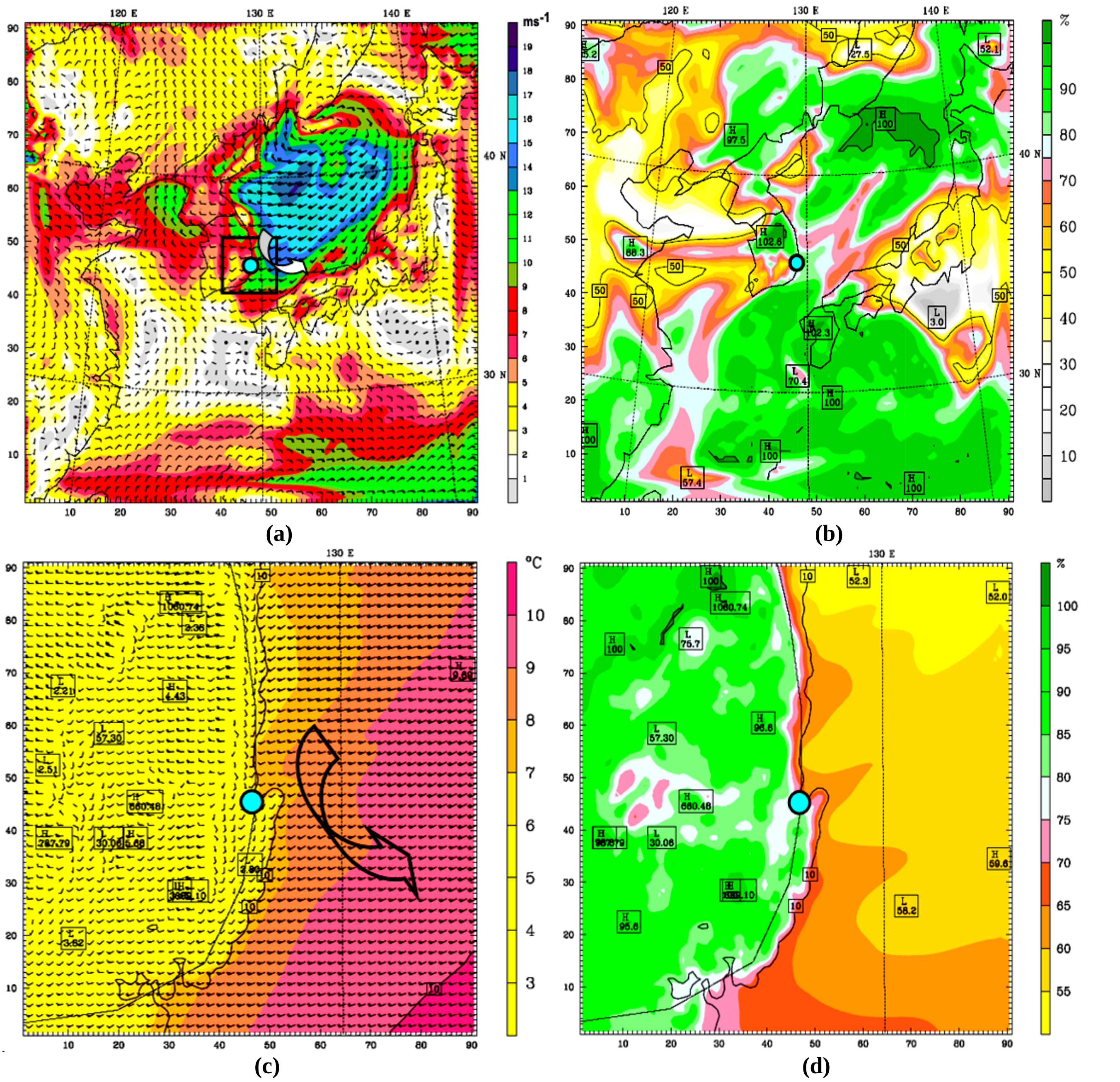


Figure 11: (a) Surface wind (m/s) at 10 m height and (b) relative humidity (%; RH) at 1km height in the first domain of a 27km horizontal grid at 2100LST, February 22, 2005. (c) Air temperature (^{0}C) with wind speed (m/s) and (d) relative humidity (%) at 10m height in the 3rd domain of a 3km horizontal grid. Strong southwesterly wind in the eastern coastal and open seas caused southeastward wind driven currents. Strong southerly of 10 ~ 16m/s with warmer air of 8 ~ 11^{0}C with temperature differences of 1 ~ 4^{0}C between air and sea surface water blew from Kyushu Island of Japan over the cool pool in the open sea of Pohang city in (a) and (c). Nocturnal radiation fog formed in the inland area (3, 35) in (d), but no fog existed in the open sea, due to the dissipation of fog droplets by the strong wind.

On the other hand, as an eastward moving low pressure became more intensified (cyclogenesis) in the Korean northwestern coast caused a cyclonic wind pattern like counterclockwise, southwesterly wind prevailed in the Korea northern coastal sea and this wind could induce southeastward wind driven current, resulting in upwelling of deep cold waters toward the sea surface and simultaneously further southward intrusion of the North Korea Cold Current toward the southeastern open sea (cool pool) from Pohang city. As much warmer air by southwesterly wind moved from Kyushu Island in south toward the cool pool area, the air over the cold sea should cool down to be saturated and water vapour in air to be condensed by salty condensation nuclei, resulting in the formation of sea fog with 80% relative humidity near the sea surface and stratus cloud with 100% relative humidity at 1km height for daytime hours.

In this research, we adopted that a condition to form sea fog was to maintain relative humidity greater than or equal to

80%. However, for safe aviation purposes as in the United Kingdom, it is also considerable that sea fog can form between 75% and 80% in the wide area of the coastal and open seas.

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