Modification of Sea Water Temperature by Wind Driven Current in the Mountainous Coastal Sea

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Numerical simulation on marine wind and sea surface elevation was carried out using both three-dimensional hydrostatic and non-hydrostatic models and a simple oceanic model from 0900 LST, August 13 to 0900 LST, August 15, 1995. As daytime easterly meso-scale sea-breeze from the eastern sea penetrates Kangnung city in the center part as basin and goes up along the slope of Mt. Taegullyang in the west, it confronts synoptic-scale westerly wind blowing over the top of the mountain at the mid of the eastern slope and then the resultant wind produces an upper level westerly return flow toward the East Sea. In a narrow band of weak surface wind within 10km of the coastal sea, wind stress is generally small, less than 1x10E-2 Pa and it reaches 2 x 10E-2 Pa to the 35 km. Positive wind stress curl of 15 x 10E-5Pa m^{-1} still exists in the same band and corresponds to the ascent of 70 cm from the sea level. This is due to the generation of northerly wind driven current with a speed of 11 m s^{-1} along the coast under the influence of south-easterly wind and makes an intrusion of warm waters from the southern sea into the northern coast, such as the East Korea Warm Current. On the other hand, even if nighttime downslope windstorm of 14m/s associated with both mountain wind and land-breeze produces the development of internal gravity waves with a hydraulic jump motion of air near the coastal inland surface, the surface wind in the coastal sea is relatively moderate south-westerly wind, resulting in moderate wind stress. Negative wind stress curl in the coast causes the subsidence of the sea surface of 15cm along the coast and south-westerly coastal surface wind drives alongshore south-easterly wind driven current, opposite to the daytime one. Then, it causes the intrusion of cold waters like the North Korea Cold Current in the northern coastal sea into the narrow band of the southern coastal sea. However, the band of positive wind stress curl at the distance of 30km away from the coast toward further offshore area can also cause the uprising of sea waters and the intrusion of warm waters from the southern sea toward the northern sea (northerly wind driven current), resulting in a counter-clockwise wind driven current. These clockwise and counter-clockwise currents much induce the formation of low clouds containing fog and drizzle in the coastal region.

Key words: Non-hydrostatic model, Onshore wind, Sea-breeze, Valley wind, Internal gravity waves, Wind driven current, Wind stress, Wind stress curl, , Mountain wind, Land-breeze, Windstorm, East Korea Warm Current, North Korea Cold Current, Offshore wind

1. Introduction

In the coastal region with high steep mountains and sea greatly influenced upon atmospheric circulation near the coastal sea, sea surface states varies under the different wind speed and direction. Especially, surface elevation and water drift in the coastal sea behind the high steep mountain respond to the atmospheric condition such as the intensification of wind and the variations of air and sea surface temperatures. Raynor(5) explained that heat process in the coastal region were directly associated with wind and temperature generated by sea-land breeze. Segal(6) explained on the impact of valley and ridge thermally induced circulations on regional pollutant transport.

The primary purpose of this study is to

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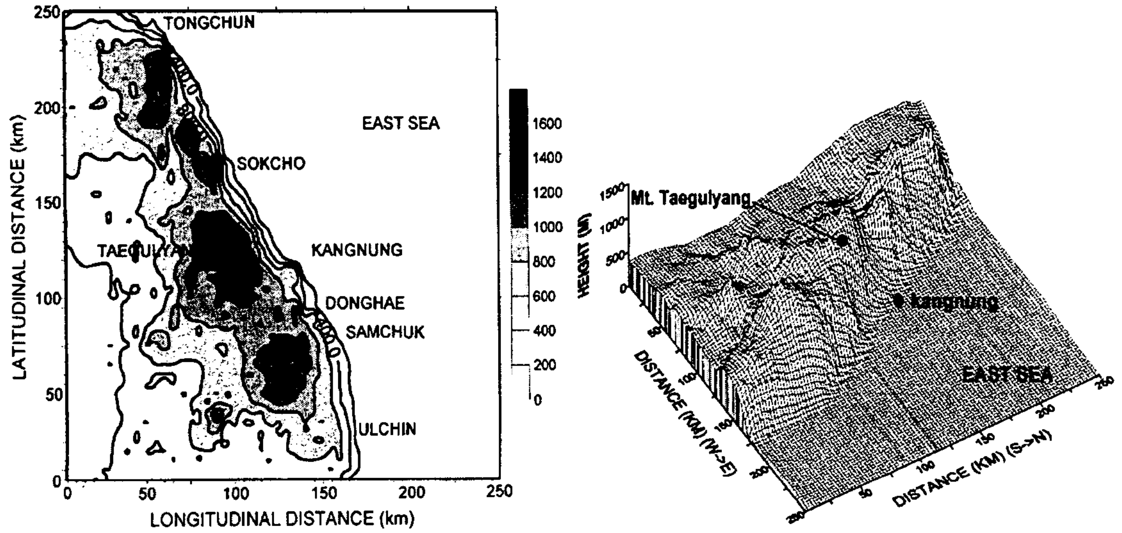
investigate how much the sea surface elevation and sea surface drift can be induced by the strong windstorm blowing over the high steep mountains into the coastal sea. The secondary was given to explain the contribution of wind driven current to the distributions of sea surface temperature and moisture and the association of permanent ocean currents flowing adjacent to Korean peninsula.

2. Data Analysis and Numerical Model

Near the study area, high steep Tae Bak mountains lie from south toward north along the eastern coast of Korean peninsula with a narrow plain area and take another branch mountains toward south-west off Tae Bak mountains in a coarse-mesh domain. In a fine-mesh domain, the study areas consist of complex terrains, which are characterized by forest in a high steep mountain called Mt. Taegulyang (865 m) in the west, Kangnung city in the central part and sand beach with sea water in the east[1] (Fig. 1).

A three-dimensional non-hydrostatic grid point model in a complex terrain-following coordinate (x, y, z*) was adopted for a 48 hour numerical experiment from 0600 LST (Local Standard Time = 9h + Greenwich Mean Time), August 13 to 0600 LST, August 15, 1995.



(a) (b)

Fig. 1. (a) Two dimensional topography near Kangnung city. The coastal line lies from south-east toward north-west. (b) Three dimensional topography rotated with 90^0 in the right hand side from the original position consists of high steep Tae Bak mountains (maximum height: 1,563 m) along the coast and Mt. Taegulyang (865m) lies in the west of the city.

The numerical simulation on meteorological phenomena was made using Hitachi super computer at Meteorological Research Institute, Japan Meteorological Agency (JMA). Two different domains consist of 50 x 50 grid points with an uniform horizontal interval as 20km in a coarse-mesh model and 5km in a fine-mesh for one-way double nesting, respectively. Every 12 hourly global analysis data (G-ANAL) in a horizontal resolution of 1.25^0 of atmospheric pressure, wind, potential temperature, specific humidity on vertically five levels from the surface to 100 mb level (approximately 13 km height) made by the JMA were horizontally and vertically interpolated for our two models of 16 levels with different horizontal resolutions.

Predicted data by the coarse-mesh model were treated as lateral boundary data in a fine-mesh model. Sea surface temperature as initial input data in two model domains was obtained from sea surface temperature (SST) on NOAA satellite picture reanalyzed by National Fisheries Research and Development Agency.

Wind stress and wind stress curl in the

Cartesian coordinate, which influence sea surface current speed and direction and sea surface elevation can be calculated by

$$\tau_x = \rho\, C_d\, |V| u$$
$$\tau_y = \rho\, C_d\, |V| v$$
$$\nabla_{ij} \times \tau_{ij} = \partial \tau_y / \partial x - \partial \tau_x / \partial y \qquad (1)$$

where τ, τ_x and τ_y, ρ, C_d, V, u and v are wind stress($\tau = (\tau_x^2 + \tau_y^2)^{1/2}$), wind stress in the x and y directions, air density(= $1.2 kg/m^3$), drag coefficient, wind velocity($V = (u^2 + v^2)^{1/2}$).

As the drag coefficient, C_d is a function of wind speed at 10m height above the sea, sea surface temperature, T_o and air temperature, T_a at 10m height over the sea, it varies by atmospheric stability on the temperature contrast between T_o and T_a. So, its magnitude depends upon thermal distribution near sea surface for day or night and summer or winter.

In the East Sea experiment[2], following formula with a function of wind speed and atmospheric stability based on the difference between T_o and T_a in the marine atmospheric boundary layer is also suggested

$$C_d = 1.2\times 10^{-3} + 0.06\times 10^{-3}\, V/10(T_o - T_a) \qquad (2)$$

The values of C_d calculated by equation (13) were in the range of $0.82\times 10^{-3} \sim 1.19\times 10^{-3}$. The updraft of sea water from the sea water depth due to wind stress takes a form as

$$\triangle H(t) = h(t) - h(0) \qquad (3)$$

where $\triangle H(t)$, h, t and 0 are sea surface elevation for a time interval, sea water depth, artificially given time and initial time.

By assuming that density variation can be neglected and vertically integrating the continuity equation, Geisler[3]' linear theory on Ekman displacement is adopted as

$$1/h\, \partial(\triangle H)/\partial t = \partial u_s/\partial x + \partial v_s/\partial y \qquad (4)$$

Here, $\partial(\triangle H)/\partial t$, u_s and v_s are uprising velocity of water, and wind driven current speeds in x and y directions. By adopting Camerlengo (1982)'s approaching method for the steady case, horizontal momentum equation can be given in a simple way as

$$-f v_s = -\, g^* \partial h/\partial x + \tau_x(\rho_w h)^{-1}$$
$$f u_s = -\, g^* \partial h/\partial y + \tau_y(\rho_w h)^{-1} \qquad (5)$$

g^* is reduced gravitational acceleration[4], [5]. Equation (5) by differentiating can be converted as

$$f(\partial u_s/\partial x + \partial v_s/\partial y)$$
$$= (\partial \tau_y/\partial x - \partial \tau_x/\partial y)(\rho_w h)^{-1} \qquad (6)$$

By combing equation.(5) with equation (6) and deleting convergence term of the resultant equation, following equation can be given as

$$\partial(\triangle H)/\partial t = \mathrm{curl}\tau\ /(\rho_w f) \qquad (7)$$

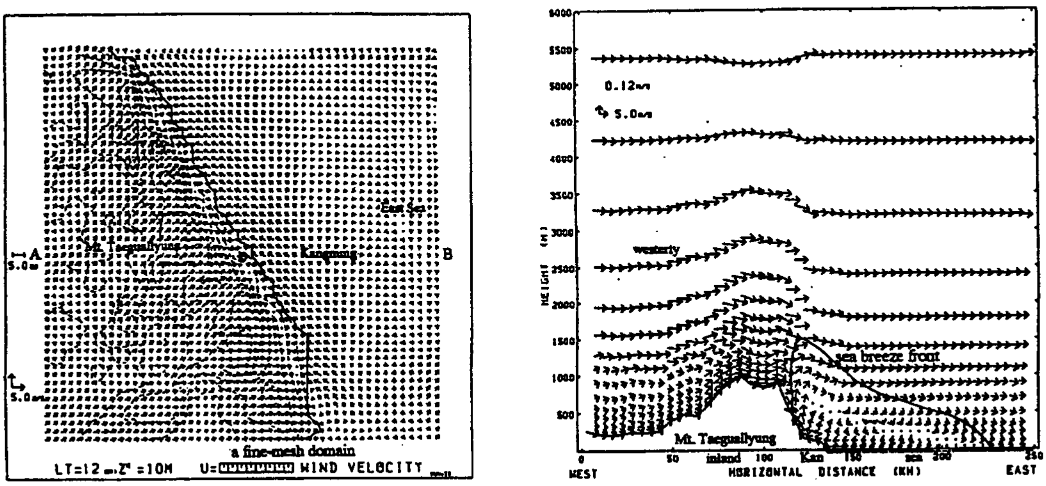
and by integrating this equation for time interval, $\triangle t$, sea surface elevation can be calculated. $\triangle H$ has a unit of cm/s and positive value means sea surface elevation. As sea water density, ρ_w is driven by a function of sea temperature (T), salinity(S) and water pressure(P_w). Since sea surface temperature and salinity at sea level in the Kangnung coastal sea are about 25^0C and $35^0/_{00}$, ρ_w(= $1062.53817 kg/m^3$) can be applicably treated as mean value.

3. Results and Discussion

At 1200LST, August 14, 1995, synoptic-scale westerly winds at 10m height over the ground surface prevail over the Yellow Sea and penerate into the Korean peninsula, passing through eastern coastal mountain regions. At this time, easterly winds from Ulchin city (37^0N) to Vladivostok (41^0N) are blowing from sea into inland sites, while southerly winds exist along the coast below Ulchin city to Pusan city (35^0N).

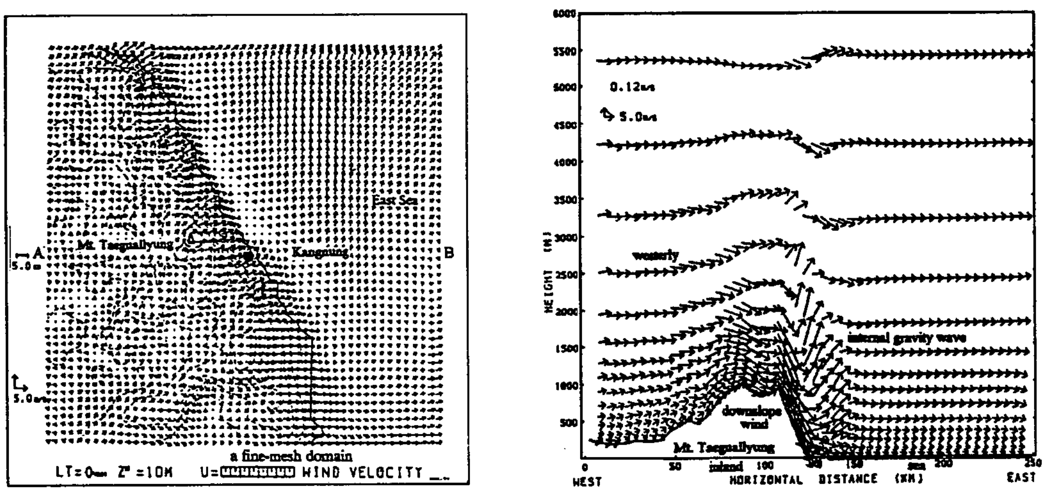
As Kangnung city in an eastern mountainous coastal region of the Korean peninsula is under the influence of south-westerly wind in the inland side and easterly wind in the sea, it is directly effected by advection of moisture induced by a sea-breeze circulation from coastal sea in the east and relatively warm and dry air from the mountains in the west. Winds at Kangnung city, which consists of Mt. Taeguallyung in the west and the East Sea in the east are south-westerly under the influence of the downslope of high mountains.

As daytime surface winds in the Kangnung coastal seas are weak and south- easterlies, the winds in the sea within 10km area away from the coast are moderate and can induce alongshore wind driven currents with speeds of about 7cm s-1 in the coast to 11cm s-1 in the offshore area toward north, that is, north-westerly wind driven current from Samchuk (SAM) toward Tongchun (TON).



(a) (b)

Fig. 2. (a) Wind fields (m s^{-1}) in a fine-mesh domainadjacent to Kangnung city at 1200LST, August 14, 1995. Thin dash line and Circle o denote topography and Kangnung. (b) Vertical profiles of wind vector (m s^{-1}) on a straight cutting line A-B (Mt. Taegualyung-Kangnung city-East Sea).



(a) (b)

Fig. 3. (a) Wind fields (m s^{-1}) in a fine-mesh domain adjacent to Kangnung city at 0000LST, August 15. Dash and circle o denote topography and Kangnung. (b) Vertical profiles of wind vector (m s^{-1}) on a straight cutting line A-B (Mt. Taegualyung -Kangnung city-East Sea).

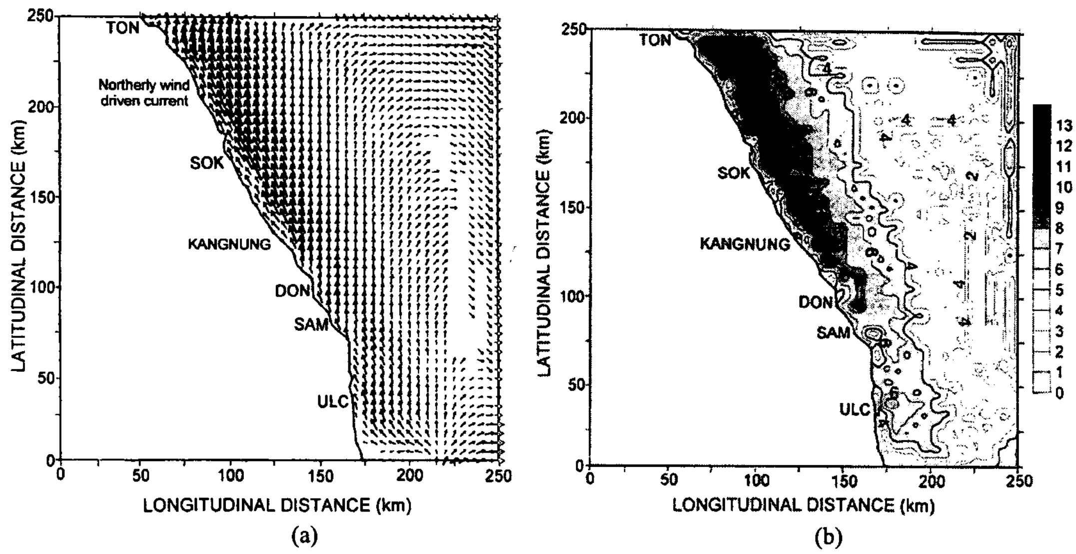


Fig. 4. (a) Vector plot of wind driven current (cm s^{-1}) adjacent to Kangnung at 0000LST, August 15. South-easterly current along the coast with the speeds of 8 cm s^{-1} ~15 cm s^{-1}, no wind driven current and north-easterly current with the speeds over 5 cm s^{-1} ~15 cm s^{-1} are generated in the narrow band of coastal sea, in the distance of 10 km ~ 20 km offshore and from 20km toward open sea, showing a counter-clockwise current from TON to SAM, respectively. (b) Contour of wind driven current speed (cm s^{-1}).

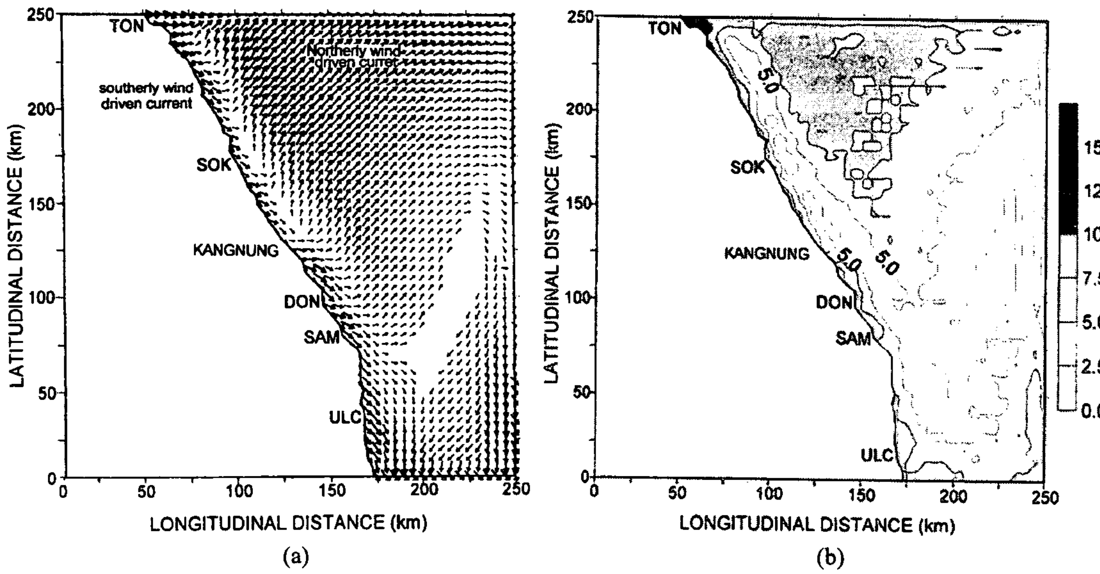


Fig. 5. (a) Vector plot of wind driven current (cm s^{-1}) near Kangnung at 1200LST, August 14, 1995. North-westerly wind driven current along the coast is weak, but northerly wind driven current in the offshore area from 15 km to 35 km is relatively strong. (b) Contour of wind driven current speed (cm s^{-1}). North-westerly wind driven current speed in the coast and northerly one in the offshore, from Samchuk (SAM) toward Tongchun (TON) are 7 cm s^{-1} to 13 cm s^{-1}.

So, the daytime south-easterly wind toward coastal inland can drive alongshore current bound for north. This alongshore wind driven current may be associated with the EKWC with summertime typical current speed of 0.5 kt (about 25 cm s-1) and speed up the intrusion of the EKWC toward north. It means that the resultant surface current speed may reach 32 cm s^{-1} ~36 cm s^{-1}.

In the open sea of the right edge in our model domain, the clockwise motion of sea water is also detected with relatively weak current speed near the calm wind zone. At night, the strong south-westerly winds in the inland coast can induce south-easterly wind driven currents of 8cm s^{-1} ~ 15 cm s^{-1}, which move from north-west toward south-east along the coastal line. Thus, this south-easterly wind driven current in the narrow band along the coast may induce the further intrusion of the NKCC existed near 400N toward south. The speed of the NKCC is known to be in the range of 0.2kt (about 10cm s^{-1} in summer) to 0.5 kt (about 25 cm s^{-1} in winter) (Dong-A encyclopedia, 1991) and in our summer experiment, the resultant surface current speed combined wind driven current with the NKCC may be close to 18 cm s^{-1} ~ 25cm s^{-1}, resulting in the variation of sea surface temperature (SST) due to the intrusion of cold waters from the northern coastal sea.

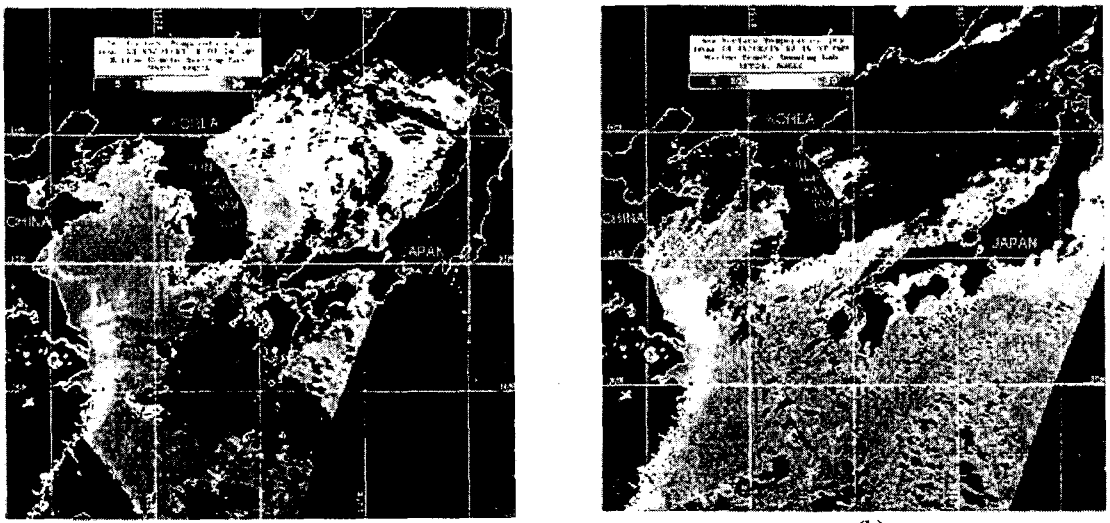
The SST distribution indicates that the sea in the north-eastern Korean coast on August 13, 1995 is in the control of the EKWC with red and yellow colors on NOAA-14 the satellite picture, maintaining the almost same temperature distribution. On the other hand, during the period of intrusion of cold waters induced by southerly wind driven current from 1800LST, August 14 through 0600LST, August 15, the yellow color of sea water along the coast on the satellite picture of August 14 is changed into the blue color of waters (cold water) in the narrow band and partly black color (cloud or fog) of August 15 (Fig. 6).

The condensation of moist air above the cold sea surface due to cold water intrusion by southerly wind driven current can make fogs or clouds with relative humidity more than 80% from 2000LST, August 14 through 0600LST, August 15 in the coastal sea. The condensation area shows black dense color on NOAA-14 satellite picture of August 15. The formation of fog was reported by Sokcho (SOK) and Donghae (DON) Meteorological Observatories, except for other cities in our model domain. Because, the coastal surface winds from 1800LST, August 14 through 0900LST, August 15 have still remained in westerly and the resultant south-easterly wind driven current should drive the cold sea waters to intrude from the north toward south along the coast.

After sunrise on August 15, the westerly coastal wind was changed into the south-easterly wind as easterly sea-breeze, which can cause northerly wind driven current with warm waters coming from the southern sea and then the coastal waters became warm again. The temperature difference between air and sea water was not enough to produce fogs, resulting in the disappearance of sea fog or low cloud over the coastal sea surface. Here, this is an interesting evidence, which shows the movement of cold waters from Heungnam city ($39^{0}55$ N) at the higher latitude than Tongchun (TON) in the north-coast of Korean peninsula toward Kangnung coast in our fine mesh-domain. This intrusion of the cold waters should be due to the roll of wind driven current generated by the downward motion of westerly wind storm along the slope of steep mountains lay from the south toward the north parallel to the coast. It means that the intensified south-westerly wind in the inland sites can make a hydraulic jump motion of air near coast and induce moderate surface wind in the coast and relatively strong surface wind in the offshore side.

So, calm zone generated by the confrontation between south-westerly inland downslope wind and south -easterly wind in the open sea is shifted from inland basin of the coast for daytime toward coastal sea away from 10km of the Kangnung coast at night. The resultant moderate westerly inland coastal wind can drive a moderate alongshore wind driven current from north-west toward south-east, but strong south-easterly wind (south-east toward north-west) in the offshore side can induce strong northerly or north-easterly wind driven current in the open sea near the Sokcho and Kangnung coastal sea, producing a wind driven counter-current with a calm zone inside of the circulation.

The intrusion of cold waters induced by the southerly alongshore current from north Korean coastal sea near Tongchun (TON) is limited to the latitudinal line of Ulchin city (ULC; 37^{0}N) and the intrusion area of cold waters well matches with blue color area along the coast in the satellite picture on August 15 as shown in Fig. 11-2. This southerly alongshore current returns toward the north, in the open sea of 30km offshore, under the push of the northerly wind driven current and the EKWC, resulting in a counter-clockwise current.



(a) (b)

Fig. 6. (a) Sea surface temperature (SST; ^{0}C) from NOAA-14, adjacent to Korean peninsula on August 13, 1995. Red and blue colors indicate warm and cold waters. Black color in the sea shows the formation of cloud. TON, SOK, KAN, SAM and ULC denote Tongchun, Sokcho, Kangnung, Samchuk and Ulchin cities. The EKWC intrudes from the Korea Strait toward north Korea, along the eastern coast of Korean peninsula. (b) SST on August 15, 1995. Cold water with blue color induced by southerly wind driven current from north toward south is observed in the narrow band of the eastern coastal sea from TON to SAM, while warm water with red color is bound for north in about 30 km offshore.

3. Conclusion

Daytime onshore wind in the coastal sea can induce north-westerly alongshore wind driven current from south toward north. In the open sea of 10 km away from the coast, strong northerly wind driven currents go up to North Korean sea. These northerly wind driven currents can be associated with the East Korean Warm Current.

On the other hand, at night, the strong downslope wind along the eastern slope of the mountains has a hydraulic jump motion bounding up to 1km height over the coast and the resultant moderate westerly coastal wind can drive a moderate alongshore southerly wind driven current, causing the formation of sea fog or low cloud in the coastal region. However, strong south-easterly wind in the offshore side of 25km away from the coast can induce strong northerly and north-easterly wind driven current, resulting a counter-clockwise current with a calm zone inside of the circulation.

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