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Evidence of Vertical Mixing Caused by High Frequency Internal Waves along the Eastern Coast of Korea

In-Seong Han*, Ju Lee[1], Lee-Hyun Jang, Young-Sang Suh and Ki-Tack Seong
Ocean Research Team, National Fisheries Research and Development Institute, Gijamg-Gun, Busan 619-902, Korea
[1]*Resource Enhancement Research Team, East Sea Fisheries Research Institute, Gangneung, Gangwon-Do 210-861, Korea*

Internal waves and internal tides occur frequently along the eastern coast of Korea. During the spring-tide period in April 2003, the East Korean Warm Current (EKWC) flowed near the Korean East Coast Farming Forecast System (KECFFS; a moored oceanographic measurement system), creating a strong thermocline at the intermediate layer. Weakened stratification and well-mixed water appeared frequently around the KECFFS, with duration of approximately 1 day. The results suggest the following scenario. Baroclinic motion related to the internal tide generated high frequency internal waves around the thermocline. The breaking of those waves then created turbulence around the thermocline. After well-mixed water appeared, a current component with perpendicular direction to the EKWC appeared within the inertial period. The change in stratification around the KECFFS locally broke the geostrophic balance as a transient state. This local vertical mixing formed an ageostrophic current within the inertial period.

Key words: Internal waves, Vertical mixing, Stratification, Tsushima Warm Current

Introduction

A number of unsolved questions remain regarding internal waves and internal tides in ocean dynamics. Factors known to influence the generation of internal tides include strong barotropic tidal currents, steep topography and the stratification structure (Baines, 1982; Hibiya, 1986). Internal waves, which usually have a semidiurnal period and wavelengths of several tens of kilometers, can be caused by tidal force and are generated around the shelf break. These high frequency internal waves tend to occur over short time scale (Apel et al., 1985; Sandstrom and Oakey, 1995) and can lead to changes in stratification, vertical mixing and the resuspension of deposited materials (Han et al., 2001). The vertical mixing and resuspension caused by the breaking of high frequency internal waves affect the habitation environment of the benthos.

The East Sea has a narrow shelf area that occupies approximately 28,000 km^2 or 20% of the total sea area and steep coastal topography (NFRDI, 2001). The East Korean Warm Current (EKWC), which is a branch of Tsushima Warm Current, flows northward or northeastward along the eastern coast of Korea throughout the year, advancing further north and closer to the coast in spring and autumn. The North Korea Cold Current (NKCC), which is a branch of the Liman Current, flows southward along the coast of North Korea. In spring and autumn, a strong pycnocline forms around the intermediate layer at depth of approximately 10-30 m. A number of studies have examined the internal waves in the East Sea, considering the steep topography, strong current system and stratification (Kim et al., 2001; Navrotsky et al., 2004; Kim et al., 2005).

The Korean East Coast Farming Forecast System (KECFFS) is a real-time mooring system that monitors and collects data on sea surface meteorological factors and underwater environments. These data have various applications. For example, various shellfish are cultivated around the eastern coast of Korea. Scallops (*Patinopectin yessoensis*) are an important species; however, mass mortality of scallops has occurred frequently around the eastern coast of Korea, possibly because of sudden change in oceanographic conditions around the intermediate and bottom layers.

*Corresponding author: hanis@nfrdi.re.kr

To examine such sudden change, we used data from the KECFFS mooring system and hydrographic surveys to investigate evidence of vertical mixing caused by internal motion.

Materials and Methods

The KECFFS has been moored 4 km from Sacheon Port, Gangneung, Korea (Fig. 1), at a depth of approximately 35 m since December 2002. Data collected by the system include water temperature, salinity, current speed and direction, pH, dissolved oxygen, air temperature, atmospheric pressure and wind speed and direction. In this study, we mainly used water temperature and current speed and direction collected at 30-min intervals. Instruments attached to the moored system measure temperature at 2-, 15- and 30-m depths. The current speed and direction are measured at the surface (Fig. 2) by a down-looking acoustic Doppler current profiler (ADCP). The ADCP records bin-average data for 2-m intervals and measures current speed and direction at layers from 2 to 30 m below the surface. We mainly used data from April 2003 because data collection was interrupted by communication and mechanical problems in other periods.

For comparison with KECFFS data, we obtained serial oceanographic data for April 2003 observed by the East Sea Fisheries Research Institute (ESFRI). The ESFRI carries out serial oceanographic investigations in the East Sea at 58 stations at bimonthly intervals. We used temperature data obtained from the surface to 200-m depth from conductivity-temperature-depth (CTD) measurement.

We also compared tidal height data provided by the National Oceanographic Research Institute (NORI) with the moored KECFFS data. Further, sea surface temperature distributions produced from National Oceanic and Atmospheric Administration (NOAA) / Advanced Very High Resolution Radiometer (AVHRR) satellite- based observations were used to analyze the current pattern around the eastern coast of Korea. The NOAA/AVHRR data were acquired from the NFRDI.

Density currents are generally generated by horizontal density anomalies, which may be created by change in stratification caused by vertical mixing (Griffin and Lebond, 1990; Hibiya, 1992). High frequency internal waves could play an important role in this vertical mixing (Matsuno et al., 1994; 2000). In the study area, the EKWC usually flows northward or northeastward.

The horizontal currents generated by changes in

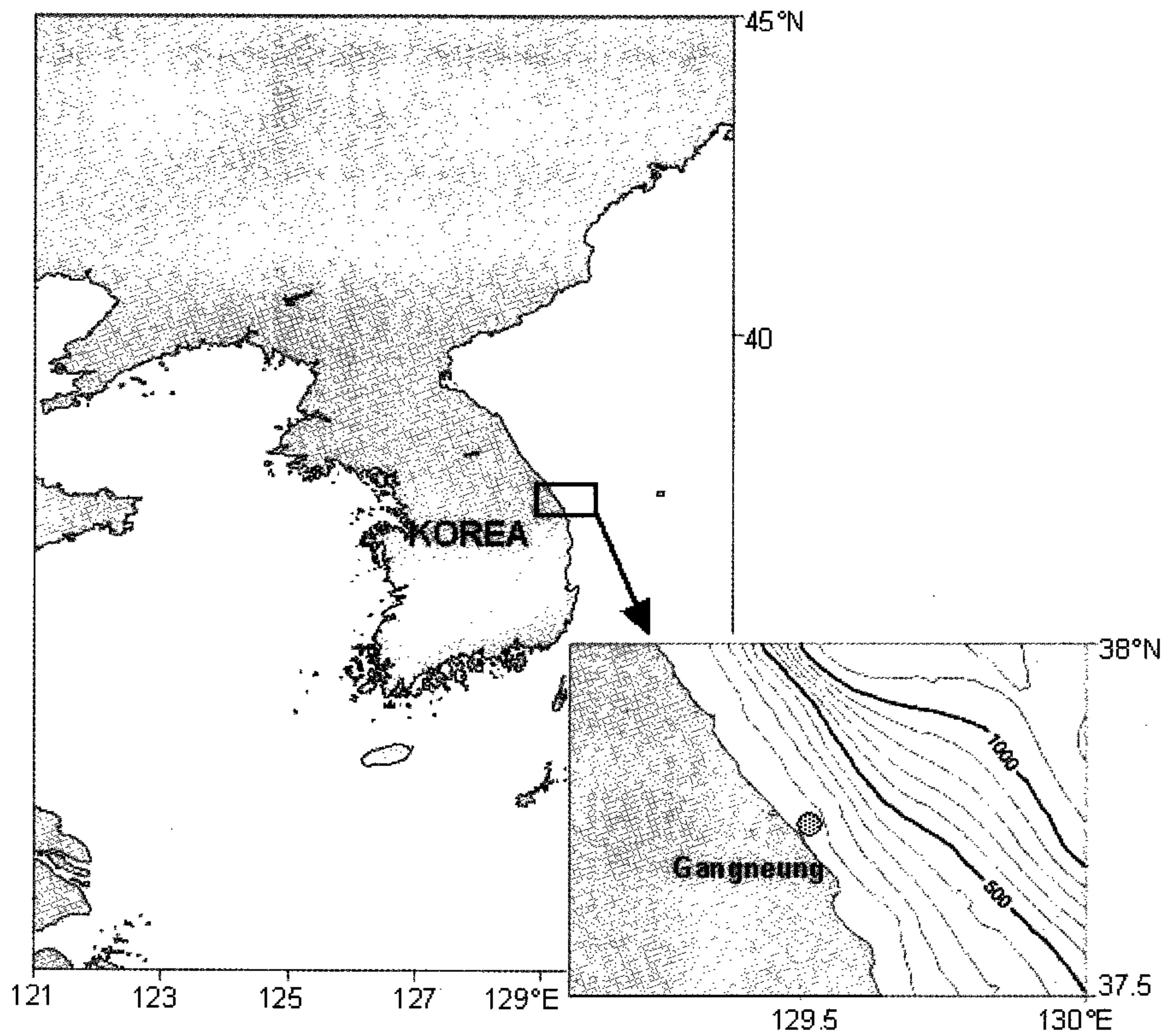

Fig. 1. Study map and the location of the KECFFS mooring site (closed circle).

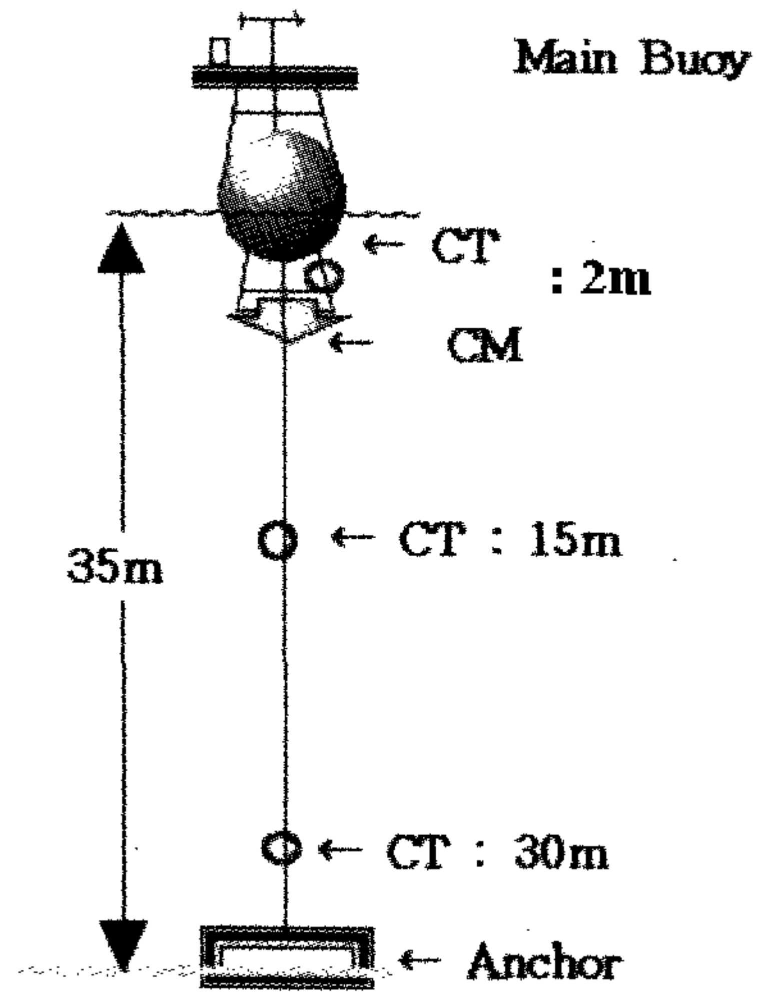

Fig. 2. Schematic view about the construction of the KECFFS. CT, conductivity and temperature sensor; CM, current meter.

local stratification are summarized below (Han et al., 2001). First, geostrophic balance assumed within the EKWC, given as:

$$fv = \frac{1}{\rho_0}\left(\frac{\partial p}{\partial x}\right) \quad (1)$$

where f, v, $1/\rho_0$ and $\partial p'/\partial x$ are the Coriolis parameter, geostrophic velocity component, specific volume and horizontal pressure gradient, respectively.

If the density distribution changes, the term $\partial p'/\partial x$ is added to the right-hand side of Eq. (1). Cross-shelf flow ($\partial u/\partial t$) is then generated as a transient state until it adjusts the geostrophic balance again, as follows:

$$\frac{\partial u}{\partial t} + fv = \frac{1}{\rho_0}\left(\frac{\partial p}{\partial x} + \frac{\partial p'}{\partial x}\right) \quad (2)$$

If we ignore the geostrophic adjustment, acceleration of the horizontal velocity would be created by the pressure gradient anomaly:

$$\frac{\partial u}{\partial t} = \frac{1}{\rho_0}\left(\frac{\partial p'}{\partial x}\right) \quad (3)$$

The ageostrophic component (u) can then be estimated using time integration of the additional pressure gradient:

$$u = \frac{1}{\rho_0}\int\left(\frac{\partial p'}{\partial x}\right)dt \quad (4)$$

To estimate a possible ageostrophic current across the shelf break, as an initial state we assume simplified stratification with a pycnocline. We then consider the pressure gradient between two points separated by a distance of 9 km. Once vertical mixing occurs around the shelf-side point, the horizontal pressure gradient should be increased. We can then calculate a generated ageostrophic current using Eq. (4). Figure 3a shows the results of 3-hr integration of Eq. (4) for three cases of stratification and artificial deformation of the stratification. Offshore flows would be formed within a layer where the stratification was relaxed. The velocities of the produced ageostrophic current are changed by the strength of the local vertical mixing. In contrast, an onshore current would be generated if the pycnocline gradient is strengthened at the shelf-side point (Fig. 3b). When the density gradient is weakened above or below the pycnocline, offshore flow is formed above or below the pycnocline, respectively (Fig. 3c).

Results

Temperature distribution around the KECFFS

The Satellite Ocean Information Laboratory of the NFRDI produces composite images of sea surface temperature once a week, based on NOAA/AVHRR data distributed online. Fig. 4 presents a composite image for the week of 8-14 April 2003. The image shows that the EKWC flowed along the eastern coast of Korea to 37.5°N and then moved away from the coast and flowed northeastward. The EKWC also flowed around the KECFFS. To examine the temperature structure around the KECFFS in detail, we analyzed serial oceanographic data obtained from 10 to 25 April 2003. Fig. 5 shows the resulting temperature distribution, temperature anomaly at the 50-m layer and vertical section around the KECFFS. A thermal front between the EKWC and NKCC appeared around the KECFFS, forming from northeastern to southwestern areas. In the eastern part of thermal front, the influence of the strong NKCC caused a negative temperature anomaly; in the west, the strong EKWC caused a positive temperature anomaly. The thermocline appeared at around 30-50 m near the KECFFS.

Temporal variation in temperature and current at the KECFFS

Three thermometers attached to the KECFFS measured temperature and its temporal variation at the upper, intermediate and lower layers at 30-min intervals from 1 to 20 April 2003 (Fig. 6), after which time mechanical problems with the thermometers halted the observations. The temperature at the KECFFS generally fluctuated in 24-hr period, similar to the diurnal tidal period. These time-series revealed significant vertical mixing on approximately 4-5, 8-9

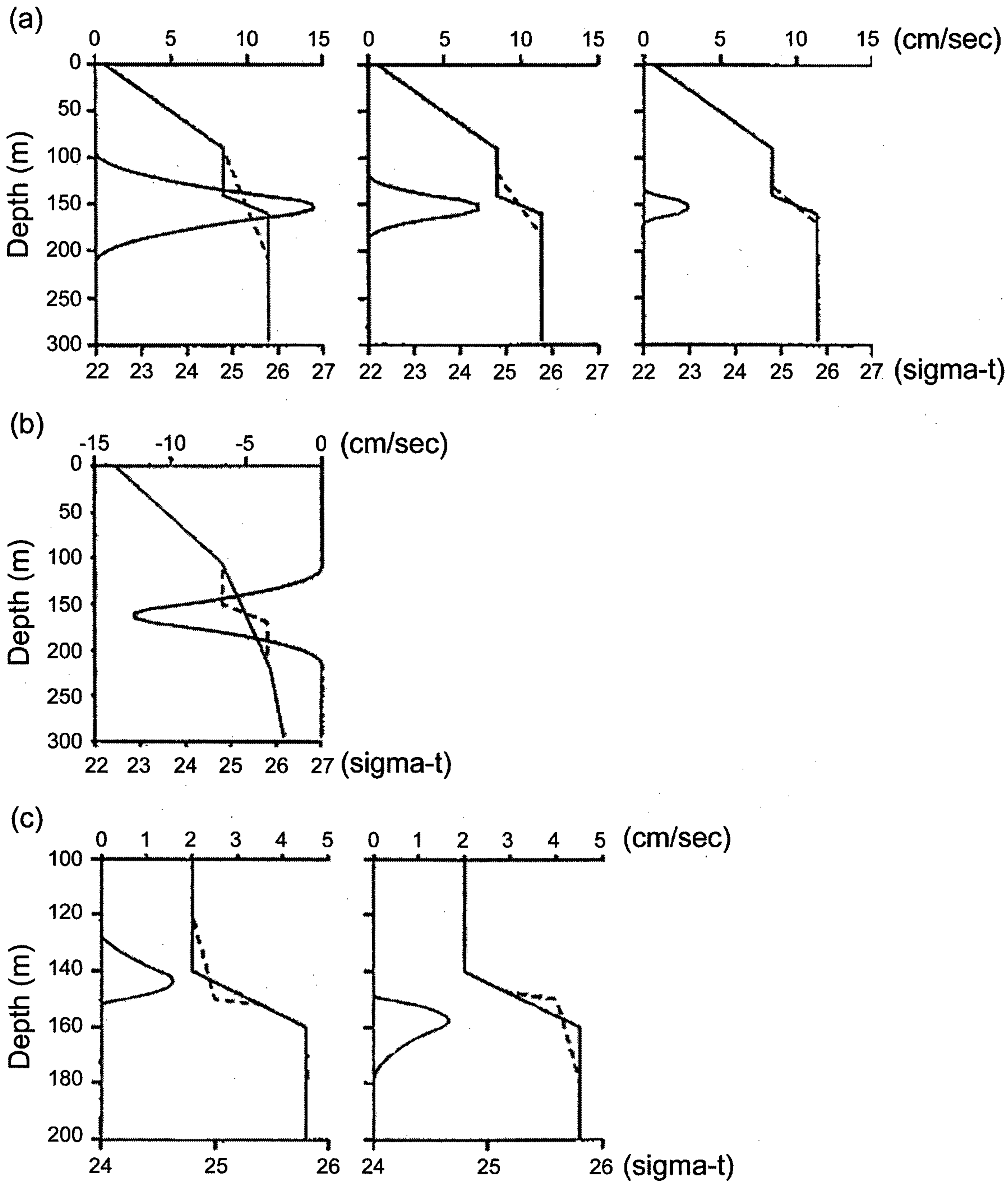

Fig. 3. Computed ageostrophic current (solid curved line) due to the change of density profiles from those represented by solid folding lines to those by dashed folding lines, when the vertical structure is (a) diffused, (b) strengthened, and (c) diffused just above and below the pycnocline.

and 18-19 April. During these periods, the temperature at intermediate and lower layers rapidly increased. In particular, a well-mixed layer formed from the upper to lower layers on approximately 9 and 18 April. Temperature at the bottom layer on approximately 8 April sharply increased by more than 5°C in just a few hours; the same tendency was found on 18 April. This rapidly increased temperature at the bottom layer was usually maintained for approximately 1 day, but then decreased rapidly. This mechanism could have generated the vertical mixing found for periods of approximately 1 day around the KECFFS.

To compare variation in the current with that in

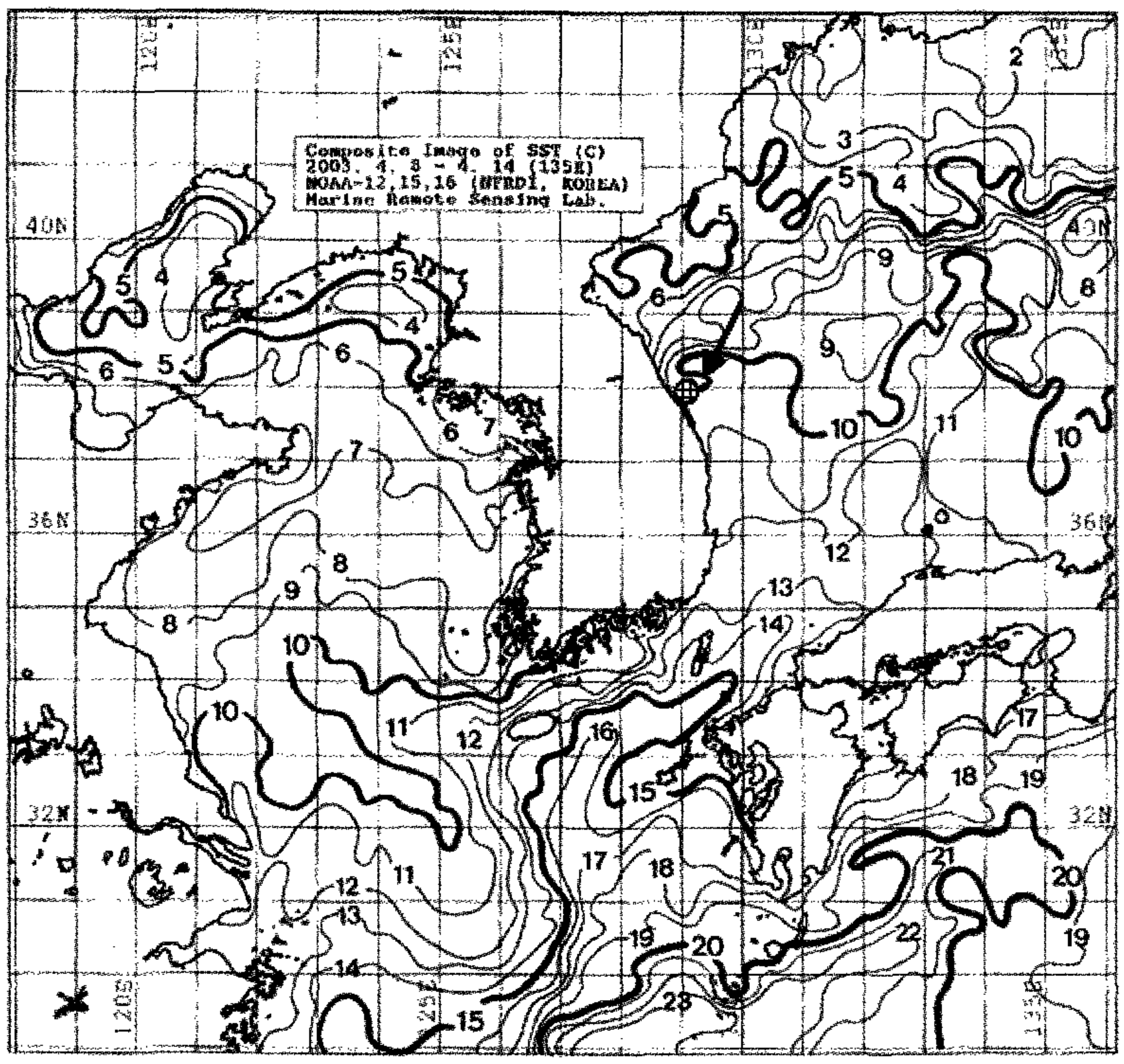

Fig. 4. Composite image of sea surface temperature by NOAA/AVHRR around the Korean Peninsula during 8-14 April 2003. Open circle (arrow mark) indicates the location of the KECFFS.

temperature at the KECFFS, we divided the current into u- and v-components from the upper to lower layers (Fig. 7). The u-component represents the eastward component; a positive value indicates eastward flow, and a negative value indicates westward flow. Similarly, the v-component indicates the northward component, with a positive value indicating northward flow and a negative value indicating southward flow. Temporal variation shorter than 12 hr in the u- and v-components was filtered out using a moving average. The moving-averaged current pattern showed significant southeastward flow on approximately 4-5, 8-9 and 18-19 April. These southeastward currents were maintained for more or less 1day and clearly corresponded with the appearance of vertical mixing. Thus, vertical mixing near the KECFFS may be related to the generation of the southeastward current. Moreover, the southeastward current was perpendicular to the flow direction of the EKWC. This suggests that a specific mechanism generates the ageostrophic current over approximately 1-day periods.

Tidal period and high frequency fluctuations

Research has shown that internal tidal energy can cause internal mixing of the thermocline around the shelf break and that the mixing energy of internal tides is occasionally greater than that of barotropic tides (New, 1988; Sherwin, 1988; Matsuno et al., 1993). Based on thermistor-chain surveys, Lie et al. (1992) reported that internal tides with semi-diurnal periods occur during periods of remarkable vertical stratification around the eastern coast of Korea. These findings suggest that the generation of internal tides around the eastern coast of Korea is affected by stratification related to the EKWC and tidal force. As noted above, the EKWC flowed near the KECFFS and a clear thermocline formed at the intermediate layer during the study period. To examine the tidal period at the KECFFS, we examined the temporal variation in tidal height at Mukho in April 2003 (Fig. 8); Mukho, which is located approximately 40 km south of the KECFFS, is the closest tidal gauge station to the study site. The spring tide at Mukho appeared on approximately 7-8 and 18-19 April. Comparison of the tidal height with the temperature (Fig. 6) and current (Fig. 7) patterns clearly revealed the appearance of distinct vertical mixing and significant southeastward current flow during the spring tide period, although the vertical mixing and southeastward ageostrophic current that occurred on approximately 4-5 April did not correspond with the spring tide. Vertical mixing on approximately 4-5 April was relatively weak compared with that on 8-9 and 18-19 April, suggesting that the vertical mixing mechanism for 4-5 April differed from that for 8-9

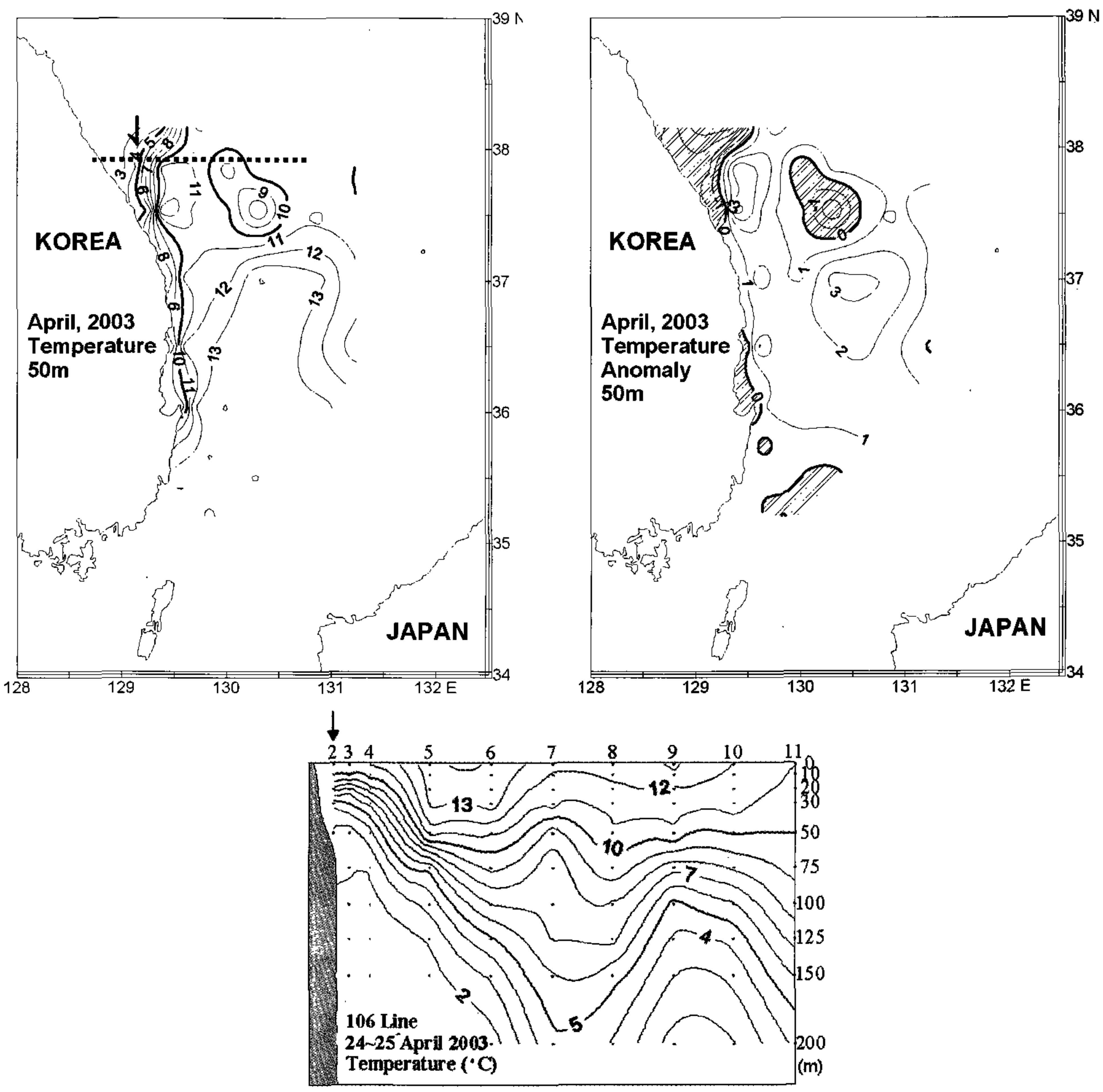

Fig. 5. Spatial distribution of temperature (upper left panel) and temperature anomaly (upper right panel), where shaded areas indicate negative anomaly, at 50 m layer and vertical distribution of temperature (lower panel) off Gangneung coast, where located as dot line in upper left panel, in April 2003. Arrow marks indicate the location of the KECFFS.

and 18-19 April.

The ADCP attached at the KECFFS collected data at 30-min intervals; this interval is too long for the examination of high frequency internal waves. Internal waves generally have short time intervals, which are smaller than the Brunt-Väisälä frequency, or a few tens of minutes (Maeda, 1979; Han et al., 1999). Despite the insufficient time interval, the behavior of high frequency internal waves at the KECFFS was examined using fluctuations of high-passed u- and v-components shorter than 6 hr at the upper (5 m depth), intermediate (15 m) and lower (25 m) layers during April 2003 (Fig. 9). The high frequency internal waves showed relatively large amplitudes for the u- and v-components on approximately 4-5, 7-8 and 17-18 April, although relatively large amplitudes also appeared at other times during the observation period. Compared with the temporal variation in the temperature and current patterns, these relatively large high frequency fluctuations occurred slightly earlier than the appearance of vertical mixing and generation of ageostrophic currents. This temporal variation also corresponded with the tidal period. Overall, the results indicate that the appearance of vertical mixing, generation of ageostrophic current, large high frequency fluctuations and spring tide occurred approximately in simultaneous. Although we could not determine the signal of the internal tides, our study suggests that the internal tides were generated during the spring tide and when a distinct thermocline was formed around the KECFFS. High frequency internal waves were then created by the internal tides around the thermocline. The generated high frequency internal waves caused turbulence around the thermocline, which then created vertical mixing in the thermocline area. The

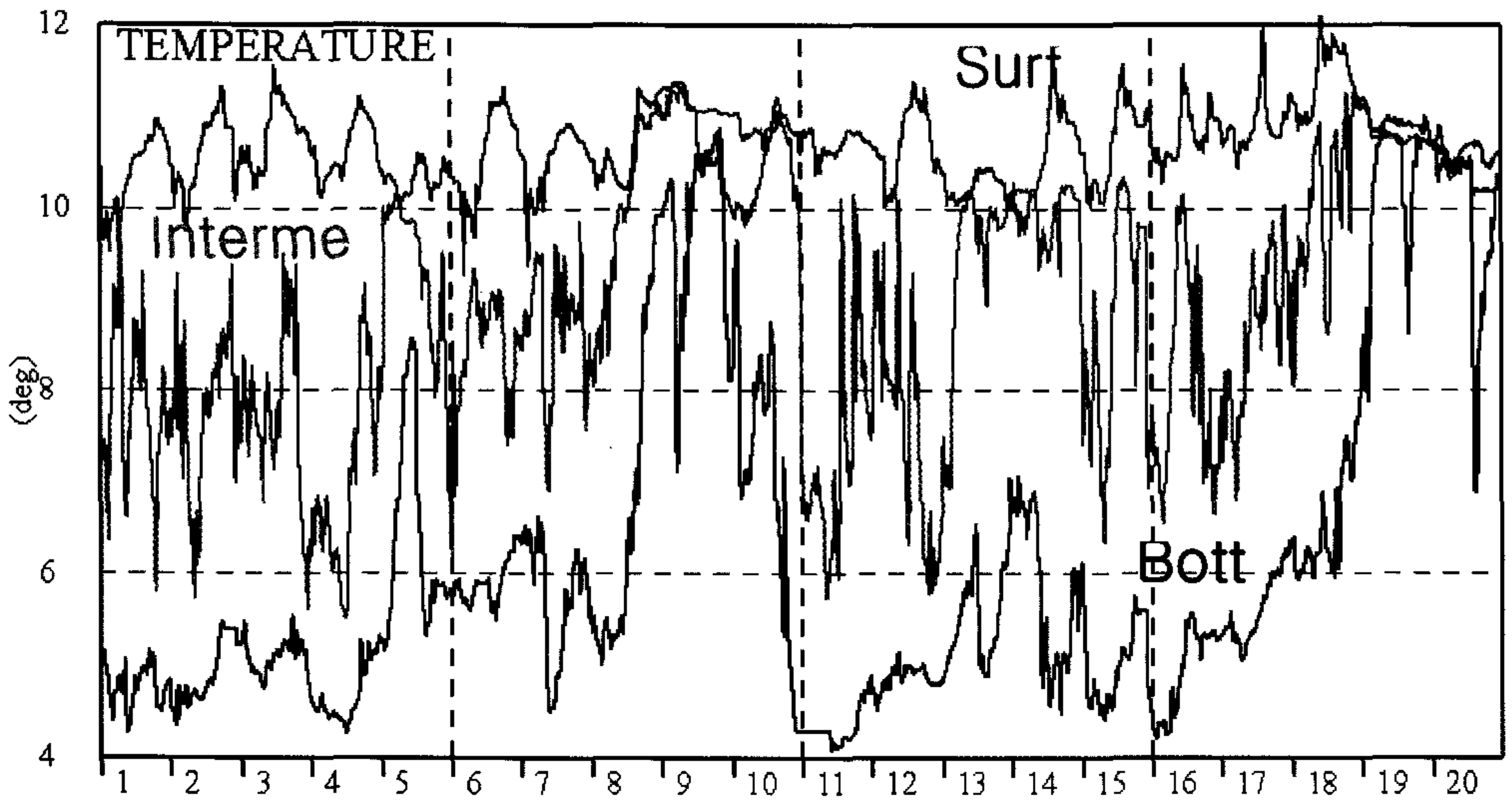

Fig. 6. Temporal variation of temperature obtained by the KECFFS at upper (2 m), intermediate (15 m) and lower (30 m) layers from 1 to 20 April in 2003.

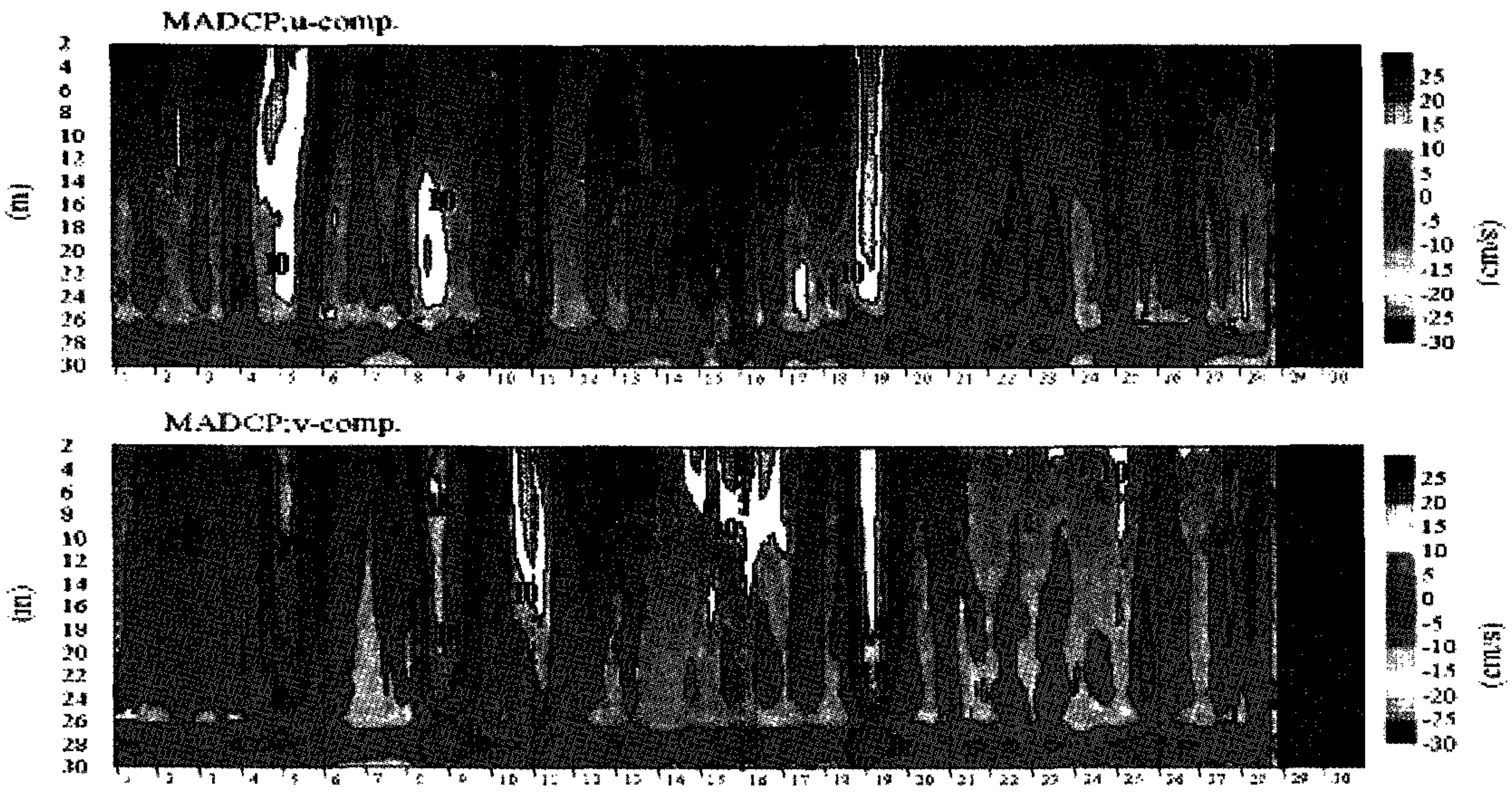

Fig. 7. Temporal variation of u-component (upper panel) and v-component (lower panel), which computed 12 hr moving average, obtained by the KECFFS from surface to 30 m depth during April 2003.

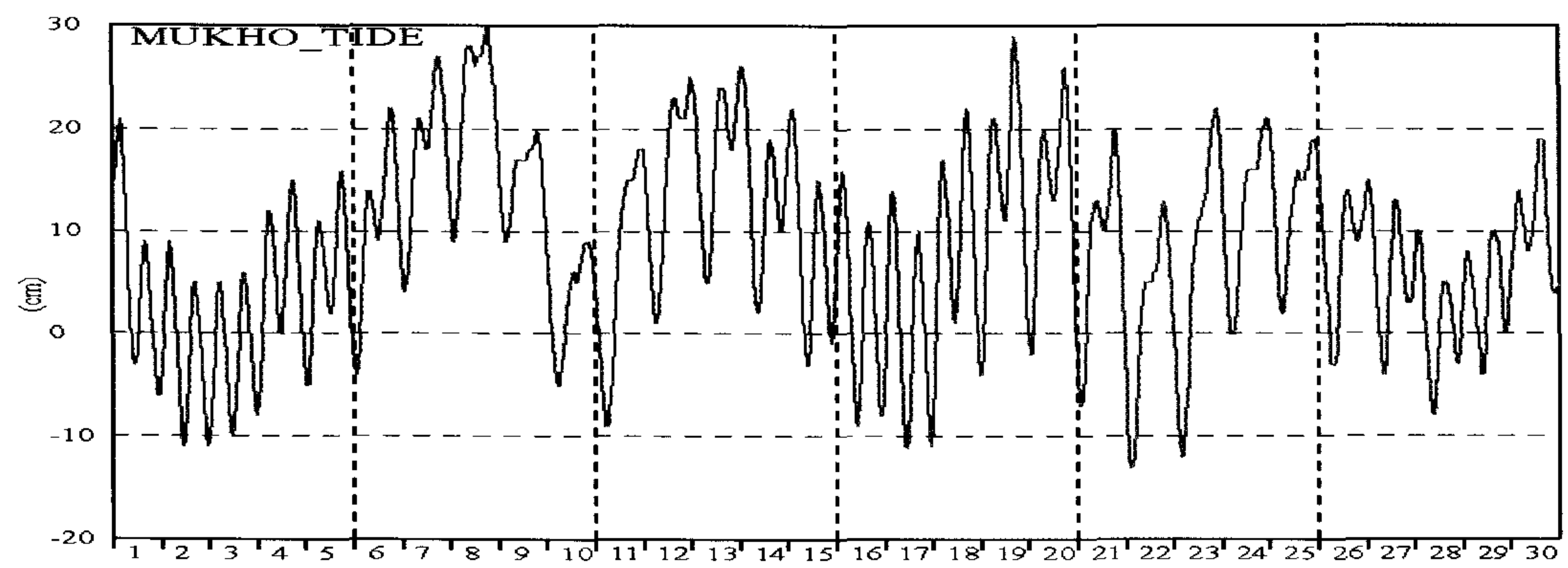

Fig. 8. Temporal variation of tidal height at Mukho (upper panel), where the tidal gauge station located nearest the KECFFS during April 2003.

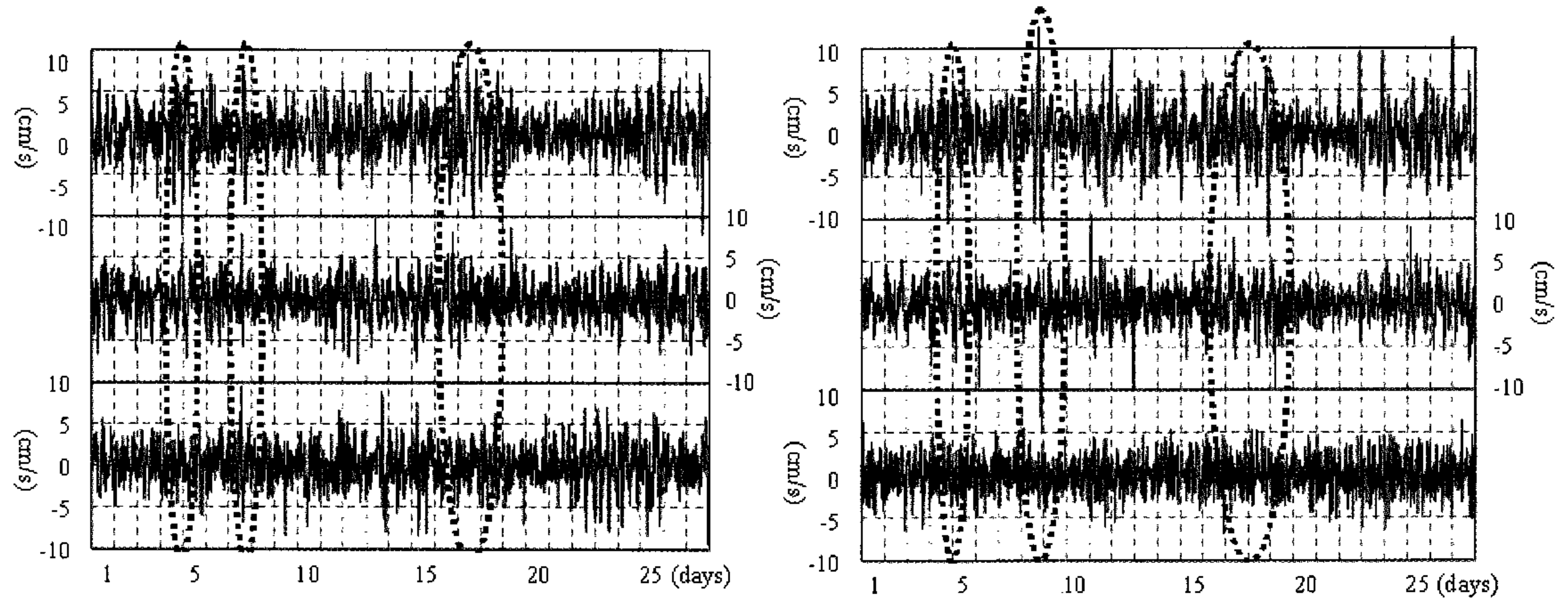

Fig. 9. Temporal variation of 6 hr high-passed u-component (left panel) and v-component (right panel) fluctuation at upper (5 m), intermediate (15 m) and lower layer (25 m) obtained by the KECFFS during April 2003. Dotted lines indicate the period occurred vertical mixing and ageostrophic current.

change in stratification around the KECFFS locally broke the geostrophic balance as a transient state. This local vertical mixing formed the ageostrophic current within the inertial period, as described above.

Discussion

Internal waves and internal tides are frequently observed around the eastern coast of Korea. Factors in the generation of these internal motions likely include the steep topography in this area, stratification related to the EKWC and tidal motion. In April 2003, strong northeastward flow of the EKWC was observed near the KECFFS and formed a thermal front with the NKCC. A clear thermocline also formed around the intermediate layer, creating strong stratification. At that time, significant vertical mixing occurred three times around the KECFFS. The verti-cal mixing broke the stratification around the KECFFS, and a well-mixed layer was generated from the upper to lower layers for more or less 1 day. Simultaneous with the vertical mixing, a southeastward current appeared at the KECFFS and was maintained for approximately 1 day, flowing perpendicular to the EKWC. This ageostrophic density current was likely related to the vertical mixing. To investigate the cause of vertical mixing, we examined tidal height data obtained at the nearest tidal gauge station. The appearance of vertical mixing and the occurrence of the ageostrophic density current almost corresponded with the spring tide period. The existence of strong stratification caused by the EKWC and strong tidal force during spring tide probably generated the internal tide around the KECFFS, although we could not directly measure these factors. High frequency internal waves were usually generated during strong internal tides around the thermocline. High-passed fluctuations shorter than 6 hr with large amplitude also appeared when the vertical mixing and ageostrophic current occurred during spring tide. However, we could not obtain direct evidence of the relationships of the internal tide, high frequency internal waves and vertical mixing. In addition to, turbulence caused by the breaking of high frequency internal waves related to internal tides, other likely causes of vertical mixing included wind stress and current. No detailed wind speed and direction or current-pattern data were available near the KECFFS. Our results suggest the following scenario. Internal tides are generated during spring tide; these internal tides then generate amplified internal waves at short time scale around the KECFFS. The amplified high frequency fluctuations around the thermocline break the stratifycation, resulting in turbulence. Turbulence generated by high frequency fluctuations around the thermocline locally mixes the water mass around the KECFFS and changes the stratification around the thermocline. As a result of the change in local stratification, an ageostrophic horizontal density current is generated around the thermocline as a transient state. We used mooring data and hydrographic survey data to examine vertical mixing related to internal motions around the eastern coast of Korea. The temperature and current patterns suggest that internal motions caused vertical mixing, although we could not compute turbulent energy dissipation and vertical eddy diffusivity caused by the limited time interval and number of thermometers. In addition, the propagation and dissipation mechanisms of the internal waves could not be determined using data from a single mooring site. Further study based on data from multiple mooring systems is needed to clarify the generation, propagation and dissipation of internal waves. Data with finer temporal resolution collected by a wider network of instruments are also required to compute turbulent kinetic energy. The clarification of this internal motion should enhance the forecasting of sudden changes in the benthic oceanographic conditions around shellfish breeding grounds based on the stratification state and tidal period.

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