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Chemical Imprints of the Upwelled Waters off the Coast of the Southern East Sea of Korea

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We made intensive observations on the coastal upwelling off the coast of the southern East Sea from June to August in 2001. The upwelling exhibited a weekly waxing and waning. The coastal upwelling of the year 2001 was characterized by abrupt outbreaks and the small local scale. Upwelling occurred more frequently off the coast of Ulsan and Gampo as reported by the earlier observers. The spread of freshly upwelled colder water was varied by each upwelling event. Generally cold waters were carried away northeastward off Pohang province. The upwelled cold waters were saltier than the resident surface waters. The pH and salinity-normalized alkalinity support the idea that the upwelled waters originate from the interior of the East Sea. The extraordinarily high concentration of dissolved oxygen suggests that the upwelled waters are closely connected to the southward flowing North Korea Cold Current. Although a lower primary productivity was reported for the upwelling region, underway surface fluorescence measurement revealed that the recently upwelled waters supported up to an order of magnitude higher algal biomass than the ambient waters. Because thermohaline circulation of the East Sea is so vigorous, with an estimated time scale of less than one hundred years, that the coastal upwelling should be considered not as an anomaly but as a regular component of a circulatory system. A quantitative understanding of upwelling seems to be a key to elucidate material cycling and the associated biological production in the East Sea.

Key words: Coastal upwelling, Dissolved oxygen, Alkalinity, Fluorescence

INTRODUCTION

Upwelling of nutrient-rich deeper waters promotes the primary production, which, via food chain transfer, supports ample fish stocks. Therefore regions of coastal upwelling are often recognized as the most profitable fishing grounds. The area of the five worlds major upwelling regions comprises no more than 0.1% of the global ocean, yet up to half the total commercial catch has been made in these regions (Ryther, 1966). In countries neighboring upwelling sites the stake of the fisheries on their national production is quite heavy; for example, up to 20% of global catch is landed in the Peruvian upwelling system alone in the eastern tropical Pacific. It is not difficult to imagine how important are the fisheries on the Peruvian national revenue.

During the summer a number of cold water events occur along the coast of the southern East Sea. These cold events occur more frequently from the coast of Ulsan to Gampo province (Lim and Chang, 1969; Gong and Park, 1969; An, 1974; Seung, 1974; Lee, 1978; Lee, 1983). While the persistent upwelling is regarded as a natural blessing, this intermittent cold water event is viewed as a nuisance for its accompanying negative effects: sea fog by cooling surface air threatens sea-farers and evokes sudden changes in local weather; a cold spell drives out the fish schools offshore and even does considerable harm on mariculture (Hahn *et al.*, 1995). Also the losses to the leisure industry are not negligible.

Previous studies focused mainly on the physical aspects of the cold events. The overall conclusion of the earlier efforts was that the cold water occurs as a result of coastal upwelling but the physics behind this phenomenon required further study. Other aspects of the coastal upwelling such as its biological impact remained grossly neglected. To delve into the unknown

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aspects of the upwelling, with a special emphasis on the origin of upwelled waters, interdisciplinary efforts were made by the group of KIOS (Korea Inter-University Institute of Ocean Science) scientists.

Participants carried out an extensive hydrographical survey for three consecutive summer seasons starting from 1999. A prominent upwelling occurred in 2001. This paper describes the first observation on some chemical properties of the upwelled waters in 2001. We chose parameters relevant to trace the origin of the upwelled waters and the chemical effects on biology. Selected parameter includes alkalinity, pH, dissolved oxygen, naturally occurring radium isotopes, fluorescence and algal photosynthetic pigments. From the above, the radium isotopic study and the algal pigment analysis will be presented separately in subsequent papers.

MATERIALS AND METHODS

Hydrographic data were collected seven times on board the R/V Tamyang from June to August in 2001. The study area covers roughly a 1°×1° sector. Five observation lines were chosen following the NFRDI (National Fisheries Research and Development Institute) regular observation scheme. Stations were placed every 10 apart on each observation line (refer to Fig. 1).

At every station a CTD-rosette (Seabird 9/11 plus equipped with Clark-type dissolved oxygen sensor) was towed and collect waters samples with 5 L Niskin bottles. Seawater pH was measured by dye (m-Cresol Purple)spectrophotometry (Clayton and Byrne, 1993). Alkalinity was measured with a HCl potentiometric titration technique (Millero *et al.*, 1993). Total alkalinity was then normalized to a salinity of 35 to remove any precipitation and evaporation effects. Fluorescence was measured by the underway system: a fluorometer (Wetlab) attached to a thermosalinograph (Seacat 21 of SBE) that also logs GPS data. Nominal values of fluorescence were used without a conversion to chlorophyll *a* concentration in order to observe just the geographical difference in algal biomass.

RESULTS AND DISCUSSIONS

Surface temperature and salinity

Surface cold water was first noticed at the southern coast around early July 2001. NFRDI officially confirmed the finding of a cold water mass and the related front on July 2. Two days later the first cold water alert was posted. There were repeated warnings (and clearance) before the final call off on August 13 (NFRDI, 2001).

In June the distribution pattern of surface tem-

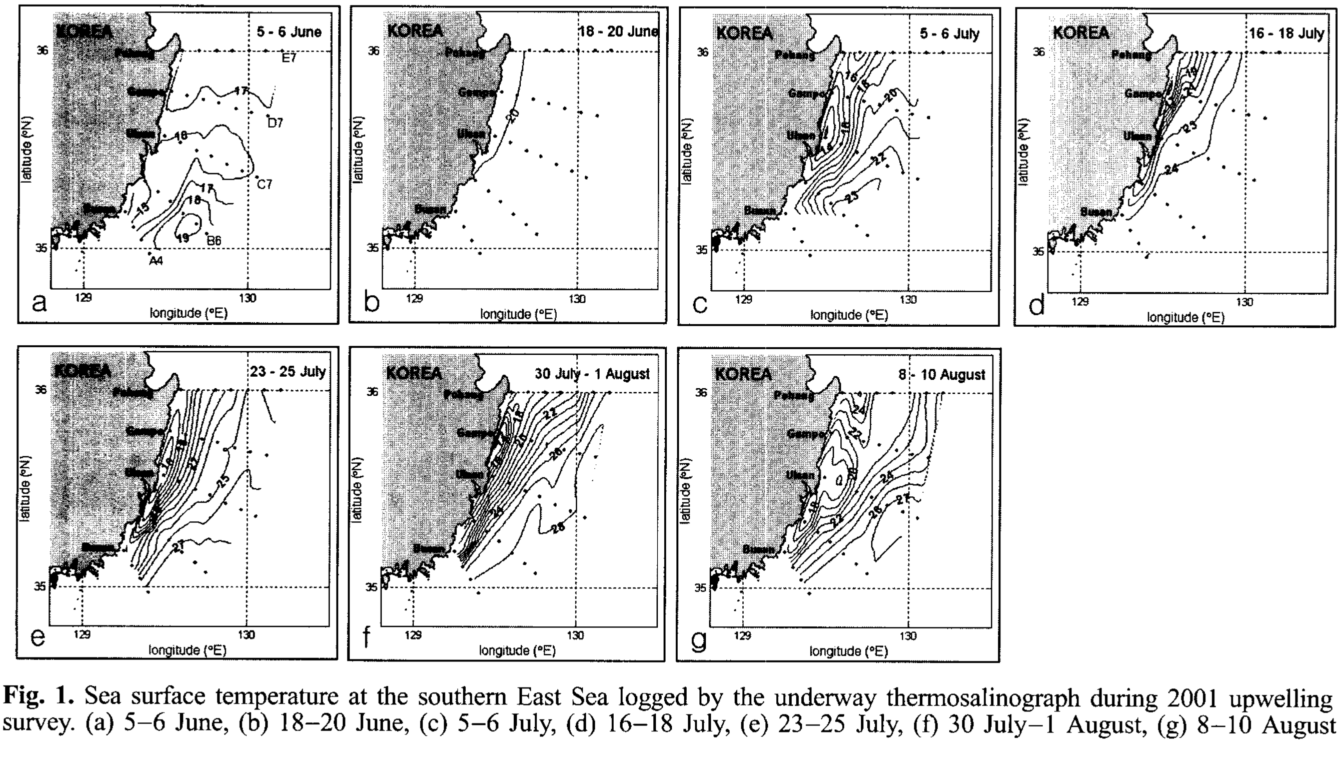

Fig. 1. Sea surface temperature at the southern East Sea logged by the underway thermosalinograph during 2001 upwelling survey. (a) 5–6 June, (b) 18–20 June, (c) 5–6 July, (d) 16–18 July, (e) 23–25 July, (f) 30 July–1 August, (g) 8–10 August.

perature represented a transitional feature from spring to summer (Fig. 1a and 1b). Isotherms showed a meridional pattern, warmer at south (18°C) than northern area (15°C) in early June. Two weeks later, surface temperature rose to 20°C. Thus regional difference in temperature became wider but there was no sign of cold water yet (Fig. 1b).

Cold water covered the coastal area of Ulsan to Gampo in early July. Temperature of the cold water was between 14°C and 16, nearly 10 lower than offshore waters of 20 to 23 (Fig. 1c). By mid July the cold water retreated to inshore in the Gampo and Pohang areas. Coastal seawater was warmed by 3°C to 4°C (Fig. 1d) by mid July. Thus it might correspond to a declining phase of the previous upwelling. Inshore waters of the Gampo to Pohang area exhibited nearly the same water temperature in late July, but the colder water covered a much larger area than in mid July. In the mean time temperature of the offshore waters continued to rise to 27°C. Because temperature of the cold core was a little bit warmer than that of early July, it is interpreted as waters upwelled a few days earlier (Fig. 1e). Later on the cold water was found in a narrow belt near the Gampo coast during late July to early August (Fig. 1f). It might be the earliest stage of upwelling we ever observed. Water temperature was as low as 15°C, and the temperature difference with the offshore waters exceeded 10°C. By mid August relatively colder waters of 18°C to 19°C spread over the Ulsan to Gampo coastal area (Fig. 1g). Offshore waters were also cooled by 1 to 2°C.

The spatial and temporal distribution of temperature reveals a periodic oscillation of cold water events. Cold water lasts roughly a week and then vanishes. If we describe it in three stages the third and sixth observations correspond to an early stage, the fourth and fifth to a stagnant stage, and the seventh to a senescent stage. Overall the best description of these cold water events would be a high variability both in terms of space and time.

Temperature and salinity sections

Surface water temperature suggests that the third and sixth surveys provide the right chance to observe the properties of freshly upwelled seawater. The sections of temperature and salinity along each observation line in early and late July are shown in Figs. 2 and 3, respectively. In early July a surface layer about 20 m thick consisted of warm (> 20°C) and less saline (salinity<34.0) waters. Down to 50 m depth was filled by waters having temperature and salinity ranges of 13-15°C and 34.0-34.2, respectively. Waters below 50 m were less than 10°C with salinity around 34.2 (Fig. 2). Thus the temperature and salinity of upwelled waters correspond to middle layer waters. As seen in Fig. 2 the bottom water did not rise up to surface. However, the shoreward tilting of the isotherms is clearly visible down to the bottom layer.

In late July, the warm surface waters of over 20°C expanded both laterally and vertically. The cold water outcropped only at the vicinity of station D1. However, cold water approached close to the surface near the coast (Fig. 3). The temperature and salinity of the upwelled waters were virtually the same as the previous ones in early July, suggesting that the same type of water had upwelled.

Since cold deep waters are not generated *in situ*, it must have been transported from elsewhere. Due to subtle differences among various water masses in the East Sea, the temperature and salinity alone are not enough to judge the origin of upwelled waters. The Tsushima Warm Current (TWC) consists of two layers, of which the lower layer has temperature and salinity close to the upwelled waters. Thus it could be the top-blown-away TWC waters. Otherwise it could be resident cold waters in the Ulleng Basin. Still there exists one more possibility. It might have originated from the south flowing North Korea Cold Current (NKCC).

Physicochemical properties of upwelled seawater

Because water temperature changes instantaneously upon contact with the atmosphere, tracing the origin of upwelled waters should be made without the aid of temperature. Therefore searching for other potential parameters is important in the study of the origin of upwelled waters.

In early July the salinity of offshore waters drops below 33 (Fig. 4a) due to the inflow of less saline waters from the South Sea and northern East China Sea that is under the heavy influence of the Changjiang discharge in the flood season (Kim and Rho, 1994). Compared with the surface waters the upwelled cold water at the Gampo is distinctively saltier (salinity >34). Cold waters near Ulsan are less saltier than that of Gampo, with salinity between 33.4 to 33.8, probably resulting from a dilution by the Taehwa River discharge during the flood season.

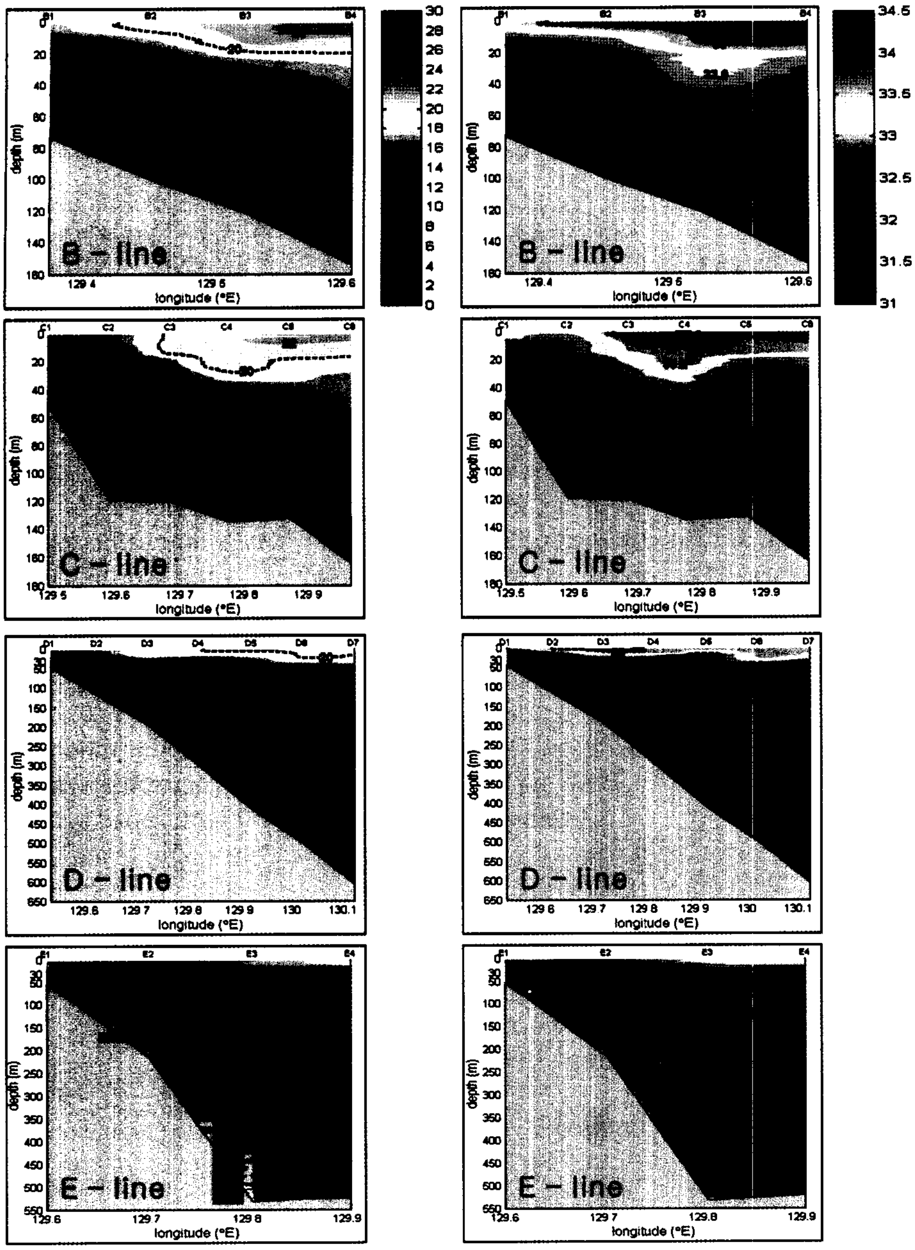

Fig. 2. Temperature (left panels), and salinity (right panels) sections along the observation lines in 5–6 July 2001.

Salinity normalized total alkalinity (NTA: measured TA/salinity × 35) was utilized to trace the source of upwelled waters. The bottom line of normalization is that waters of the same origin might have different alkalinity due to dilution and evaporation but the NTA remains unchanged (Zeebe and Wolf-Gladrow, 2001). The NTA values of the waters in the East Sea interior, Kuroshio water, and the Changjiang discharge water are known to be 2400 μmol kg^{-1} (Park, 1997), 2294.5 μmol kg^{-1} (Peng *et al.*, 1999), and 1743 μmol kg^{-1} (Peng *et al.*, 1999), respectively. The NTA of upwelled waters ranged 2400-2440 μmol kg^{-1}, leaning preferentially towards the interior of the East Sea. An NTA value of more than 2500 μmol kg^{-1} indicates the addition of riverine alkalinity (Fig. 4d).

The pH of upwelled waters was lower than the ambient surface waters. It decreases with water depth and the surface values are as low as 7.72 (Fig. 4e), which are much lower than that of ordinary surface seawater usually higher than 8. More importantly, this pH indicates that the waters are upwelled from a deeper depth than the temperature suggests.

Upwelled waters contain a large amount of dissolved oxygen (Fig. 4c). Seawater with the temperature ranging 13°C to 15 could be originated from the northward flowing EKWC or TWC. However, the extraordinarily

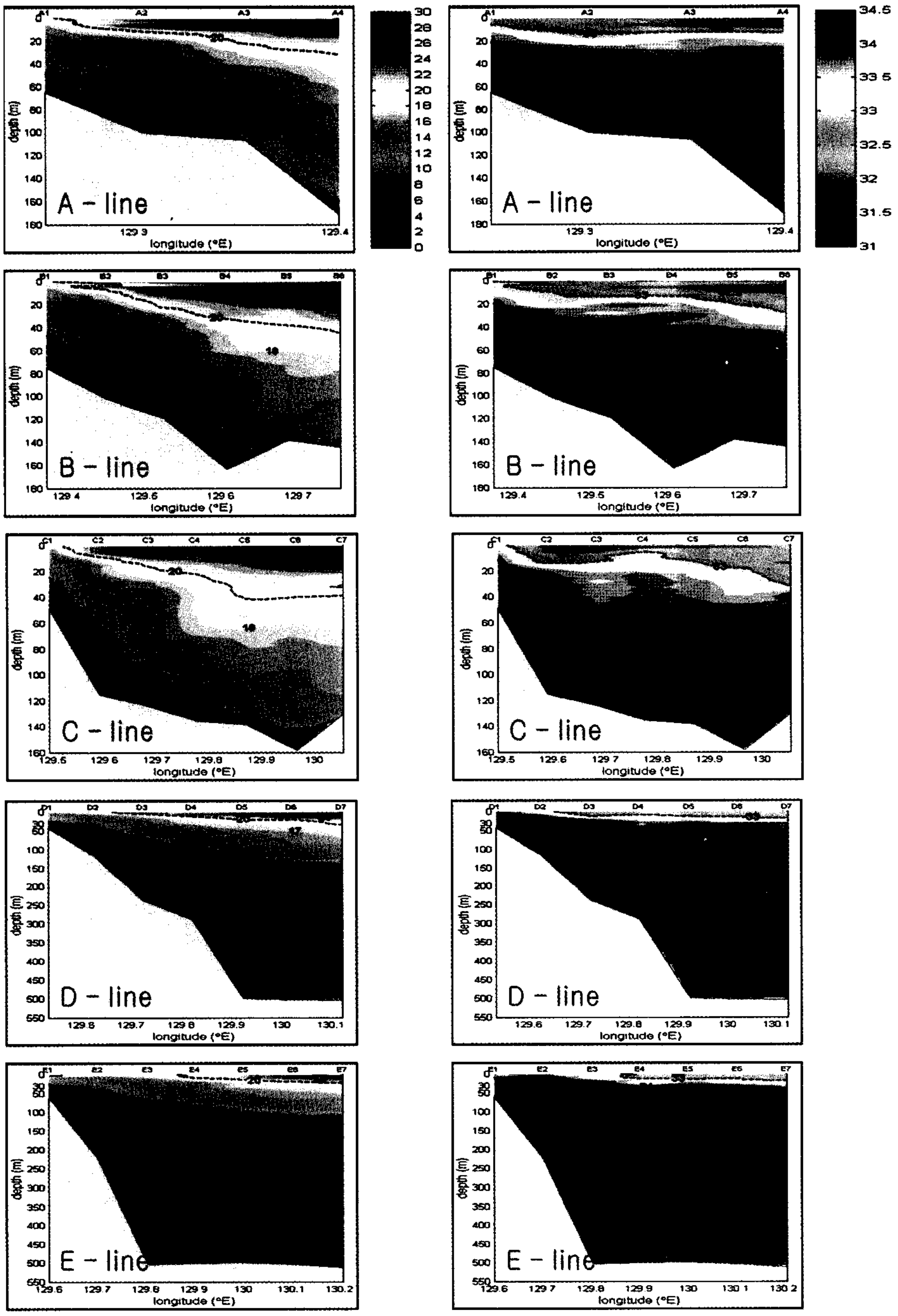

Fig. 3. Temperature (left panels), and salinity (right panels) sections along the observation lines in 30 July–1 August 2001.

high oxygen content clearly demonstrates that the upwelled waters were made in the northern East Sea, where winter cooling generates oxygen-rich cold deep waters. In the case of the East China Sea, waters with such a temperature range are depleted of oxygen due to their longer segregation from the atmosphere.

Stations with surface temperature between 13°C to 15°C were C1, D1 and E2 in early July. Salinity of the surface cold water ranged from 33.8 to 34.1. The density of upwelled waters was higher than that of ambient waters (25.14 to 25.29; see Table 1). Also given in Table 1 are the dissolved oxygen, pH and NTA values of the upwelled waters of early July. The upwelled waters are characterized by rich oxygen, low pH, and higher alkalinity.

In late July waters colder than offshore waters by 10°C appeared inshore, but were restricted to a more limited area than those of early July (Fig. 1f). The salinity of these cold waters was around 34, close to those found in early July and the difference with offshore waters was reduced (Fig. 5a). The site showing the highest dissolved oxygen content coincides

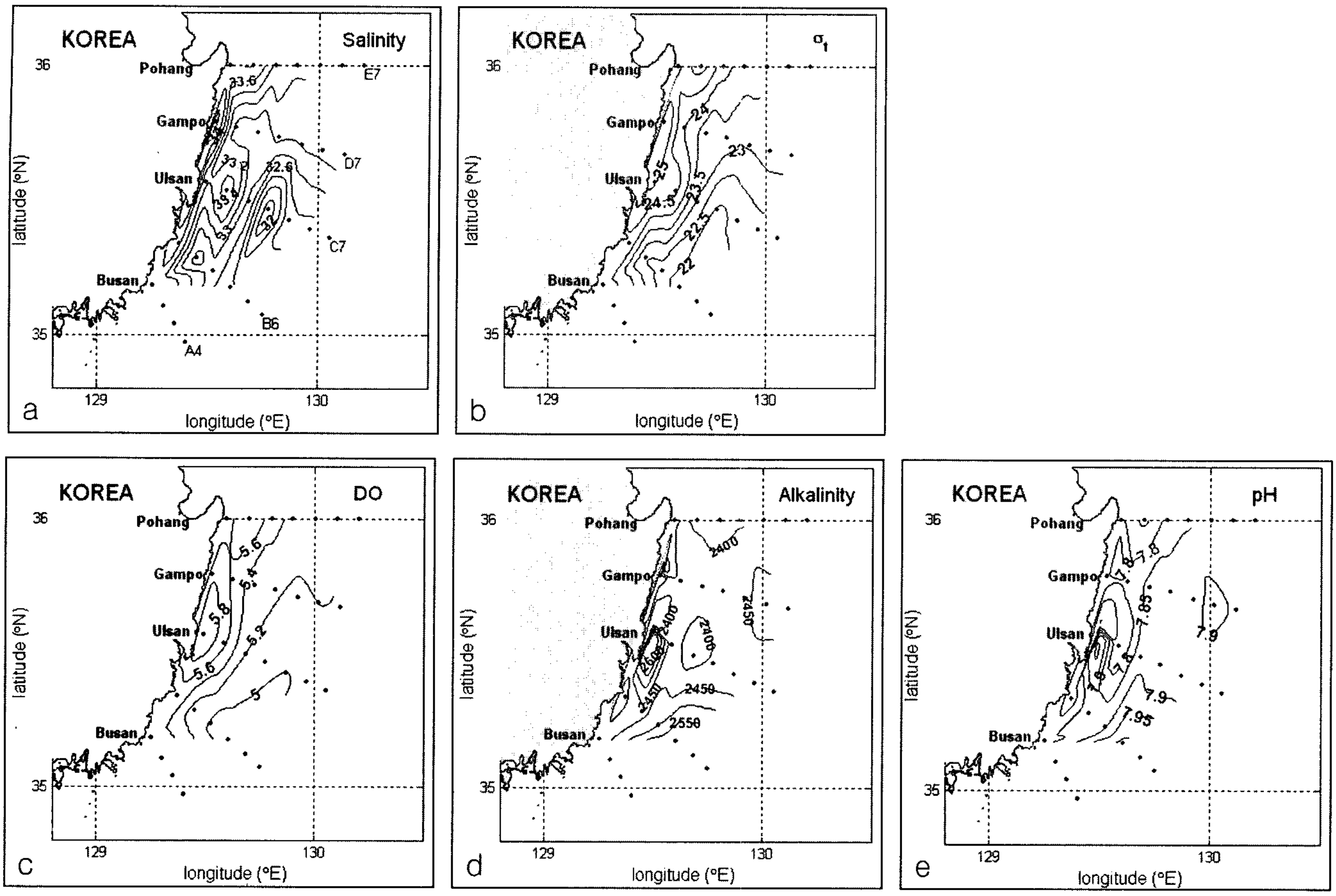

Fig. 4. Maps showing the distribution of surface water parameters measured on 5 –6 July 2001: (a) salinity, (b) sigma-t, (c) dissolved oxygen (ml · l^{-1}), (d) alkalinity (μmol · kg^{-1}), (e) pH.

Table 1. Properties of upwelled seawater observed during 5 –6 July and 30 July–1 August 2001 at the southern coast of East Sea.

Sampling Date	Temperature (°C)	Salinity	D. O. (ml · l^{-1})	σ_T	pH	NTA (μmol·kg^{-1})
5/7–6/7 2001	13–15	33.8–34.1	5.7–6.0	25.14–25.29	7.74–7.94	2359–2465
31/7–1/8 2001	13–15	34.06	5.84	25.47	7.71	2460

with the lowest water temperature. Isopleths of various parameters aligned parallel to coastline with a slight tilting towards the right. The values of pH and alkalinity of the cold water were lower than those of ambient waters (Fig. 5) as in previous cases. NTA was higher in late July. The Changjiang discharge is certainly the most likely source of excess alkalinity. However, some must be supplied directly from the coastal discharge.

The temperature of the freshly upwelled waters in late July was 13 to 15°C. Characteristic values of other parameters are quite close to those in early July (Table 1). Density of seawater seems the most useful parameter to delineate the extent of the upwelled waters and its advection (Fig. 4b and Fig 5b).

Source water

Judging from the values of the physicochemical parameters, the upwelled waters do not originated from the Tsushima Warm Current. A temperature of 13 to 15°C is within the range of TWC, but the salinity is lower than known values of 34.30 to 34.60 for the TWC (Park, 1978). The strongest evidence against the TWC origin is the high oxygen content. Dissolved oxygen (DO) content of 5.7 to 6.0 ml l^{-1} is unrealistically high for the waters of subtropical origin. The pH value of 7.71 to 7.94 is far too low for a subsurface origin, and matches better with a deeper origin. NTA is also substantially higher than the typical Kuroshio end member value, as a result of the riverine addition of alkalinity.

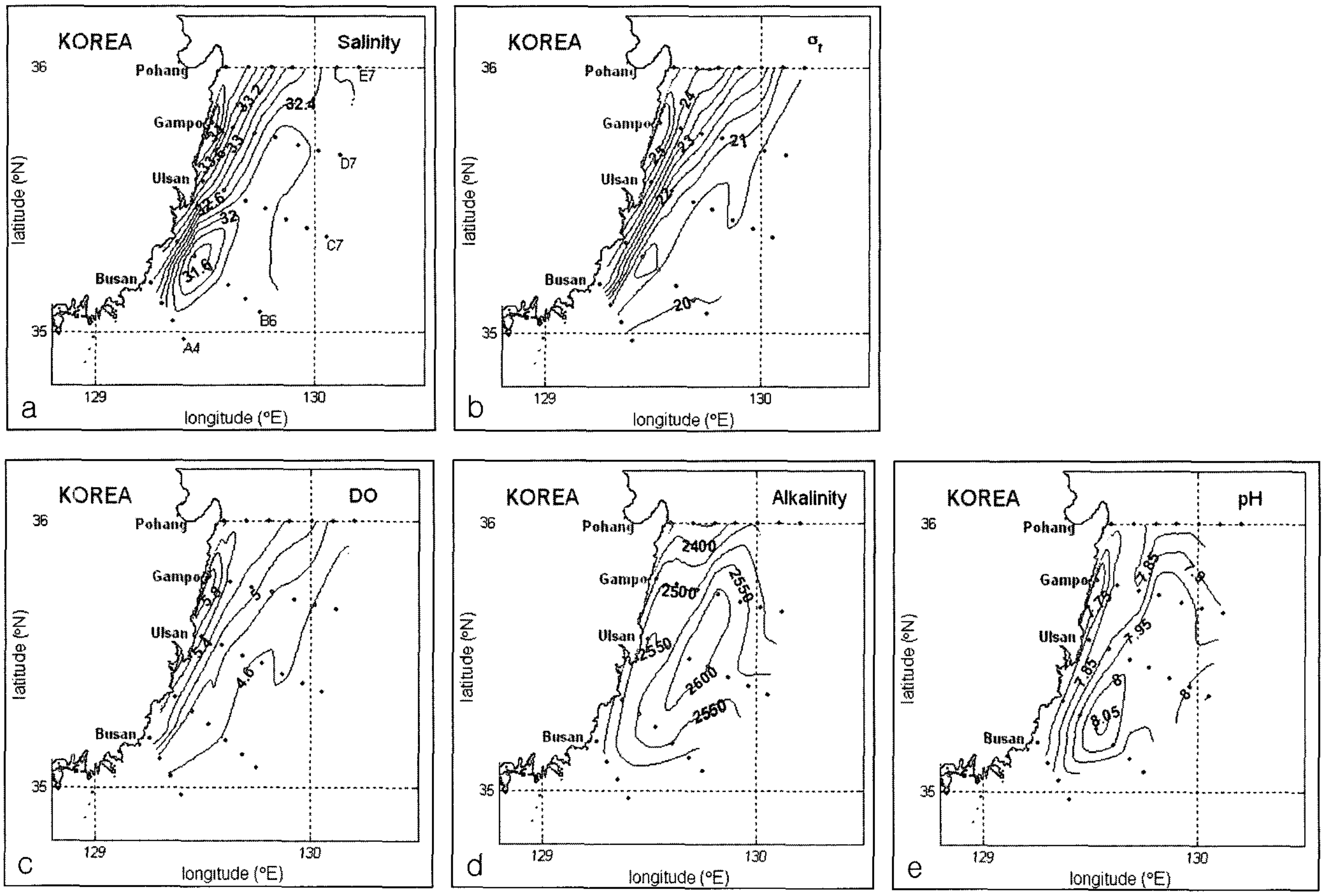

Fig. 5. Maps showing the distribution of surface water parameters measured on 30 July – 1 August 2001: (a) salinity, (b) sigma-t, (c) dissolved oxygen (ml · l^{-1}), (d) alkalinity (μmol · kg^{-1}), (e) pH.

The source water should reside in the interior of the East Sea. Previous studies suggested two probable sources: East Sea Proper Water (T=1°C, S=33.96-34.10) by Gong and Park (1977) and North Korea Cold Water with its high oxygen content (>6.0 ml l^{-1}) and less saline characteristics (S<34) by Kim and Kim (1983). However, upwelled waters have quite different characteristics from these two water types. To make things worse the difference in temperature and salinity between ESPW and NKCW is somewhat ambiguous (Park, 1978).

A more plausible criterion would be the dissolved oxygen. NKCW is at the surface up north from at the subpolar front and then subsides between the TWC and ESPW to become intermediate water. Therefore NKCW should contain more oxygen than the Proper Water which lies below 200 m (Lim and Chang, 1969; Park, 1978). The lowest value of DO in NKCW is 6.0 ml l^{-1}, whereas that of ESPW is 4.3 ml l^{-1} with a maximum of 6.5 ml l^{-1}. The reported values of DO for the water types are listed in the Table 2. These values are compared with DO values at

Table 2. Dissolved oxygen concentrations of North Korea Cold Water and East Sea Proper Water in the East Sea

Source water	DO (ml · l^{-1})	Min-Max	References
NKCW (North Korea Cold Water)	6.5–7.5	6.0–< 6.8	Park (1978)
	< 6.8		Kim and Kim (1983)
	6.0–6.45		Yang *et al.* (1991)
ESPW (East Sea Proper Water)	5.2–6.0	4.3–6.5	Park (1978)
	5.5–6.5		Kim and Kim (1983)
	4.3–5.0		Yang *et al.* (1991)

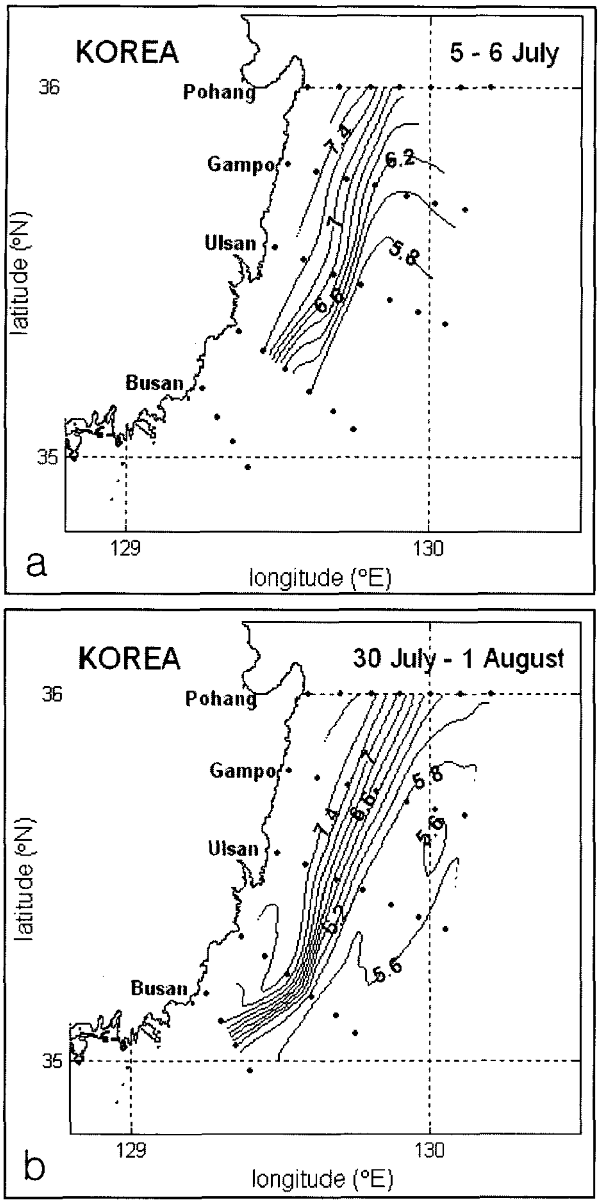

Fig. 6. Horizontal distribution of dissolved oxygen (ml l^{-1}) at the 100 m depth: (a) 5–6 July and (b) 30 July–1 August.

100 m isopleths during the upwelling season (Fig. 6).

Concentrations of dissolved oxygen increased towards the coast. The maximum value reached up to 7.4 ml l^{-1}. Contours of dissolved oxygen aligned parallel to the coastline. The concentration and contour shape prefer the NKCW as the origin of the upwelled waters. Unlike our a priori expectation pinning down the origin of upwelled waters requires basin-wide analysis of water masses. Since NKCW dynamics has not been studied recently, the conclusion has only a tentative utility. Redefining the water type characteristics is urgent to understand the basin scale circulation. The difficulties in classifying the various water types are due mostly to their subtle differences in temperature and salinity as a result of a vigorous conveyer belt (Kang *et al.*, 2003). Utilizing other potential parameters such as DO, PH, alkalinity, etc. are highly recommended.

The East Sea is unique in that it has its own thermohaline circulation (Kim *et al.*, 2002a). Since deep waters are made only in winter time at the northern Japan Basin, the Ulleng Basin is fed deeper waters from the Japan Basin. The stronger the deep conveyor belt, the more deep water should wells up to the surface. Is the summertime coastal upwelling inherent to the East Sea conveyer belt? This question is important not only in closing the circulation loop but also in the context of biological production, which is briefly considered in the next section.

Biological Implications

Regarding the coastal upwelling somewhat detrimental effects on the fish catch and mariculture were rumoured. Its effect on phytoplankton growth has not been documented. Since quantitative analysis of the phytoplankton community is beyond the scope of this study, only the response of algal community to the eutrophication by upwelling will be mentioned based on underway fluorescence monitoring.

As expected the fluorescence fluctuated widely both in terms of space and time (Fig. 7). Nutrients in the coastal area have two distinctive sources: from land via rivers and streams, and coastal upwelling. Without significant contribution from these two sources fluorescence remained low and varied little in June (Fig. 7a and 7b). During the upwelling period, the fluorescence soared by an order of magnitude (Fig. 7c and 7f). However, careful examination reveals that a considerable portion of the enhanced algal activity can be attributed to a terrestrial nutrient input during the flood season. The riverine contribution is noticeable in early July (Fig. 7c), when the surface waters off the Ulsan coast were under the influence of the Taehwa River discharge. The fluorescence peaks during the upwelling period dropped near to half-level in between the events. Still it was substantially higher compared with that of pre-upwelling.

This observation has two interesting implications for the algal community. Firstly, without upwelling nutrientpoor open waters would be expected to expand quite close to the shorelines. This means a lower primary production throughout the stratified season.

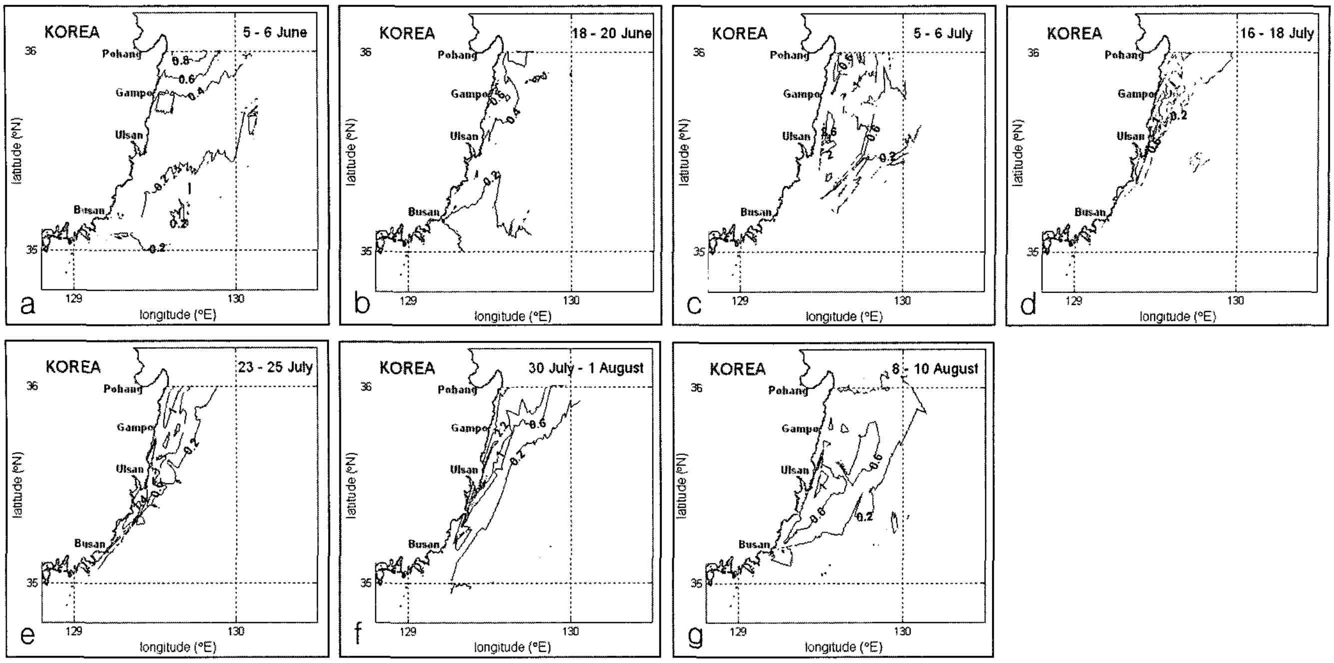

Fig. 7. Surface seawater fluorescence measured at the southern East Sea logged by the underway fluorometer/thermosalinograph during 2001 upwelling survey: (a) 5–6 June, (b) 18–20 June, (c) 5–6 July, (d) 16–18 July, (e) 23–25 July, (f) 30 July–1 August, (g) 8–10 August.

With upwelling, however, algae of up to an order of magnitude more biomass are supported in summer. Moreover the subsequent advection of upwelled water to offshore fed organisms which would otherwise be living in a dessert like environment. Secondly, a sporadic supply of nutrients to the upper mixed layer in warm stratified season is expected to prevent a possible harmful algal bloom. The primary production in a strongly stratified season is dominated by the flagellates that are responsible for the recent toxic algal blooms in Korean waters (Lee *et al.*, 2002). The nutrient supply should suppress the monopoly of flagellates and rejuvenate the diatom community back into competition.

Concluding remarks

Regions of active upwelling in the low and mid-latitude are peculiar in that they are frequently accompanied by a well-developed oxygen minimum layer underneath, as witnessed in the Galapagos upwelling region. More often the downward flux of particulate organic matter from the surface exceeds the supply of dissolved oxygen. However, such oxygen depletion was not documented and found in our case. This may reflect the spatiotemporal dimension of the upwelling being too small to boost biological production. Indeed only once in a three-year trial did we hit upon a sizable upwelling. This reveals the highly variable nature of our coastal upwelling.

On the other hand, historic records of the ancient civilization depicted this area as very prolific. Petroglyphs at the Bankudae at about 10 km upstream of the Taewha River, are engraved with numerous whales of at least six discernable species and ancient whaling practices. We know that enhanced biological production shortens the food chain, as seen in Peruvian upwelling system. Thus upwelling-induced high biological production seems to be a plausible explanation for a large herds of whales documented till the early part of the 20th century.

Early workers considered the southerly ultimately drives upwelling (Lee and Na, 1985 and references cited therein), which is in turn a component of the Asian Monsoon system. Since the development and the location of highs and lows determines the Monsoon, it is natural to suppose that small scale local upwelling is linked to the much larger climatological phenomenon. The East Sea operates its own active conveyer belt with an estimated turnover time of less than one hundred years (Kim *et al.*, 2002b). This means that the amount of deep water produced in winter should be counterbalanced by upwelling. At a first glance it seems warming will reduce the upwelling potential. Given that the response of biological production to the global warming is of specific concern, one needs to pay more attention to the dissolved oxygen because the dissolved oxygen of interior waters reflects both the history of circulation and biological production in surface waters. In a warmer world, oxygen might become the key parameter to look at in the East Sea, as various doomsday scenarios already predict (Chen *et al.*, 1999; Nof, 2001).

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