Interdisciplinary Studies on Environmental Chemistry—Marine Environmental Modeling & Analysis, Eds., K. Omori, X. Guo, N. Yoshie, N. Fujii, I. C. Handoh, A. Isobe and S. Tanabe, pp. 105–115.

Variations of Seawater Temperature and Coastal Winds from 2003 to 2009 at the Bungo Channel, Japan

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(Received 19 December 2010; accepted 12 January 2011)

Abstract—We examined seawater temperatures at 5 m depth, surface air temperatures, and surface wind speeds along the eastern coast of the Bungo Channel from 2003 to 2009. The analysis showed an increasing trend in mean water temperature in the past 7 years, particularly in winter (Oct., Nov., and Dec.). The increasing trend of seawater temperature was more apparent at shallow stations than at deep stations, indicating an active influence of the surface air temperature on the seawater. The mean surface air temperature also increased in winter, but not in other seasons. The speed of the surface air temperature increase was faster than that of water temperature in winter, reducing the difference between them, which reduced heat losses from sea to air in winter and helped increase water temperature. The reduction of the air-sea temperature difference also reduced the degree of destabilization of the atmosphere, which inhibited the downward transfer of momentum to the surface and reduced the surface wind speed.

Keywords: coastal wind, global warming, sea surface temperature

INTRODUCTION

Observation- or simulation-based studies have revealed a positive correlation between surface winds and sea surface temperature (SST) over the open ocean (Chelton *et al*., 2001, 2004; Xie, 2004; Small *et al*., 2008). Instability in the air over warm water intensifies the vertical exchange of momentum, while the change in air pressure gradients also accelerates surface winds (Lindzen and Nigam, 1987; Hayes *et al*., 1989; Wallace *et al*., 1989). These effects generally induce stronger winds over regions with warm SST, leading to a positive correlation of SST and surface winds.

Since the 1970s, global average temperature has increased 0.2°C decade^{-1} (Kundzewicz *et al*., 2007). Rouse (2009) and Desai *et al*. (2009) have reported an increase in both water temperature and air temperature at Lake Superior and a reduction in the temperature difference between the air and water, which destabilized the atmospheric surface layer and accelerated the surface winds.

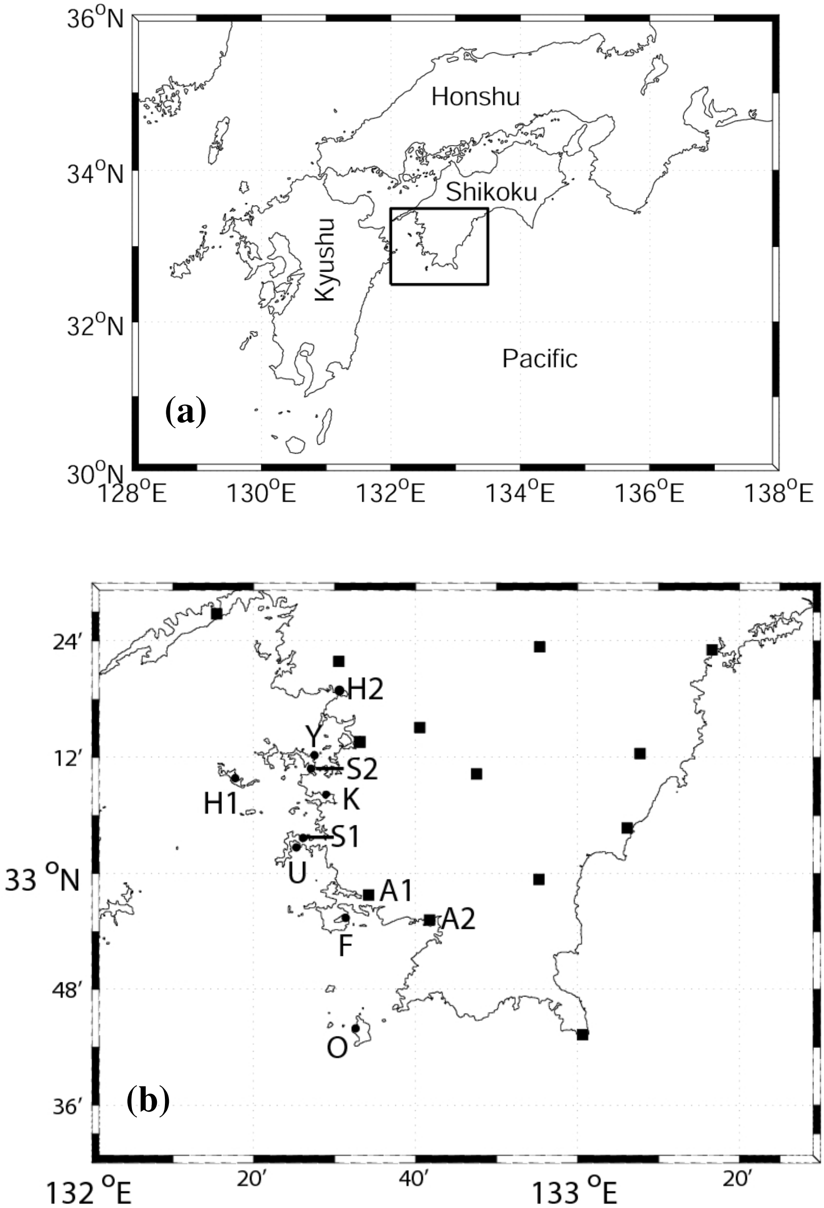

Fig. 1. (a) Location of study area; (b) water temperature monitor stations (dots) and AMeDAS stations (squares). The nine water temperature monitor stations are Okinoshima (O), Fukuura (F), Uchiumi (U), Shimonada (S1), Kitanada (K), Hiburijima (H1), Shitaba (S2), Yusu (Y), and Hoketsu (H2). A1 and A2 are two AMeDAS stations in Fig. 5.

Global warming could modify sea surface temperature in coastal seas as well and could influence coastal winds. The Seto Inland Sea is a semi-enclosed coastal sea surrounded by the Honshu, Shikoku, and Kyushu Islands of Japan (Fig. 1a). SST has reportedly increased in the Seto Inland Sea for the past several decades, particularly in winter (Kimura, 2004). The change in SST could influence surface air temperature as well as surface winds, which should be closely associated with the emission, deposition, diffusion, and transport of pollutants in the Seto Inland Sea.

For this reason, SST, surface air temperature, and coastal wind speeds in the western part of the sea from 2003 to 2009 were examined in this study. We discuss the relationship between them, which will be helpful for understanding the influence of climate change on the fate of pollutants.

STUDY AREA AND DATA

The study area is around the eastern coast of the Bungo Channel, located at the western Seto Inland Sea. This region is one of the pathways connecting the Seto Inland Sea with Pacific (Fig. 1a).

Every 2 hours, water temperature at 5 m depth was automatically collected by the Uwa water temperature monitor system, which is operated by the Center for Marine Environmental Studies (CMES), Ehime University. This system has nine stations along the eastern coast of the Bungo Channel (Fig. 1b). Data from 2003 to 2009 collected by the monitor system were used in this study.

Meteorological data including air temperature and wind speed were collected routinely by the Automated Meteorological Data Acquisition System (AMeDAS), which is operated by the Japan Meteorological Agency (JMA). The surface air temperature at 2 m above the ground and surface wind speeds at 10 m above the ground collected by the AMeDAS from 2003 to 2009 were used in this study.

RESULTS AND DISCUSSIONS

Variations in water temperature

The 25-month running mean of monthly water temperature shows that water temperatures were higher at the southern Bungo Channel compared to the northern channel, and an increasing trend was apparent from 2003 to 2009 (Fig. 2a).

To quantitatively examine the variation, a 1-σ least-squares regression analysis was used to analyze annual mean water temperature (Fig. 2b). The trends in water temperature depend on the location of stations (Fig. 3a). At the shallow water stations (F, S1, K, S2, Y) close to the coastline, annual mean water temperature increased at about 0.04–0.06°C year^{-1}; at the deep water stations (O, U, H1) offshore, the annual mean water temperature decreased.

Variations of seasonal mean temperature were also examined with the same method (Fig. 3b). There were increasing trends at most stations in summer, autumn, and winter. Increasing trends were more apparent in winter than in other

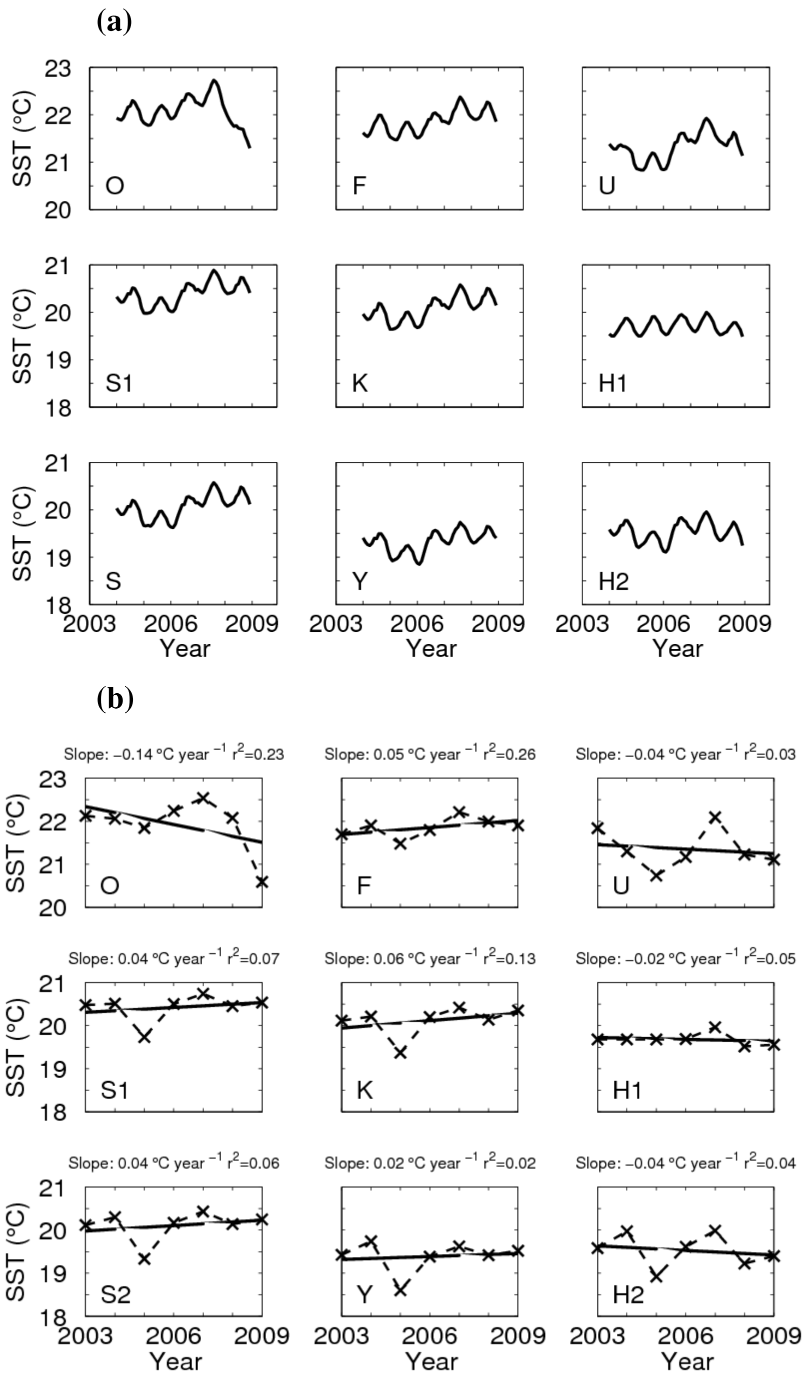

Fig. 2. (a) The 25-month running mean of water temperature at 5 m depth from 2003 to 2009; and (b) the annual mean water temperature from 2003 to 2009 (crosses) and 1-σ least-squares regression line (solid lines), where r^2 is the coefficient of determination.

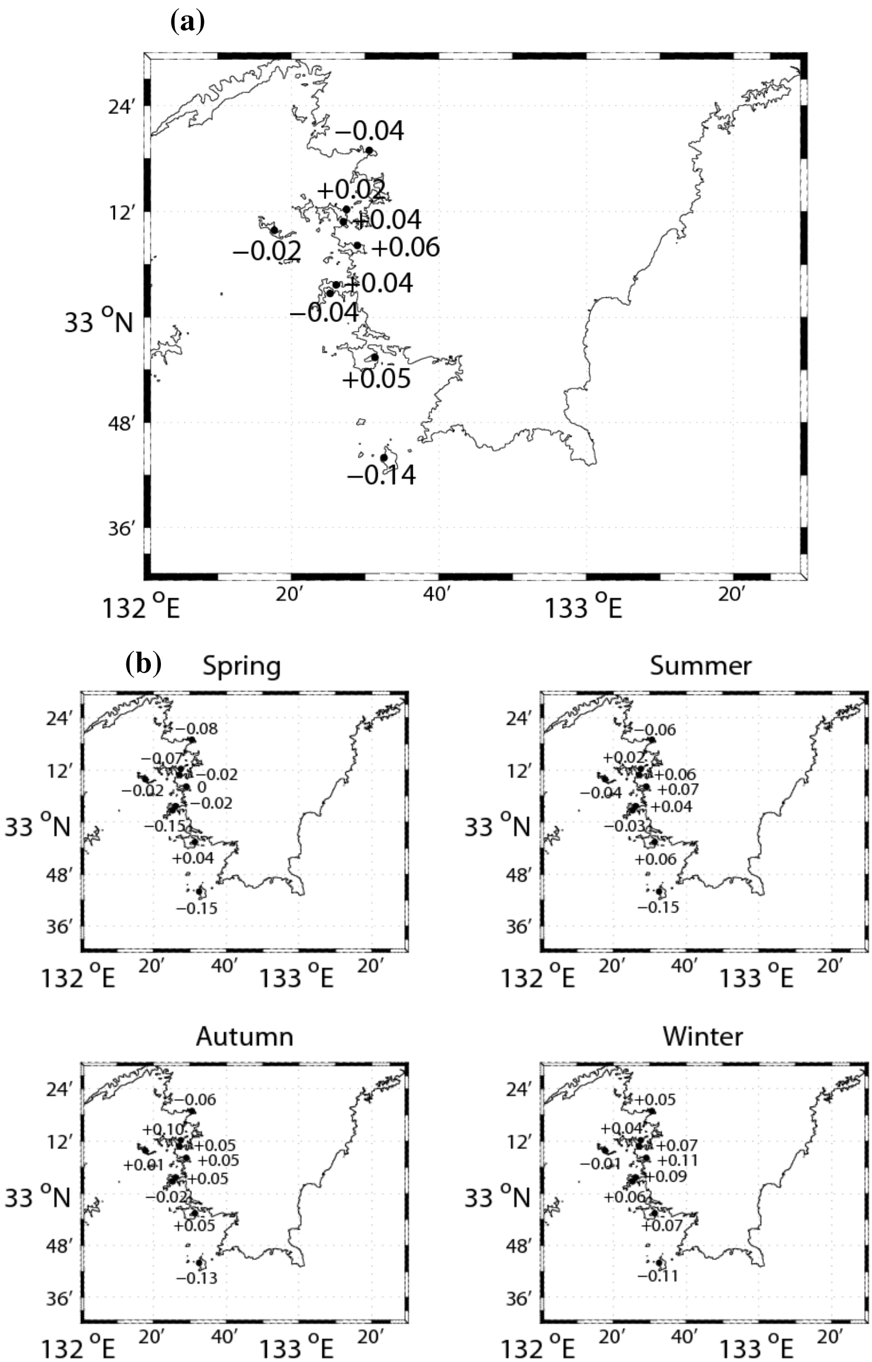

Fig. 3. (a) Spatial distribution of 1-σ least-squares regression slopes (°C year^{-1}) of annual mean water temperature; (b) the same as (a) but for seasonal mean water temperature.

seasons. This result is consistent with Kimura (2004), who reported increasing SST based on monthly data in the Bungo Channel from 1967 to 2002. The winter increasing trends were slightly larger at shallow water stations than at deep water stations.

The spatial distribution of trends indicates that the variations of seawater temperature could be essentially affected by variation of atmospheric conditions, rather than oceanic conditions. Therefore, in the following discussion, the surface air temperatures near the eastern Bungo Channel are analyzed.

Variations in surface air temperature

Trends of annual and seasonal mean surface air temperature around the Bungo Channel were also calculated using the 1-σ least-squares regression analysis used for water temperature analysis. The annual mean surface air temperature did not increase at most stations, except at some southern stations (Fig. 4a). The magnitudes of variation were on the order of 10^{-2}°C year^{-1} (Fig. 4a).

Seasonal mean air temperature exhibited larger trends (10^{-1}°C year^{-1}) than annual mean surface air temperature (Fig. 4b). The mean at most stations decreased from spring to autumn, but increased in winter. The opposite trends in seasonal mean air temperatures resulted in a small trends in annual mean air temperature. There were simultaneous increases in surface air temperature and water temperature in winter, indicating a possible link between them.

We compared the water temperature at station F, and the surface air temperature at stations A1 and A2 in Fig. 5. The increases in surface air temperatures at stations A1 and A2 were faster than those of water temperature (Figs. 5a and 5c), leading to a reduction in the air-sea temperature differences in winter (Figs. 5b and 5d).

Because seawater temperature was higher than air temperature in winter in our study area, heat was released from sea to air through sensible and latent heat fluxes that were proportional to the air-sea temperature difference, which is the fundamental reason for the water temperature decrease in winter. Accordingly, it is expected that less heat was released from the ocean to the atmosphere in warm winters than in cold winters, because of the smaller sea-air temperature differences in warm winters.

Global warming changed the air temperature more quickly and decreased temperature differences between sea and air, which is expected to reduce the heat fluxes from the sea into the air in winter. This explains why water temperature increased in the coastal ocean in winter.

Variations in surface wind speed

To determine trends in wind fields, 1-σ least-squares regression analysis was applied to the surface wind speed again. Except for two or three stations, wind speed at most stations generally decreased, regardless of the annual mean (Fig. 6a) and seasonal means (Fig. 6b). The reduction of air-sea temperature differences

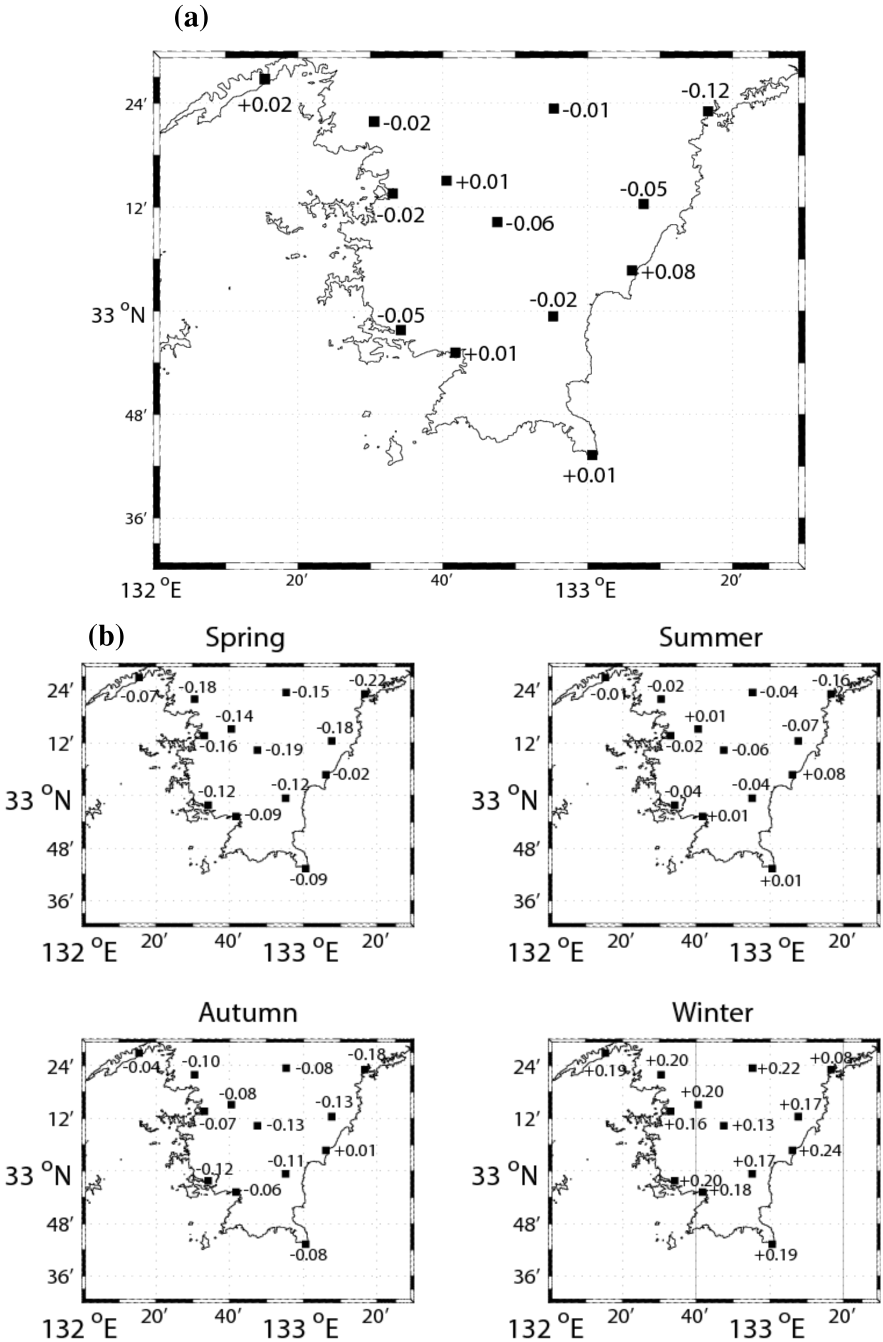

Fig. 4. (a) Spatial distribution of 1-σ least-squares regression slopes (°C year^{-1}) of annual mean surface air temperature from 2003 to 2009; (b) the same as (a) but for seasonal mean surface air temperature.

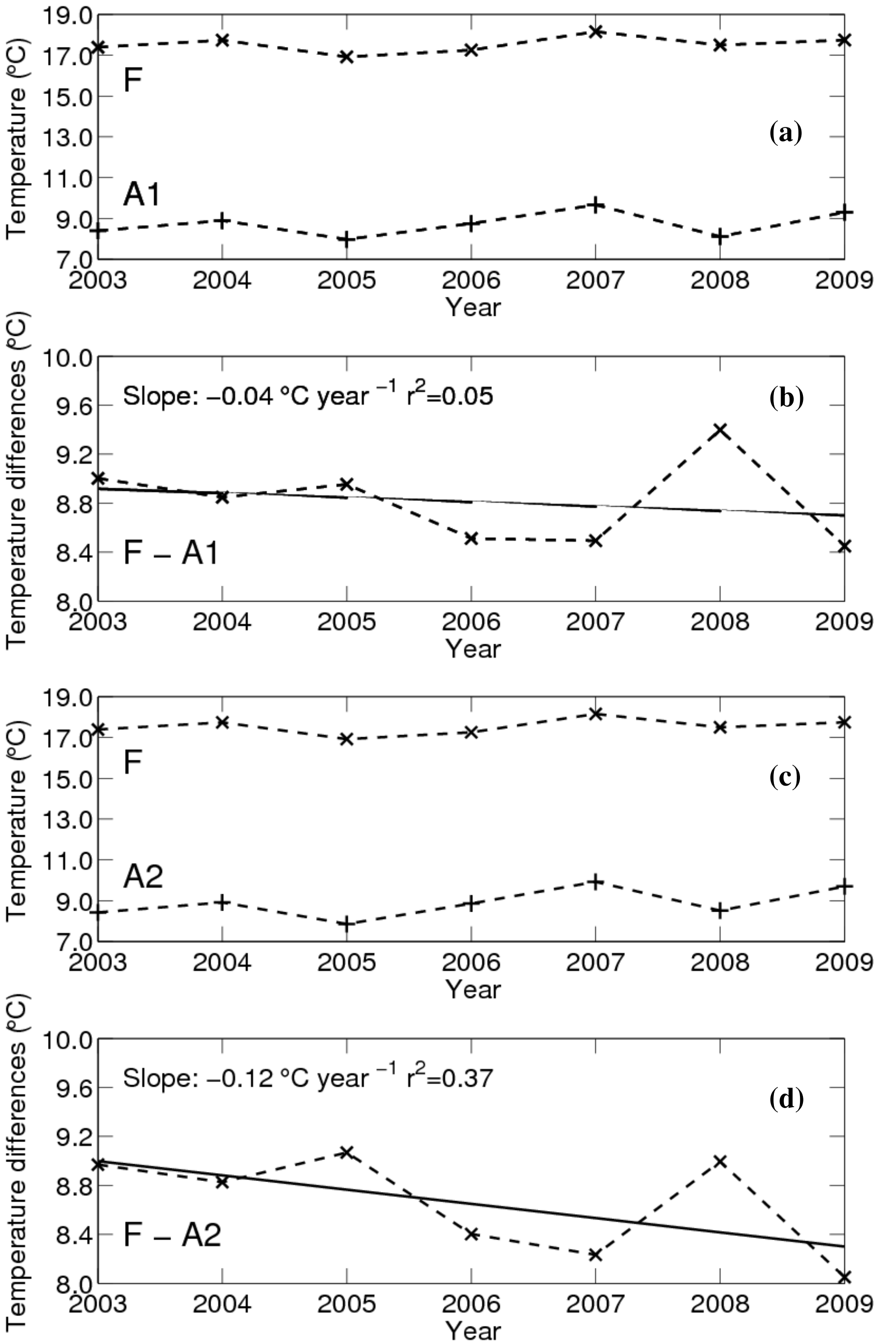

Fig. 5. (a) Mean water temperature at station F (crosses) and mean surface air temperature at station A1 (plus signs) in winter (December–February), and (b) their differences; (c), (d) the same as (a) and (b) but for stations F and A2.

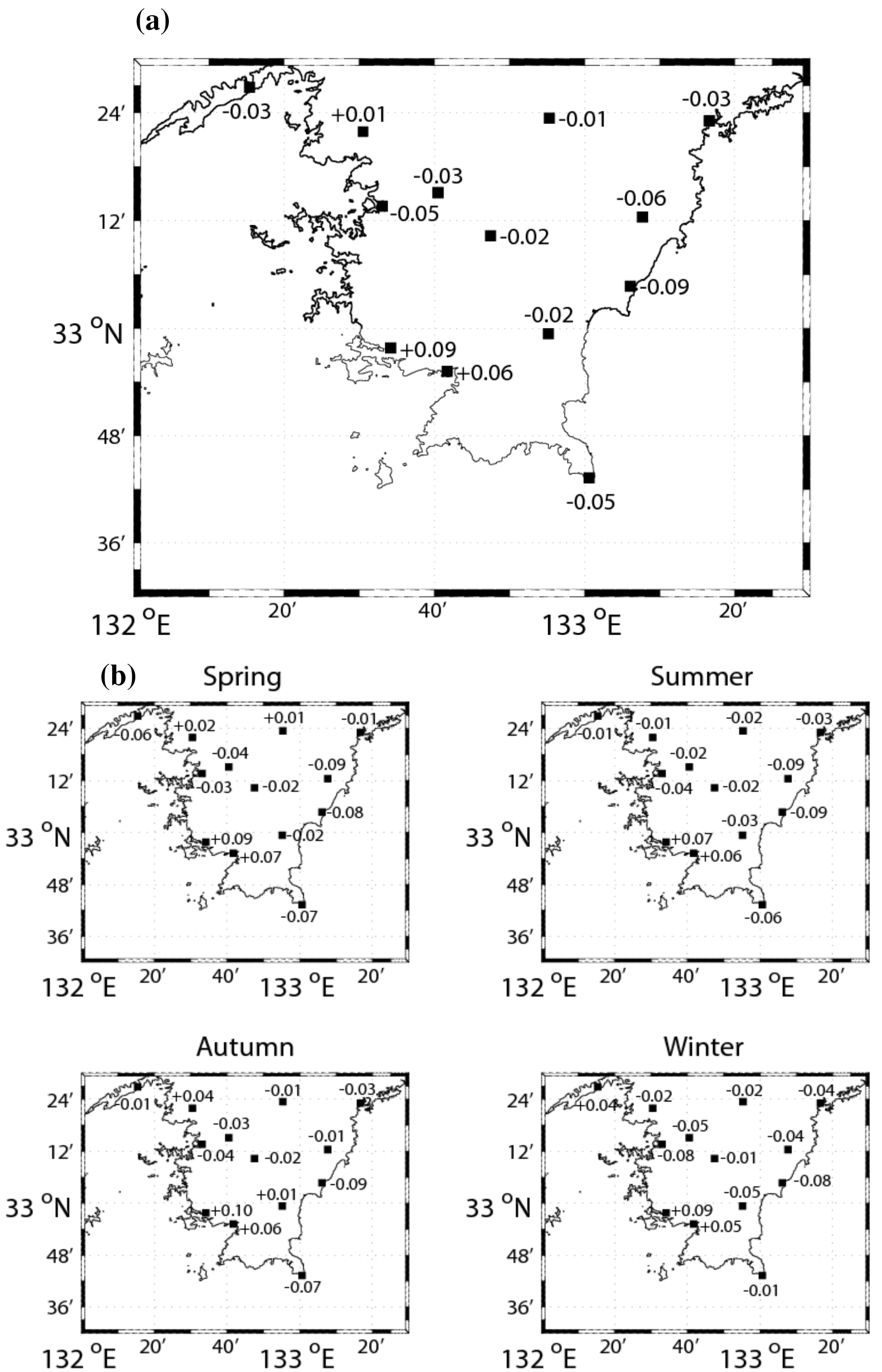

Fig. 6. (a) Spatial distribution of the 1-σ least-squares regression slopes (ms^{-1} year^{-1}) of annual mean surface wind speed from 2003 to 2009; (b) the same as (a) but for seasonal mean surface wind speed.

reduced heat losses from the sea to the air in winter. Consequently, the degree of destabilization of the atmosphere is reduced in winter, which inhibits the downward transfer of momentum to the surface and decreases the surface wind speed. We still have no clear explanation for the increasing trends in surface wind speeds at two stations near the southwestern area of Shikoku Island, but we attribute them to local reasons not uncovered by this analysis.

SUMMARY

Analysis of hydrometeorology data at Bungo Channel shows that mean water temperatures increased from 2003 to 2009, particularly in winter (Oct., Nov., and Dec.). Increasing trends of seawater temperature were more apparent at shallow stations than at deep stations, indicating an active influence of surface air temperature on sea water. The mean surface air temperature also increased in winter, but not in other seasons.

The rate of increase of surface air temperature was faster than that of water temperature in winter, lessening the difference between the two, and reducing heat losses from sea to air in winter that helped increase water temperature. The reduction of the air-sea temperature difference also reduced the degree of destabilization of the atmosphere, which inhibited the downward transfer of momentum to the surface and reduced the surface wind speed.

Acknowledgments—This study was supported by the Global COE (Centers of Excellence) Program and the Grants-in-Aid for Scientific Research (22106002) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

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