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Atmospheric sounding over the winter Kuroshio Extension: Effect of surface stability on atmospheric boundary layer structure

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[1] Shipboard radiosonde surveys were conducted during the 2003-04 winter east of Japan to study atmospheric boundary layer (ABL) structure over the Kuroshio Extension. ABL displayed large variations in vertical structure, most of which are attributable to changes in atmospheric surface stability. Where the surface atmosphere was unstable (neutral) as measured by the sea-air temperature difference, surface turbulent heat flux increased (decreased) and a mixed-layer developed (undeveloped) with weakened (intensified) vertical wind shear. A linear regression analysis indicates that ABL height tends to increase by 1km as the sea-air temperature difference increases by 7°C or surface turbulent heat flux by 500 Wm^{-2}. While meridional thermal advection by weather disturbances seems to cause much of atmospheric stability variability during the 43-day surveys, the strong sensitivity of vertical mixing and wind shear to stability is consistent with the observed in-phase co-variability of SST and surface wind from satellite on monthly and longer timescales. **Citation:** Tokinaga, H., Y. Tanimoto, M. Nonaka, B. Taguchi, T. Fukamachi, S.-P. Xie, H. Nakamura, T. Watanabe, and I. Yasuda (2006), Atmospheric sounding over the winter Kuroshio Extension: Effect of surface stability on atmospheric boundary layer structure, *Geophys. Res. Lett.*, *33*, L04703, doi:10.1029/2005GL025102.

1. Introduction

[2] The Kuroshio Extension (KE) east of Japan forms a robust sea surface temperature (SST) front with SST gradients often exceeding 5°C/100 km. Owing to a sharp cross frontal contrast in heat release to the atmosphere, this oceanic frontal zone may play a crucial role in intensifying atmospheric baroclinicity and thereby maintaining the North Pacific storm track [*Nakamura and Sampe*, 2002; *Nakamura et al.*, 2004; *Xie et al.*, 2002]. Recent satellite observations show that surface wind speed increases over the KE's warm meanders while decreasing over detached cold eddies [*Nonaka and Xie*, 2003]. This in-phase relationship between SST and surface wind speed, opposite to the traditional view that strong wind speed cools the ocean surface, is indicative of an ocean-to-atmospheric influence. Similar ocean frontal effect on the atmosphere is found in other extratropical regions [*Xie*, 2004] such as the Gulf Stream [*Sweet et al.*, 1981] and Antarctic Circumpolar Current [*O'Neill et al.*, 2003].

[3] Such a surface wind response to ocean frontal variability as above is often explained with a vertical mixing mechanism proposed by *Sweet et al.* [1981] and *Wallace et al.* [1989]: On the warmer flank of the front, the surface atmosphere is unstable and the intensified mixing brings large momentum from above to accelerate the surface wind. Limited synoptic atmospheric soundings across the Gulf Stream [*Sweet et al.*, 1981] and along the Pacific equatorial front [*Hashizume et al.*, 2002] show marked changes in atmospheric boundary layer (ABL) structure, including its height and wind shear, across the fronts that are consistent with this vertical mixing mechanism. In a climatological study based on historical ship observations, *Tokinaga et al.* [2005] detected large variations in atmospheric stability as measured by the difference between SST and surface air temperature (SAT) over the Brazil/Malvinas Confluence, with increased (reduced) surface wind speed where the surface atmosphere is unstable (stable).

[4] Thus in-situ observations are necessary to study the atmospheric adjustment to oceanic fronts. Here we report the results from vertical soundings of the atmosphere over the KE during the winter of 2003–2004, the first in this region to our knowledge. We detect large variations in surface atmospheric stability and associated changes in ABL height and wind shear. In the rest of the paper, Section 2 briefly describes the observations, followed by the presentation of the results in Section 3. Section 4 is a summary.

2. Observations

[5] Joint ocean-atmospheric surveys were conducted over the KE and its recirculation on board research vessels *Shoyo-maru* and *Kaiyo-maru* of the Japan Fisheries Agency from 19 December 2003 to 8 January 2004 and from 24

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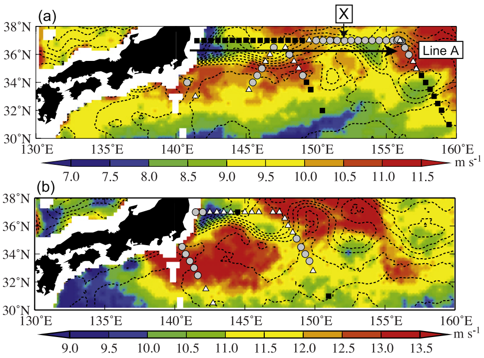

Figure 1. Sounding sites (black squares: SST-SAT < 1°C; white triangles: 1°C < SST-SAT < 5°C; gray circles: SST-SAT > 5°C) on (a) the *Kaiyo-maru* cruise from 24 February to 17 March 2004, and (b) the *Shoyo-maru* cruise from 19 December 2003 to 8 January 2004. Superimposed are SST (dashed contour at 1°C intervals) and surface wind speed (color in m s^{-1}) averaged during each cruise based on TRMM satellite observations. The solid line and cross in Figure 1a indicate the cross section "Line A" and site for the particular sounding shown in Figures 2 and 3, respectively.

February to 17 March 2004, respectively. A total of 96 Global Positioning System (GPS) sondes were launched at approximately 0.5° longitude-latitude intervals along ship tracks in 30°–37°N, 141°–160°E (Figure 1). During the cruises, the Tropical Rainfall Measurement Mission (TRMM) satellite [*Wentz et al.*, 2000] captured the KE front in SST in 35°–37°N, 141°–160°E that extended from Japan eastward with some meanders. In Figure 1, radiosonde stations are classified into three groups according to the values of an atmospheric stability parameter at the surface S = SST-SAT: neutral (S < 1°C in black squares), modestly unstable (1 < S < 5°C in triangles), and highly unstable (S > 5°C in grey circles). Near the KE front, wind speeds tend to increase (decrease) over warm (cold) water in these multi-week mean maps from satellite. As will be seen, vigorous weather disturbances were found to be a major factor for surface atmospheric stability variability in our soundings.

[6] Two types of GPS sondes (Vaisala RS80-GH and RS92-SGP) were used, measuring air temperature, relative humidity, pressure, and wind velocity. These variables have been linearly interpolated to vertical levels at 10 m intervals. We use the data from the surface to 3.5 km height to focus on the ABL. Shipboard meteorological observations of SST and SAT at 1-minute intervals were used to calculate the near-surface stability parameter S = SST-SAT. Surface latent and sensible heat fluxes (Q_e, Q_h) are calculated from surface meteorological data using the aerodynamic bulk formula of *Kondo* [1975].

3. Results

3.1. Cross Section A

[7] Following the mean orientation of this SST front, the *Kaiyo-maru* sailed eastward along 37°N from 141.5°E on 25 February to 156°E on 28 February 2004 ("Line A" hereafter; Figure 1a), launching 30 sondes. A distinct SST maximum observed around 151.5°E was due to a warm meander of the KE front (Figure 1a). Both surface wind and SAT display a sudden transition around 149.5°E (Figures 2b and 2c). To the west the winds were calm at 10 m s^{-1} or less under the almost neutral stratification. On February 26 a low pressure developed near Hokkaido Island (140°–145°E, 40°–45°N), which deepened the next day to 964 hPa in center pressure at the sea level while moving northeastward (not shown). This well-developed low induced the cold advection off southern coast of Japan. According to the weather map on 1800 UT 26 February 2004, surface winds around Line A changed into northwesterlies after the passage of the associated cold front, while southwesterlies prevailed before the passage. In fact, surface winds observed onboard intensified to 15 m s^{-1} or above around 1800 UT 26 February 2004, while changing their direction from southwesterly into northwesterly. The cold advection depressed SAT by 5°C, leaving the ABL highly unstable east of 150°E along Line A.

[8] Figure 2a displays the longitude-height section of virtual potential temperature (θ_v) and scalar wind speed ($|u_a|$) along Line A. Vertical gradients of θ_v and $|u_a|$ show clear association with the near surface static stability. Over the stably stratified region west of 149°E, reduced surface sensible heat flux suppressed the formation of a mixed layer, and therefore vertical θ_v gradient in the ABL was as strong as in the free atmosphere except in the lowest 300 m. In 146°–148°E, vertical shear was very strong with wind speed increasing from about 10 m s^{-1} at the surface to ~20 m s^{-1} at 1.2 km height. East of 149°E, in contrast, the

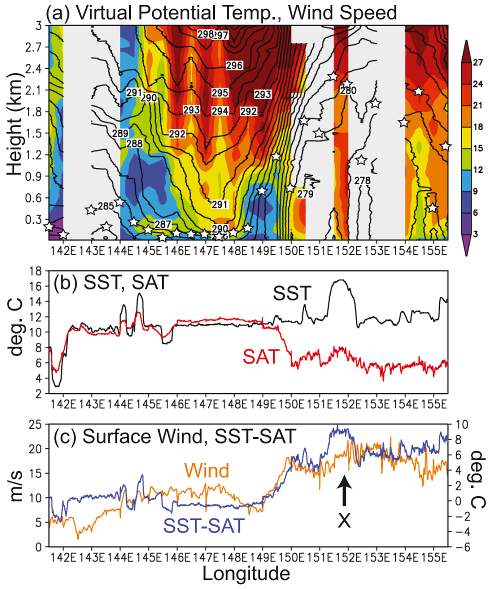

Figure 2. (a) Longitude-height section of scalar wind speed (color in m s^{-1}) and virtual potential temperature (contour at 1K intervals) along 37°N during the *Kaiyo-maru* cruise. Open stars denote the ABL height defined as the lowest height where virtual potential temperature increases by 1°C from the surface. Grey shade denotes soundings without reporting wind. (b) SST (black line in °C) and SAT (red line in °C). (c) SST-SAT (blue line in °C) and surface wind speed (orange line in m s^{-1}). The cross in Figure 2c corresponds to the particular sounding shown in Figure 3.

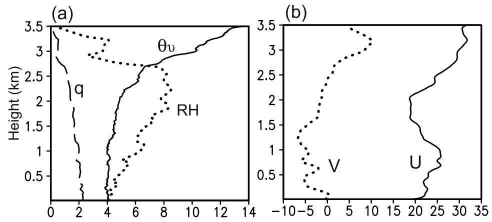

Figure 3. Sounding at 152°E, 37°N at 0341 UT 27 February 2004: (a) virtual potential temperature −275 (K; solid line), specific humidity (g kg^{-1}; dashed line), and relative humidity × 10^{-1} (%; dotted line), (b) zonal (m s^{-1}; solid line) and meridional wind velocities (m s^{-1}; dotted line). Surface turbulent heat flux reached 864 W m^{-2}, the highest among all the soundings during the cruise.

ABL was highly unstable, characterized by a well-defined mixed layer of 1.5 km deep that was maintained by the intense turbulent heat release due to strong wind (>15 m s^{-1}) and large air-sea temperature difference (∼6°C; Figure 2c). Here the ABL top is defined as the lowest level where θ_v increases by 1°C from the surface.

[9] The ABL height reached its maximum of about 2 km over the SST maximum associated with the warm meander of the KE front. There, the SST-SAT difference and surface wind speed were as strong as 8.4°C and 20 m s^{-1}, respectively, resulting in surface turbulent heat flux ($Q_e + Q_h$) exceeding 800 W m^{-2}, the maximum of all our sounding stations. At this location (as indicated with "X" in Figures 1a and 2c), the sounding reveals the presence of a deep mixed layer, where height dependence was small in specific humidity and meridional wind (northerly at 10 m s^{-1}; Figure 3). Although the specific humidity recorded low values in the ABL (∼2 g kg^{-1}) due to the advection of cold and dry air from the north, relative humidity exceeded 80% in the upper mixed layer, suggesting the presence of a cloud layer capped by a temperature inversion with its base at 2.7 km. Such cumulus/stratocumulus clouds often develop in the cold surges after the cold front passage. Indeed, satellite images (not shown) and our weather log indicate that the sky over this station was covered with stratocumulus.

3.2. ABL Structure

[10] The above observations along Line A indicate the importance of the surface stability parameter S in determining the ABL structure, which is explored further in this subsection by using all the soundings and surface meteorological data from both the *Kaiyo-maru* and *Shoyo-maru* cruises. The scatter diagrams in Figures 4a and 4b show that the ABL height is correlated positively with both the stability parameter S and surface turbulent heat flux with their coefficients of r = 0.68 and 0.67, respectively, both of which are above the 99% confidence level. Linear regression estimates indicate that the ABL height increases by 1 km as the SST-SAT difference increases by 7°C or turbulent heat flux by 500 W m^{-2}.

[11] Our soundings show that the near-surface atmospheric stability was influenced not only by SST but also by weather disturbances. Figure 3c shows a scatter plot between SST-SAT and surface meridional wind based on our continuous surface observations. The significant negative correlation (r = −0.7) between the two quantities indicates that synoptic southerly (northerly) winds increase (reduce) surface static stability through warm (cold) advection.

[12] Figure 5 shows vertical profiles of θ_v and wind speed, each of which has been composited separately for the following two categories of our soundings based on the surface stability S. A total of 25 soundings fall into the highly unstable category for S > 5°C while 24 into the neutral group for S < 1°C. The θ_v profile for the unstable stratification category (Figure 5a) features the well-defined surface mixed layer of 0.75 km high, above which the stratification still remains weak up to about 1.3 km. Except in the frictional surface layer as thin as 150 m, there is not much change in wind speed throughout this mixed/weakly stratified layer, probably due to intense vertical mixing. In the θ_v profile for the neutral stratification category (Figure 5a), by contrast, there is no surface mixed layer with stratification developing right above the surface. Because of the suppressed mixing, the vertical wind shear above the frictional surface layer is substantially stronger than in the case of unstable stratification (Figure 5b). Although wind is weaker above the frictional surface layer in the unstable composite, it becomes stronger by 1.5 m s^{-1} at the sea surface than in the neutral composite, as a result of enhanced vertical mixing. The unstable stratification, which developed behind cold fronts, tended to be associated with lower-tropospheric temperatures 8°C–10°C lower than for the neutral category (Figure 5a).

4. Summary

[13] Distinct temporal and spatial changes in ABL structure were observed over the KE by shipboard soundings during the winter of 2003–2004. The analysis of 96

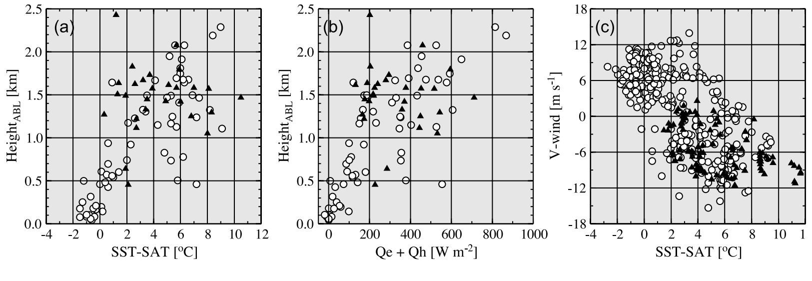

Figure 4. Scatter plots between ABL height and (a) SST-SAT, and (b) surface turbulent heat flux ($Q_e + Q_h$), and (c) between SST-SAT and surface meridional wind during the *Shoyo-maru* (triangle) and *Kaiyo-maru* (open circle) cruises. Correlation coefficients are 0.68 (Figure 4a), 0.67 (Figure 4b), and −0.70 (Figure 4c).

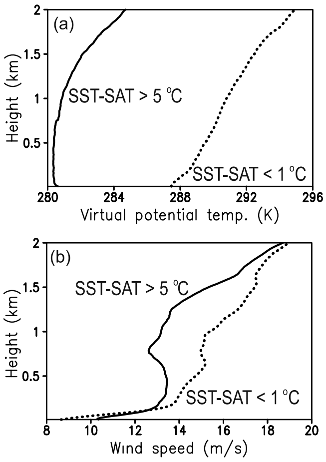

Figure 5. Composite vertical profiles of (a) virtual potential temperature (K), and (b) wind speed (m s^{-1}) for SST-SAT > 5°C (solid line) and SST-SAT < 1°C (dotted line). A total of 25 (24) soundings are used for the unstable (neutral) composite.

soundings shows large effects of surface atmospheric stability on the ABL's vertical structure. Under stable/neutral stratification, no surface mixed layer tended to form with strong wind shear developing in the vertical. Under unstable stratification, by contrast, large turbulent heat flux was observed at the sea surface and the well-defined surface mixed layer developed up to 2.5 km high, in which vertical shear was weak except in the thin frictional surface layer. During the 43-day cruise surveys, meridional wind fluctuations associated with weather disturbances—between 15 m s^{-1} southerly and 15 m s^{-1} northerly—were the major cause of the variability observed in the surface stability through their thermal advection.

[14] Of limited durations, our cruise surveys were unable to extract unambiguously SST effects on the ABL structure in the presence of strong weather disturbances. The strong dependence of ABL structure–vertical wind shear in particular–on surface atmospheric stability provides indirect support for the SST-induced vertical mixing mechanism for co-variability between SST and surface wind observed over the KE [*Nonaka and Xie*, 2003]. This SST effect would become more apparent when the effect of weather disturbances is properly removed. Such an SST effect is hinted as one of the deepest mixed-layer heights is observed over a warm SST meander under modest northerly winds (Figure 3). Indeed, there is a pronounced maximum in the SST-SAT difference on the warmer flank of the KE front in the long-term mean climatology of historical ship observations (not shown). Finally we note that it is the KE front that maintains sharp temperature gradients within ABL for weather disturbances to advect.

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References

Hashizume, H., S.-P. Xie, M. Fujiwara, M. Shiotani, T. Watanabe, Y. Tanimoto, W. T. Liu, and K. Takeuchi (2002), Direct observations of atmospheric boundary layer response to SST variations associated with tropical instability waves over the eastern equatorial Pacific, *J. Clim*, *15*, 3379–3393.

Kondo, J. (1975), Air-sea bulk transfer coefficients in diabatic conditions, *Boundary Layer Meteorol.*, *9*, 91–112.

Nakamura, H., and T. Sampe (2002), Trapping of synoptic-scale disturbances into the North-Pacific subtropical jet core in midwinter, *Geophys. Res. Lett.*, *29*(16), 1761, doi:10.1029/2002GL015535.

Nakamura, H., T. Sampe, Y. Tanimoto, and A. Shimpo (2004), Observed associations among storm tracks, jet streams, and midlititude oceannic fronts, in *Earth's Climate: The Ocean-Atmosphere Interaction*, *Geophys. Monogr. Ser.*, vol. 147, edited by C. Wang, S.-P. Xie, and J. A. Carton, pp. 329–345, AGU, Washington, D. C.

Nonaka, M., and S.-P. Xie (2003), Co-variations of sea surface temperature and wind over the Kuroshio and its extension: Evidence for ocean-to-atmospheric feedback, *J. Clim.*, *16*, 1404–1413.

O'Neill, L. W., D. B. Chelton, and S. K. Esbensen (2003), Observations of SST-induced perturbations of the wind stress field over the Southern Ocean on seasonal timescales, *J. Clim*, *16*, 2340–2354.

Sweet, W., R. Fett, J. Kerling, and P. La Violette (1981), Air-sea interaction effects in the lower troposphere across the north wall of the Gulf Stream, *Mon. Weather Rev.*, *109*, 1042–1052.

Tokinaga, H., Y. Tanimoto, and S.-P. Xie (2005), SST-induced surface wind variations over the Brazil-Malvinas Confluence: Satellite and in situ observations, *J. Clim.*, *18*, 3470–3482.

Wallace, J. M., T. P. Mitchell, and C. Deser (1989), The influence of sea surface temperature on surface wind in the eastern equatorial Pacific: Seasonal and interannual variability, *J. Clim.*, *2*, 1492–1499.

Wentz, F. J., C. Gentemann, D. Smith, and D. Chelton (2000), Satellite measurements of sea surface temperature through clouds, *Science*, *288*, 847–850.

Xie, S.-P. (2004), Satellite observations of cool ocean-atmosphere interaction, *Bull. Am. Meteorol. Soc.*, *85*, 195–208.

Xie, S., J. Hafner, Y. Tanimoto, W.T. Liu, H. Tokinaga, and H. Xu (2002), Bathymetric effect on the winter sea surface temperature and climate of the Yellow and East China Seas, *Geophys. Res. Lett.*, *29*(24), 2228, doi:10.1029/2002GL015884.

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