Ocean thermal advective effect on the annual range of sea surface temperature

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[1] Spatial variations in the seasonal cycle of sea surface temperature (SST) are studied over the western North Pacific using a high-resolution climatology. In addition to monsoon, bathymetry and tidal mixing, western boundary currents and their extensions/branches are found to have a significant effect on the annual range of SST, with reduced values on the paths of warm currents and increased ones on the paths of cold currents. This is due to the asymmetric effect of ocean currents on SST in time: small in summer but large in winter when both the deepened mixed layer and increased SST gradients enhance the relative importance of ocean thermal advection to balance the heat flux to the atmosphere. Along with recent studies of decadal variability, our results reaffirm the role of ocean dynamics in climate. **Citation:** Liu, Q., S.-P. Xie, L. Li, and N. A. Maximenko (2005), Ocean thermal advective effect on the annual range of sea surface temperature, *Geophys. Res. Lett.*, *32*, L24604, doi:10.1029/2005GL024493.

1. Introduction

[2] The seasonal cycle is the largest and best observed climate variation on Earth. To first order, it is a direct result of the seasonal variation in incoming solar radiation but significantly modified by additional factors such as the surface properties, the circulation and interaction of the ocean and atmosphere. The seasonal cycle in surface air temperature (SAT) is generally much larger over continents than over the oceans of the same latitudes because the heat content of soil involved in seasonal variations is much smaller than that of the ocean. This land-sea contrast is so large that one does not need a world map to identify major continents in the extratropics from a map of the annual SAT range [e.g., *Gill*, 1982]. Here the annual range is defined as the difference between the maximum and minimum values of a long-term climatology.

[3] Ocean currents transport large amounts of heat and are considered as an important mechanism for sea surface temperature (SST) variations. This effect of ocean currents on SST's seasonal cycle has not been adequately mapped and studied because the paucity of ship-based observations does not resolve major currents that are generally only 100 km wide. The advent of space-borne Advanced Very High Resolution Radiometer (AVHRR) in 1981 makes routine SST measurements possible over the global ocean. The frequent presence of clouds poses a serious challenge for infrared SST measurements but long-term accumulation of AVHRR observations now allows the compilation of a reliable and high-resolution SST climatology. Here, we analyze such a high-resolution SST climatology and study the spatial structure of the SST annual range and the effects of major ocean currents in particular.

[4] The paper is organized as follows. Section 2 introduces the datasets. Section 3 describes the general features of the SST annual range while Section 4 focuses on the advective effect by major ocean currents in the western North Pacific and its marginal seas. Section 5 is a summary.

2. Data

[5] The global SST climatology of *Armstrong and Vazquez-Cuervo* [2001], based on satellite AVHRR measurements for a 15-year period of 1985–1999 and available at a pentad (5 days) interval and on a 9 km grid, is used for the SST annual range analysis.

[6] To calculate surface geostrophic current, we use the Aviso sea level anomaly (SLA) dataset that merges European Remote Sensing (ERS) and TOPEX/Poseidon (T/P) altimetry observations [*Ducet et al.*, 2000], available at a 10-day interval on a $0.25° \times 0.25°$ grid for the period from October 1992 to August 2001. To obtain the full sea surface height (SSH) we add the 1992–2002 mean dynamic topography derived from a synthesis of the GRACE, Aviso, drifter and NCAR/NCEP wind data based on a momentum balance requirement [*Maximenko and Niiler*, 2005; *Niiler et al.*, 2003].

[7] The COADS (Comprehensive Ocean and Atmosphere Dataset) surface net heat flux climatology on a 1° grid is also used here. To calculate the ocean advective effect on SST, we use the Naval Research Laboratory mixed-layer depth monthly climatology derived from historical hydrographic data on a 1° grid [*Kara et al.*, 2003; http://www7320.nrlssc.navy.mil/nmld/nmld.html].

3. SST Annual Range

[8] Figure 1 shows the SST annual range based on the AVHRR observations over the western North Pacific and surrounding seas. Over the open ocean, the annual range increases northward up to 40°N with little zonal variations, as one would expect from the seasonal cycle in solar forcing. The annual range displays rich variations in the marginal seas near the continent, however. In order to

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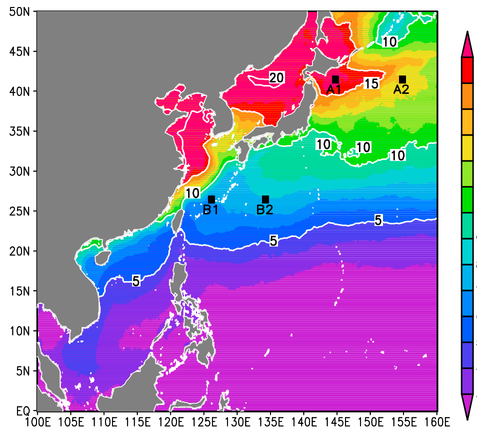

Figure 1. Annual range of SST (°C) over the western North Pacific and its marginal seas. Dark squares mark the following locations: A1 (41–42°N 144–145°E), A2 (41–42°N 155–156°E); B1 (26°N–27°N, 125.5°E–126.5°E), B2 (26°N–27°N, 133.5°E–134.5°E).

understand these variations, let us consider the mixed layer temperature equation [e.g., *Qiu*, 2000]:

$$\frac{\partial T_m}{\partial t} = -\mathbf{u}_m \cdot \nabla T_m + \frac{Q_{net}/\rho c_p - w_e(T_m - T_d)}{h_m}, \qquad (1)$$

where h_m and T_m are the mixed layer depth and temperature, respectively, Q_{net} is the net air-sea heat flux, ρ and c_p are the density and specific heat at constant pressure of sea water, $\mathbf{u}_m$ is the current velocity vertically averaged in the mixed layer, which is composed of surface geostrophic current and Ekman flow, w_e is the entrainment velocity, and T_d is the temperature beneath the mixed layer. Here we have neglected turbulent mixing in the horizontal for simplicity, which can be important near strong currents with strong mesoscale eddy activity.

[9] In general, spatial variations in winter SST are more important in shaping the annual-range distribution than those in summer SST (Figures 1 and 2). The region centered along the Kuril Islands in the northeastern corner of our analysis domain is an exception where the minimum in the SST annual range (Figure 1) is due to strong tidal mixing over the steep topography [*Nakamura et al.*, 2004] that keeps the summer SST considerably cooler than the surrounding water (Figure 2, bottom).

[10] SST annual range displays a general increase toward the Asian coast that is due to winter cold surges from the continent. The greatest annual range (>20°C) is observed in the Bohai Sea, a shallow sea semi-enclosed by the northern China. In winter, the northeast monsoon brings cold and dry continental air in contact with this sea and the surface cooling is so intense that sea ice forms in part of the Bohai Sea. The entire Yellow Sea and much of the East China Sea to the south are over the continental shelf where winter SST follows the bathymetry [*Xie et al.*, 2002], which limits the depth of the winter mixed layer under the strong surface cooling by the northeast monsoon. Shallow bathymetry also plays a role in setting a zone of high annual range along the northern coast of the South China Sea by allowing effective cooling of coastal water where advection of cold water by a southwestward current along the east and south coasts of China [*Hu*, 1994] also contributes. The rest of the paper discusses such advective effects by ocean currents in other regions.

4. Heat Advection by Ocean Currents

[11] From April to June, solar radiation increases and the mixed layer shallows rapidly. In the Kuroshio Extension region, for example, the mixed layer depth decreases from 250 m in March to 25 m or less in summer. The increased solar heating, together with the decreased mixed layer depth, makes the surface heat flux the dominant term in equation (1) during summer, masking out ocean current effects on SST (Figure 2, bottom).

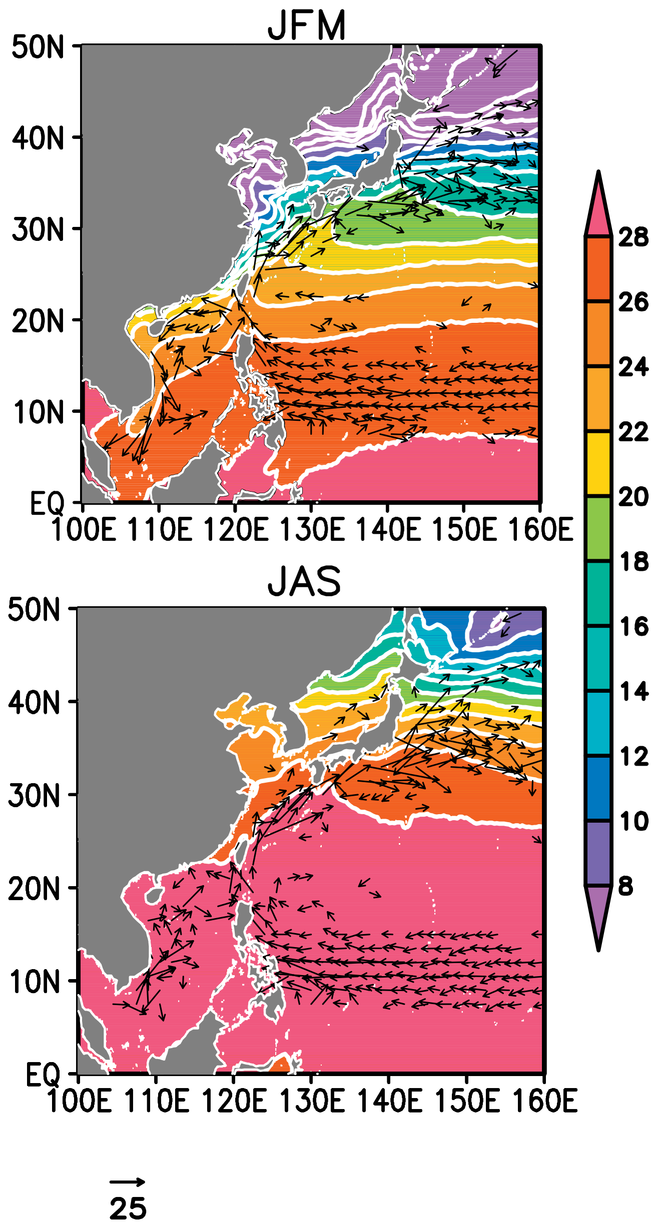

Figure 2. AVHRR SST climatology (color bar in °C) and surface geostrophic currents (only vectors larger than 10 cm/s are shown) for winter (JFM) and summer (JAS) in the western North Pacific.

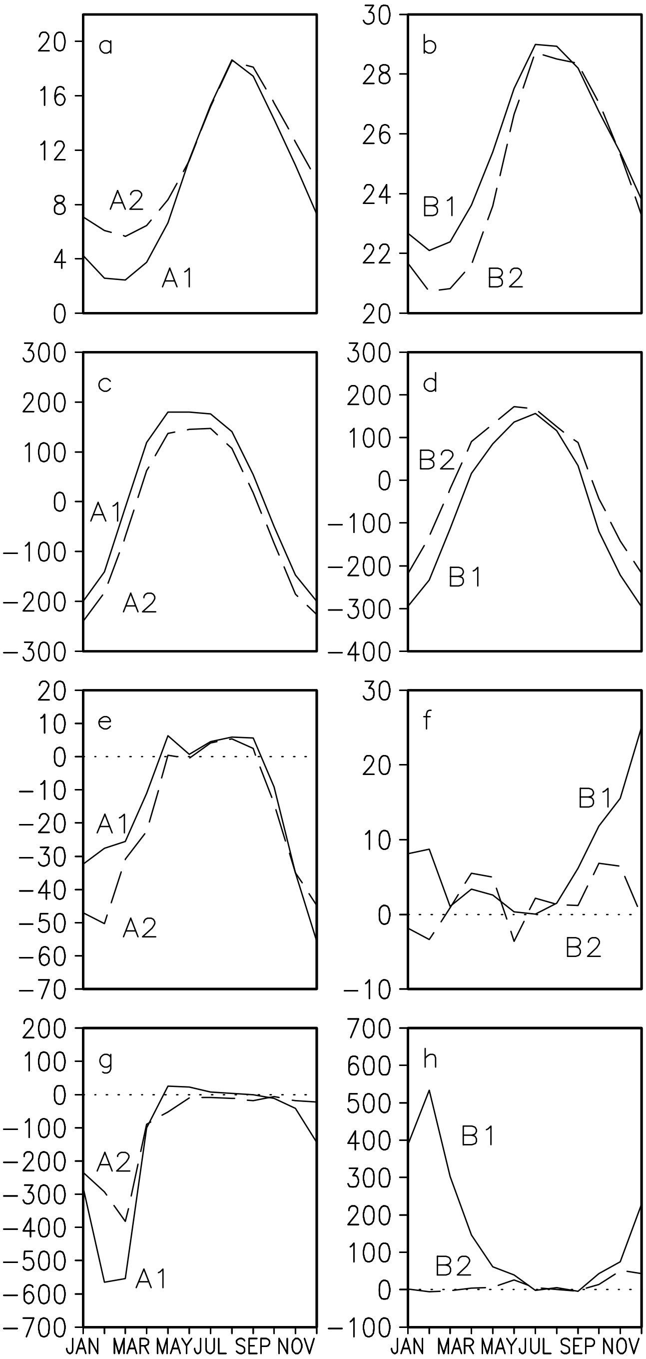

Figure 3. Annual cycles of SST (the first row in °C), net heat flux (the second row in W/m^2), thermal advections of Ekman currents multiplied by the heat capacity of the mixed layer (the third row in W/m^2) and thermal advections of geostrophic currents multiplied by the heat capacity of the mixed layer (the fourth row in W/m^2) on the paths of major ocean currents (solid curves) and representative open-ocean locations at the same latitudes (dashed curves) respectively. The left column and the right column are corresponding to the pairs A1-A2 and B1-B2 respectively.

[12] In winter, ocean advective heat transport generally intensifies as SST gradients increase with the enhanced meridional gradient in solar radiation and in the presence of the cold Asian continent. This increased ocean heat transport, together with the deepened mixed layer (increased h_m in equation (1)), increases the relative importance of the advection term, enabling it to imprint on winter SST and hence the SST annual range (e.g., along the Kuroshio; Figures 1 and 2, top). (See a related discussion on advective effects on interannual SST variability by *Tomita et al.* [2002].) A warm current flowing down the SST gradient reduces the annual range by keeping winter SST higher than the surrounding while a cold current increases the annual range. The following analysis supports this asymmetric effect of ocean heat advection on SST between winter and summer.

[13] Surface geostrophic current vectors are superimposed in Figure 2 to infer their advective effects. Along the continental shelf break south of Vietnam that separates the shallow Sunda shelf to the west and the deep South China Sea basin to the east, a strong southward current—which *Liu et al.* [2004] call the Sunda Slope Current—develops in winter as the western boundary current in response to wind stress curls of the northeast monsoon, advecting cold water from the north and producing a cold tongue (Figure 2, top) [*Liu et al.*, 2004]. This contrasts with summer SST that is nearly uniform in the horizontal. Thus the cold advection leaves a distinct maximum in SST annual range along the continental slope near the Sunda shelf.

[14] The Kuroshio is the major warm current in the western North Pacific, beginning its northward flow west of the Philippines, continuing north along the continental break in the East China Sea, and finally separating from the Japanese coast at around 35°N. The Kuroshio's effect on SST is most readily seen in snapshot satellite images as a stream of warm water. It also leaves a visible signature in the climatological SST annual range as a local minimum that is about 1°C less in value than over the open ocean at the same latitudes. At the Tokara Strait south of Japan's Kyushu Island, the Kuroshio's main stream exits the East China Sea but a minor branch continues northwest of Kyushu and enters the Sea of Japan through the Tsushima Strait between Korea and Japan. This minor Tsushima branch of the Kuroshio leaves a tongue of minimum annual range on its path in the East China Sea, in the Tsushima Strait, and off the coast of Honshu Island in the Sea of Japan.

[15] Next we carry out a local analysis of the seasonal cycle at the following locations on the paths of major western boundary currents: A1 for the cold Oyashio west of the northern Japan, and B1 for the warm Kuroshio in the East China Sea. The selected points are marked in Figure 1. Figure 3 compares the seasonal cycles of SST, thermal advection by geostrophic currents, thermal advection by Ekman Current, and net surface heat flux in these western boundary currents with those at open-ocean locations at the same latitudes. The SST differences between the western boundary current and interior regions are most pronounced in winter (January–March) while diminishing in summer, consistent with the increased temperature advection due to increased SST gradients and/or changes in current velocity. Deepening of the winter-time mixed layer further amplifies the importance of this advective effect of geostrophic currents relative to the surface heat flux. We have computed the thermal advection by the surface Ekman flow and found that it is generally one order of magnitude smaller than that

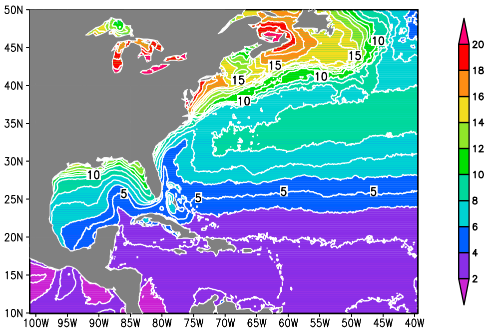

Figure 4. SST annual range (°C) over the Northwest Atlantic.

by geostrophic western boundary currents. The South China Sea south of 10°N is an exception where the Ekman advection is strong because of low latitudes, displacing the cold tongue west of the Sunda Slope that steers a strong southward cold current in winter (Figure 2, top) [*Liu et al.*, 2004]. Surface heat flux is a damping that acts to reduce the ocean advective effect in winter, by cooling the ocean more over the warm Kuroshio Current than the interior and vice versa over the cold Oyashio. Thus, the effect of the western boundary current on SST annual range is mainly due to its effect on winter SST. Cold currents (A1 in Figure 1) enhance the annual range while warm currents (B1) reduce it.

5. Discussion

[16] We have analyzed the annual range of SST over the western North Pacific using a high-resolution climatology based on long-term satellite observations. While the annual range over the open ocean is relatively zonally uniform, it increases toward the Asian coast and displays rich variations in the marginal seas because of bathymetry and/or tidal mixing. The thermal advection by ocean currents is shown to have a significant effect on SST annual range, by its asymmetrically large influence on winter SST but without changing summer SST much. As a result, warm currents such as the Kuroshio and its Tsushima branch reduce the annual range of SST while cold currents such as the Oyashio and the South China Sea's Sunda Slope Current increases it.

[17] The ocean advection effect on SST and its annual range is not unique to the western North Pacific and is observed around the world ocean. Figure 4 shows a remarkable example over the western North Atlantic. A tongue of minimum annual range is found over the Loop Current in the Gulf of Mexico, with another forming at the Florida Strait and extending northeastwards along the path of the Gulf Stream. The extension of the latter minimum annual-range tongue/band can be traced all the way to 50°W, separating a region of huge annual range on Grand Banks, and a band of weaker but still distinct maximum in the subtropical gyre to the south. The northern wall of the Gulf Stream is as distinct in this annual range map as in often-seen winter-SST maps.

[18] Western boundary currents and their extensions are the major mechanism for open-ocean frontogenesis. Recent satellite observations reveal that these currents affect local wind and cloud through their effect on SST [*Xie*, 2004; *Chelton et al.*, 2004]. The Kuroshio south of Japan occasionally changes into a so-called large meander path and stays in it for prolonged periods up to years [*Kawabe*, 1995]. Results from an ultra-high resolution (0.1°) ocean model hindcast indicate that the Kuroshio and Oyashio Extensions migrate meridionally in large amplitudes on decadal and longer timescales (M. Nonaka, personal communication, 2005) (see also *Qiu* [2000] for supporting satellite observations for a limited period). Our results here suggest that such slow variations in western boundary currents and their extensions have a significant regional effect on the seasonal cycle, a hypothesis that needs to be tested with further observations and modeling.

[19] **Acknowledgments.** The merged SLA dataset is obtained from the CLS Aviso, France, and AVHRR data from the NASA Jet Propulsion Laboratory. This work is supported by Natural Science Foundation of China (grants 40333030 and 40276009), US National Aeronautic and Space Administration, and Japan Agency for Marine-Earth Science and Technology. IPRC/SOEST publication 358/6693.

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