Ocean-atmosphere Coupling Over Mid-latitude Ocean Fronts Observed from Space

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Abstract

At the Kuroshio Extension, sea surface temperature (SST) governs the frontal-scale variability of momentum exchanges between the ocean and the atmosphere (stress) through buoyancy production of turbulence. The high and low stress magnitudes are found over high and low SST centers, with convergence centers in between as revealed by the scatterometer on QuikSCAT. The ocean effects are manifested through the depth of the troposphere, as shown by the Atmospheric Infrared Sounders (AIRS), the Tropical Rainfall Measuring Mission (TRMM) and the reanalysis products of the European Center for Medium-range Weather Forecast (ECMWF). Away from the surface, where turbulence transfer dominates, other atmospheric forcing, such as pressure gradient force, shift the distributions of convergence, vertical velocity, rainfall, and other atmospheric parameters to center on high and low SST.

1 Introduction

Past numerical modeling studies did not show significant effect of local SST change over extra-tropical ocean on large-scale circulation above the atmospheric boundary layer (e.g., Lau and Nath 1994; Kushnir et al. 2002; Liu and Wu 2004). Frankignoul (1985) did show very weak coupling and Deser et al. (2007) showed surface influence through eddy process. Recent studies, however, suggested spatial resolution of the models makes a difference (Smirnov et al. 2014).

Liu et al. (2007) postulated that mid-latitude ocean fronts may have sufficient energy to influence large-scale atmospheric circulation and demonstrated the surface effect on atmospheric temperature way above the boundary layer, using measurements by AIRS over the Agulhas Extension Current. Strong precipitation has also been associated with the Kuroshio and Gulf Stream (Pan et al. 2002; Minobe et al. 2008) and may signify the effect of SST high in the atmosphere.

In this study, we reveal the ocean influences, through surface stress, not only in the atmosphere boundary layer, but also in the troposphere, at low frequencies and frontal spatial scales, over the Kuroshio Extension.

2 Interaction at the Surface

We have investigated how the slow and small-scale ocean processes affect the fast and large-scale atmospheric circulation through the exchange of momentum (e.g., Liu et al. 2007; Liu and Xie 2008). Fig. 1a, from Liu and Xie (2008) show the spatial coherence between SST and the equivalent neutral wind (ENW), the standard geophysical product of the scatterometer. A two-

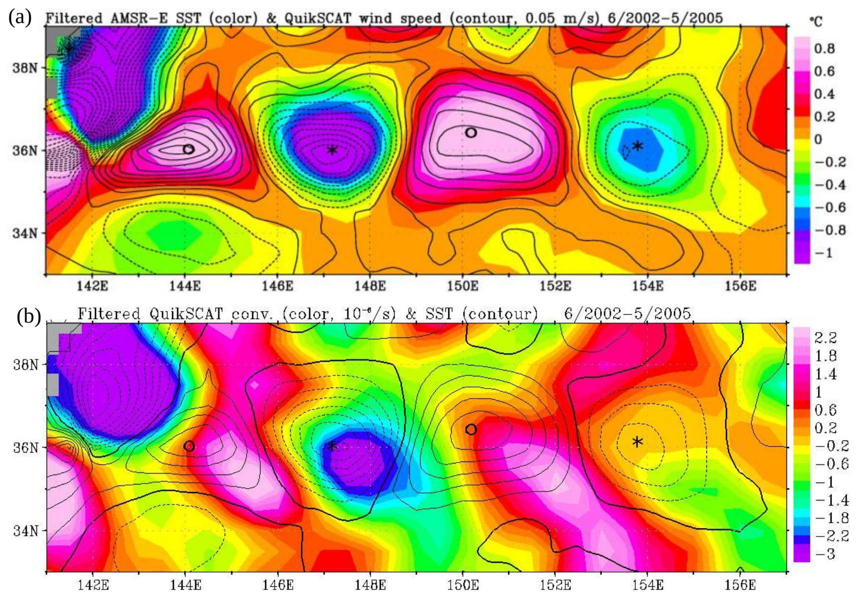

Fig. 1 Maps of filtered (a) SST (color) superimposed by magnitude of ENW (contour, 0.05 m/s interval), and (b) ENW convergence (color, 10^{-6}/s), superimposed by SST isotherms (0.2°C interval), averaged from June 2002 to May 2005.

dimensional filter was applied to isolate the frontal scale features. High magnitudes are found over warm water and low magnitudes are found over cool water. The circles and crosses mark the locations of high and low SST centers and will be used in all the figures of this study.

The coherence was first explained by enhanced vertical mixing in the atmospheric boundary layer (e.g., Liu et al. 2000; Hashizumi et al. 2002), as postulated by Wallace et al. (1989). The postulation evolves bringing strong winds aloft down to the warm surface, in variant with the upward vertical velocity shown in ECMWF products (Section 3). Because the flow encompasses the whole boundary layer, various atmospheric factors, such as, pressure gradient force, Coriolis force, baroclinicity, Ekman transport need to be considered and they have srrong regional and temporal variations. The spatial coherence, however, is ubiquitous, and has been obseerved under very different atmospheric conditions, e.g., over tropical instability waves, over mid-latitude ocean fronts in all ocean basins, under continental cold air outbreak, and over the cold wake of hurricanes (see the review by Liu and Xie 2013). The mechanism underlying the coherence may be more basic. We postulated that scatterometers measure surface stress more than winds, and stress is turbulent transfer of momentum. Turbulence is produced by local buoyancy and wind shear, and at turbulence scales, other factors affecting atmospheric circulation are not effective. When buoyance dominates over shear production, surface stress must be coherent with SST.

Fig. 1b shows that the convergence of ENW is in quadrature with SST, high values and low values are located between warm and cold centers. The three years of longitude-time variations in Fig. 2a and 2b demonstrate the consistence of the coherence of the surface parameters. ECMWF has been operationally assimilating scatterometer ENW as 10 m wind; the distributions of the surface wind magnitudes relative to SST are similar to those of ENW.

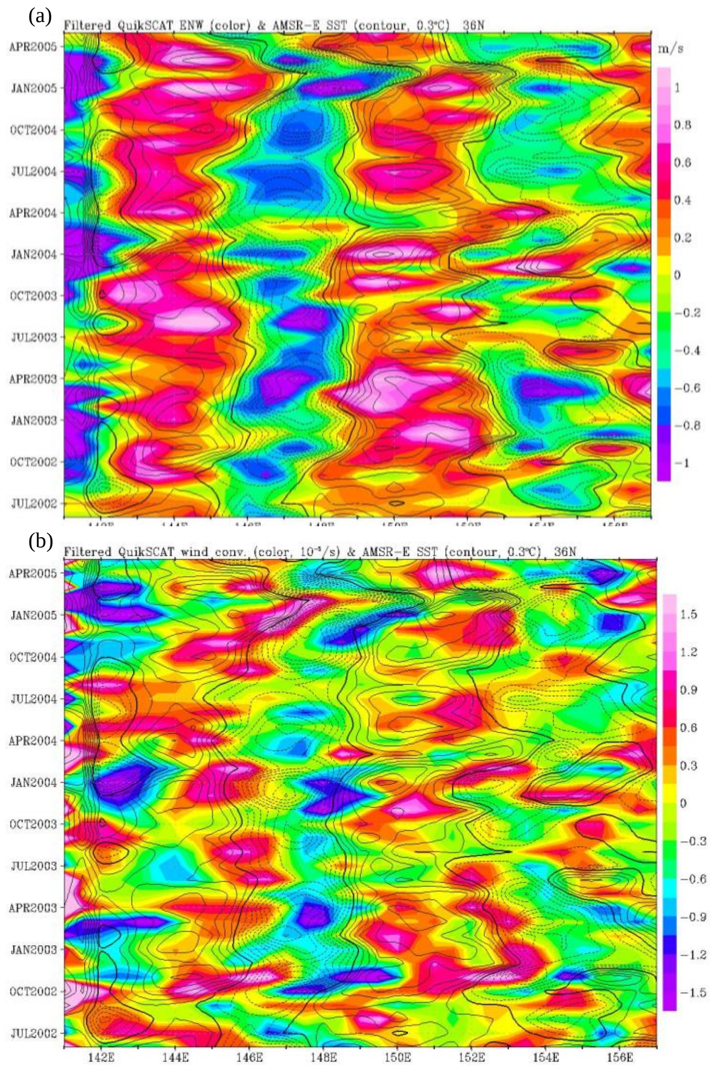

Fig. 2 Time-longitude variations of filtered (a) magnitude of ENW (color, m/s), and (b) ENW convergence (color, 10^{-5}/s), superimposed by SST isotherms (0.3°C interval) at 36°N.

3 Vertical Distribution

Fig. 3a and Fig. 3b (from Liu, Xie, and Niiler 2009, presented at Amer. Meteor. Soc. annual meeting at Phoenix, AZ) show penetration of the ocean signal up in the atmosphere. The AIRS temperature sounding has been used over the Agulhas Extension and its accuracy is discussed by Liu et al. (2007). The rain profiles shown are measured at the northern limit of the TRMM Precipitation Radar (PR) coverage. The Agulhas Extension Current is out of the coverage of the PR, and PR rain profile was not included in Liu et al. (2007).

PR gives more direct measurement of rain profile (as shown in Fig. 3a), but is more limited in coverage than the Microwave Imager (TMI) on TRMM. TMI provides rain water estimation in the atmosphere, with better spatial coverage. The vertical rain water distribution, from TMI, shown in Fig. 4a, is similar to Fig. 3a, with highs and lows of rain water between highs and lows SST centers. The effects of SST variability are felt above 4 km, with slight westward tilt. The

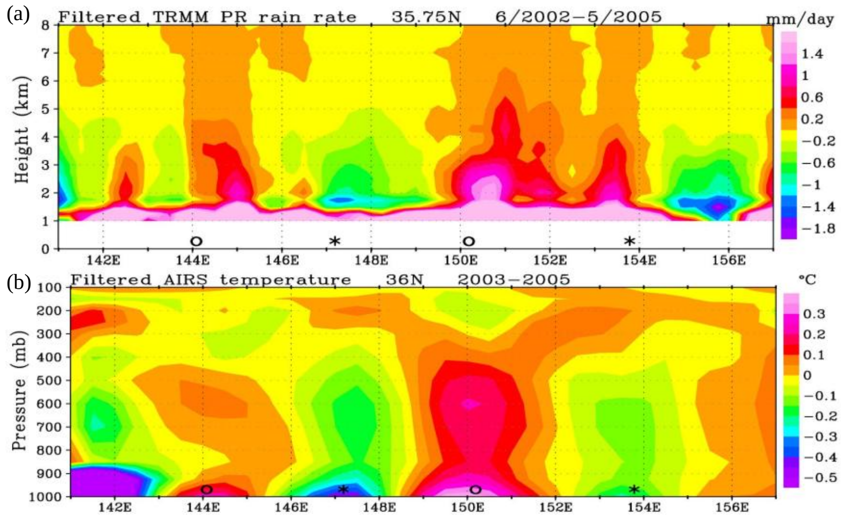

Fig. 3 Vertical profiles of filtered (a) rain rate from TRMM PR (2B31), and (b) temperature measured by AIRS at 36°N, averaged from June 2002 to May 2005. Circles and stars represent centers of warm and cold SST anomalies.

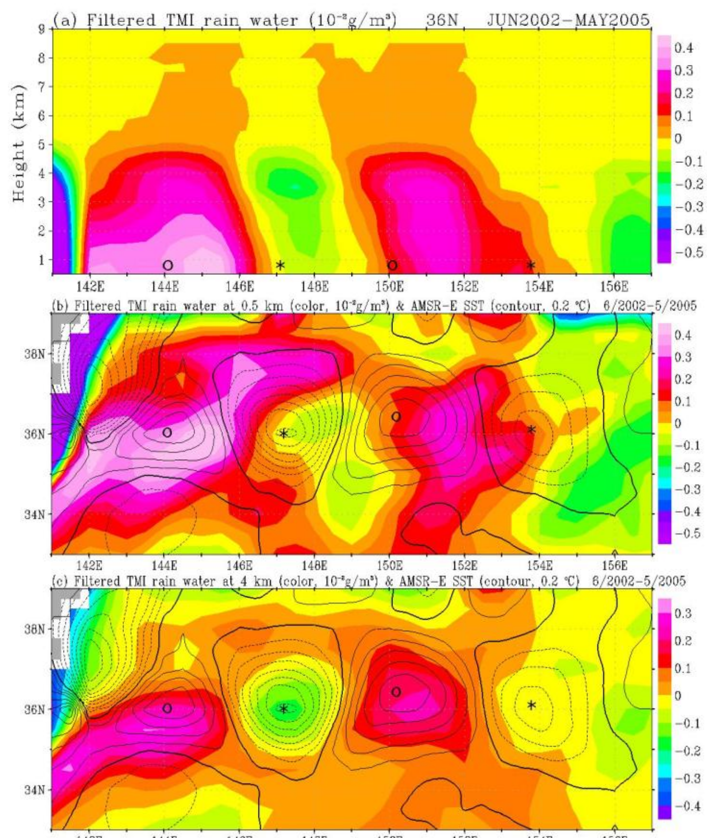

Fig. 4 (a) Vertical profiles of filtered rain water from TMI (3B31) at 36°N. Filtered rain water in color at (b) 0.5 km, and (c) 4 km, superimposed by SST isotherms (0.2°C interval). All data are averaged from June 2002 to May 2005.

map of Fig. 4b shows that high and low rain water centers are between high and low SST near the surface, and Fig. 4c shows that the rain water centers, aligned more closely with SST at 4 km, in agreement with the tilts of the profile shown in 4a.

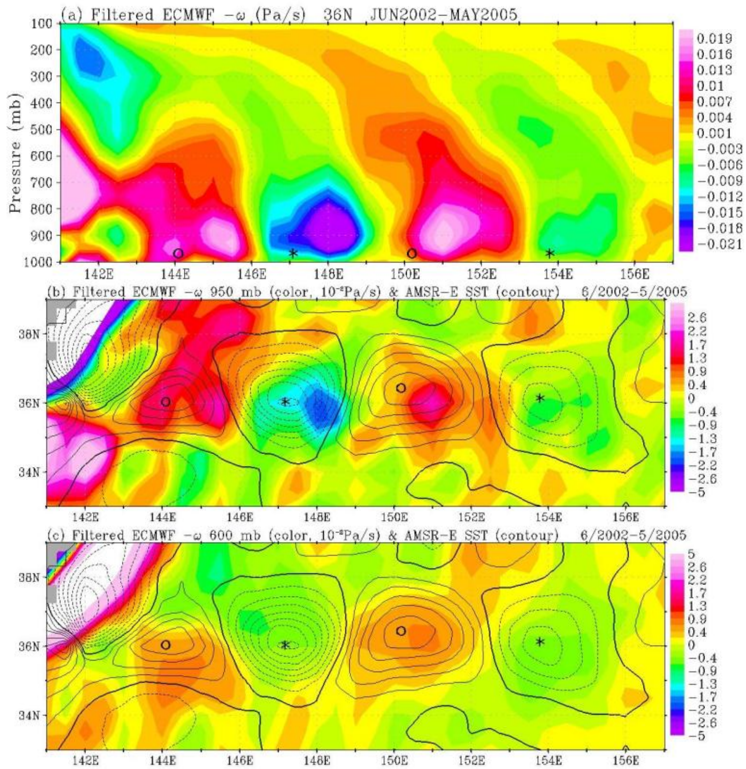

Fig. 5 (a) Vertical profiles of filtered vertical velocity (-ω, Pa/s) from the ECMWF ERA-interim at 36°N. Filtered vertical velocity in color at (b) 950 mb, and (c) 600 mb, superimposed by SST isotherms (0.2°C interval). Positive vertical velocity represents upward motion. All data are averaged from June 2002 to May 2005.

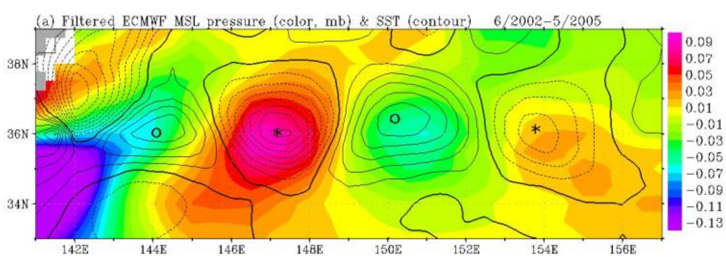

Fig. 6 Maps of filtered sea level pressure (color, mb) from the ECMWF ERA-interim, superimposed by SST isotherms (0.2°C interval), averaged from June 2002 to May 2005.

The ERA-interim data of ECMWF were used to study the dynamic response. The profiles of pressure vertical velocity (ω multiplied by -1), with positive represent upward motion, are shown in Fig. 5a. The distribution bears similarity with the rain water. High and low centers are located between SST centers at the surface. The map at 950 mb (Fig. 5b) shows the centers of high and low are located to the east of the SST centers. The map at 1000 mb is noisier and is not shown. Higher up at 600 mb (Fig. 5c) the high and low -ω centers have moved closer to the SST centers.

4 Reconciling Boundary Layer Hypotheses

In modeling the atmospheric boundary layer, Brown and Liu (1982) started with geostrophic winds (a balance between Coriolis and pressure gradient forces) at the top. Frictional force and baroclinicity were added to change the flow in the boundary layer. The frictional force dominates and the other forces lose their significance as the surface was approached. The cyclonic and anticyclonic flows over low and high-pressure centers are deflected in the layer, with winds converging into low pressure centers over warm water, and diverge over high pressure over cool water, in consistent with the hypothesis of Lindzen and Nigam (1987). Although the pressure deviations are very small as revealed by the ECMWF results, Fig. 6 shows that SST centers are collocated with high and low pressure centers. Wind speed should be low over convergence and divergence centers. This scenario is different from the scatterometer observations, if we assume that scatterometer measures surface winds.

As expounded by Liu and Xie (2008, 2013), scatterometer measures stress, the mesoscale variability is largely driven by ocean parameters (see also Monahan 2008), and not by atmospheric pressure gradient force. Stress has to be in spatial coherence with SST, as discussed in Section 2. As we move up from the surface, atmospheric forcing become effective, and the convergence, ω, and rain centers become aligned with SST centers.

5 Implication and Future Study

Ocean temperature drives the momentum flux (stress) that couples the ocean with the atmosphere. The oceanic effects are felt above the atmospheric boundary layer through the troposphere at long time scales. In the past, we did not have stress measurements. The variability of stress is derived from the variability of wind through a drag coefficient; they have similar distributions. Scatterometer measurements suggest that the distribution of stress may be different from wind distribution aloft. The difficulty in explaining the ubiquitous spatial coherence between scatterometer measurement and SST may be resolved by the recognizing the difference between stress and wind distributions caused by the ocean. Stress convergence is shown to be modified by atmosphere forces into distribution of wind convergence, vertical velocity, and rainfall, away from the confine of the surface.

Our results are supported by an ongoing study on regressing the atmospheric parameters against the climate index of the Kuroshio Extension that is derived from ocean integrated heat content (Wang and Liu 2014).

Acknowledgment

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