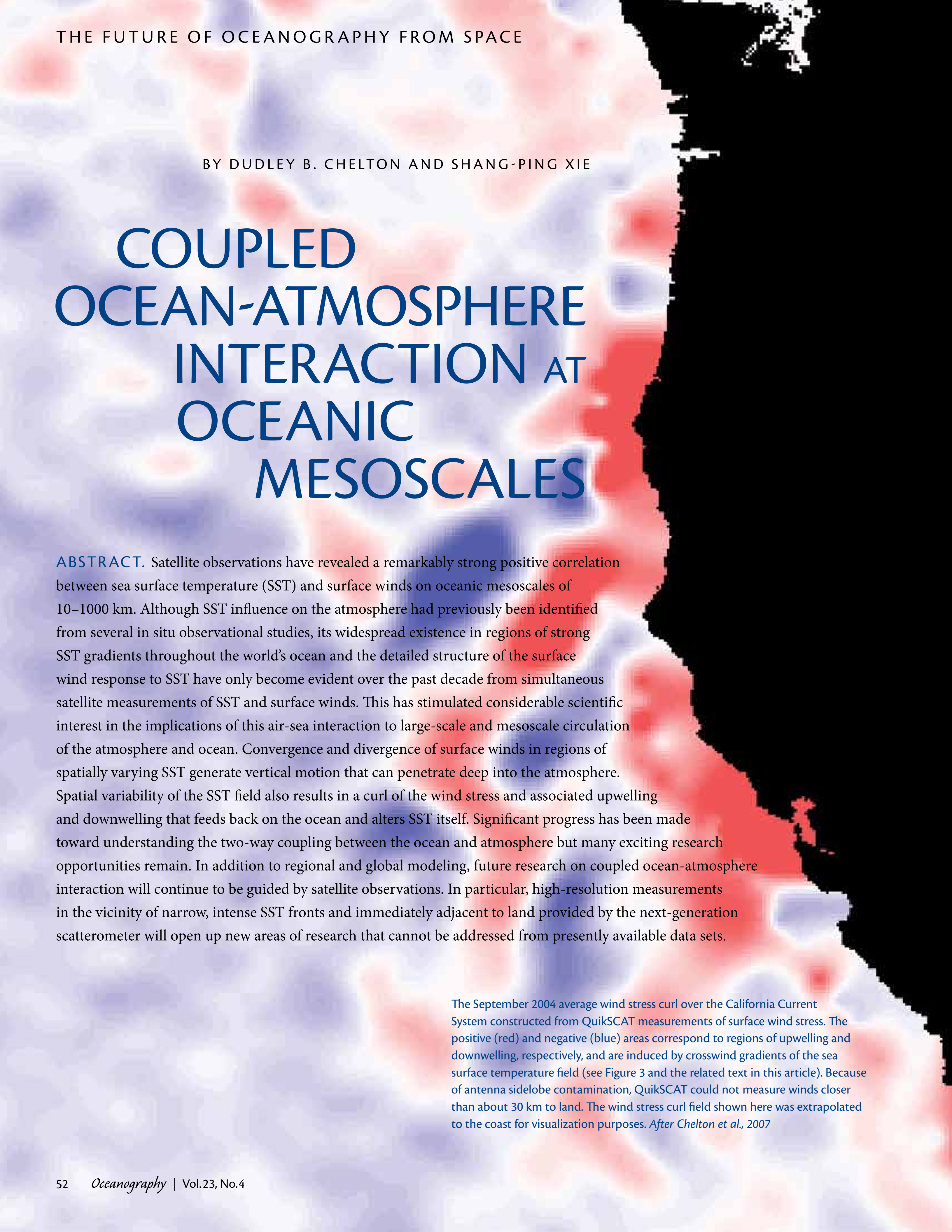
BY DUDLEY B. CHELTON AND SHANG-PING XIE

# COUPLED OCEAN-ATMOSPHERE INTERACTION AT OCEANIC MESOSCALES

ABSTRACT. Satellite observations have revealed a remarkably strong positive correlation between sea surface temperature (SST) and surface winds on oceanic mesoscales of 10–1000 km. Although SST influence on the atmosphere had previously been identified from several in situ observational studies, its widespread existence in regions of strong SST gradients throughout the world's ocean and the detailed structure of the surface wind response to SST have only become evident over the past decade from simultaneous satellite measurements of SST and surface winds. This has stimulated considerable scientific interest in the implications of this air-sea interaction to large-scale and mesoscale circulation of the atmosphere and ocean. Convergence and divergence of surface winds in regions of spatially varying SST generate vertical motion that can penetrate deep into the atmosphere. Spatial variability of the SST field also results in a curl of the wind stress and associated upwelling and downwelling that feeds back on the ocean and alters SST itself. Significant progress has been made toward understanding the two-way coupling between the ocean and atmosphere but many exciting research opportunities remain. In addition to regional and global modeling, future research on coupled ocean-atmosphere interaction will continue to be guided by satellite observations. In particular, high-resolution measurements in the vicinity of narrow, intense SST fronts and immediately adjacent to land provided by the next-generation scatterometer will open up new areas of research that cannot be addressed from presently available data sets.



The September 2004 average wind stress curl over the California Current System constructed from QuikSCAT measurements of surface wind stress. The positive (red) and negative (blue) areas correspond to regions of upwelling and downwelling, respectively, and are induced by crosswind gradients of the sea surface temperature field (see Figure 3 and the related text in this article). Because of antenna sidelobe contamination, QuikSCAT could not measure winds closer than about 30 km to land. The wind stress curl field shown here was extrapolated to the coast for visualization purposes. *After Chelton et al., 2007*

## INTRODUCTION

The air-sea interface is of great interest to oceanographers and atmospheric scientists alike. Winds blowing across the sea surface are the primary forcing mechanism for ocean circulation. Winds also generate evaporative cooling of the sea surface, a major mechanism for the ocean to balance the radiative heat flux across the ocean surface. Water vapor released into the atmosphere by evaporation is mixed throughout the marine atmospheric boundary layer (the lowest 1–2 km of the atmosphere) and transported into the overlying troposphere that extends to a height of about 12 km. When this water vapor condenses to form clouds and precipitation, the associated release of latent heat is a source of energy driving atmospheric circulation. The coupled interaction between the ocean and the atmosphere at the sea surface is thus key to understanding both oceanic and atmospheric circulation, and is therefore critically important for weather forecasting and determining the roles of the ocean and atmosphere in climate variability.

Most of what was known before the turn of this century about the space-time variability of winds over the ocean was based on reports from ships of opportunity. The sparse distribution of these observations restricted the resolution to scales larger than several hundred kilometers, and large areas outside of standard shipping routes were seldom sampled. Analyses of these coarse-resolution ship observations in conjunction with coupled climate modeling on similarly coarse scales generally find a negative correlation between sea surface temperature (SST) and surface wind speed (Xie, 2004, and references therein). Except in the tropics, this interaction at large scales is interpreted as the ocean passively responding to wind-induced latent and sensible heat flux (i.e., a one-way forcing of the ocean by the atmosphere).

The advent of satellite-borne microwave radar scatterometers that measure the global surface wind field with a high spatial resolution of about 25 km, as described by Chelton and Freilich (2005), and microwave radiometers that measure SST in nearly all weather conditions with a spatial resolution of about 50 km, as described by Wentz et al. (2000) and Chelton and Wentz (2005), has revealed that ocean-atmosphere interaction is fundamentally different on oceanic mesoscales of 10–1000 km. Surface wind speed is found to be locally higher over warm water and lower over cool water (i.e., a positive correlation that is opposite to that found on large scales).

The fact that a positive correlation between SST and surface winds occurs only on small scales implies that associated ocean-atmosphere interaction is driven by spatial variations of SST. The transition to negative correlation on scales larger than about 1000 km is presumably related to the equilibrium adjustment time of the marine atmospheric boundary layer and thus likely differs somewhat from one region to another, depending on the ambient wind speed and other factors.

In regions of meandering SST fronts, mesoscale SST modifications of the surface wind field result in convergences and divergences of the surface winds and associated pressure perturbations that generate vertical motions that can penetrate into the troposphere, thus potentially influencing global weather patterns. SST-induced wind stress variations also feed back on the ocean surface in the form of wind-induced turbulent heat flux and mixing, as well as wind stress curl driven upwelling that generates ocean currents and can modify the SST itself. This article summarizes the progress in understanding the characteristics, physics, and significance of this two-way coupled ocean-atmosphere interaction on oceanic mesoscales.

## HISTORICAL BACKGROUND

High-resolution observational studies of the two-dimensional horizontal structure of mesoscale SST influence on low-level winds mandate the use of satellite measurements of winds and SST. To investigate an SST influence on surface winds hypothesized from an analysis of historical ship observations in the eastern tropical Pacific by Wallace et al. (1989) and from buoy observations in the same region by Hayes et al. (1989), Xie et al. (1998) conducted the first satellite-based study of the coupling between SST and surface winds using surface vector wind observations from the scatterometer on the European Remote Sensing satellite. They showed that surface wind divergence anomalies in the eastern tropical Pacific propagate westward at the same speed as the SST signatures of tropical instability waves (TIWs).

The greatly improved sampling provided by the wide-swath QuikSCAT scatterometer that was launched in June 1999, in combination with all-weather microwave measurements of SST from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI; Wentz et al., 2000), facilitated numerous detailed investigations of the space-time structure of the response of the surface wind field to TIW-induced SST variations in the eastern tropical Pacific region (Liu et al., 2000; Chelton et al., 2001; Polito et al., 2001; Hashizume et al., 2002; Chelton, 2005).

TMI measurements of SST were used by Nonaka and Xie (2003) to investigate the coupling between winds and SST on the southern flank of the Kuroshio Extension. Because of the low inclination of the TRMM orbit, however, TMI data are unable to provide the all-weather observations needed for detailed investigation of ocean-atmosphere interaction at latitudes higher than 38°. The availability of global microwave measurements of SST from the Advanced Microwave Scanning Radiometer (AMSR-E; Chelton and Wentz, 2005) on the Earth Observing System Aqua satellite beginning in June 2002 enabled the first detailed observational studies of mid-latitude ocean-atmosphere coupling at oceanic mesoscales. In the first such study, O'Neill et al. (2005) found a very strong positive correlation between QuikSCAT winds and SST measured by AMSR-E over the Agulhas Return Current in the Southwest Indian Ocean. As reviewed by Small et al. (2008), analyses of AMSR-E and QuikSCAT observations expanded rapidly thereafter. SST influence on surface winds has been found in every region of strong SST fronts investigated from these satellite observations. Moreover, Sampe and Xie (2007) found that extreme wind events occur much more frequently over the warm flanks of SST fronts in the North Atlantic and Southern Ocean.

Coupling between the ocean and atmosphere at mid latitudes is most clearly seen by averaging over a few weeks or more (O'Neill et al., 2005; Chelton et al., 2007), which reduces the effects of energetic synoptic weather variability that often masks the comparatively subtle air-sea interaction. The persistence of the SST-induced small-scale features of the surface wind field in the vicinity of meandering SST fronts is on the order of a month or longer, controlled by the dynamical persistence of the current meanders. Similar persistence of the surface wind response to SST is evident over mesoscale ocean eddies when viewed in a rotating and translating coordinate system that moves with the eddies and is orientated relative to the direction of the ambient wind (Park and Cornillon, 2002; Park et al., 2006).

## SURFACE WIND RESPONSE TO SST

The 10-year record of QuikSCAT measurements of surface winds, in combination with the TMI and AMSR-E measurements of SST, have provided critically important high-resolution observations for validation of numerical model simulations and for investigation of the dynamics and thermodynamics of SST influence on surface winds. As reviewed in detail by Small et al. (2008), this ocean-atmosphere interaction is instigated by SST modification of atmospheric stability near the sea surface, with consequent changes of the surface wind and stress as well as latent and sensible heat fluxes. Because of the large disparity in the intrinsic scales of variability in the atmosphere and ocean, atmospheric temperature cannot fully adjust to sharp SST gradients near oceanic fronts, resulting in large variations in atmospheric stability measured by the air-sea temperature difference.

Observed SST-induced perturbations of surface stress are partly attributable to stability-related changes in the drag coefficient, but this appears to account for only a small fraction of the total observed and modeled SST influence on surface wind stress (Wai and Stage, 1989; Small et al., 2003, 2008; O'Neill et al., 2005; Larry O'Neill, Naval Research Laboratory, and colleagues, *pers. comm.*, 2010). Changes in wind stress are mostly attributable to SST-induced changes in wind speed. Surface wind increases over warm water in association with decreased stability through enhanced vertical mixing by large eddies that deepen the boundary layer and draw momentum from the upper boundary layer down to the sea surface. Surface winds and wind stress decrease over cold water in association with increased stability that decouples the surface winds from the stronger winds aloft. Surface wind speed and stress are thus both positively correlated with SST (see, for example, Figures 1a and 4c).

This simple conceptual description of SST-induced changes in surface wind and stress belies the complexity of the myriad processes that are involved in low-level wind response to SST. Air

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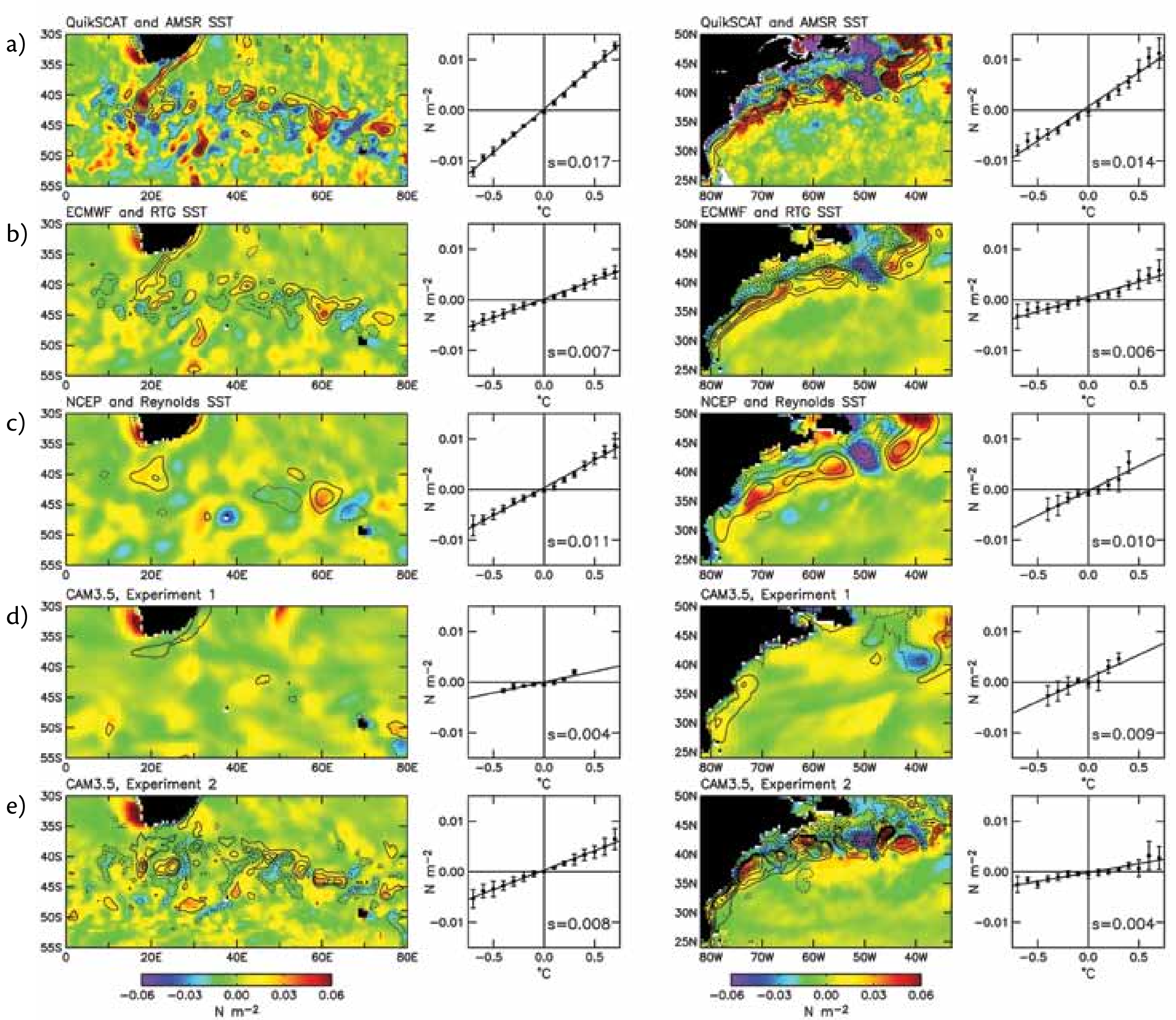


Figure 1. Maps and binned scatter plots for two-month averages (January–February 2008) of spatially high-pass-filtered sea surface temperature (SST; which has zero mean, by definition) overlaid as contours on spatially high-pass-filtered wind stress magnitude for the Agulhas Return Current region (left) and the Gulf Stream region (right). (a) QuikSCAT observations of wind stress and Advanced Microwave Scanning Radiometer (AMSR-E) observations of SST. (b) European Centre for Medium-range Weather Forecasts (ECMWF) wind stress and Real-Time Global (RTG) SST. (c) US National Centers for Environmental Prediction (NCEP) wind stress and Reynolds SST. (d) Wind stress and SST from the National Center for Atmospheric Research Community Climate System Model (NCAR CCSM3.5) coupled climate model with atmosphere and ocean grid resolutions of 0.5° and 1.125°, respectively. (e) Wind stress and SST from the same NCAR CCSM3.5 coupled climate model with atmosphere and ocean grid resolutions of 0.5° and 0.1°, respectively. Positive and negative high-pass filtered SST are shown as solid and dotted lines, respectively, with a contour interval of 1°C and with the zero contours omitted for clarity. The CCSM3.5 model simulations are not intended to represent actual years, so the two-month averages in panels d and e are for a representative January–February time period. The solid circles and error bars in the binned scatter plots are, respectively, the overall average and the standard deviation of the individual binned averages over eight January–February time periods for panels a–c and four January–February time periods for panels d and e.

temperature and moisture adjustments to latent and sensible heat fluxes generate pressure gradients across SST fronts that can drive secondary circulations in the boundary layer. The various effects have been diagnosed from numerical model simulations, which indicate that vertical turbulent mixing, pressure gradients, and nonlinear advection are all important to the momentum balance in the boundary layer (e.g., Small et al., 2005; O'Neill et al., 2010b; see also the review by Small et al., 2008). Idealized experiments by Spall (2007a) suggest that the relative importance of the vertical mixing and pressure mechanisms depends upon cross-frontal wind velocity. When the cross-frontal wind is strong, the atmospheric boundary layer temperature response is weak and the vertical mixing mechanism becomes dominant. For the moderate cross-frontal winds that are more typical of oceanic conditions, both mechanisms appear to be important.

The SST influence on winds summarized above is modified in some regions by the fact that stress at the sea surface is determined by the relative motion between the ocean and atmosphere at the air-sea interface. The relative wind measured by scatterometers is directly related to stress. Because surface currents can be strong in regions of strong SST fronts, they can alter the relationship between surface stress and SST that would otherwise exist in the absence of currents (Cornillon and Park, 2001; Kelly et al., 2001; Chelton et al., 2004; Park et al., 2006).

A paradoxical feature of the observed influence of SST on surface winds is that wind speed and wind stress magnitude are both linearly related to SST, despite the nonlinear relation between wind speed and wind stress. Larry O'Neill, Naval Research Laboratory, and colleagues (*pers. comm.*, 2010) derived an analytical relationship that shows the wind stress magnitude on oceanic mesoscales is linearly proportional to the surface wind speed on the same scales with a proportionality factor that depends on the larger-scale ambient wind speed. This dependence on ambient winds is easily understood qualitatively because the change in wind stress is related to the square of the total wind speed, rather than to just the SST-induced perturbation wind speed. A given SST-induced wind-speed change thus results in a much greater change of wind stress in high-wind conditions than in low-wind conditions. For example, a 1 $ms^{-1}$ increase in ambient winds of 10 $ms^{-1}$ results in a stress increase that is about a factor of two larger than that from a 1 $ms^{-1}$ increase for ambient winds of 5 $ms^{-1}$.

In addition to explaining why both wind speed and wind stress are linearly related to SST, the dependence of the coupling on the ambient wind speed explains the observed larger temporal and geographical variations in the coupling coefficient between wind-stress magnitude and SST compared with that between wind speed and SST. The seasonal cycle serves as a good example of large temporal variations of the coupling. Because large-scale winds are stronger in winter in most regions, coupling between SST and wind stress is generally stronger in winter than in summer. The seasonal difference in coupling can be a factor of five over the Gulf Stream and Kuroshio Extension (Larry O'Neill, Naval Research Laboratory, and colleagues, *pers. comm.*, 2010), where seasonal variations in the large-scale wind field are large. In the Southern Ocean where seasonal variability of large-scale winds is smaller, the coupling is only about a factor of two larger in winter than in summer. Seasonal variations in coupling imply a seasonal modulation of SST-induced wind stress curl feedback effects on ocean circulation; these effects are discussed in a later section.

A consequence of SST influence on surface winds is that spatial variability of SST generates divergence and curl of the surface wind field (Figure 2). Divergence of surface wind and stress are both found to be linear functions of the downwind component of the SST gradient; the curl of surface wind and stress are likewise both found to be linear functions of the crosswind component of the SST gradient (Chelton et al., 2001, 2004; O'Neill et al., 2003, 2005; Larry O'Neill, Naval Research Laboratory, and colleagues, *pers. comm.*, 2010). Figure 3 shows these relations for wind stress divergence and curl in the Agulhas Return Current and Gulf Stream regions. It is visually apparent that the correlations between the curl fields and crosswind SST gradients are consistently smaller than correlations between the divergence fields and downwind SST gradients (e.g., Figure 3). This is due in part to the above-noted effects of ocean surface currents, which affect wind stress curl and relative wind vorticity measured by scatterometers, but have very little effect on wind and stress divergence because ocean currents are nearly nondivergent. Surface ocean currents therefore have a negligible effect on wind stress divergence and relative wind divergence measured by scatterometers (Chelton et al., 2004).

Most studies of the divergence and curl responses of surface winds to downwind and crosswind SST gradients have focused on regions of strong SST fronts associated with meandering currents. Park and Cornillon (2006) showed that divergence and curl of surface winds also develop over Gulf Stream eddies in association with SST distribution in the interiors of the eddies.

The divergence and curl responses to spatially varying SST have important implications for both the atmosphere and the ocean. In the case of the atmosphere, SST influence can penetrate into the troposphere from the vertical motion induced by convergence and divergence of the surface wind field. In the case of the ocean, the upwelling and downwelling that are associated with the wind stress curl alter the ocean circulation, and therefore the SST itself.

Another paradoxical feature of the observed air-sea interaction is that the coupling coefficients between the wind stress divergence and the downwind SST gradient are consistently larger than those between the wind stress curl and the crosswind SST gradient (Figure 3), and likewise for vector wind divergence and vorticity. By explicitly relating wind divergence and vorticity to crosswind and downwind gradients of wind speed and direction using natural coordinates defined by the wind direction, O'Neill et al. (2010a) showed that wind speed gradients contribute equally to the curl and divergence responses to SST. The differences between the curl and divergence responses are thus attributable to the effects of SST on wind direction. SST-induced crosswind and downwind gradients in wind direction reduce the curl response to crosswind SST gradients through rotation while simultaneously enhancing the divergence response to downwind SST gradients through confluence and difluence. SST-induced surface pressure gradients play an important role in this wind directional dependence on SST.

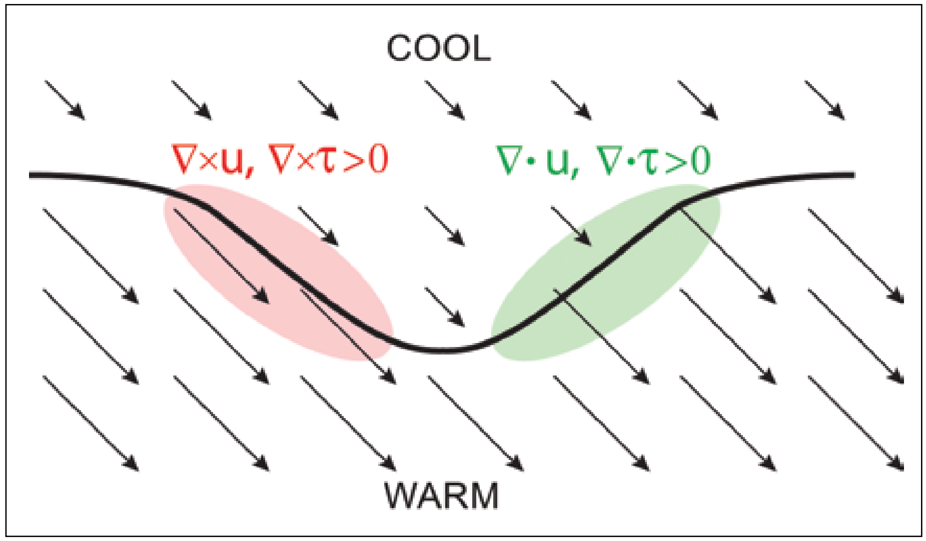


Figure 2. Schematic illustration of the divergence and curl of the wind and wind stress fields that result from spatial variations of the SST field. Near a meandering SST front (the heavy black line), surface winds are lower over cool water and higher over warm water, shown qualitatively by the lengths of the vectors. Acceleration where winds blow across the SST front generates divergence (green area). Lateral variations where winds blow parallel to the SST front generate curl (red area). The divergence and curl perturbations are proportional to the downwind and crosswind components of the SST gradient, respectively (see Figure 3).

## SST INFLUENCE IN NUMERICAL WEATHER PREDICTION AND COUPLED CLIMATE MODELS

A question of great interest to weather forecasters, and to researchers using atmospheric models for studies of climate variability or to force ocean circulation models, is the degree to which the observed SST influence on surface winds is reproduced in models. For grid resolutions that are used in present-day numerical weather prediction (NWP) models, this depends sensitively on the resolution of the SST fields that are used for the surface boundary condition in the models. This is readily apparent in the wind fields from the European Centre for Medium-range Weather Forecasts (ECMWF) operational NWP model. In May 2001, the SST boundary condition in the ECMWF model was changed from the low-resolution Reynolds SST analyses (Reynolds et al., 2002) to the higher-resolution Real-Time Global (RTG) SST analyses (Thiébaux et al., 2003). This change resulted in an abrupt increase in the intensity of wind speed variations on scales of 100–1000 km (Chelton, 2005; Chelton and Wentz, 2005; Maloney and Chelton, 2006; Song et al., 2009).

Further evidence of the importance the resolution of the SST boundary condition can be inferred from the consistent lack of small-scale variability in the surface wind fields from the

US National Centers for Environmental Prediction (NCEP) operational NWP model, which continues to use the Reynolds analyses as the surface boundary condition in the present-day forecast model. The intensity of small-scale features in the NCEP wind fields has not changed significantly over the past decade, despite several improvements in model grid resolution over that time period.

The spatial structure of observed small-scale variability in the surface wind stress field is well represented in the ECMWF model. It is evident from Figure 1b, however, that this small-scale variability is about a factor of two weaker than in the QuikSCAT observations in Figure 1a. The underestimation of wind stress curl and divergence in the ECMWF model is a factor of two to four, depending on location (Figure 3) and time of year (not shown here). Small-scale variability is barely detectable in the NCEP model as a consequence of its much coarser SST boundary condition (Figure 1c).

Because of computer resource limitations, the grid resolutions used for long simulations with most present-day global

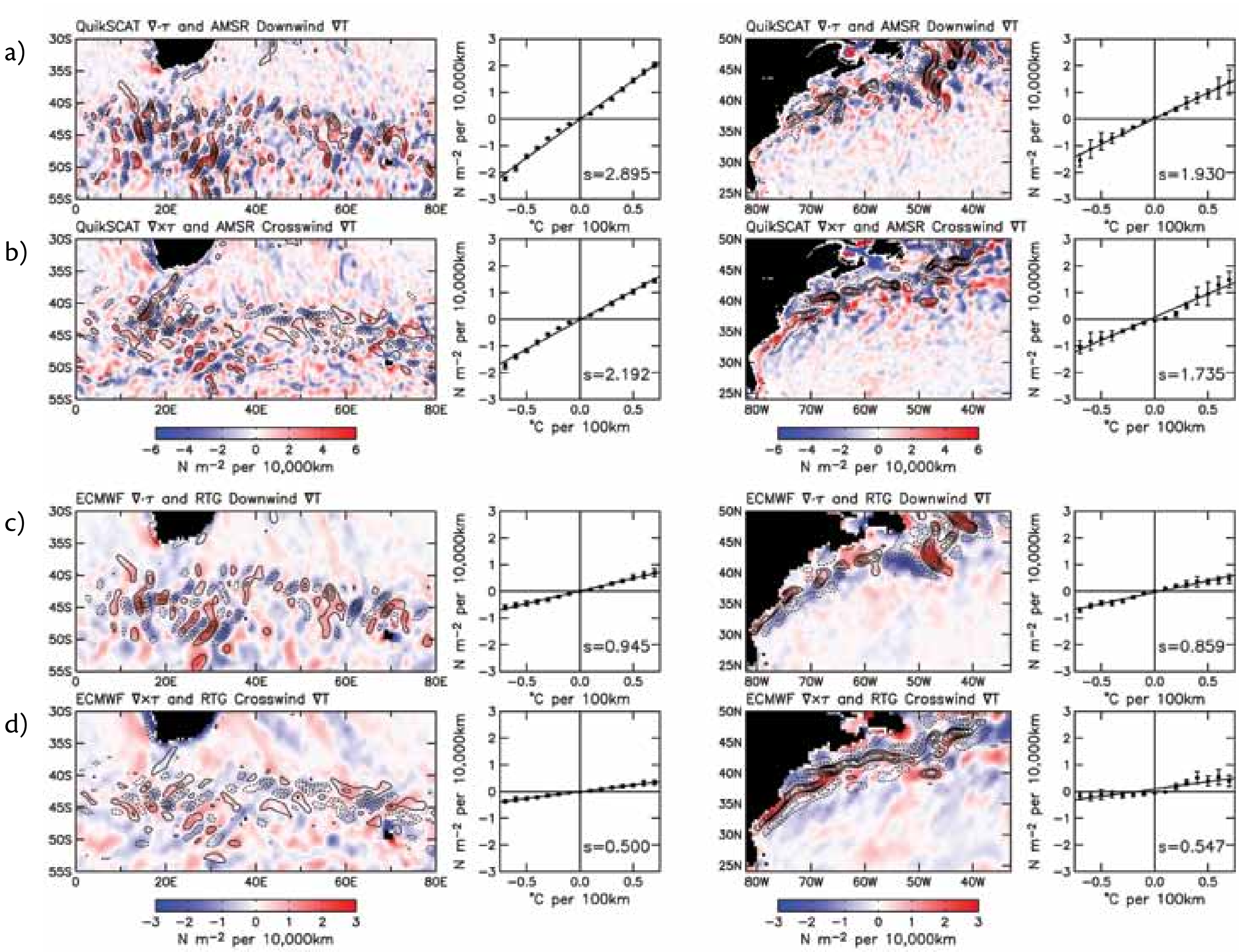


Figure 3. Maps and binned scatter plots for two-month averages (January–February 2008) of spatially high-pass-filtered downwind and crosswind SST gradients overlaid, respectively, as contours on the associated wind stress divergence (panels a and c) and curl (panels b and d). Winds and SST were obtained from QuikSCAT and AMSR-E in panels a and b, and from ECMWF and RTG SST analyses in panels c and d. Positive and negative high-pass-filtered SST gradient components are shown as solid and dotted lines, respectively, with a contour interval of 0.5°C per 100 km and with the zero contours omitted for clarity. The binned averages and standard deviations were computed as in Figure 1 over eight January–February time periods. Note the different dynamic ranges of the color bars used for QuikSCAT and ECMWF.

coupled ocean-atmosphere models are too coarse to resolve mesoscale SST influence on surface winds. With sufficient grid resolution, however, the coupling becomes evident (Maloney and Chelton, 2006; Bryan et al., 2010). This difference can be seen by comparing SST and surface wind stress fields from two runs of version 3.5 of the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3.5; Bryan et al., 2010). With a grid resolution of 0.5° for the atmosphere model and a coarse grid resolution of 1.125° for the ocean model, a positive correlation between SST and wind stress is visually apparent, but with spatial scales that are grossly too large (Figure 1d). When the ocean grid resolution is increased to 0.1°, the coupled patterns of SST and wind stress are clearly defined and much smaller in scale (Figure 1e).

Although the resolution of the SST boundary condition, or the grid resolution of the ocean model in the case of coupled models, is critically important to atmospheric model representations of SST-induced variability in the surface wind field on oceanic mesoscales, it is not the only factor limiting the accuracies of atmospheric models. The ocean-atmosphere coupling in these models can be quantified by the slope of the linear relation between SST and surface wind speed or wind stress. As the binned scatter plots in Figure 1 show, coupling is smaller than the observed coupling by a factor of two to four for all of the NWP and climate models considered here. Thus, even if a perfect SST boundary condition were used for these models, they would underestimate the surface wind and stress responses.

The underrepresentation of surface wind response to SST in the ECMWF model was investigated in detail from sensitivity studies conducted with the Weather Research and Forecasting (WRF) mesoscale atmospheric model for the Agulhas Return Current region (Song et al., 2009). The conclusions of this study are likely relevant also to the NCEP model and the CCSM3.5 coupled models considered above, as well as to most other atmospheric models. Aside from the importance of the resolution of the SST boundary condition discussed above, the primary factor limiting the accuracy of the coupling appears to be the parameterization of vertical mixing. When configured with horizontal and vertical grid resolutions comparable to those in the ECMWF model and with the Mellor and Yamada (1982) parameterization of vertical mixing, the WRF model accurately reproduces the ECMWF surface wind response to SST (Figure 4a,b), which is about a factor of two weaker than the coupling deduced from the satellite observations. When the sensitivity of the Mellor-Yamada mixing to atmospheric stability is increased by a factor of five as recommended by Grenier and Bretherton (2001), the observed surface wind response to SST in the QuikSCAT observations is accurately represented in the WRF model (Figure 4c,d). The sensitivity of vertical mixing to SST-induced variations in the stability of the boundary layer thus appears to be too weak by about a factor of five in the parameterization used in the ECMWF model. This results in underestimation by about a factor of two in surface wind response to SST.

In addition to the details of the parameterization of vertical mixing, the degree of underestimation of the coupling between SST and surface winds in models likely depends also on the models' vertical grid resolution. For example, the atmosphere component of the US Navy Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) of wind response to SST over the California Current System considered by Haack et al. (2008) underestimates the surface wind response to SST by only about 20%, despite the use of the Mellor and Yamada (1982) mixing parameterization. Their configuration of the COAMPS model has 15 grid points in the boundary layer, compared with 11 grid points in the WRF model summarized above. In the COAMPS model configured by Perlin et al. (2007) to use the Mellor and Yamada (1982) mixing parameterization with 31 grid points in the boundary layer, there was no apparent underestimation of the surface wind response to SST.

The underrepresentation of the SST influence on surface winds in most atmospheric models has two important implications. First, since the surface wind response to SST is underestimated, any tropospheric response to SST will also be underestimated. The influence of this ocean-atmosphere interaction on the general circulation of the atmosphere may therefore be considerably misrepresented in present NWP and coupled climate models. Second, ocean models forced with the surface winds from NWP models, or coupled to similar atmospheric models, will underestimate any feedback effects that SST-induced small-scale wind forcing may have on ocean circulation. These two issues are addressed further in the next two sections.

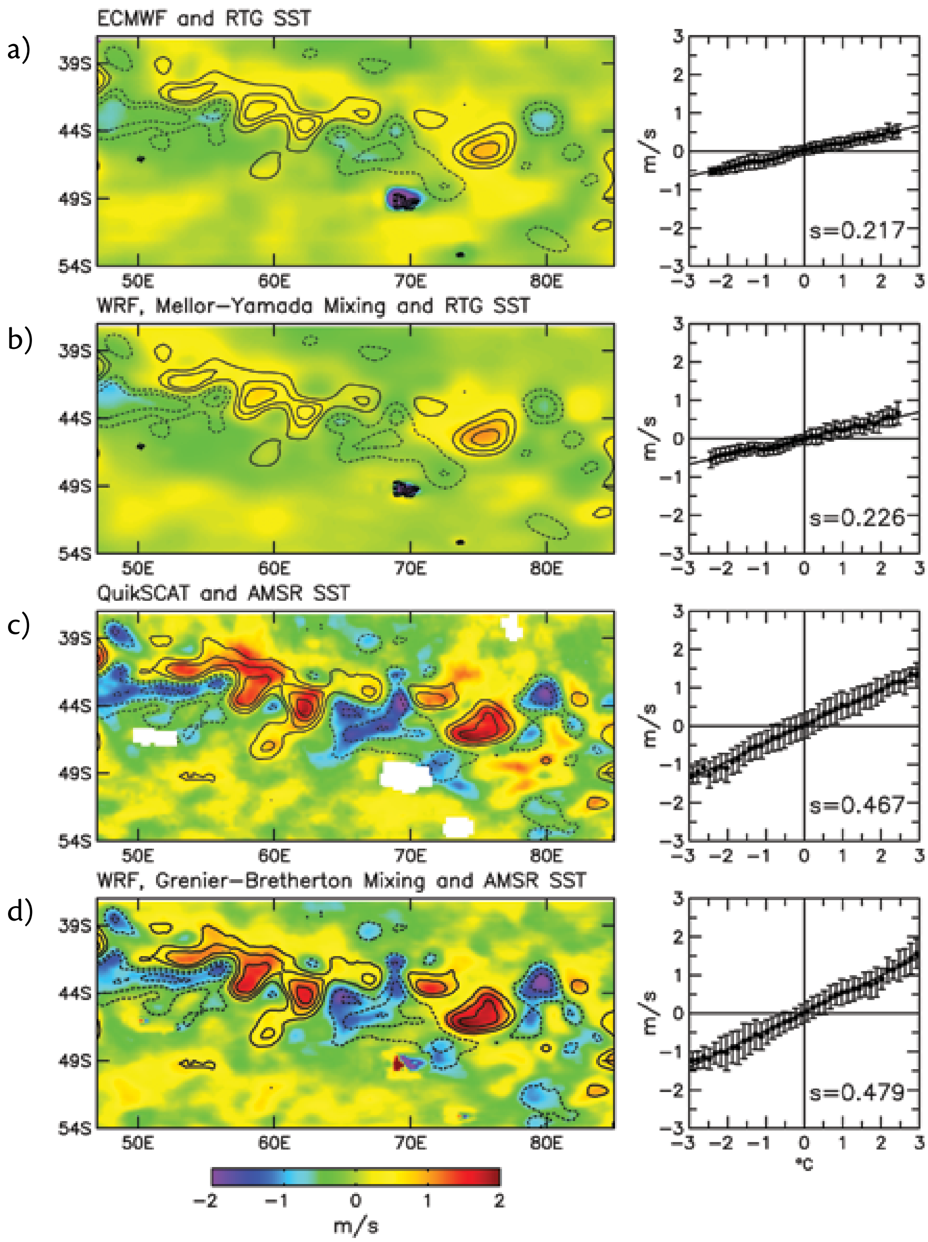


Figure 4. Monthly averages for July 2002 of spatially high-pass-filtered SST (contours in all panels) and (a) 10-m wind speed from the ECMWF operational model, (b) 10-m wind speed from the WRF model with Mellor and Yamada (1982) parameterization of vertical mixing, (c) 10-m equivalent neutral wind speed from QuikSCAT observations, and (d) 10-m equivalent neutral wind speed from the WRF model with Grener and Bretherton (2001) parameterization of vertical mixing. SST is from RTG in panels a and b and from AMSR-E in panels c and d. Positive and negative high-pass-filtered SSTs are shown as solid and dotted lines, respectively, with a contour interval of 1°C and with the zero contours omitted for clarity. *Modified from Song et al. (2009)*

## SST INFLUENCE ON CLOUDS AND TROPOSPHERIC WINDS

The preceding discussion has emphasized the mesoscale SST influence on winds within the marine atmospheric boundary layer. Evidence is accumulating that ocean frontal effects can extend beyond the boundary layer into the free troposphere and may therefore have far-reaching effects on the large-scale circulation of the atmosphere. Mesoscale features in the SST field can generate vertical motion by convective heating of the lower atmosphere and by surface convergence and divergence of cross-frontal surface winds. The vertical velocities from either of these effects act to deepen the boundary layer and can penetrate into the troposphere. The most favorable conditions for tropospheric influence are in regions where convection and low-level convergence occur together.

The tropospheric response to mesoscale features in the SST field and the possible implications of this indirect coupling for the large-scale circulation of the atmosphere are in the early stages of study. The Gulf Stream region in the Northwest Atlantic has been an area of particular interest (Sweet et al., 1981; Wai and Stage, 1989; Warner et al., 1990; Song et al., 2006; Minobe et al., 2008, 2010). Conditions there are often very favorable for SST influence on the troposphere. Seaward of Cape Hatteras where it separates from the coast, the Gulf Stream in winter is characterized as a narrow ribbon of warm water. The water on the landward flank of the sharp SST front associated with the Gulf Stream is very cold. When wintertime northwesterly winds blow off the North American continent, the cold, dry continental air is subjected to rapid heating from below as it encounters the warm water of the Gulf Stream. This heating from the large air-sea temperature difference is intensified by surface evaporation driven by the large air-sea humidity difference and the increasing wind speed from SST-induced acceleration (divergence) of the winds as they approach the Gulf Stream. After crossing the warm ribbon of water in the Gulf Stream, deceleration over the somewhat cooler water on the seaward flank generates surface convergence (Figure 5a).

If the wind adjustment across an SST front were strictly one dimensional from vertical mixing of momentum controlled by local stability, and if surface friction and exchange with the free troposphere were negligible, vertical motion would be confined to within the atmospheric boundary layer. Such a response often takes place in atmospheric models when the atmospheric boundary layer is capped by a stable temperature inversion that limits the vertical extent of SST influence on the atmosphere. Along the seaward side of the Gulf Stream, however, the deep ascending motion that occurs over the band of surface wind convergence in the ECMWF model of atmospheric winds analyzed by Minobe et al. (2008) (Figure 5b) is inconsistent with the adjustment expected from one-dimensional mixing. This is a clear indication of the importance of other mechanisms for deep tropospheric response.

Numerical simulations of cross-frontal winds over the Gulf Stream suggest the importance of secondary circulations and atmospheric pressure adjustment (Wai and Stage, 1989; Warner et al., 1990; Song et al., 2006; Minobe et al., 2008, 2010). Minobe et al. (2008) noted that the upward motion on the seaward side of the Gulf Stream is deeper in the vertical than the descending motion on the landward side, suggesting that latent heat release plays a role in communicating SST influence from the atmospheric boundary layer to the troposphere. The tropospheric response in the Gulf Stream region is likely also helped by developing storms that have deep vertical structure and are energized by the vertically sheared winds in this region. The net result of all of these processes is that a band of strong upward motion is established along the seaward side of the Gulf Stream that extends deep into the troposphere (Figure 5b). The relative importance of these various processes near SST fronts in other regions is a topic of active research.

The significance of this SST-induced upward motion is readily apparent in Figure 5c from the narrow band of heavy rain that has long been known to exist along the seaward side of the Gulf Stream (Hobbs, 1987). Consistent with coastal radar measurements of a sharp rise in echo height over the Gulf Stream (Trunk and Bosart 1990), this is also a region of enhanced lightning activity (Minobe et al., 2010). Models indicate that the surface wind convergence that anchors the deep upward motion

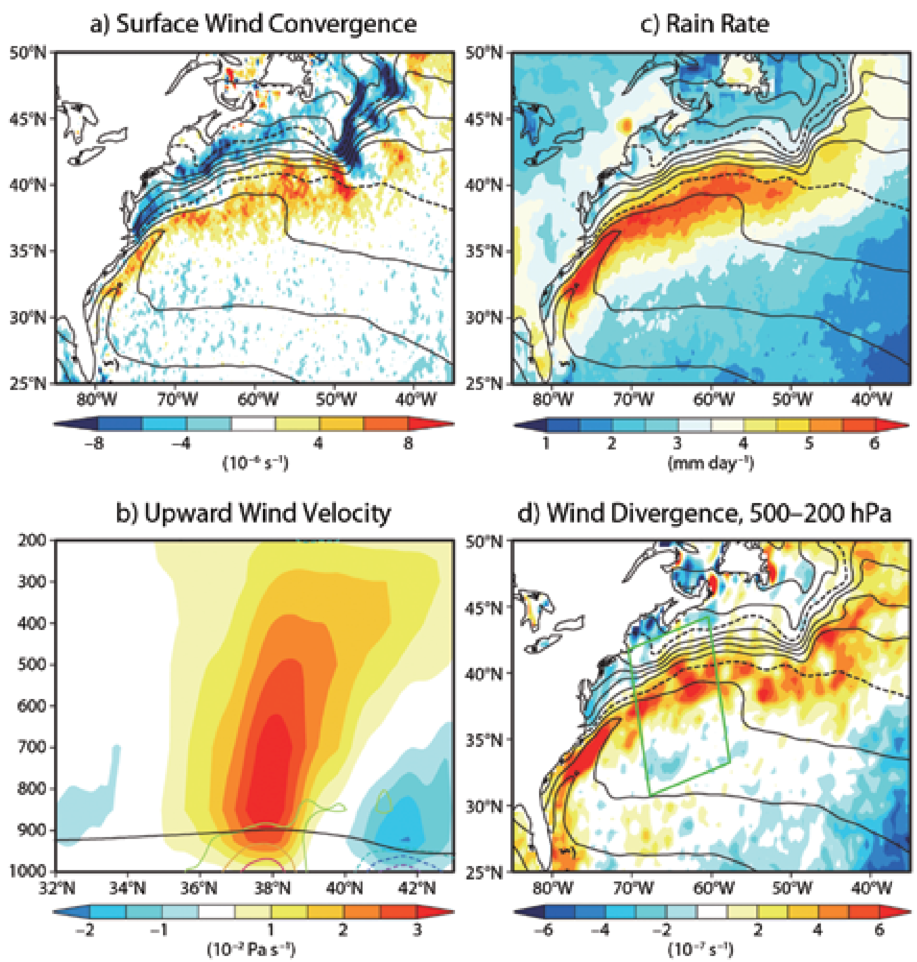


Figure 5. Annual means of (a) surface wind convergence from QuikSCAT observations of surface winds, (b) vertical velocity in pressure coordinates from the ECMWF model, (c) rain rate from the Tropical Rainfall Measuring Mission satellite observations, and (d) upper-tropospheric divergence from the ECMWF model averaged over the pressure range 500–200 hPa. The contours in panels a, c, and d show SST with a contour interval of 2°C. The black line in panel b is the boundary layer height, and the other contours plot wind convergence averaged in the along-front direction across the green box in panel d with a contour interval of $10^{-6}$ $s^{-1}$ (solid for convergence and dashed for divergence, with the zero contours omitted for clarity). *Modified from Minobe et al. (2008)*

is associated with wind divergence in the upper troposphere (Figure 5d). Such upper-level divergence can force stationary Rossby waves with energy propagation along the westerly wind jet (Hoskins and Valdes, 1990), thereby influencing the large-scale circulation of the atmosphere.

> "SATELLITE OBSERVATIONS HAVE ENABLED RAPID PROGRESS IN THE UNDERSTANDING OF THIS MESOSCALE COUPLED OCEAN-ATMOSPHERE INTERACTION OVER THE PAST DECADE."

The rain band associated with the Gulf Stream has a pronounced seasonal cycle. Convection typically reaches the middle troposphere during winter but extends throughout the troposphere during summer when SST rises above the deep convective threshold of about 26°C (Minobe et al., 2010). This importance of absolute SST values to the vertical extent of ocean frontal effects is corroborated by observations near the North Pacific Subtropical Countercurrent. A deep atmospheric response is observed along the SST front associated with this current during spring when the seasonal warming becomes conducive to deep convection (Kobashi et al., 2008).

The Gulf Stream is the warmest among major mid-latitude oceanic fronts. The tropospheric response is likely weaker and more complicated elsewhere. Although not as extensive as in the Gulf Stream region, deep atmospheric response to oceanic fronts has been detected along the Kuroshio Extension east of Japan (Tokinaga et al., 2006; Xu et al., 2010). A band of surface wind convergence forms along the warm flank of the Kuroshio Extension, much as it does in the Gulf Stream region. The associated vertical motion raises cloud top heights and enhances lightning activity.

SST fronts also influence the development of mid-latitude storms, a process referred to as cyclogenesis. Vertically sheared winds in the Northwest Atlantic and Northwest Pacific frequently stimulate the growth of atmospheric eddies that intensify to become storms (Hoskins and Hodges, 2002). The transports of heat and momentum by these eddies modify the atmosphere's large-scale circulation. In atmospheric models, spatial smoothing of the SST boundary condition significantly changes storm-track activity in these regions (Taguchi et al., 2009; Kuwano-Yoshida et al., 2010). A high-resolution SST boundary condition is therefore crucially important for weather forecast models to represent this cyclogenesis accurately. By energizing storms, a sharp SST front in the mid latitudes can anchor the axis of westerly winds at the sea surface (Nakamura et al., 2008). These surface westerlies can then feed back on ocean circulation, strengthening the flow and the SST front itself.

SST is well below the convective threshold over most of the ocean, and the boundary layer is often capped by a temperature inversion, below which low clouds often develop. The correlation between SST and low cloud cover is ubiquitously negative on scales larger than about 1000 km, forming a positive feedback via the cloud-shielding effect on surface solar radiation (Xie, 2004, and references therein). On oceanic mesoscales, however, enhanced vertical mixing over warm mesoscale SST anomalies transports moisture to the upper boundary layer, facilitating cloud formation. This results in a positive correlation between SST and low-level clouds and a negative cloud-radiative feedback on SST. For example, Deser et al. (1993) showed that patches of low clouds form over warm meanders of the Pacific equatorial front associated with tropical instability waves while clouds are suppressed over cool meanders.

Similar modulations of low-cloud development are observed across the Gulf Stream front (Young and Sikora, 2003) and in the Agulhas Return Current region (Lutjeharms et al., 1986; O'Neill et al., 2005; Bryan et al., 2010). The influence of SST on clouds, both directly by its effects on vertical mixing and through its influence on divergence and convergence of surface winds and the associated vertical velocity field, is also evident on the small scales of Gulf Stream eddies (Park et al., 2006).

Thermal advection is an important factor for low cloud formation, and its variability is locally enhanced along SST fronts. Rapid transitions in cloud regime take place as weather disturbances pass by and alter the direction of cross-frontal flow (Norris and Iacobellis, 2005). Atmospheric soundings across the Kuroshio Extension capture the complexity of the manner in which SST fronts affect the cloud field (Tanimoto et al., 2009). When the winds blow equatorward across the SST front, cold advection intensifies vertical mixing in the boundary layer, and stratocumulus clouds with elevated bases develop over the warm flank of the front. In contrast, when winds blow poleward across the SST front, warm and moist subtropical air comes in contact with the cold sea surface, resulting in the formation of low-level fog on the cold flank of the SST front (Tokinaga et al., 2009).

SST variability also has potentially important effects on the Earth radiation budget (Bryan et al., 2010). The low clouds, capped by a temperature inversion, that are present over much of the subtropical and subpolar oceans have high water content and are highly reflective of solar radiation, but emit longwave radiation similar to that emitted by the surface. Inadequate representation of these low clouds is a long-standing problem in climate models (Yu and Mechoso, 1999). The difficulty of maintaining low-level subtropical cloud decks in the models is partially responsible for the failure of the models to keep the intertropical convergence zone (ITCZ) north of the equator over the Pacific and Atlantic oceans (de Szoeke and Xie, 2008). The response of low clouds to global warming has been flagged as a major source of uncertainty in future climate projections (Soden and Held, 2006).

Mesoscale SST variability and its observed influence on vertical mixing and the divergence and convergence of surface winds, and hence on low-level clouds and their albedo effects on the Earth radiation budget, can be exploited to assess the performance of coupled climate models. With numerous realizations in space and time, the observed covariability between SST and clouds on oceanic mesoscales serves as an important benchmark to validate the models (Maloney and Chelton, 2006; Bryan et al., 2010).

## FEEDBACK EFFECTS ON OCEAN CIRCULATION

SST-induced perturbations of the surface wind stress field can feed back to the ocean in the form of both upper-ocean wind mixing and wind-driven upwelling. Both effects can alter SST, thus resulting in two-way coupling between the ocean and atmosphere. Upwelling in the open ocean, referred to as Ekman pumping, penetrates below the oceanic mixed layer and is proportional to wind stress curl. Upwelling and downwelling (i.e., negative upwelling) in the Northern Hemisphere are associated with positive and negative wind stress curl, respectively. The opposite associations occur in the Southern Hemisphere because of the change of sign in the Coriolis parameter. Because Ekman pumping acts as a source of vorticity, which controls the large-scale circulation of the ocean, the feedback effects from SST-induced wind stress curl anomalies can significantly alter ocean circulation. This SST-induced wind stress curl forcing is usually stronger in winter than in summer because of the seasonal modulation of the coupling between wind stress and SST discussed earlier.

Because wind stress curl anomalies that are associated with mesoscale SST variations are linearly related to the crosswind SST gradient, the feedback effects of Ekman upwelling tend to be strong where the SST gradient vector is oriented perpendicular to the wind (i.e., where the winds blow parallel to isotherms). In regions of strong SST fronts, the small-scale variability of Ekman pumping velocity has a larger dynamic range than that of the large-scale variability (e.g., O'Neill et al., 2003; Chelton et al., 2007; Haack et al., 2008). The SST-induced Ekman upwelling thus consists of order-1 perturbations of the large-scale background Ekman upwelling. Because their persistence time scales are a month or longer, small-scale features in the wind stress curl field are important to ocean circulation. For example, a zonal band of strong wind stress curl just north of the equatorial cold tongue that is established in the time-averaged wind stress curl field from the influence of SST on surface wind stress (Chelton et al., 2001) significantly increases the transport of the northern branch of the South Equatorial Current (Kessler et al., 2003).

The SST influence on surface wind stress revealed by QuikSCAT data is thus indicative of full two-way coupling between the ocean and atmosphere. The ramifications of this two-way coupling are in the early stages of investigation. Most of the studies to date have been based on models with empirical coupling schemes. Pezzi et al. (2004) considered an ocean model of TIWs in the Pacific Ocean forced with steady, large-scale winds that were augmented by small-scale perturbations that were linearly related to the model SST anomalies based on coupling coefficients estimated from QuikSCAT observations. This two-way empirical coupling resulted in a modest (~10%) but significant negative feedback on TIWs that reduced the temperature and meridional velocity variability and dampened the growth rate of the TIWs. The net effects of these changes were to decrease the meridional fluxes of heat and momentum, thereby altering the mean state in a manner that resulted in moderate cooling of the equatorial cold tongue and strengthening of the Equatorial Undercurrent. Similar results have been obtained from a full-physics coupled model that was run for seven years to investigate TIWs in the Atlantic (Seo et al., 2007a).

Another empirically coupled model of the tropical Pacific Ocean concludes that the feedback effects of TIW-induced SST variations of the wind stress field may also be important to El Niño-Southern Oscillation (ENSO) variability (Zhang and Busalacchi, 2008, 2009). Cooling of the equatorial cold tongue by the two-way coupling can modulate the amplitude and timing of transitions between the El Niño and La Niña phases of the ENSO cycle. The TIW-induced coupling between SST and wind stress may therefore contribute to the observed irregularity of ENSO variability. This effect is missing in global coupled models because their grid resolutions are generally not sufficient to resolve TIW variability. Zhang and Busalacchi (2009) suggest that empirical coupling could be included in low-resolution climate models as a simple way to parameterize this process.

The damping of TIWs found in the coupled modeling studies summarized above is at least qualitatively consistent with the analytical theory developed by Spall (2007b) for winds blowing across an unstable, meandering SST front with empirical coupling between SST and wind stress consistent with QuikSCAT observations. For conditions such as those found in the TIW regions of the Pacific and Atlantic oceans in which winds blow from the cold side to the warm side of the SST front, the feedback effects of SST-induced changes in wind stress curl result in negative feedback that reduces the growth rate of instabilities. The opposite occurs when winds blow across SST fronts from warm to cold water, in which case positive feedback increases the instability growth rate. The feedback effects from cross-frontal winds are most pronounced in conditions of strong ocean stratification, weak background mean flows and low latitudes, such as are found in the TIW regions. They are less likely to be important in mid-latitude regions of strong zonal currents (Spall, 2007b).

Hogg et al. (2009) recently investigated the importance of two-way coupling between winds and SST on oceanic mesoscales to the large-scale ocean circulation at mid latitudes from an idealized ocean model consisting of a rectangular basin forced by a smooth and constant meridional profile of zonal winds. SST-induced perturbations of the large-scale wind stress field were computed empirically from the model SST field based on linear coupling coefficients deduced from the QuikSCAT observations. The meandering SST front associated with the mid-latitude jet thus generated Ekman pumping anomalies in the western basin close to the separation point of the western boundary current where SST anomalies are largest. This small-scale Ekman pumping destabilized the flow, which reduced the eastward transport of the zonal jet and weakened both gyres by 30–40%.

Despite their small scales, the SST-induced perturbations of the wind stress field can thus result in feedback effects that significantly modify the large-scale ocean circulation. The mechanisms for these feedback effects are not entirely clear, but appear to be distinct from the Spall (2007b) mechanism for cross-frontal winds described above that is not applicable to conditions in which the large-scale winds blow parallel to the SST front, as in the Hogg et al. (2009) simulation. They speculate that the weakening of eastward jet and gyre circulations is attributable to a destabilization of the jet from a southward movement of the jet driven by the small-scale SST-induced Ekman pumping near the western boundary separation point.

Several recent studies have investigated mid-latitude ocean-atmosphere coupling in the California Current System (CCS), which is a region of strong influence of SST on the surface wind stress field (Chelton et al., 2007). Jin et al. (2009) investigated the two-way coupling in CCS from an idealized numerical simulation with a meridional boundary and QuikSCAT-based empirical coupling between mesoscale SST and the wind stress field. The model was forced with uniform equatorward winds that were modified at each time step to conform to the empirical coupled relations among SST gradients, wind direction, and the local curl and divergence of the wind stress.

The feedback effects in this empirically coupled model alter all of the well-known large-scale and mesoscale features of eastern boundary current systems. The cold upwelled water at the coast causes the nearshore winds to diminish. This generates a band of positive wind stress curl within about 100 km of the coast that weakens the equatorward surface current, broadens and strengthens the poleward undercurrent, weakens the alongshore SST front, and slows the development of baroclinic instability, thereby weakening the mesoscale eddy field. On oceanic mesoscales, the SST signatures of eddies generate wind stress curl patterns that modify the eddy field. Because of ageostrophic effects, the SST gradients associated with cyclonic eddies are stronger than those of anticyclonic eddies (Jin et al., 2009). The feedback effects of SST-induced perturbations of the wind stress curl field therefore preferentially disrupt the coherent evolution of cyclonic eddies, resulting in a greater abundance of anticyclonic eddies. The negative feedback effects of this SST-induced small-scale variability of the wind stress curl field on the mesoscale eddy field are missing from uncoupled ocean models, which may limit the accuracy of their simulations of ocean circulation, not just in eastern boundary current regions but throughout the world's ocean.

Coupling between wind stress and SST in the coastal upwelling regime has also been investigated using a full-physics coupled ocean-atmosphere model with idealized coastal geometry. In a two-dimensional version of the model run for three days, Perlin et al. (2007) found a coupling between wind stress and SST very similar to the observed coupling in QuikSCAT observations. An initially uniform equatorward wind stress was reduced by as much as 50% over cold, upwelled water adjacent to the coast over the three-day simulation, resulting in a strong positive wind stress curl near the coast (Figure 6). The results are very similar to those obtained from the empirically coupled simulation by Jin et al. (2009).

From the tropical and mid-latitude model simulations that have been conducted to date, it is clear that two-way coupling from the feedback effects of SST-induced wind stress curl variability can significantly alter ocean circulation. Because these small-scale features are absent or too weak in many of the atmospheric models used to force ocean models in uncoupled configurations, it may intuitively seem better to force the ocean models with the more accurate QuikSCAT-based wind stress fields. As cautioned by Chelton et al. (2007) and Hogg et al. (2009), however, this may not be advisable. Unless the ocean model produces an SST field that is quantitatively compatible with the QuikSCAT winds, the model SST field may evolve in a manner that is inconsistent with the coupling between SST and winds in the real world, thus potentially producing undesirable

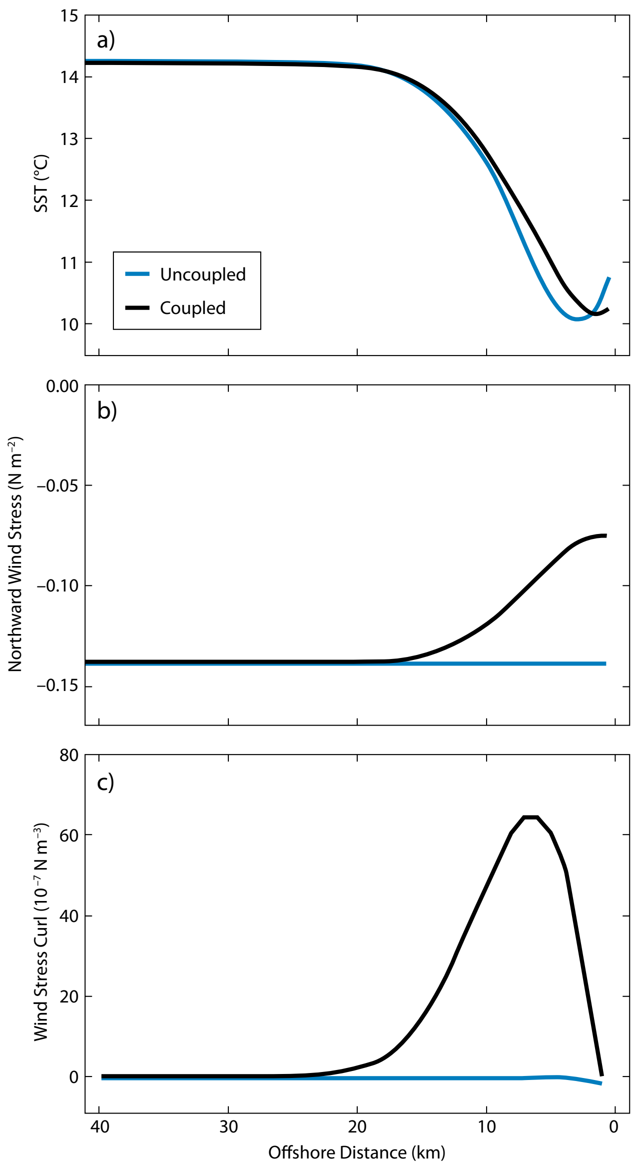


Figure 6. Cross-shore profiles from a two-dimensional model of an eastern boundary current upwelling regime run with full-physics coupling (black lines) and in an uncoupled configuration (blue lines): (a) SST, (b) alongshore wind stress (negative for upwelling-favorable equatorward winds), and (c) wind stress curl. *Modified from Perlin et al. (2007)*

features in the ocean model simulation. A better approach may therefore be to force ocean models with deliberately smooth wind stress fields and augment this smooth forcing with small-scale perturbations of the wind stress field determined from the model SST using empirical coupling by procedures such as those summarized above.

The ideal approach is to use fully coupled ocean-atmosphere models rather than ocean-only models forced by imposed wind stress fields. Although sufficient grid resolution to resolve the coupling on oceanic mesoscales is only beginning to become feasible with global coupled models (e.g., Bryan et al., 2010), this can readily be achieved with regional coupled models. Care must be taken, however, to assure that the coupling is accurately represented in the coupled models. The coupling intensity in models evidently depends on more than just model configuration since the model developed by Seo et al. (2007a) accurately represents the coupling in the TIW region but considerably underestimates the coupling in the CCS region.

> "...FUTURE RESEARCH ON COUPLED OCEAN-ATMOSPHERE INTERACTION WILL CONTINUE TO BE GUIDED BY SATELLITE OBSERVATIONS."

## SUMMARY AND CONCLUSIONS

The discovery of the ubiquity of the covariability between mesoscale features in the SST field and surface winds in regions of strong SST fronts throughout the world's ocean is one of the significant successes of satellite remote sensing of the ocean. Satellite observations have enabled rapid progress in the understanding of this mesoscale coupled ocean-atmosphere interaction over the past decade. The details of the influence of SST on surface winds have been thoroughly documented from simultaneous measurements of surface winds by the QuikSCAT scatterometer and satellite measurements of SST.

Early studies of SST influence on surface winds used infrared measurements of SST, which are available only during clear-sky conditions (e.g., Xie et al., 1998). The regions where this air-sea interaction occurs are frequently cloud covered. Indeed, as discussed earlier, this air-sea interaction often generates clouds near SST fronts. Since the advent of all-weather SST measurements (except in rainy conditions) by the microwave TMI and AMSR-E, nearly all observational studies of this phenomenon have been based on microwave observations. (Notable exceptions include Park and Cornillon, 2002; Park et al., 2006; and Song et al., 2006.) The ability to measure SST through clouds generally outweighs the resolution limitations of the coarse footprint size of about 50 km for microwave observations, particularly for coupled SST-wind analyses because presently available scatterometer measurements of surface winds have only slightly higher resolution.

Although satellite observations have provided detailed descriptive and statistical characterization of SST influence on surface winds, they are not sufficient to understand all of the physical processes involved in this air-sea interaction. The dynamics and thermodynamics of this coupling have been elucidated from analytical and numerical modeling studies. The satellite observations are crucially important for validating these models.

In ongoing research, the satellite observations of ocean-atmosphere coupling are also providing important metrics for assessment of global numerical weather prediction models and coupled climate models. In the case of NWP models, the surface wind response to SST is strongly dependent on the spatial resolution of the SST boundary condition. Analogously, model grid resolution is critically important for the ocean component of coupled models. Satellite observations have also drawn attention to the importance of the parameterization of vertical mixing in models, most of which appear to underestimate the sensitivity of mixing to atmospheric stability. These satellite observations also offer robust benchmarks for validating and improving surface winds and low-level clouds in coupled climate models.

SST influence on surface winds has stimulated exciting research opportunities in atmospheric sciences. The significance of mesoscale SST influence on the troposphere is only beginning to be explored. It is clear from the studies conducted to date, however, that the coupling between SST and the troposphere can be strong and may therefore be important to the large-scale circulation of the atmosphere. Investigations of the dynamical response of the troposphere to SST-induced perturbations of winds in the boundary layer have thus far relied on models of tropospheric winds. Because most models underestimate the surface wind response to SST, they likely also underestimate the tropospheric response. Understanding the importance of SST to the large-scale circulation of the atmosphere therefore requires improvements in the models. Observational studies will likely also be critically important to understanding the SST influence on the troposphere. In particular, satellite measurements of vertical profiles of atmospheric temperature, humidity, clouds, and precipitation can provide detailed information about the vertical structure of tropospheric response to SST on oceanic mesoscales.

Satellite observations have also stimulated exciting research opportunities in oceanography. The significance of the feedback effects of SST-induced Ekman pumping anomalies on ocean circulation and on SST itself are also only beginning to be explored. While most of the modeling studies conducted to date have been very idealized, they show that the two-way coupling can have a strong influence on ocean circulation. This is motivating the development of both regional and global coupled models, which may become the norm for ocean modeling in the not-too-distant future. The two-way coupling is likely also important to marine ecosystem dynamics through the Ekman pumping of nutrients into or out of the euphotic zone where they are needed for primary production by phytoplankton. This could have important ramifications for the global carbon budget.

The satellite observations of covariability of SST and surface winds on oceanic mesoscales are thus providing the impetus for a wide variety of atmospheric and oceanographic research. Rapid progress in understanding of the wide-ranging importance of this ocean-atmosphere coupling can be expected in the coming years. Satellite measurements of SST and ocean surface vector winds will continue to play a vital role in this research. As noted above, satellite measurements of vertical profiles of temperature, humidity, clouds, and precipitation will provide important new information on SST's influence on the troposphere. In addition, the next-generation synthetic aperture radar (SAR) scatterometer called the Extended Ocean Vector Winds Mission (XOVWM) will enable studies of surface wind response to SST on scales nearly an order of magnitude smaller than can be resolved by QuikSCAT (Gaston and Rodrìguez, 2008; Rodrìguez et al., 2009). This will provide detailed information about the physical processes involved in the adjustment of the marine atmospheric boundary layer in the immediate vicinity of strong and narrow SST fronts.

Because XOVWM is a SAR-based radar, it does not have the antenna sidelobe limitations that contaminate wind retrievals closer than about 30 km to land with presently available scatterometers. Together with its ~ 5 km spatial resolution, XOVWM will provide high-resolution measurements of winds immediately adjacent to land where the wind field is influenced by a complex combination of processes that includes the effects of SST discussed here as well as orographic effects of land on air flow and the influence of diurnal and seasonally varying sea-breeze effects from daytime and summer heating over land. This will open up altogether new research on coastal meteorology that cannot be addressed from present scatterometer technology.

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