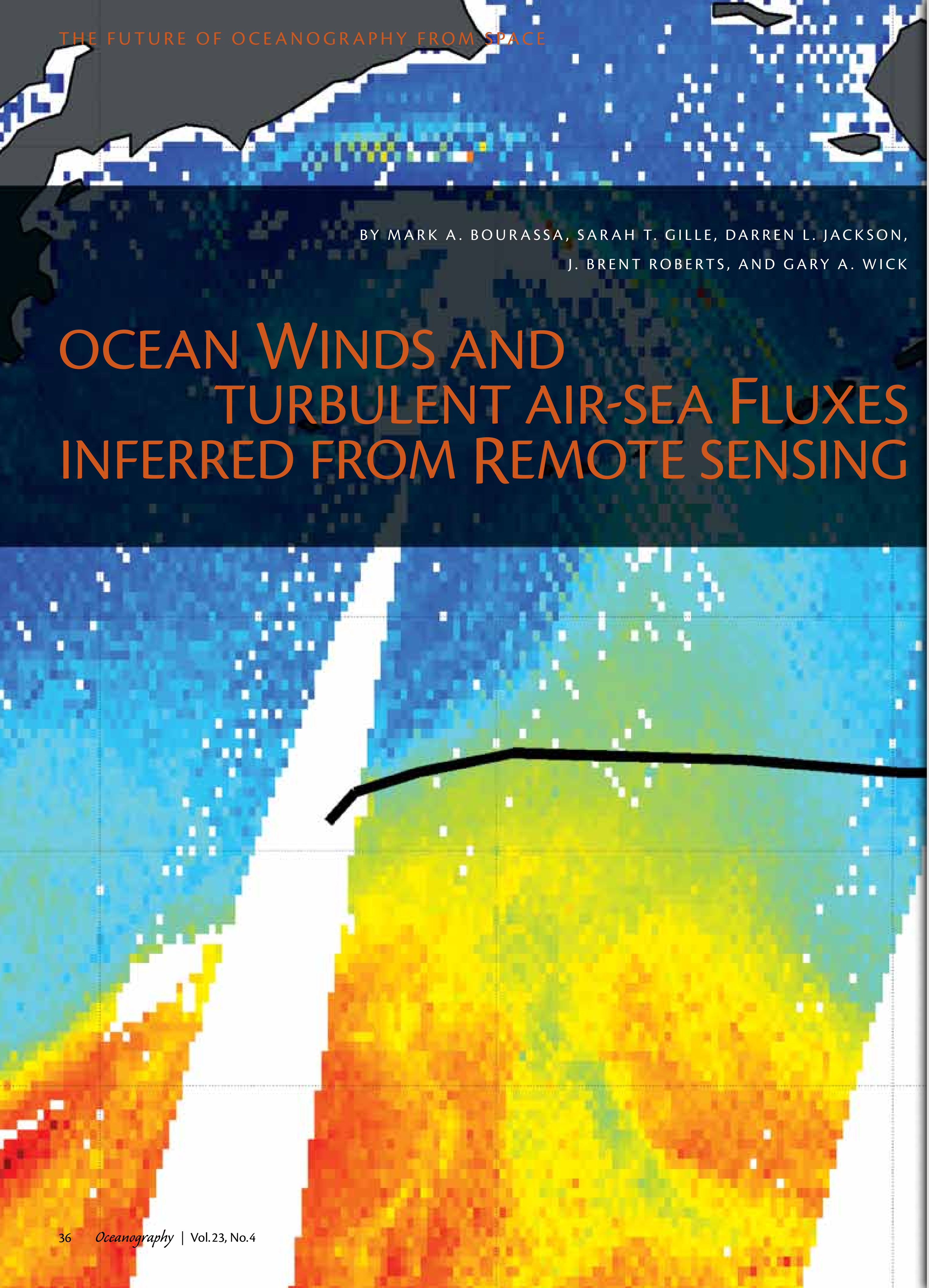

BY MARK A. BOURASSA, SARAH T. GILLE, DARREN L. JACKSON,
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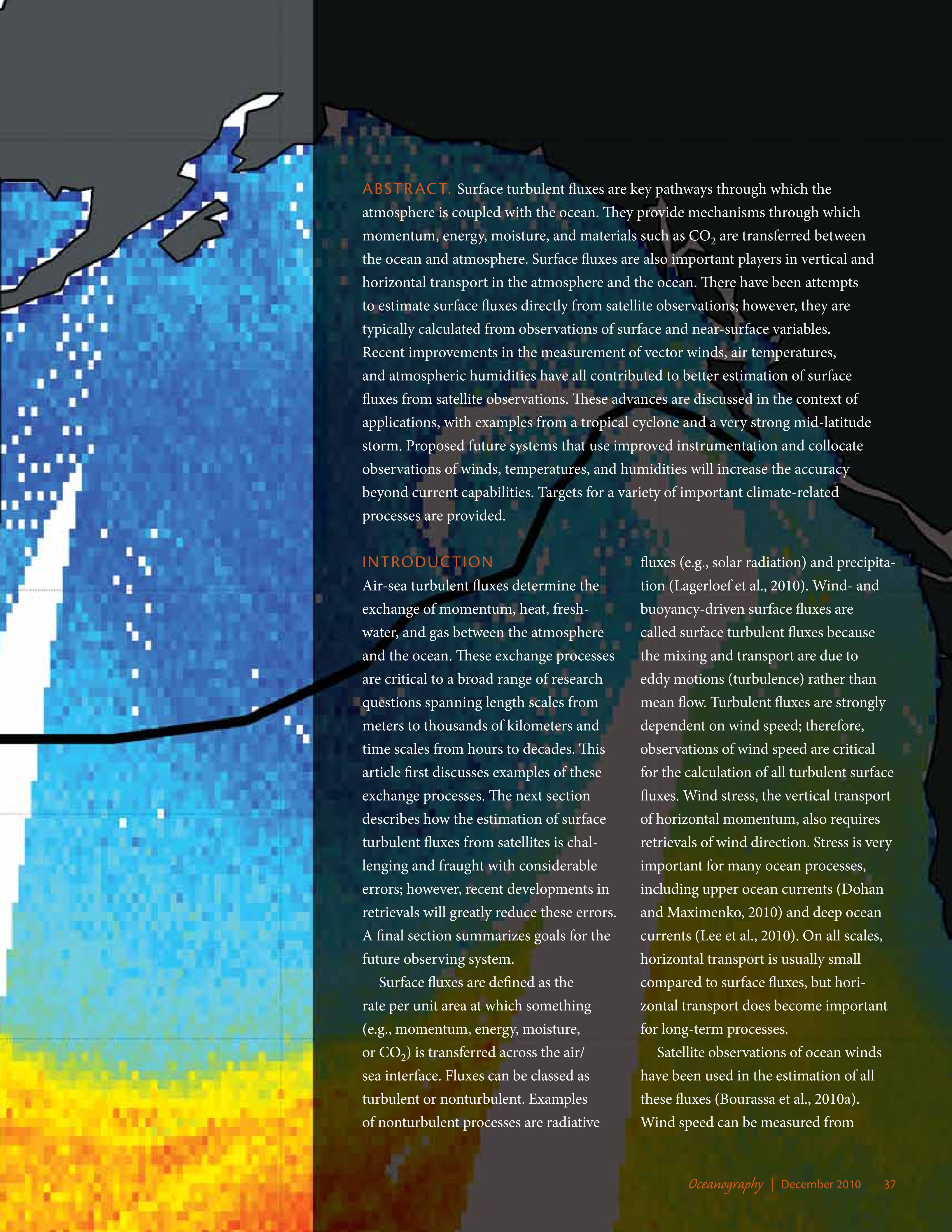
OCEAN WINDS AND TURBULENT AIR-SEA FLUXES INFERRED FROM REMOTE SENSING



ABSTRACT. Surface turbulent fluxes are key pathways through which the atmosphere is coupled with the ocean. They provide mechanisms through which momentum, energy, moisture, and materials such as CO_2 are transferred between the ocean and atmosphere. Surface fluxes are also important players in vertical and horizontal transport in the atmosphere and the ocean. There have been attempts to estimate surface fluxes directly from satellite observations; however, they are typically calculated from observations of surface and near-surface variables. Recent improvements in the measurement of vector winds, air temperatures, and atmospheric humidities have all contributed to better estimation of surface fluxes from satellite observations. These advances are discussed in the context of applications, with examples from a tropical cyclone and a very strong mid-latitude storm. Proposed future systems that use improved instrumentation and collocate observations of winds, temperatures, and humidities will increase the accuracy beyond current capabilities. Targets for a variety of important climate-related processes are provided.

INTRODUCTION

Air-sea turbulent fluxes determine the exchange of momentum, heat, freshwater, and gas between the atmosphere and the ocean. These exchange processes are critical to a broad range of research questions spanning length scales from meters to thousands of kilometers and time scales from hours to decades. This article first discusses examples of these exchange processes. The next section describes how the estimation of surface turbulent fluxes from satellites is challenging and fraught with considerable errors; however, recent developments in retrievals will greatly reduce these errors. A final section summarizes goals for the future observing system.

Surface fluxes are defined as the rate per unit area at which something (e.g., momentum, energy, moisture, or CO_2) is transferred across the air/sea interface. Fluxes can be classed as turbulent or nonturbulent. Examples of nonturbulent processes are radiative fluxes (e.g., solar radiation) and precipitation (Lagerloef et al., 2010). Wind- and buoyancy-driven surface fluxes are called surface turbulent fluxes because the mixing and transport are due to eddy motions (turbulence) rather than mean flow. Turbulent fluxes are strongly dependent on wind speed; therefore, observations of wind speed are critical for the calculation of all turbulent surface fluxes. Wind stress, the vertical transport of horizontal momentum, also requires retrievals of wind direction. Stress is very important for many ocean processes, including upper ocean currents (Dohan and Maximenko, 2010) and deep ocean currents (Lee et al., 2010). On all scales, horizontal transport is usually small compared to surface fluxes, but horizontal transport does become important for long-term processes.

Satellite observations of ocean winds have been used in the estimation of all these fluxes (Bourassa et al., 2010a). Wind speed can be measured from individual passive instruments and active instruments. Passive instruments measure electromagnetic energy radiated from the water surface at several wavelengths. The radiances at these frequencies are typically linearly combined with the goals of accounting for attenuation and emission in the atmosphere, thereby improving the estimate of the surface value (Goodberlet et al., 1989). More complicated radiative transfer models have also been used for satellite wind speed retrievals (Wentz, 1997). Wind speed is related to differential emission signatures generated by wind-induced effects on surface roughness and white capping. Wind instruments typically measure microwaves, which easily pass through clouds but present some difficulties with accurate retrievals through rain (Draper and Long, 2004; Weissman

THE SATELLITE OBSERVING SYSTEM FOR SURFACE VECTOR WIND AND STRESS

Scatterometers are currently considered to be the most practical satellite wind instruments (Bourassa et al., 2010b; see Freeman et al., 2010, for an explanation of how scatterometers work). The QuikSCAT scatterometer provided more than a decade of high-quality ocean vector wind observations with better sampling than any other scatterometer. Regrettably, QuikSCAT ceased to operate in November 2009, leaving a gap in this high-quality climate record. The European Advanced Scatterometer (ASCAT) is currently operational; however, it offers approximately half the sampling of QuikSCAT, and the two instruments have not been intercalibrated. ASCAT uses a different microwave frequency: C-band vs. QuikSCAT's Ku-band. Proper intercalibration of these two types of instruments is an ongoing effort. Current findings are that QuikSCAT retrievals are slightly noisier than ASCAT retrievals; however, QuikSCAT is much more sensitive at low wind speeds (< 4 m s^{-1}) and high wind speeds (> 15 m s^{-1}). In contrast, passive polarimetric wind directions are relatively poor for low and moderate wind speeds (a substantial majority of ocean winds); however, they are relatively effective for very high wind speeds. A review of the US satellite program (NRC, 2007) gave NOAA a mandate to fly a new generation of wind instrument, the eXtended Ocean Vector Wind Mission (XOVWM), which combines the advantages of scatterometry (Ku-band and C-band), passive polarimetry, and synthetic aperture radar. Initial studies of XOVWM capability indicate good-to-excellent sensitivity to winds up to 70 m s^{-1}, greatly improved accuracy in rain, approximately 1-km resolution, and the ability to retrieve winds in the coastal zone close to land, where current scatterometers and radiometers do not function. Preliminary studies based on combining a QuikSCAT-like scatterometer and a radiometer indicated a root-mean-square error of roughly half that of QuikSCAT. This finding suggests a reduced bias can be achieved, provided sufficient comparisons to validation data. To date, funding has not been identified, and NOAA has not initiated a mission. Vector wind observations are necessary for a wide range of applications: stress, surface water wave generation, atmospheric and oceanographic upwelling and downwelling, horizontal transport in the upper and deep oceans as well as the atmospheric boundary layer, and cross-shelf transport.

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and Bourassa, 2008). Many instruments are capable of measuring wind speed (Bourassa et al., 2010b). Active instruments (e.g., QuikSCAT) detect surface roughness by sending a pulse of electromagnetic energy to the surface and measuring the fraction that returns to the satellite. This ratio is very stable over the life of a satellite: active sensors have much smaller calibration drift than passive sensors. Observing the same location from different view angles also allows active sensors (e.g., scatterometers) and passive polarimetric sensors (WindSat) to retrieve the wind direction. Such instruments cannot be in geostationary orbits because they must move relative to the surface in order to observe the surface from a sufficient variety of angles.

Sea surface temperatures are also sufficiently well observed for most turbulent surface flux applications (Donlon et al., 2007). In contrast, near-surface atmospheric humidity and temperature have historically been difficult to retrieve via remote-sensing methods because of the much larger signal from the ocean surface. Sea surface temperature (SST) and atmospheric temperature and humidity have been retrieved using linear combinations of the observed radiances. One of the great difficulties of atmospheric temperature and humidity observations is that they are retrieved with frequencies that are quite sensitive to liquid water (i.e., excessive cloud cover), resulting in a lack of data in many areas that have very active weather and large fluxes (see Esbensen et al., 1993, for a description of problems with moisture retrievals). There have been considerable improvements in the last decade as discussed below. The great improvement for SST observations (Donlon et al., 2007) has been intercalibration of multiple SST sensors. New techniques for retrieving atmospheric temperature and humidity (Jackson et al., 2006, 2009; Roberts et al., 2010; and see later discussion) have led to considerable improvements in accuracy over a wider range of conditions.

EXAMPLE APPLICATIONS AND SAMPLING ISSUES

Applications

Science questions that rely on air-sea turbulent fluxes are numerous, encompassing climate science, tropospheric dynamics, and upper-ocean physics. The specific requirements for air-sea fluxes depend on the scales of the processes under consideration. We cannot hope to inventory all possible applications here, but we highlight a selection to indicate the requirements flux observations need to meet. Table 1 gives estimates of observational accuracy (in the mean) and example requirements. These requirements are based on the observational capabilities of instrumentation for research vessels, and will likely require some modification for satellite observations. Issues in meeting these accuracy requirements are discussed in the last section of this article. Most applications require combinations of spatial and temporal sampling, achieved most practically with a satellite-based

Table 1. Accuracies (Biases) and Applications

Variable	R/V or Direct Observation	NDBC Buoys	CO_2 Budget	Global Climate Change	Ice Sheet Evolution	Annual Ice Mass	Upper Ocean Heat Content	Open Ocean Upwelling	Dense Water Formation
Stress (Nm^{-2})	Very small	NA	0.01	TBD	TBD	TBD	TBD	TBD	TBD
Sensible + Latent ($W\ m^{-2}$)	Very small	NA	-	< 0.25	0.5	2.5	5	5	5
Vector Wind	0.14		TBD	TBD	TBD	TBD	TBD	TBD	TBD
Wind Speed ($m\ s^{-2}$)	0.2	1.0	1.0	0.01	0.02	0.1	0.2	0.2	0.2
SST (K)	0.1	1.0	2.5	0.005	0.01	0.05	0.1	0.1	0.1
Air Temperature (K)	0.2	1.0	> 10	0.01	0.02	0.1	0.2	0.2	0.2
Humidity ($g\ kg^{-1}$)	0.3	*	> 10	0.015	0.03	0.15	0.3	0.3	0.3

The research vessel errors in this table refer only to biases (Fairall et al., 1996; Bradley and Fairall, 2007). The CO_2 numbers are based on a requirement of ± 20% accuracy in the transfer velocity consistent with a climate requirement to constrain basin-wide fluxes to 0.2 Pg C yr^{-1} (R. Wanninkhov, NOAA/AOML, *pers. comm.*, 2009). TBD indicates "to be determined." If there is sufficient sampling to resolve the synoptic scale and diurnal cycle, the sample size will be sufficiently large that random variability can be ignored for many climate applications. National Data Buoy Center (NDBC) buoys measure relative humidity or dew point temperature with estimated biases of 3% or 1 K. The conversion to specific humidity is a nonlinear function of temperature. These humidity sensors are nonfunctional roughly 30% of the time.

observing system. For additional examples, see Lee et al. (2010), Chelton and Xie (2010), Eakin et al. (2010), Kwok et al. (2010), Lagerloef et al. (2010), and Yoder et al. (2010).

On a planetary scale, air-sea fluxes determine the net oceanic uptake of heat and CO_2, both on a cyclical seasonal scale and as part of a long-term trend resulting from natural and anthropogenically forced low-frequency variability. Air-sea turbulent sensible and latent heat fluxes vary in magnitude through the course of the year, with sensible heat fluxes also changing sign. In most places, the ocean takes up heat during the summer and releases it in winter. Seasonal flux differences are typically about 50 W m^{-2}. Low-frequency variability is also prominent because of modes of naturally coupled ocean-atmosphere processes such as the El Niño-Southern Oscillation (ENSO). Superimposed on these seasonal and natural cycles is a smaller, long-term radiative forcing due to increased anthropogenic heat storage. However, this signal, estimated to be about 0.85 W m^{-2} (Hansen et al., 2005), is so small that it defies our existing flux instrumentation. Instead, long-term trapping of heat in the ocean is best monitored by assessing changes in upper-ocean heat content (e.g., Johnson et al., 2007; Levitus et al., 2009).

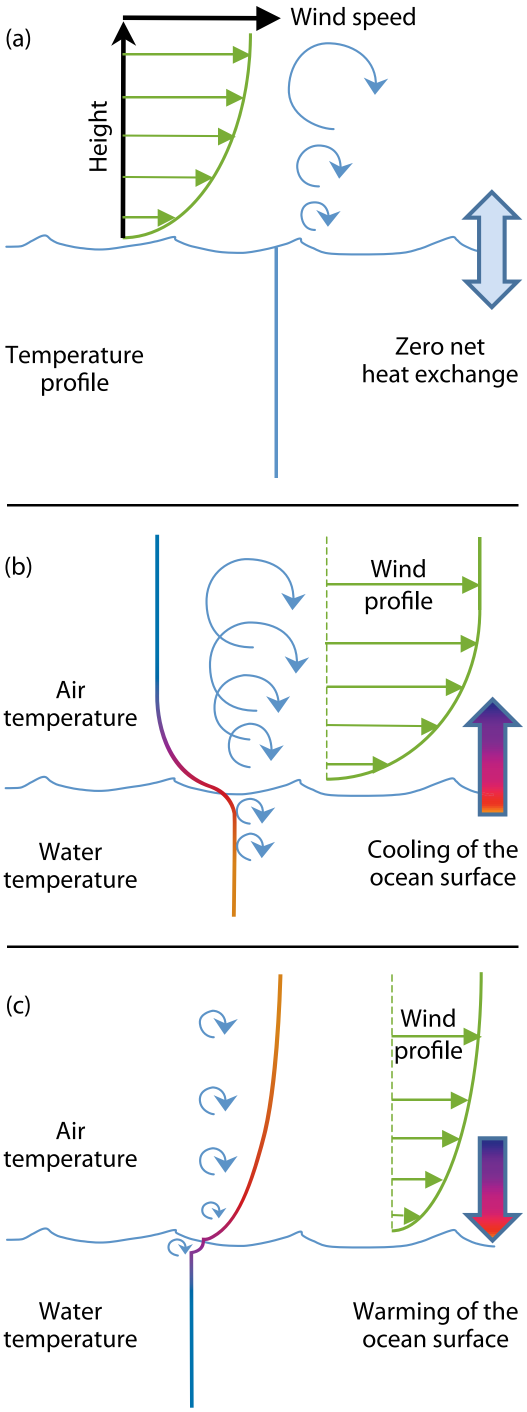

Figure 1. Changes in temperature of the ocean surface can cause large changes in the surface turbulent fluxes. If there is no heating or cooling of the ocean surface (a), the ocean mixing near the surface is almost completely due to winds and waves. The green curve represents the profile of wind speed, with smaller speeds near the surface. The red profile indicates relatively warm water and the blue profile relatively cold water. The profile for atmospheric moisture is usually similar to the temperature profile. If the surface is relatively warm compared to the air (b), the atmospheric boundary layer is unstable, which increases mixing and turbulent fluxes. If the ocean loses heat to the atmosphere, the surface becomes relatively cold compared to water deeper in the mixed layer, with results similar to unstable conditions in the atmosphere. If the ocean surface is cold relative to the air and water (c), then atmospheric and oceanic vertical mixing are reduced, and fluxes are reduced.

Understanding the physics behind ocean storage of heat and CO_2 depends on understanding the oceanic mixed layer. The mixed layer is typically represented as a homogeneous layer of water at the top of the ocean that readily communicates with the atmosphere (Figure 1a); however, there is a great deal of very-near-surface variability related to heat and momentum fluxes (Figure 1b,c). The mixed layer deepens in late winter in response to turbulent heat loss to the atmosphere. This deepening occurs because the upper water becomes relatively dense, which results in convective instability within the water column (Figure 1b). Strong winds, usually more common in winter than in summer, can also deepen the mixed layer. In summer, oceanic heat gain from the atmosphere creates a layer of less-dense water at the ocean surface, resulting in a shallower mixed layer (Figure 1c) and more mixing in the atmospheric boundary layer (Figure 1b). These processes, which govern the depth of the oceanic mixed layer, have a big impact on how much heat the ocean actually stores (Eakin et al., 2010). In a detailed assessment of an ensemble of 19 climate projection models run as part of the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report, Boé et al. (2009) show that models starting with deeper winter mixed layers in the twentieth century result in larger oceanic uptake of heat and CO_2 through the course of the twenty-first century. These flux imbalances ultimately result in a cooler atmosphere (and warmer ocean) by the 2070–2099 time period.

The global poleward transport of heat, often termed the meridional overturning circulation, also depends on air-sea fluxes. In the North Atlantic, the Gulf Stream brings warm surface water northward. Wintertime air-sea fluxes create denser, colder water that sinks to mid-depth, forming North Atlantic Deep Water that returns southward. In the Southern Hemisphere, mid-depth water travels south along constant density surfaces that rise to the ocean surface within the Antarctic Circumpolar Current (Speer et al., 2000). Water that moves along these density surfaces can then warm at the ocean surface, transforming from deep water into intermediate water (e.g., Cerovecki et al., 2008). Both the Northern and Southern hemisphere parts of this meridional overturning circulation are sensitive to the strength of the wind and the magnitude of the heat fluxes.

Although it is sometimes tempting to think of meridional heat transport and air-sea heat exchange as global-scale processes, recent investigations suggest that they are strongly sensitive to small spatial-scale changes in SST (e.g., Chelton et al., 2004; Xie, 2004; Small et al., 2008; Cronin et al., 2010; Chelton and Xie, 2010). Major currents such as the Kuroshio Extension, the Gulf Stream, and the Agulhas Retroflection are sites of strong temperature gradients. Wind changes speed as it blows across these temperature gradients, in turn generating significant gradients in momentum and turbulent heat fluxes. Surface currents associated with the SST fronts can be strong enough to further complicate the surface stress field by significantly altering the relative motion of the ocean and atmosphere at the air-sea interface (Cornillon and Park, 2001; Kelly et al., 2001). Because the currents meander in space, the spatial patterns of heat and momentum fluxes also change in time (Fu et al., 2010; Chelton and Xie, 2010). These ocean current effects on the wind stress curl field likely feed back to the ocean circulation but are often difficult to identify unambiguously because of the transient nature of most meandering currents. Importantly, processes contributing to fluxes interact with each other nonlinearly, and the resulting net fluxes differ from those that would be obtained from large-scale averaged fields (Josey et al., 1995; Gulev et al., 2007a,b). Similarly, orographically induced strong winds (e.g., Xie et al., 2005) can produce locally intense fluxes.

> “RECENT IMPROVEMENTS IN THE MEASUREMENT OF VECTOR WINDS, AIR TEMPERATURES, AND ATMOSPHERIC HUMIDITIES HAVE ALL CONTRIBUTED TO BETTER ESTIMATION OF SURFACE FLUXES FROM SATELLITE OBSERVATIONS.”

Sampling and Resolution Requirements

“Sampling” of a process involves more than characterizing the spatial and temporal resolutions for a given sensor (Schlax et al., 2001). Most studies of processes important to the upper ocean, whether observation or model based, require the knowledge of several fields of variables. For example, studying air-sea exchange of heat and moisture requires knowledge of sea surface temperature, wind speed, near-surface air temperature, near-surface humidity, and surface pressure. Characterizing “sampling” based on any one of these variables is insufficient. Sampling must be described within the context of all important variables contributing to a process. Understanding sampling of heat exchange, for example, may require combining the sampling information from several sensors, many of which are situated on separate satellite platforms. Often, a satellite mission focuses on one major component of a process, such as wind speed (e.g., QuikSCAT; Graf et al., 1998). In some cases, observations from multiple satellites are used to estimate one or two of these variables (e.g., Jackson et al., 2006, 2009). One key question becomes: *When are observations sufficiently close in both space and time to estimate fluxes?* Another key question is: *How often are observations required to provide sufficiently accurate estimates of fluxes?*

The need for temporal resolution can be determined from natural variability and accuracy requirements or from the time scales of processes being examined (e.g., diurnal variability for land-sea breezes). Winds change relatively rapidly, indicating that synoptic-scale variability should be well sampled. For example, if variability on the synoptic scale and finer is ignored, monthly average fluxes in the mid latitudes are typically underestimated by 30 W m^{-2} (Paul Hughes and Ryan Maue, Florida State University, *pers. comm.*, 2006), which is far worse than biases due to current calibration issues. The strong winds and dry cold air (Figure 1b) associated with atmospheric cold fronts make disproportionately large contributions to the average heat fluxes (Figure 2 provides an extreme example). These examples are great improvements over estimates based on earlier techniques because of the better representation of the air-sea differences (Jackson et al., 2009; Roberts et al., 2010) that are so important for estimating turbulent fluxes. For such high wind speed conditions, random errors on air temperature and humidity contribute to relatively large errors in fluxes, meaning that there should be sufficient accuracy and/or sampling in space and time to reduce this random error. Enhanced spatial resolution, without substantial decrease in accuracy, can help reduce these random errors. The spatial scale of processes being examined tends to be a stronger constraint on spatial resolution,

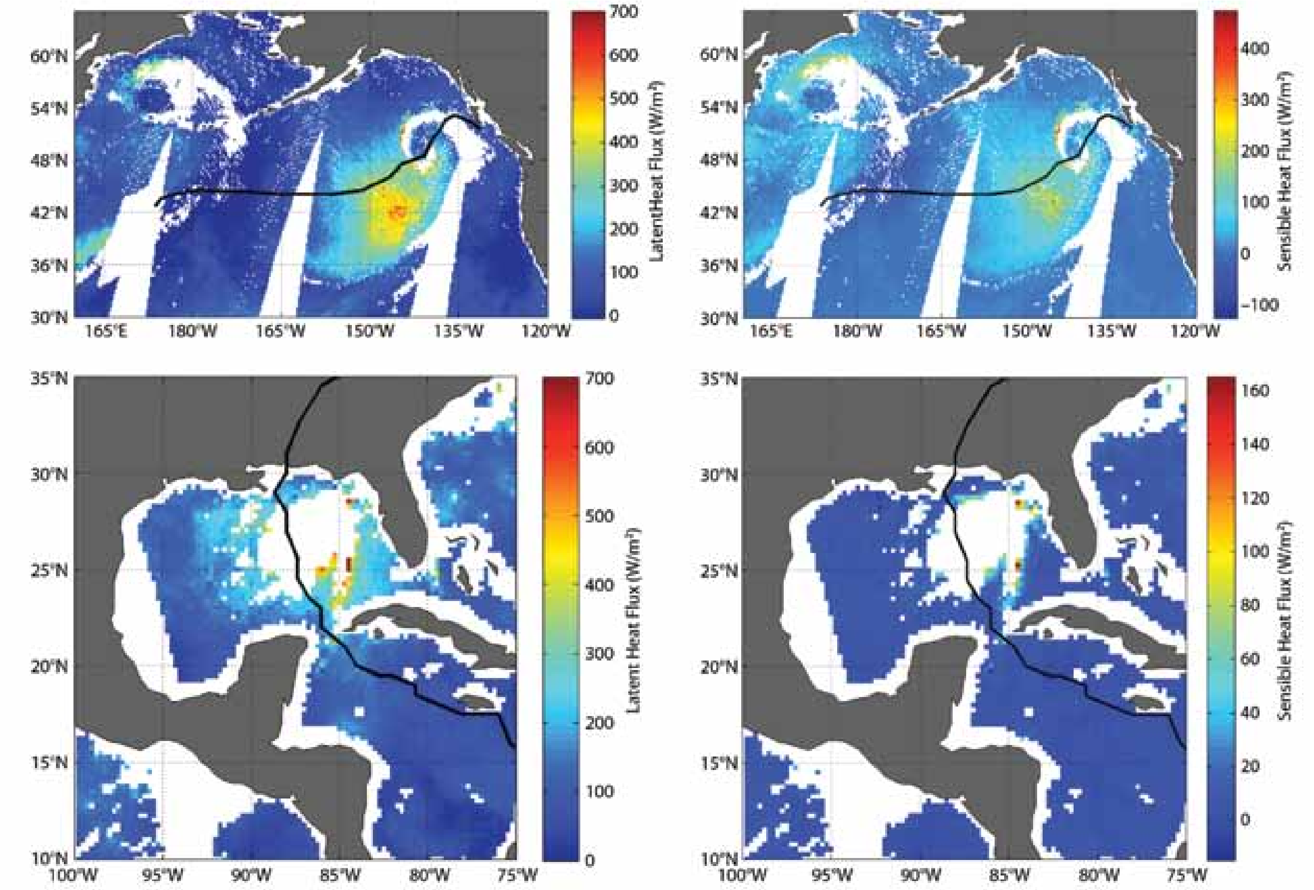

Figure 2. Satellite-based estimates of the latent heat flux (left column) and sensible heat flux (right column) for an intense mid-latitude storm (top row) and for Hurricane Ivan, 2004 (bottom row). Missing values occur between swaths and where there was too much precipitation, masking out much of the interesting area for hurricanes (this is much less of a problem for fluxes behind mid-latitude storms). These retrievals are based on new and greatly improved observations of atmospheric temperature and humidity that greatly improve estimated turbulent heat fluxes. The solid black line shows the cyclone trajectory.

with roughly 25 km desired from most open-ocean studies, roughly 5 km for most mid-latitude weather, and 1 km for near-coastal and hurricane studies.

HISTORICAL CHALLENGES AND RECENT IMPROVEMENTS

Historical challenges in observing air-sea fluxes include insufficient sampling, biases, large random errors in air temperature, and no accounting for how surface water waves modify fluxes. A lack of intercalibration has also been a tremendous problem, resulting in spurious trends and variability that have more to do with the observing system than any natural processes. Intercalibration of winds and sea surface temperatures has been greatly improved in recent years. Intercalibration for atmospheric temperature and humidity is just beginning. Errors related to surface pressure are very small in comparison to other problems; therefore, improved estimation of surface pressure has had a low priority.

Stress

Stress, the vertical transport of horizontal momentum, is relatively accurately observed. Stress is a function of the wind vector relative to the surface, buoyancy (largely a function of the air-sea difference in temperature), sea state, and air density. Note that observations that provide only speed or magnitude (typical of most wind observations) are insufficient for most applications involving dynamics. Variability in air density is small compared to errors in the wind, air-sea temperature difference, and influence of sea state. Satellite winds have traditionally been calibrated to equivalent neutral winds (Ross et al., 1985), which is like stress in the sense that equivalent neutral wind accounts for the dependency on buoyancy. Recent studies (Bourassa et al., 2010b) have found that scatterometers, and presumably other wind-sensing instruments, respond to stress rather than wind, accounting for variability due to wind, buoyancy, surface currents (Cornillon and Park, 2001; Kelly et al., 2001; Chelton et al., 2004), waves (Quilfen et al., 2001; Bourassa, 2006), and air density (Bourassa et al., 2010a). We anticipate that satellite-derived stresses will soon be available from reprocessed QuikSCAT observations, with regional and seasonal biases proportionally smaller than for stresses determined from the Jet Propulsion Laboratory's retrievals of QuikSCAT winds. This is a tremendous advantage for improved accuracy in other turbulent fluxes because stress is more closely related to fluxes than wind: stress observations are believed to account for all sea-state-related variability in surface fluxes of momentum, heat, and moisture. The knowledge gained from QuikSCAT retrievals of stress will be used to calibrate future scatterometers, and will contribute to a better understanding of local changes in sea level (Willis et al., 2010). Because sea state is not well observed from space, this approach will remove one source of error in studies of climate change.

Heat and Moisture Fluxes

Direct measurement of turbulent fluxes requires dedicated field experiments in which turbulence measurements can be made from in situ research vessels and buoys. This approach cannot be employed for examining the exchange over the global ocean. Instead, parameterizations have been developed that can be used to accurately estimate the turbulent exchange given "bulk," or mean-value, measurements of sea surface temperature, wind speed, and near-surface air temperature and humidity (e.g., Fairall et al., 1996). Fluxes are larger when wind speed (relative to the surface) is greater and when the surface values of temperature (sensible heat flux) or humidity (moisture flux and latent heat flux) are larger than the values in the air above the surface (Figure 1b). Two examples of satellite-estimated fluxes (Figure 2) show great promise and demonstrate problems that remain to be solved. The patterns and magnitudes of these fluxes are reasonably consistent with expectations; however, the lack of observations in areas with rain (e.g., much of Hurricane Ivan and the fronts and core of the mid-latitude storm) show that this technique will miss fluxes in some areas where they are large and difficult to extrapolate.

The use of bulk variables allows estimation of surface heat and moisture exchanges anywhere when all necessary variables are measured. While in situ platforms such as buoys and ships are invaluable and generally have adequate temporal sampling, they are only point measurements that sample a very small fraction of the global ocean. Given these inherent limitations of in situ measurements, progress in measuring heat and moisture exchange over the ocean has increasingly been made through the use of satellite-based measurements. Satellites are able to improve the spatial and temporal coverage of many of these important surface variables; however, in situ data are an essential source of comparison data for tuning and validating satellite retrieval techniques.

Measurement of T_{air} and Q_{air}

Latent and sensible heat fluxes are proportional to the product of wind speed (Figure 3) and either the difference between atmospheric humidity at the sea surface and atmospheric humidity a few meters above the surface (Figure 3) or, similarly, the difference in temperature (Figure 3). Measurement of near-surface (approximately 10 m) air temperature (T_{air}) and humidity (Q_{air}) via satellite remains an area of intensive ongoing progress. A recent comparison of satellite-based surface heat and moisture exchange products (Clayson, 2009) reveals the largest source of spread between products to be rooted in Q_{air} and T_{air} retrievals rather than satellite wind speeds. Retrieval of these near-surface quantities from satellite-measured radiances is challenging. Clouds hinder observations in the infrared (IR). Coarse spatial resolutions hinder microwave observations. Both types of observations have coarse vertical resolutions due to the nature of atmospheric retrievals. Even high-spectral-resolution IR sounders such as the Atmospheric Infrared Sounder have only a 1-km vertical level output (Aumann et al., 2003). This depth can be on the order of the entire boundary layer; however, a roughly 10-m measurement is required. Passive microwave sensors, particularly those of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I; Hollinger et al., 1991) provide yet another route to retrieval of near-surface moisture and temperature. However, many SSM/I frequencies are more responsive to the total columnar water vapor burden, or precipitable water (PW), than to a precise near-surface amount (e.g., Liu, 1986; Schulz et al., 1993; Jackson et al., 2009).

Earlier studies found a strong link between PW and Q_{air} on monthly time scales (Liu, 1986). Because of the strong relationship between humidity and air temperature via the Clausius-Clapeyron relationship, use of a known Q_{air} with an assumed relative humidity, usually of 80%, T_{air} can be estimated through simple inversion of the moisture saturation vapor pressure equations; however, such estimates of T_{air} have large random errors and regional biases. Although the PW-Q_{air} relationship generally holds

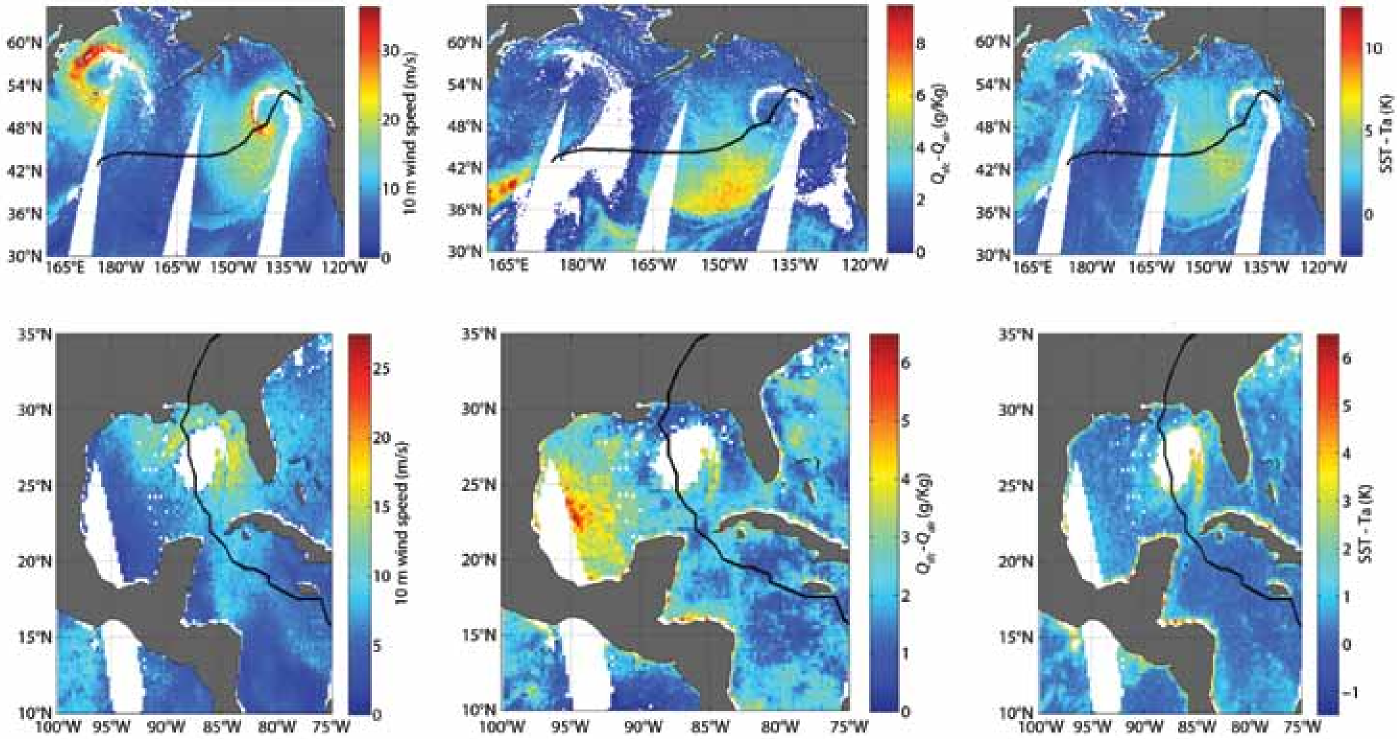

Figure 3. Wind speeds (left column), air/sea differences in humidity (middle column), and air/sea differences in air temperature (right column) for the same cases as in Figure 2. The fluxes are proportional to the product of these wind speeds and differences. The wind speeds are from Remote Sensing Systems v6 Special Sensor Microwave/Imager product.

on monthly time scales, it often breaks down for instantaneous retrievals. Further improvements have been made based upon radiative transfer studies that show certain channels of the SSM/I contain some boundary-layer moisture information (Schulz et al., 1993). This has led to the production of empirical multiple linear regressions based upon collocated brightness temperatures and in situ measurements. Since these early studies, empirically based regressions have been employed as the status quo, with minor improvements (Schlüssel et al., 1995; Bentamy et al., 2003). Much less progress on the retrieval of near-surface air temperature has been made over the same period.

Recent work has sought to improve the methodologies and results of these early studies. The work of Jackson et al. (2006, 2009) and Jackson and Wick (2010) improves the retrieval of both T_{air} and Q_{air} (Figure 4) through the use of combined and single-sensor instrument retrievals. Sounding data from the Advanced Microwave Sounder Unit (AMSU-A) has been combined with the passive microwave frequencies of SSM/I in an empirical retrieval of both air temperature and humidity. The primary benefit of including the sounder data results from the ability to correct for variability higher in the atmospheric column that is not correlated to surface variations. While present sounders do not resolve well the near-surface layer, the information on moisture and temperature structure in the atmosphere complements the SSM/I data, which is sensitive to the total column amounts. However, the necessary sensors for this retrieval are on separate satellite platforms, reducing the coverage of any retrieved product because of the need for collocated footprints. The recent study of Roberts et al. (2010) has also improved upon previous retrieval algorithms (Figure 4). Inclusion of near-surface information through a first-guess SST with SSM/I brightness temperatures in a novel, nonlinear neural network approach has led to improved accuracies in Q_{air} and T_{air}. One great benefit of this approach is that SSM/I brightness temperatures are the only satellite-based information needed to obtain increased coverage. Examples of the SSM/I retrievals show great amounts of cold and dry air moved to the south behind the eastern storm (Figure 4, top row) and typical tropical conditions away from Hurricane Ivan (bottom row). Multisensor methods for the retrieval of

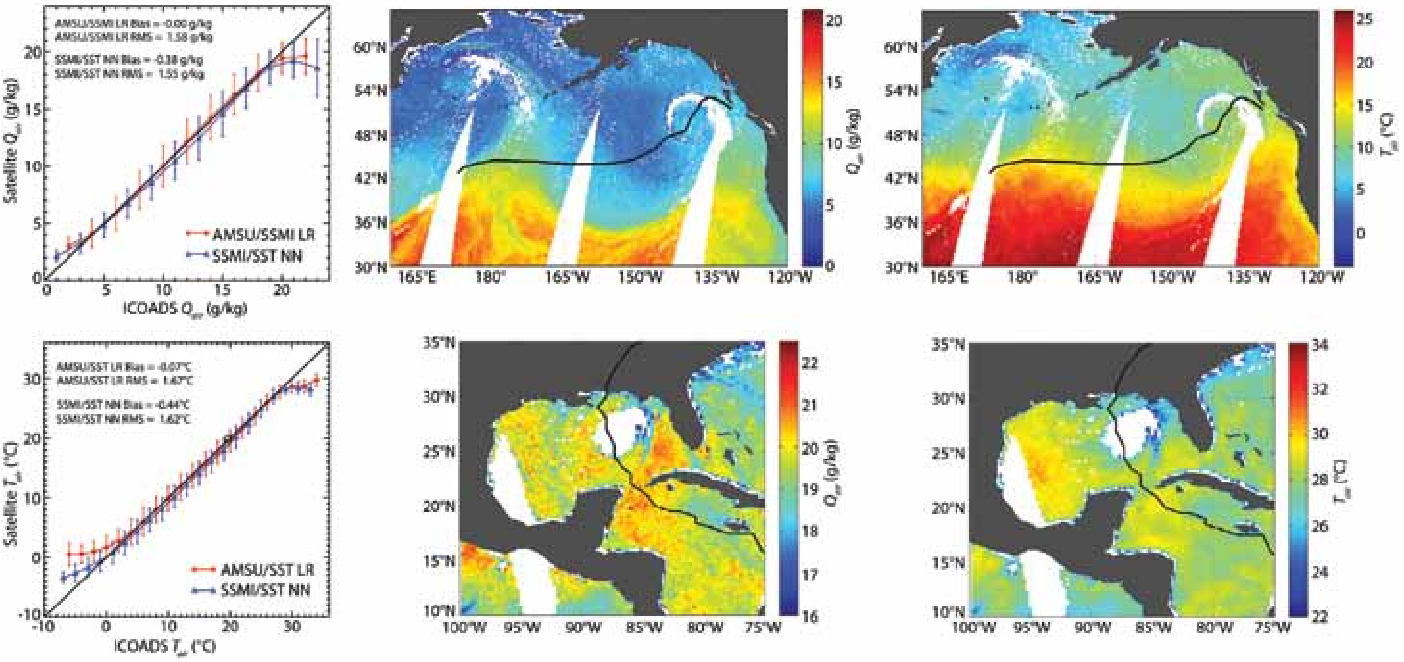

Figure 4. Validation of satellite retrievals of humidity at a height of 10 m above the water surface (top left) and air temperature at the same height (bottom left), and examples of humidity (middle column) and air temperature (right column) for the same cases as in Figure 2.

near-surface air temperature and specific humidity offer potential for improvement in accuracy, but the benefits can be countered by sampling challenges.

Gas Fluxes

The flux of gas across the air-sea interface is commonly estimated using a bulk relationship similar to the heat and moisture fluxes. The flux is given by the concentration difference across the interface (expressed in terms of the difference in partial pressures of the gas in the surface seawater and the atmosphere above the interface) multiplied by the gas transfer velocity and the solubility of the gas in water. The formulation differs from that of the heat and moisture fluxes in that the combination of the exchange coefficient and wind speed is replaced with a transfer velocity. To derive the gas flux from space, both the concentration difference and transfer velocity must be estimated from satellite-derived quantities. Unfortunately, none of the needed parameters are retrieved directly by present satellites.

> “PROPOSED FUTURE SYSTEMS THAT USE IMPROVED INSTRUMENTATION AND COLLOCATE OBSERVATIONS OF WINDS, TEMPERATURES, AND HUMIDITIES WILL INCREASE THE ACCURACY BEYOND CURRENT CAPABILITIES.”

While methods for determining the transfer velocity have been developed for multiple gases (e.g., Fairall et al., 2000), remote estimation of concentrations and fluxes have focused primarily on CO_2. For CO_2, the primary source of variability in the partial pressure difference is the oceanic partial pressure of CO_2 (pCO_2). Atmospheric pCO_2 variability is much smaller both spatially and temporally and is not a major limiting factor in the accuracy of the derived flux products except downwind from land and blooms (how far downwind remains to be determined). Efforts to date have relied largely on broad extrapolation of available direct in situ measurements and worldwide networks (e.g., Etcheto et al., 1999; Olsen et al., 2004; Feely et al., 2006). Initial applications of infrared sounder-derived information on CO_2 concentrations higher in the atmosphere to surface flux estimates have largely been unsuccessful (Chevallier et al., 2005). Improvements in satellite-based estimation of atmospheric pCO_2 are possible through observations from the Greenhouse gases Observing SATellite (GOSAT) launched in 2009.

Oceanic pCO_2 is more variable, and remote measurements are needed to spatially and temporally interpolate available direct observations. Previous efforts to map variations in surface pCO_2 have employed relationships with SST (e.g., Boutin et al., 1999; Olsen et al., 2004; Feely et al., 2006), SST and chlorophyll *a* (Ono et al., 2004; Rangama et al., 2005), and recently, dissolved inorganic carbon (obtained from SST, chlorophyll *a*, and salinity) and total alkalinity (obtained from salinity; Sarma et al., 2006). These methods, however, exhibit significant differences between regions and seasons, and no clear approach has yet been identified to systematically relate variations in pCO_2 to remotely sensed parameters on a global scale. Research continues on globally valid approaches with improved accuracy.

The greatest source of uncertainty in the derived flux products lies in obtaining suitable values for the gas transfer velocity. Estimates of the air-sea flux of CO_2 have largely used simplified models based solely on wind speed (e.g., Wanninkhof, 1992). Uncertainty exists as to the appropriate relationship to wind speed: both quadratic (Wanninkhof, 1992) and cubic (Wanninkhof and McGillis, 1999) relationships have been used. These simplified models fail to capture all the processes influencing gas transfer. Surfactants, rain, microscale wave breaking, and biological processes may significantly affect gas transfer, particularly at lower wind speeds. Present work is focused on developing approaches that better capture these dependencies.

The greatest sensitivity of the derived transfer velocities is to variations in the wind speed. The results in Figure 5 (Jackson and Wick, 2009b, and recent work of authors Jackson and Wick) show global monthly averaged estimates of CO_2 transfer velocity and associated uncertainties computed using the model of Fairall et al. (2000). Note that nearly 95% of the uncertainty is contributed by errors in estimating the wind speed. The next largest contributor is SST. Based on these results, the wind speed must be measured to an accuracy of ~ 1 m s^{-1} to provide a 20% uncertainty in the transfer velocity. This places strong requirements on the procedures used to grid and average the wind speed. The total uncertainty at wind speeds above ~ 15 m s^{-1} is still largely uncharacterized because of a lack of observations and an incomplete understanding of the role of bubble processes.

Two approaches for estimation of gas transfer velocities derived solely from satellite observations have been developed. One approach uses the COARE V3.0 bulk flux algorithm (Fairall et al., 2003) and satellite-based estimates of the input parameters (Jackson and Wick, 2009a). The other approach attempts to directly relate the transfer velocity to variations in ocean surface roughness, thereby simultaneously accounting for wind speed, sea state, and relevant biological processes. Frew et al. (2007) and Glover et al. (2007) provide details of the application of this technique using altimetric data. Recent work by these investigators extended the technique to the use of scatterometry data, providing enhanced global coverage.

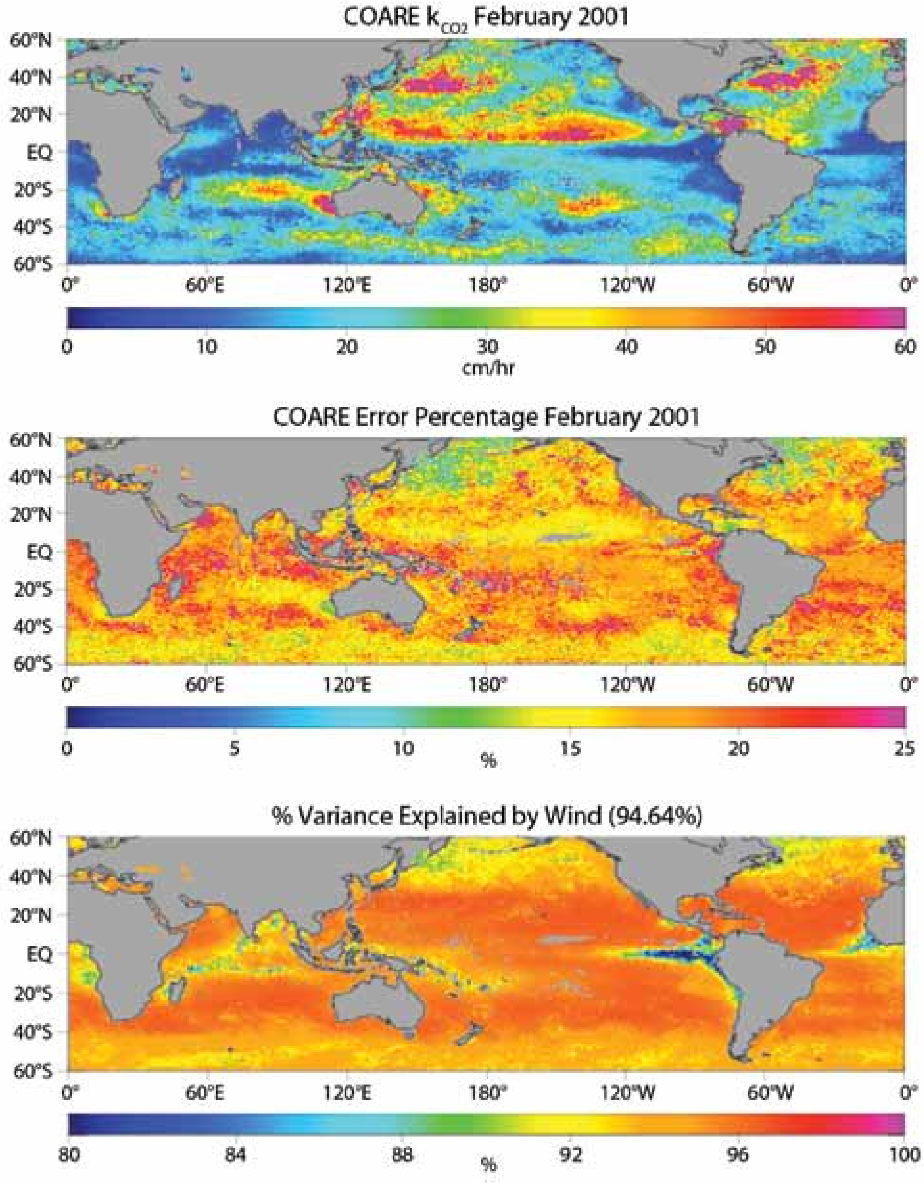

Figure 5. Modeled CO_2 gas transfer velocity and associated uncertainty. The upper panel shows the monthly averaged CO_2 gas transfer velocity for February 2001 computed using the Fairall et al. (2000) model. The corresponding estimated uncertainty expressed as a percentage is shown in the middle panel. The lower panel shows the fraction of the uncertainty due to uncertainty in the measured wind speed as a function of location.

GOALS FOR THE FUTURE OBSERVING SYSTEM

There are several considerations key to improving the accuracy of satellite-derived surface turbulent fluxes. Coincidentally, the requirements for these improvements will also increase the accuracy of radiative fluxes, which are sensitive to the amount of water vapor in the atmospheric boundary layer. The key considerations are validation and intercalibration, determining the needed sampling and resolution required to achieve desired accuracy, and improved calibration to reduce biases.

Specialized observations of fluxes from research vessels have sufficient accuracy and temporal sampling for many climate-related applications; however, they are limited to a few specialized cruises, with spatial sampling so sparse that for satellite applications they are suitable only for rough calibration. The much more plentiful standard meteorological observations from ships and buoys have too much uncertainty in the mean for many climate-related applications, but have sufficient temporal sampling along major ship routes. Recent studies (Wentz et al., 2007; Jackson et al., 2006, 2009; Roberts et al., 2010) indicate that current and past satellite observations can be tuned to be sufficiently accurate (in terms of bias) for many climate-related applications. Future systems, with accuracies improved by a factor of two, will be highly desirable for studies of annual changes in the sea ice mass (Kwok and Sulsky, 2010), among other topics. Goals for future missions could include sufficient accuracy for annual sea ice evolution, and work toward the accuracies required for global climate change. Achieving these goals will also require coordination of satellite orbits to provide sufficient sampling of the diurnal and inertial cycles.

For satellite calibration purposes (Table 1), we need more in situ observations outside of the tropics and away from coasts (or satellite observations with sufficient resolution to work near coastal buoys). Air temperature and humidity retrieval would greatly benefit from data over cold water, a condition that is poorly sampled with the historical observing system. TAO/Pirata/Rama buoys cover parts of the tropics, but relatively few measurements are made outside of the tropics. Exceptions include the Kuroshio Extension System Study (KESS) and CLIvar MOde Water Dynamic Experiment (CLIMODE) flux moorings and the planned OceanSITES network. Argo floats don't measure atmospheric variables, and surface drifters have relatively poor accuracy and spatial sampling when they do so. The traditional routes of Volunteer Observing Ships (VOS) do not cover large portions of the ocean (i.e., Southern Ocean). Research vessels offer an alternative source of relatively high-quality data (due largely to the practice of recording data at rates of one observation per minute or better). The Shipboard Automated Meteorological and Oceanographic System (SAMOS) Initiative (Smith, 2004; Smith et al., in press) has made excellent progress toward providing quality-assured data from many US-based research vessels in near-real time (Table 1). Similar processing of data from select older cruises (e.g., those of the Antarctic support vessels *Laurence M. Gould* and *Nathaniel B. Palmer*) would be extremely useful for global calibrations that are applicable to high latitudes. An important goal is to obtain observations from high wind speed (> 15 m s^{-1}) conditions. These hazardous operating conditions are rare but make disproportionately large contributions to mean fluxes and play significant roles in important oceanic and atmospheric processes. Lastly, spurious trends due to changing calibration characteristics are more likely to be identified and corrected if there is periodic comparison to in situ observations.

> “TECHNIQUES ARE BEING DEVELOPED TO PROVIDE A WEALTH OF SURFACE TURBULENT FLUX INFORMATION FROM SATELLITES.”

Long-term climate data records invariably rely on combining instrument records from separate platforms. Individual satellites have unique fields of view, footprint size, sampling, and error characteristics. Different types of satellites (and in situ observations) respond to different physics, and these differences must also be considered for long-term climate analyses. Combining these records can easily cause erroneous trends in the resulting climate data record. Objective analyses developed for climate studies must be improved to better account for these considerations. These problems can be reduced if the satellite missions for similar observations overlap. It would also be useful to have different types of instruments measuring the same parameter very closely collocated in space and time. For example, most satellites accomplish close collocations by using multiple instruments on the same satellite. Another approach is to use a series of closely spaced satellites in the same orbit. For rapidly changing variables (such as wind), this approach would enable a much better understanding of the differences between such instruments. Reduced sampling is a serious downside to this approach to improving calibration.

Process studies are needed to determine accuracy requirements for surface turbulent fluxes, particularly vector winds and vector stress (Table 1). It is accepted that vector winds (or stress) are needed for many applications (Bourassa et al., 2010b); however, detailed requirements are yet to be determined. The USCLIVAR Working Group on High-Latitude Surface Fluxes (Bourassa and Gille, 2008) queried scientists studying high-latitude processes about the accuracy of fluxes needed for their studies. This survey revealed that accuracy requirements were often poorly known, and only crude estimates could be provided for most processes. The Scatterometry and Climate Workshop, held August 19–21, 2009, in the Washington, DC, area, resulted in the conclusion that accuracy requirements for vectors are quite similar to the requirements for scalar winds, except that the requirements apply to each vector component.

Very-long-term processes require biases of < 1 W m^{-2}, which are not achievable with today's observing system. The fine spatial and temporal scales needed for small-scale processes might not be consistent with global requirements for sufficient sampling over the entire global ocean. The most fruitful way forward might be to continue ongoing missions (e.g., programs for Advanced Microwave Scanning Radiometer [AMSR], AMSU, SSM/I, and scatterometers) for global coverage of turbulent fluxes and to add a few specialized missions that not only can contribute to global coverage and improved temporal sampling but also can provide the finer spatial resolution needed for many process studies (e.g., the Dual Frequency Scatterometer [DFS] or the eXtended Ocean Vector Wind Mission [XOVWM] scatterometer). Vector wind or stress data are often highly desirable for such process studies, and the derived ocean transport is often important.

Techniques are being developed to provide a wealth of surface turbulent flux information from satellites. The ongoing efforts to accurately retrieve air temperature, humidity, and stress indicate that these new techniques will have sufficient accuracy to meet the 5 W m^{-2} estimated requirements for upper ocean heat content, open ocean upwelling, dense water formation, and many other climate-related processes. It is highly likely that future instruments could be designed to meet the 2.5 W m^{-2} requirement for studying annual changes in sea ice mass. The accuracies required for ice sheet evolution and global climate change are unlikely to be met with the next generation of satellites. Winds are highly variable in short time spans and small distances; therefore, it is very important to measure them frequently from space. Variability in winds accounts for much of the variability in surface fluxes. Unless the future observing system has sufficient temporal sampling to approximate the diurnal cycle, variability on the synoptic scale and finer will be aliased, and undersampling will cause an underestimation of surface turbulent fluxes. Such sampling requires a constellation of at least three satellites. Maximum benefit of the satellite observing system can be achieved through international collaboration on data sharing, orbit planning (i.e., temporal sampling), in situ calibration, and intercalibration.

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