Satellite Observations of the Ocean: A View from the Research Community

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Summary

Satellite measurements of oceanic and air-sea interaction quantities now play a fundamental role in oceanographic and climate research, as well as in weather and ocean state prediction. The technical ability to make accurate and useful ocean measurements from space has been demonstrated and consistent, decadal time series of a few key ocean quantities have been obtained. Spaceborne ocean observations have revealed new phenomena and allowed scientific studies of processes on critical space and time scales that were previously inaccessible using only data from *in situ* observing systems. However, several significant obstacles must be surmounted before a comprehensive satellite ocean observing system for research and operations will become a reality. These challenges include the need for better temporal sampling and spatial resolution than is possible with individual satellite missions and present instruments; development and refinement of spaceborne techniques for measuring additional ocean quantities such as sea-surface salinity and the variables that control internal oceanic mixing processes; and, most importantly, national and international commitments to acquire simultaneous, multi-decadal ocean data sets. This latter challenge appears to require establishment of predictable and efficient programmatic mechanisms for transitioning techniques and satellite missions – originally developed and demonstrated in the research context – to the operational observing systems designed to supply consistent, accurate, and timely measurements for decades into the future.

1. Introduction

The last two decades have conclusively demonstrated the importance of satellite remote sensing to the understanding of ocean and climate processes. Only satellite-borne instruments can make frequent, high resolution, and spatially extensive global measurements of atmospheric forcing and upper ocean response. Over the past quarter century, engineers and scientists have collaborated to design and validate spaceborne ocean-observing instruments, and NASA and international space agencies have flown focused ocean research missions. The scientific and operational communities have used the data from individual missions and from multi-satellite constellations to expand our understanding of oceanic and climate phenomena and to increase the accuracies of weather and climate predictions. Present satellite sensor systems include all-weather active radar measurements of ocean topography, waves, and near-surface vector winds; all-weather, passive microwave measurements of ocean wind speed, sea surface temperature (SST) and sea ice; passive infrared observations of cloud-free SST during both day and night; and passive daytime visible observations of cloud-free ocean color. These measurements allow estimation of air-sea fluxes of momentum, heat, and moisture with unprecedented accuracy; they also provide detailed information on upper ocean physical and biological processes.

Ocean remote sensing data have become an integral part of oceanographic and climate research. In a recent review of the last century of oceanographic research, Walter Munk stated that "Satellites constitute the most important [oceanographic] technology innovation in modern times," (Munk, 2002). Courses focusing on oceanic and ocean-related atmospheric remote sensing are offered by 20 of the 28 graduate degree-granting institutions making up the Consortium for Oceanographic Research and Education (CORE). Of the 364 papers published during 2001 in *Journal of Geophysical Research – Oceans*, 111 (30% of the total) directly used spaceborne remote sensing data. Only 40 of these 111 papers acknowledged support from NASA or an international space agency – thus 64% of the papers that examined satellite ocean remote sensing measurements were funded by "traditional," non-space oceanographic funding agencies.

Measurements from satellite-borne ocean observing instruments have revealed new phenomena and allowed scientific studies of processes on space and time scales that were inaccessible using only data from traditional in situ observing systems. Satellite data have shown, for the first time, that tidal dissipation in the deep ocean accounts for nearly 30% of the total oceanic dissipation and contributes half of the estimated 2 TW of mixing energy needed to sustain the large-scale thermohaline circulation (Egbert and Ray, 2000). Satellite wind measurements have enabled unique quantitative analyses that shed light on lower tropospheric turbulence mechanisms and the role of convection (Patoux and Brown, 2001). Satellite measurements of sea-surface height have demonstrated the inadequacy of the classical Rossby wave theory for large-scale upper ocean response to transient forcing (Chelton and Schlax, 1996); provided the first quantitative, global description of the annual cycle of large-scale oceanic variability (Stammer (1997; see also Fu and Chelton, 2001); and allowed first-ever calculations of the frequency-wavenumber spectra and propagation characteristics of oceanic mesoscale variability (Le Traon and Morrow, 2001).

All-weather passive microwave measurements of sea-surface temperature (Wentz et al., 2000, Donlon et al., 2001, 2002), the latest addition to the suite of ocean quantities being observed by satellite instruments, are revolutionizing air-sea interaction studies (Chelton et al., 2000; Day, 2000) and contributing to analyses of hurricane and marine storm intensity and evolution (Gentemann et al., 2000).

Analyses of spaceborne measurements of sea-surface temperature, winds, and atmospheric water have illuminated details of tropical air-sea interactions that influence climate such as the equatorial cold tongue in the east-central Pacific (Chelton et al., 2001), and that allow relatively small land masses such as the Hawaiian Islands to influence surface and subsurface ocean temperatures and currents over distances of many thousands of kilometers (Xie et al., 2001). Multi-decadal satellite data sets of integrated water vapor, sea-surface temperature, and near-surface air temperature have shown strong quantitative relationships between these variables on interannual and decadal time scales, allowed accurate climate parameterizations, and demonstrated a consistent warming and moistening trend of the marine atmosphere over the last 15 years (Wentz and Schabel, 2000).

Close coupling of biological characteristics and upper ocean physical processes has been identified and examined on meso- and regional scales using satellite measurements of sea-surface temperature, ocean color, winds, and ocean topography (e.g., Solanki et al., 2001; Askari, 2001). Examination of extensive, high spatial resolution measurements of ocean color and surface roughness (from spaceborne synthetic aperature radars) has allowed identification and correlation of areas of plankton blooms resulting from coastal upwelling with suppressed roughness owing to biological surfactants, suggesting the potential for utilizing ocean color and radar backscatter data synergistically to differentiate between natural and anthropogenic slicks on the sea surface (Svejkovsky and Shandley, 2001).

Satellite measurements of many ocean and near-surface atmospheric quantities are now available in near-real-time and are being routinely assimilated into global atmospheric forecast/analysis systems at major U.S. and international meteorological centers (see, for example, Atlas et al., 2001 and references therein). Air-sea flux information derived from these operational numerical weather prediction systems are widely used to force numerical ocean circulation models, and thus satellite contributions to increasing the accuracy of numerical weather prediction yields direct benefits to oceanographic research and prediction.

Owing to their frequent global coverage and generally constant accuracy, remotely sensed data sets will form a crucial part of any ocean data assimilation/ forecasting system. It is thus essential to examine the unique challenges as well as the unique potential of satellite-borne ocean observations, in order to assure that the nation and the international community construct a balanced, comprehensive ocean observing system that maximizes the benefits for both operational and scientific activities.

2. Ocean Remote Sensing Challenges

Satellite ocean remote sensing systems are, and will continue to be, a critical component of the ocean observing system. As suggested by the scientific and operational advances outlined in the previous section, we have demonstrated the ability to obtain meaningful, well-characterized measurements of key ocean forcing and response quantities from space. Thanks to a combination of planning and luck, a broad set of ocean remote sensing instruments and missions is presently acquiring data simultaneously, allowing investigations of detailed ocean response to atmospheric forcing, and linkages between physical and biological ocean processes, that were impossible to elucidate with more limited measurement suites. Implementation and maintenance of a comprehensive spaceborne ocean measurement system, however, requires surmounting additional unique scientific/technological and programmatic/political challenges that are in many ways new to the oceanographic community. This section briefly summarizes the most important of these issues.

2a. Scientific/Technological Challenges

The wide range of important oceanic time and space scales, and their intrinsic coupling, represents the most challenging problem in justifying, designing, and implementing an ocean observing system. In many cases, significant aspects of the large-scale (1000's of kilometers), long period (annual-to-interannual) oceanic circulation are determined by small-scale, short-period variations in atmospheric forcing, and small-scale and/or relatively ephemeral oceanic processes (e.g., Large et al., 1991; Milliff et al., 1996, 1999, 2001). As summarized by Munk (2002), 99% of the oceanic kinetic energy is associated with mesoscale currents having time and space scales less than about 100 days and 100 km; fundamental forcing and response processes can have typical time scales as short as inertial periods at mid-latitudes and diurnal periods in the tropics (Milliff et al., 2001).

However, even in coastal regions where the importance of small-scale cross-shore variations are manifest, there is no clear decoupling of space and time scales – cross-shore and longshore scales may differ substantially, short time scales may not be associated with small spatial scales, and remote forcing on yet different scales may generate signals which propagate as waves that profoundly influence the local coastal circulation.

Understanding and eventually accurately predicting ocean and climate conditions thus requires global measurements of the important small-scale forcing and response processes. These measurements must be sustained over multi-decadal ocean and climate time scales in order both to provide adequate frequency resolution, and to provide adequate statistics for analyses of processes on the annual and interannual time scales which characterize the ocean's basin-scale ability to adjust to transient, localized forcing. Perhaps the major oceanographic accomplishment of the late 20th century was the recognition that "dozens of [apparent] low frequency phenomena … are the illegitimate offspring of an aliased liaison" (Munk, 2002) – in other words, inadequate sampling led to incorrect quantitative characterizations and even more inaccurate physical models for ocean circulation phenomena which do not, in reality, exist!

To be scientifically valid, the future ocean observing system must measure the important small scale processes, globally, for multi-decadal periods. While individual spaceborne instruments have significantly better spatial resolution and coverage than any traditional earth-bound technique, satellite revisit times (dictated by orbital mechanics and measurement geometry) are often longer than required, leading to inadequate sampling. In cases of measurement approaches which rely on visible or infrared radiation which cannot penetrate to the ocean surface through clouds, sampling is even more intermittent, as significant ocean areas are cloud-covered up to 90% of the time (Rossow and Schiffer, 1991). As with the present spaceborne atmospheric observing constellation, multiple measurement systems in coordinated orbits will often be necessary to achieve proper sampling (Schlax et al., 2001; Chelton and Schlax, 2002; Schlax and Chelton, 2002).

The spatial resolution of some present satellite instruments will need to be improved to allow resolution of small-scale features, especially near coasts. Present passive microwave instruments suffer from land contamination through antenna sidelobes, thus prohibiting accurate geophysical measurements within 50-100 km of land (including small islands). Contamination and other technical difficulties restrict active microwave scatterometer (for vector wind measurements) and altimeter (for sea-surface topography, currents, and wave heights) data within a few tens of kilometers of land. With the flights of calibrated spaceborne Synthetic Aperture Radar [SAR] instruments such as the European Space Agency's ERS-1 and ERS-2 missions, the Canadian/NASA RADARSAT mission, and the recent launch of the European Space Agency's ENVISAT mission, high resolution wind measurements have been obtained in coastal areas, although with grossly inadequate sampling frequencies and swath widths. The potential of spaceborne, broad-swath SAR measurements for the measurement and monitoring of many important marine quantities is outlined in a dedicated volume of the *Johns Hopkins APL Technical Digest, 2000*.)

As well as implementing a satellite observing system with adequate sampling for the variables and techniques that have already been demonstrated, a comprehensive future system would contribute greatly to research if it measured additional important quantities. For example, sea-surface salinity is the key tracer for freshwater fluxes to and from the ocean resulting principally from precipitation, evaporation, ice melting, and river runoff. A three-year SSS salinity mission was chosen as one of the NASA Earth System Science Pathfinder (ESSP) selections in 2002, with flight planned for mid-decade. Similarly, although it is known that bathymetric roughness on scales down to 12 km wavelength generate turbulence that substantially mixes heat within the ocean, only 0.1% of the deep ocean floor has been mapped on these scales. Lack of high resolution bathymetry in the deep ocean hinders understanding of ocean turbulence processes and may be a significant barrier to increased accuracy in predictions of present ocean circulation models (Smith and Sandwell, 1994). Acquisition of such bathymetric data from ships is unrealistically expensive and slow – simulations suggest that rapid, accurate, and extensive high resolution ocean floor topography estimates may be obtainable from specially designed spaceborne microwave altimeters.

Detailed calibration and validation of new measurements and new techniques are essential if the data are to be exploited rapidly and fully by both the research and operational communities. It is well-understood that quantitative knowledge of measurement error characteristics is critical for the proper assimilation of data into numerical models. However, even non-model-based use of data for operational activities such as weather forecasting and marine hazard prediction requires detailed understanding of the strengths and weaknesses of the measurements. Discussing the use of QuikSCAT scatterometer data for identifying incipient tropical cyclones (Sharp et al., 2002) and improving hurricane forecasts, Evan Forde recently noted "Forecasters will use no satellite or tool until it's proven itself. The stakes are too high … The people at the [NOAA] Hurricane Center were cautious to accept QuikSCAT but now they're looking at it every day" (Iannotta, 2002).

2b. Programmatic Challenges

The most important programmatic issues associated with spaceborne ocean observing systems result from their cost; the long time scales required to design, build and launch any satellite systems; and the need to obtain consistent ocean measurements for multi-decadal periods which far exceed the design lifetimes of individual research missions. Historical and ongoing successful ocean observing satellite missions attest to our technical ability to obtain important measurements from space, and the missions have demonstrated the scientific and operational utility of the data and the unique advantages of spaceborne platforms. However, launch costs, even into low earth orbit, greatly exceed \$10K/kg (NRC, 2000*a*), and launch opportunities are limited. These factors combine to increase the costs of spacecraft and instruments in a variety of ways, including increased miniaturization; construction of multi-sensor missions which inevitably require engineering compromises regarding measurement and orbit geometry and for which the schedule is dictated by that of the slowest instrument or subsystem; and the need to design for increased on-orbit reliability given the costs of repair or replacement (NRC, 1995). Thus, although space is clearly a harsh environment, the costs for spaceborne hardware are typically two orders of magnitude larger than the costs for similar capabilities designed to operate in similarly harsh terrestrial environments (including in the deep ocean; Haynes, 1988).

As with almost all other Earth observing satellites, ocean observation missions typically cost in excess of \$100M (for example, the total cost allocated by NASA for small, focused, rapid development, PI-led Earth System Science Pathfinder missions is \$125M per mission). At this funding level, missions undergo significant scrutiny from the science community, the administration, and Congress, discouraging technological risk-taking and increasing time to launch. Equally important, at these costs satellite observing systems cannot be considered “scalable” in the sense that one can build a portion of a satellite or a small satellite and simply add to the observing capability as funds become available. In contrast, one can build additional moorings or add additional in situ sensors in a straightforward manner.

As noted in section 2a above, ocean and climate studies require multi-decadal time series which resolve short term variability within a framework of long term change. Individual Earth-observing satellite mission hardware is typically designed for 2-5 year lifetimes. This is particularly true for NASA ***research missions*** that demonstrate the measurement technology, establish and then improve the accuracy of the geophysical products (through ground processing algorithm refinement), and provide an initial data set for geophysical analyses (science) and operational demonstrations. However, while extremely valuable for some high frequency process studies and for the design of future observing systems, these relatively short-duration (2-5 year) data sets are inadequate for studying critical interannual and decadal scale ocean and climate phenomena.

The oceanographic community has benefited greatly from the unanticipated long lifetimes of some NASA research missions. For example. the Coastal Zone Color Scanner (CZCS), designed to measure chlorophyll concentration in water, sediment distribution, and sea-surface temperature of coastal and open ocean waters under cloud-free conditions, was launched in late 1978 on the NASA Nimbus 7 mission. Although the planned mission lifetime was only a few years, the CZCS continued to operate until 1986. Similarly, the NASA/CNES TOPEX/Poseidon ocean radar altimeter mission was launched in August, 1992 for a planned 3-year baseline mission with possible extended lifetime to 6 years. The spacecraft and instruments have performed flawlessly and continue to operate today, more than a decade later. As a result of its decadal lifetime in addition to the quality of its measurements, Walter Munk considered TOPEX/Poseidon to be "the most successful ocean experiment of all times" (Munk, 2000).

While serendipitously long mission durations should be (and are) exploited by the research community, they are no substitute for the detailed planning and coordination required for a comprehensive, long-term ocean observing satellite constellation. Indeed, extended research missions even present problems for NASA itself in the present budgetary environment. Although the marginal costs of extended operations, ground processing, and research support are small compared with the investments required to build and launch an Earth satellite mission, without additional funding the agency may find itself victimized by its own successes, as money that could and should be invested by NASA to develop the next generations of technology and advanced scientific analyses is instead used to continue acquisition of data from extended research missions (an equally worthy cause).

I believe that research-quality spaceborne ocean observations must eventually be acquired by an operational satellite observing constellation, similar to those presently conducted under the auspices of DoD (e.g., the Defense Meteorological Satellite Program, DMSP) and NOAA (e.g., the Polar Orbiting Environmental Satellite System, POES, and its geostationary equivalent, GOES) in support of the nation's and the world's need for meteorological data. (The two operational US polar orbiting meteorological satellite systems will be merged into the single NPOESS system near the of this decade.) The operational observing systems are designed and operated to provide adequate sampling, near-real-time data continuously (24 hours per day, seven days per week), with predictable formats and product quality. Most importantly, the operational satellite constellations are designed to provide continuous, consistent data streams for decadal (and longer) time periods, well in excess of the lifetimes of the individual satellite missions that collectively make up the constellation.

The transition from research to operations is a problem common to all observing systems, but the planning time scales, system costs and stringent scientific requirements make this transition especially challenging for satellite systems in general, and oceanographic systems in particular. Sensors and their associated processing algorithms are in a state of continual improvement as knowledge and technology improve. In the area of flight hardware, continuous improvement of technology is difficult to accommodate by the operational agencies if they use "block" purchases of multiple copies of a satellite system in order to reduce costs. If the research community is to contribute improvements to algorithms, they require access to the raw data and ancillary data that describe sensor operations, calibration, and testing (NRC,2000*b*).

There is presently no clear, predictable path to integrate research and operational satellite missions, although NASA, NOAA, and the NPOESS Integrated Program Office have achieved much of substance in their well-planned, but (apparently) essentially ad hoc NPOESS Preparatory Program. Both NOAA and NASA have recognized the importance of transition from research to operations, and they have commissioned NRC studies on both transition in general and extension of Earth-observing *research* missions, some of which have operational potential. Of all the Earth science disciplines, it seems likely that oceanography will benefit most directly from the successful establishment of a transition infrastructure – as noted above, the stringent sampling and resolution criteria and the long time scales that characterize many ocean processes require an observing system beyond the capabilities of any research agency alone.

3. Conclusions and Recommendations

Spaceborne measurements of ocean forcing and response are essential for ocean research and for weather, ocean, and climate prediction. Only space-based measurements have even the *potential* for acquiring measurements with the necessary accuracy, global coverage, and resolution. The U.S., especially (and appropriately) through the efforts of NASA, has been at the forefront of developing ocean remote sensing techniques, demonstrating, validating, and refining a range of ocean-related geophysical products, and acquiring initial scientifically useful (although not necessarily adequately sampled) data sets through research missions. The oceanographic research community has embraced the satellite measurements; researchers have contributed directly to establishing the requirements for research missions and to characterizing and exploiting the resulting data sets. Continued progress requires surmounting three main technical and programmatic challenges:

1) Developing and demonstrating techniques for extending the set of ocean variables that can be measured accurately from space, including (for example) sea-surface salinity and quantities related to deep ocean mixing processes;
2) Increasing the temporal and spatial resolution of the full suite of spaceborne ocean measurements to extend both the geographical (e.g., into the societally critical coastal zone) and the phenomenological extent of the data sets; and
3) Extending the duration of the full, simultaneously measured ocean (and associated forcing) data set to allow resolution of important decadal ocean and climate processes – time scales well beyond the design lifetime of individual satellite measurements, but well within the demonstrated capability of operational satellite constellation programs.

The first two challenges are primarily technical, and programs exist within NASA, NOAA, and DoD to surmount them, given appropriate, but realistic, funding. The third challenge requires transition of the suite of spaceborne ocean measurements from the primarily research mission context to that of an operational observing system. Neither the national nor the international infrastructure exists to accommodate this task, and few examples of similar transitions exist. However, unless and until such a transition takes place, the dream of a comprehensive ocean observing system to support both research and operations will remain unfulfilled, and the significant national investment to date will yield maximum returns.

References:

Askari, F., 2001: Multi-sensor remote sensing of eddy-induced upwelling in the southern coastal region of Sicily. *Int. J. Rem. Sens.*, **22**, 2899-2910.

Atlas, R., R.N. Hoffman, S.M. Leidner, J. Sienkewicz, T.-W. Yu, S.C. Bloom, E.Brin, J. Ardizzone, J. Terry, D. Bungato, and J.C. Jusem, 2001: The effects of marine winds from scatterometer data on weather analysis and forecasting. *Bull. Am. Met. Soc.*, **82**, 1965-1990.

Chelton, D.B., F.J. Wentz, C.L. Gentemann, R.A. de Szoeke, and M.G. Schlax, 2000: Satellite microwave SST observations of transequatorial tropical instability waves. *Geophys. Res. Lett.*, **27**, 1239-1242.

Chelton, D.B., S.K. Esbensen, M.G. Schlax, N. Thum, M.H. Freilich, F.J. Wentz, C.L. Gentemann, M.J. McPhaden, and P.S. Schopf, 2001: Observations of coupling between surface wind stress and sea surface temperature in the eastern tropical Pacific. *J. Clim.*, **14**, 1479-1498.

Chelton, D.B. and M.G. Schlax, 1996: Global observations of oceanic Rossby waves. *Science*, **272**, 234-238.

Chelton, D.B. and M.G. Schlax, 2002: The Accuracies of Smoothed Sea Surface Height Fields Constructed from Tandem Altimeter Datasets. *J. Atmos. Oceanic Tech.* (submitted).

Day, Charles, 2000: Two satellites observe details of ocean-atmosphere coupling. *Physics Today*, June 2000, 23-24.

Donlon, Craig, C. Gentemann, and F.J. Wentz, 2001: Measuring surface temperature with microwave sensors. *Backscatter*, **12**, 37-39.

Donlon, C. J., P. Minnett, C. Gentemann, T. J. Nightingale, I. J. Barton, B. Ward and J. Murray, 2002: Towards improved validation of satellite sea surface skin temperature measurements for climate research. *J. Clim.*, **15**, 353-369.

Egbert, G.D. and R.D. Ray, 2000: Significant dissipation of tidal energy in the deep ocean inferred from satellite altimeter data. *Nature*, **405**, 775-778.

Fu, L.-L. and D.B. Chelton, 2001: Large-scale ocean circulation. In *Satellite Altimetry and Earth Sciences*, L.-L. Fu and A. Cazenave, eds., Academic Press, 133-168.

Gentemann, C.L., D.K. Smith, and F.J. Wentz. 2000: Microwave SST correlations with hurricane intensity. *Proc. 24th Conf. Hurricanes and Tropical Cyclones*, American Meteorological Society.

Haynes, W., 1988: The issue is cost. *Space Studies Inst.*, Update, **13** No. 2, 1-5.

Iannotta, B., 2002: NOAA asked to assume responsibility for QuikScat. *Space News*, 7 Oct 2002, 34.

Johns Hopkins APL Technical Digest, 2000: Coastal and marine applications of wide-swath SAR, **21**, 176pp.

Large, W.G., W.R. Holland, and J.C. Evans, 1991: Quasi-geostrophic ocean response to real wind forcing: The effects of temporal smoothing. *J. Phys. Oceanogr.*, **21**, 998-1017.

LeTraon, P.Y. and R. Morrow, 2001: Ocean currents and eddies. In *Satellite Altimetry and Earth Sciences*, L.-L. Fu and A. Cazenave, eds., Academic Press, 171-215.

Milliff, R.F., W.G. Large, W.R. Holland, and J.C. McWilliams, 1996: The general circulation responses of high-resolution North Atlantic ocean models to synthetic scatterometer winds. *J. Phys. Oceanogr.*, **26**, 1747-1768.

Milliff, R.F., W.G. Large, J. Morzel, G. Danabasoglu, and T.M. Chin, 1999: Ocean general circulation model sensitivity to forcing from scatterometer winds. *J. Geophys. Res.*, **104**, 11,337-11,358.

Milliff, R.F., M.H. Freilich, W.T. Liu, R. Atlas, and W.G. Large, 2001: Global ocean surface vector wind observations from space. In *Observing the Oceans in the 21st Century*, C.J. Koblinsky and N.R. Smith (Eds), 102-119.

Munk, W., 2002: The evolution of physical oceanography in the last hundred years. *Oceanography*, **15**, 135-141.

National Research Council (NRC), 1995: *Earth Observations from Space: History, Promise, and Reality.* Washington, D.C., National Academies Press, 310pp.

National Research Council (NRC), 2000*a*: *The Role of Small Satellites in NASA and NOAA Earth Observation Programs.* Washington, D.C., National Academies Press, 92pp.

National Research Council (NRC), 2000*b*: *Issues in the Integration of Research and Operational Satellite Systems for Climate Research. Part II: Implementation.* Washington, D.C., National Academies Press, 82pp.

Patoux, J. and R.A. Brown, 2001: Spectral analysis of QuikSCAT surface winds and two-dimensional turbulence. *J. Geophys. Res.*, **106**, 23,995-24,005.

Rossow, W.B. and R.A. Schiffer, 1991: ISCCP cloud data products. *Bull. Am. Met. Soc.*, **72**, 2-20.

Schlax, M.G., D.B. Chelton, and M.H. Freilich, 2001: Sampling errors in wind fields constructed from single and tandem scatterometer datasets. *J. Atmos. Oceanic Tech.*, **18**, 1014-1036.

Schlax, M.G. and D.B. Chelton, 2002: The Accuracies of Crossover and Parallel-Track Estimates of Geostrophic Velocity from TOPEX/POSEIDON and Jason Altimeter Data. *J. Atmos. Oceanic Tech.*, (submitted).

Sharp, R.J., M.A. Bourassa, and J.J. O'Brien, 2002: Early detection of tropical cyclones using SeaWinds-derived vorticity. *Bull. Am. Met. Soc.*, **83**, 879-889.

Smith, W.H.F. and D.T. Sandwell, 1994: Bathymetric prediction from dense satellite altimetry and sparse shipboard sampling. *J. Geophys. Res.*, **99**, 21,803-21,824.

Solanki, H.U., R.M. Dwivedi, and S.R. Nayak, 2001: Synergistic analysis of SeaWiFS chlorophyll concentration and NOAA-AVHRR SST features for exploring marine living resources. *Int. J. Rem. Sens.*, **22**, 3877-3882.

Stammer, D., 1997: Steric and wind-induced changes in TOPEX/Poseidon large-scale sea surface topography observations. *J. Geophys. Res.*, **102**, 20,987-21,009.

Svejkovsky, J. and J. Shandley, 2001: Detection of offshore plankton blooms with AVHRR and SAR imagery. *Int. J. Rem. Sens.*, **22**, 471-485.

Wentz, F.J. and M. Schabel, 2000: Precise climate monitoring using complementary data sets. *Nature*, **403**, 414-416.

Wentz, F.J., C. Gentemann, D. Smith, and D. Chelton, 2000: Satellite measurements of sea surface temperature through clouds. *Science*, **288**, 847-849.

Xie, S.-P., W.-T. Liu, Q. Liu, and M. Nonaka, 2001: Far-reaching effects of the Hawaiian Islands on the Pacific ocean-atmosphere system. *Science*, **292**, 2057-2060.