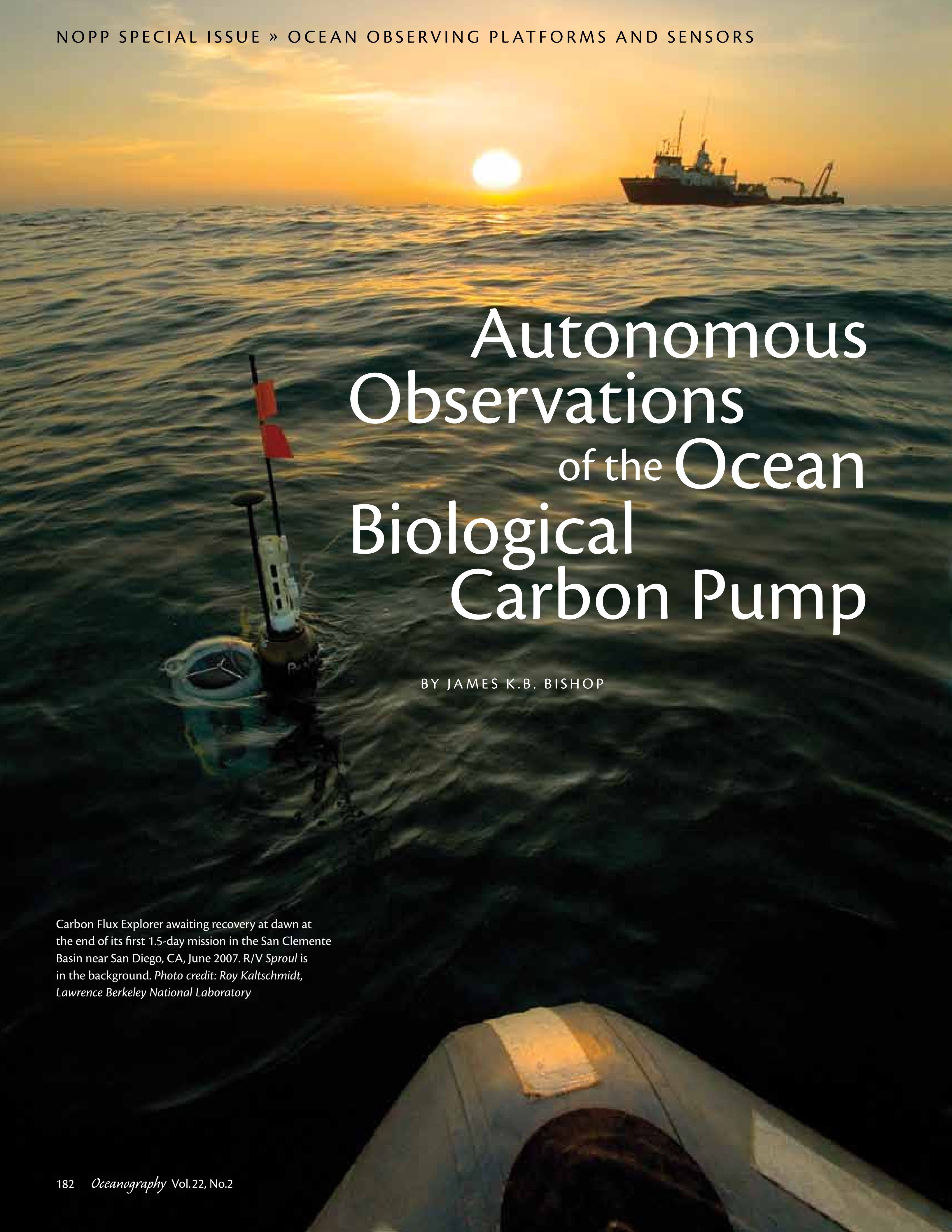
Autonomous Observations of the Ocean Biological Carbon Pump

BY JAMES K.B. BISHOP



Carbon Flux Explorer awaiting recovery at dawn at the end of its first 1.5-day mission in the San Clemente Basin near San Diego, CA, June 2007. R/V *Sproul* is in the background. *Photo credit: Roy Kaltschmidt, Lawrence Berkeley National Laboratory*

ABSTRACT. Prediction of the substantial biologically mediated carbon flows in a rapidly changing and acidifying ocean requires model simulations informed by observations of key carbon cycle processes on the appropriate spatial and temporal scales. From 2000 to 2004, the National Oceanographic Partnership Program (NOPP) supported the development of the first low-cost, fully autonomous ocean profiling Carbon Explorers, which demonstrated that year-round, real-time observations of particulate organic carbon (POC) concentration and sedimentation could be achieved in the world's ocean. NOPP also initiated the development of a particulate inorganic carbon (PIC) sensor suitable for operational deployment across all oceanographic platforms. As a result, PIC profile characterization that once required shipboard sample collection and shipboard or shore-based laboratory analysis is now possible to full ocean depth in real time using a 0.2-W sensor operating at 24 Hz. NOPP developments further spawned US Department of Energy support to develop the Carbon Flux Explorer, a free vehicle capable of following hourly variations of PIC and POC sedimentation from the near surface to kilometer depths for seasons to years and capable of relaying contemporaneous observations via satellite.

We have demonstrated the feasibility of real-time, low-cost carbon observations that are of fundamental value to carbon prediction and that, when further developed, will lead to a fully enhanced global carbon observatory capable of real-time assessment of the ocean carbon sink, a needed constraint for assessment of carbon management policies on a global scale.

INTRODUCTION

The entire amount of marine phytoplankton biomass turns over, on average, once every one to two weeks, yet these short-lived phytoplankton fix carbon at a rate of 40–50 petagrams (Pg) C y^{-1} and account for roughly half of global primary productivity (Antoine et al., 1996; Falkowski et al., 1998; Field et al., 1998; Westberry et al., 2008). Approximately 10 Pg C y^{-1} is exported below 100 m to the deep sea, mostly carried by sinking particles (Figure 1). This very fast process, commonly referred to as the ocean's "biological carbon pump" (Broecker and Peng, 1982; Volk and Hoffert, 1985), is important to the long-term regulation of atmospheric CO_2 (Siegenthaler and Sarmiento, 1993) as it is one principal determinant of the vertical distribution of carbon in the ocean and hence of the surface partial pressure of CO_2 governing air-sea CO_2 exchange.

Figure 1 represents a steady-state view of the carbon cycle with the down arrows of carbon export in balance with a net upwelling of water enriched with remineralized CO_2. The fact that the strength of the biological carbon pump has been estimated through a grand averaging of decades of sparse ship observations of nutrient and carbon gradients in waters of the ocean's main pycnocline means that it is not presently possible to determine from the observations if and how the biological carbon pump may be changing in response to rising atmospheric CO_2 levels through increasing ocean acidification and warming-induced changes in stratification and circulation.

The effectiveness of the biological pump may be negatively impacted by the now readily detected ocean uptake of the anthropogenic CO_2 added to the atmosphere since the Industrial Revolution. The pH of today's surface ocean waters has decreased by ~ 0.1 units since the Industrial Revolution and is projected to decrease by another 0.3 units by 2100 (Sabine et al., 2004; Feeley et al., 2004). Current models predict that continued ocean acidification will lead to a decline in the productivity of calcium-carbonate-forming coral reef communities, calcifying shellfish, zooplankton (foraminifera and pteropods), and phytoplankton (coccolithophores) in the coming decades (Orr et al., 2005; Kleypas et al., 2006; Fabry et al., 2008).

Toward Better Ocean Carbon Cycle Predictions

The only way to predict future trajectories of the global carbon cycle is through computer model simulations that accurately represent the substantial biotic carbon flows in the ocean. The parameterizations embedded within models for biotic carbon cycle processes are necessarily crude as they represent the sum of knowledge derived from observations that are sparse in time and space (Dickey et al., 2006; Buesseler et al., 2007a). A crucial parameter in these models is the carbon remineralization length scale, which summarizes how rapidly particulate organic carbon (POC) below the surface mixed layer (~100-m thick) is converted to dissolved inorganic carbon (DIC, the sum of CO_2, H_2CO_3, HCO_3^-, and CO_3^{2-} species) as the particles sink through the water column. A small remineralization length scale means that conversion of sinking POC back to CO_2 occurs closer to the surface,

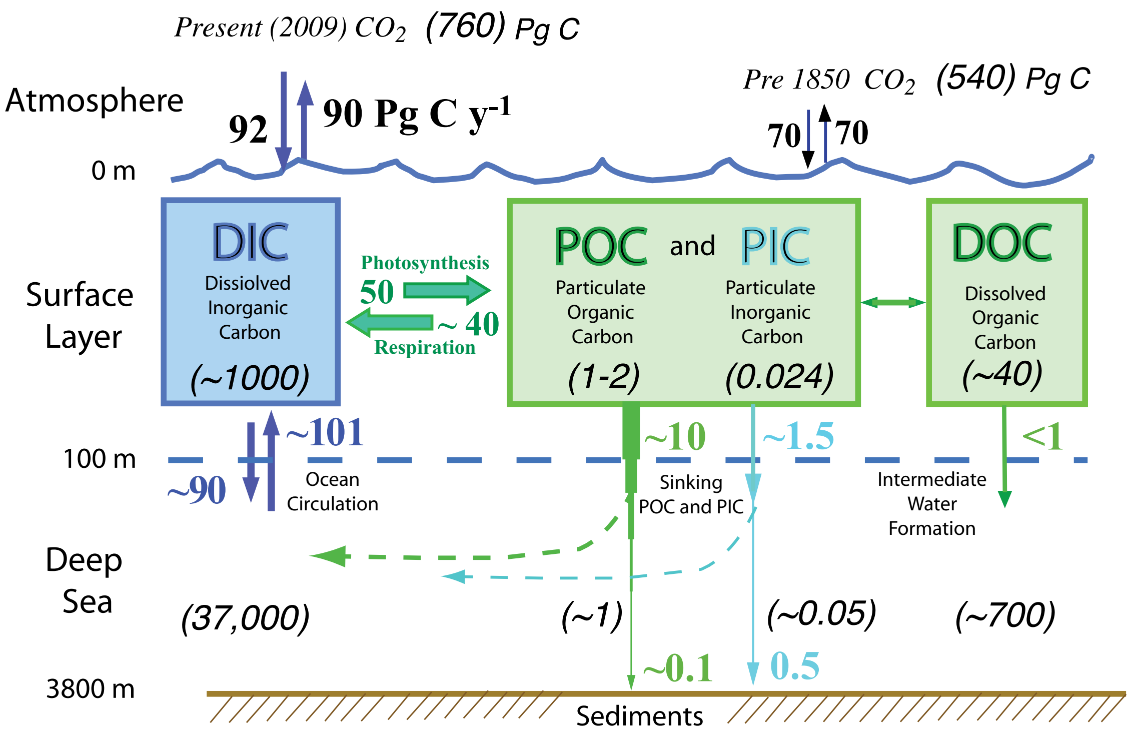


Figure 1. Steady-state representation of the carbon pools (Pg C, in italics and parentheses) and transports (Pg C y^{-1}, next to arrows) for the mid 1990s representing the synthesis of decades of ship observations. The diagram is based on recent summary views of the large-scale carbon cycle (Denman et al., 2007; Sarmiento and Gruber, 2006) with updates on particulate inorganic carbon fluxes and stocks (Berelson et al., 2006; author's unpublished data), and the author's extrapolation of Hansell et al. (2002) data on dissolved organic carbon transports due to intermediate water formation. PIC is composed of calcium carbonate minerals, calcite and aragonite. Light dashed lines denote remineralization of POC and PIC back to DIC. The biological carbon pump (leading to carbon sedimentation) is very fast and dynamic, and poorly observed in space and time. The central unanswered question is whether or not carbon sedimentation is changing in a rapidly changing world. What changes are in store for the future? Our focus is on development of autonomous sensors for particulate organic carbon (POC) and particulate inorganic carbon (PIC) concentration and flux.

thus upwelling would bring water enriched in CO_2 back to the surface faster and thus decrease the capacity of the ocean to take up CO_2 from the atmosphere. Many ocean biogeochemistry models still use a single space- and time-invariant remineralization formula ($\Phi_Z = \Phi_{100}(Z/100)^{-b}$; b = 0.86; Z is depth in meters; Φ_{100} is sinking carbon flux at 100 m) derived from Martin et al.'s (1987) fair weather observations in the North Pacific, and cannot capture the roles of different biological regimes, or the impact of changes in ballast (or dense biogenic mineral particles such as calcium carbonate or opaline silica that give sinking aggregate particles negative buoyancy; Armstrong et al., 2002) among other things, on the global carbon cycle.

Already, limited ship observations provide compelling evidence that simple parameterizations of sedimentation are unrealistic. For example, Buesseler et al. (2007a) found very different remineralization length scales during summertime conditions in oliogotrophic waters near Hawaii (Martin b factor ~ 1.4) vs. productive waters of the Oyashio Current (b ~ 0.3) near Japan; Lam and Bishop (2007) showed that carbon remineralization length scales (independent of ballasting effects) were very different during summer conditions north and south of the Antarctic Polar Front.

Some model parameterizations of carbon sedimentation and remineralization have evolved past the simple Martin formula but remain correlative and rely

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heavily on records from moored sediment traps deployed below 1000 m, much deeper than the typical remineralization depth (Armstrong et al., 2002; Dunne et al., 2005; Gehlen et al., 2006; Lutz et al., 2007), and extrapolations of sparse (and fair weather) near surface observations. POC fluxes in the upper kilometer of the ocean are very underobserved and require great effort because all observations to date have required ships to be present (Buesseler et al., 2007b). Virtually no observations of particulate inorganic carbon (PIC) sedimentation have been made in the upper kilometer, yet the understanding of PIC dynamics is of fundamental importance to the biological carbon pump.

Calcium carbonate particles (predominantly coccoliths), when incorporated into organic-matter-rich aggregates, are important contributors to excess density (i.e., the "ballast"), which causes these particles to sink (Armstrong et al., 2002). Little is known about how carbonate particle productivity will change and impact sedimentation. Riebesell et al. (2000), in laboratory cultures, found strong suppression of coccolithophore productivity with increasing CO_2. Iglesias-Rodriguez et al. (2008a), using a different laboratory methodology, recently reported the opposite result. A decrease in supply of carbonate ballast to aggregates could present an unexpected and amplifying feedback, as the remineralization of more slowly sinking aggregates would occur shallower in the water column and thus increase near-surface carbon concentrations and slow down carbon uptake from the atmosphere. If the supply of ballast increases, higher particle sinking rates would lead to an enhanced biological carbon pump and increased CO_2 uptake. The sign of the change of coccolithophore productivity under increasing CO_2 is currently a debated point (Riebesell et al., 2008; Iglesias-Rodriguez et al., 2008b). In other words, we don't know if the 10 Pg C y^{-1} bio-carbon pump (Figure 1) will be short-circuited or enhanced through changed carbonate ballasting. In situ knowledge of carbonate dynamics would resolve these issues.

"...UNDERSTANDING THE COUPLING BETWEEN SHORT-LIVED SURFACE PROCESSES AND CARBON SEDIMENTATION IS HUGELY LIMITED BY A LACK OF OBSERVATIONS."

CARBON EXPLORERS AND SENSORS

Autonomous technology, which promises to overcome the space-time gap in ocean bio-carbon observations, was first developed with National Oceanographic Partnership Program (NOPP) support (details in the last section of this paper).

This article focuses on low-cost, low-power carbon sensors and telemetry-enhanced ocean-profiling Lagrangian floats, and the use of these integrated systems to follow day-to-day variations of carbon biomass and flux. As will be shown below, Lagrangian platforms are ideally suited for carbon sedimentation measurements. The international program Argo (CLIVAR, 1999; Roemmich, this issue) has seeded the world's ocean with thousands of profiling Lagrangian floats to gather temperature and salinity profiles and information on mid-depth circulation for investigation of the ocean's climate state. Argo floats are designed to profile to the surface from kilometer depths once every 10 days and record deep currents between profiles over five years. The Carbon Explorer, described next, was born from float technology developed for Argo but is designed to observe carbon processes on faster biological time scales needed for process understanding.

The Carbon Explorer

Since 2001, high-frequency (diurnal) exploration of particulate carbon dynamics in the upper 1000 m in the ocean has been possible using sensor-enhanced, ocean-profiling Argo-style floats, called Carbon Explorers (CEs, Figure 2a). The profiling vehicle for CE is a modified Sounding Oceanographic Lagrangian Observer (SOLO) float developed by NOPP partners at the Scripps Instrument Development Group (Russ Davis, Jeffrey Sherman, and Lloyd Regier). Explorers carry a transmissometer sensor developed by NOPP partner WET Labs Inc., which yields a remarkably accurate estimate of POC concentration (Bishop et al., 2002; Bishop and Wood, 2008), and a light-scattering sensor (Seapoint Inc.) in addition to sensors for temperature and salinity measurements. The transmissometer has also been used to determine systematic sedimentation fluctuations at depth (Bishop et al., 2004), which we call the Carbon Flux Index (CFI, Figure 2b). CFI is the systematic measure of the rate of particle accumulation on the upward-looking transmissometer window during the time that the float is

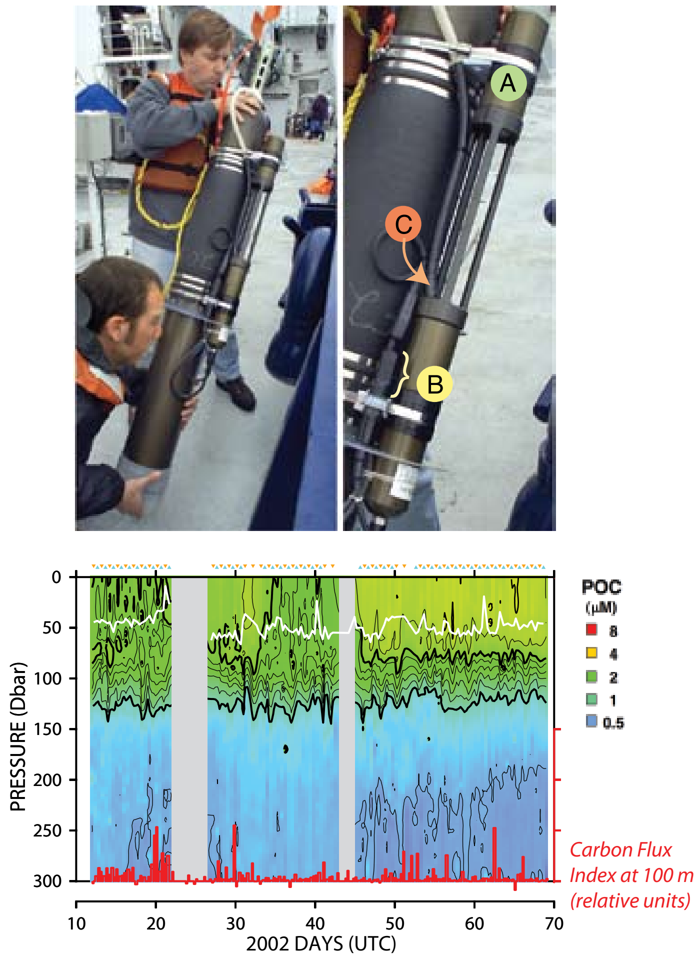

Figure 2. (Top) Carbon Explorer showing optical transmissometer (A) and scattering (B) sensors. The transmissometer has been configured to permit determination of the systematic variations of carbon sedimentation. While the float is at depth between profiles, particles accumulate on the upward-looking window of the transmissometer (C). Prior to profile operations, the transmissometer is read, the window flushed clean with flowing seawater, and the transmission reading determined a second time. The difference in transmission normalized by time at depth between profiles is the Carbon Flux Index (CFI). (Bottom) Particulate organic carbon (POC) concentration time series from the Antarctic Circumpolar Current near 55°S, 170°W (from Bishop et al., 2004). The POC time series was constructed from dawn, mid-day, and dusk profiles from 1000, 300, and 300 m, respectively. Systematic variation of CFI measured at 100 m is shown in red.

drifting at depth between profiles. The combination of in-water physical parameters (T, S, density) and particle-sensitive optics, along with satellite remotely sensed properties (winds, clouds, color) provides a powerful framework for understanding bio-carbon dynamics in the ocean.

Carbon Explorer Science

Carbon Explorers, yo-yoing up and down in the upper kilometer of the water column every day, have revealed exciting new insights into the biological pump. Biological productivity in the ocean requires not only light and macronutrients (e.g., NO_3, PO_4) but also micronutrients such as iron. The three great ocean regions (Southern Ocean, Equatorial Pacific, and subarctic North Pacific) exhibiting high macronutrients and low productivity (HNLC) are assumed to be lacking in micronutrients. Mineral aerosols (dust), lofted from arid regions and transported long distances in the atmosphere before deposition to the surface, are hypothesized to be a major source of iron to the ocean. With the first deployment of two Carbon Explorers in the North Pacific in April 2001, Bishop et al. (2002) documented for the first time the direct enhancement of marine productivity after an Asian dust storm, but found that episodes of dust-iron-enhanced marine productivity lasted only two weeks, much shorter than commonly believed. Prior to Carbon Explorer, no ship expedition in the world's ocean had captured a time series of the biological response to dust deposition. Dust storms crossing over the north Pacific occur on average once every three years, and it turned out that the April 2001 Gobi Desert dust event that we observed was one of the biggest dust storms crossing the North Pacific in decades. Simply stated, by "being there" for an entire year we had a one in three chance of observing a dust storm.

In 2002, CEs followed an iron "fertilization" experiment in the HNLC Southern Ocean for two months, from the beginning to the end of the experiment, and continued monitoring for another year after the ships had departed. CEs recorded strong biological/carbon sedimentation response to purposeful iron amendment of low silicate-high nitrate waters near 55°S, 172°W during the Southern Ocean Iron Experiment (SOFeX; Coale et al., 2004). Two Explorers—one deployed in iron-amended waters and one deployed nearby as control—while drifting for hundreds of kilometers in the Antarctic Circumpolar current, completed 180 profiles, each to depths as great as 1000 m, three times per day, until the effects of SOFeX iron were no longer seen. The finding of enhanced carbon export north of the Antarctic polar front in low-silica, high-nitrate waters was unexpected, and invalidated the central hypothesis of SOFeX that iron amendment of low-silica waters would lead to a null result (Bishop et al., 2004).

The SOFeX Explorers continued operation in the stormy Southern Ocean following natural carbon cycle processes for another year (Bishop and Wood, in press). One CE, deployed at 66°S, 172°W, operated through the Antarctic winter in the ice edge zone, in 24-hour darkness, and returned an uninterrupted data stream to shore.

Track Record

Overall, the 12 CEs deployed to date have proved to be operationally robust (only one ended its mission prematurely and a thirteenth CE was lost on deployment after colliding with the ship). The record demonstrates the utility of faster and bidirectional ORBCOMM Inc. telemetry: mission parameters could be changed post deployment, and enough power was saved to permit the additional optical sensors and increases in profiling cycles. CEs typically achieved ~ 350,000 m of round-trip profiling distance per float. The optical sensors remained usable throughout the mission, suffered minimal biofouling effects, and, with a single exception, all outlived the floats.

Work is required to transition CEs from ORBCOMM to Iridium telemetry to address data gaps for Explorers deployed in waters poleward of 50°N and 50°S. CEs have been proven for both long-term monitoring and process studies.

Sensor for Particulate Inorganic Carbon

As mentioned above, CO_2 acidification of the ocean is expected to impact calcifying plankton, and may impact carbon sedimentation in unexpected ways. Fewer than several dozen PIC profiles of the world's ocean have been published on shore-based laboratory analysis of filtered seawater samples; a shipboard method for PIC used optical backscattering measurements before and after acidification of ship-collected water samples (Balch et al., 2002). There was a need for an autonomous, chemistry-free sensor.

The PIC sensor (Figure 3A) developed with NOPP partner WET Labs Inc. is designed to permit rapid profiling of the ocean's water column. It detects photons that interact with the strongly birefringent calcite and aragonite mineral forms of calcium carbonate. Mineral particles in the ocean are by far dominated by calcium carbonate particles, which have an oceanic concentration range of 0.005 to 40 µM (Guay and Bishop, 2002).

In a modification of a 25-cm pathlength WET Labs Inc. C-Star transmissometer, light from a light-emitting diode laser source is filtered such that it is polarized in the horizontal plane while the detector on the other end of a 25-cm open-water path is guarded by a second high-efficiency polarizer oriented to select only for vertically polarized light. In this way, the primary beam of light from the laser is blocked from passing to the detector. Suspended calcium carbonate minerals in the optical path partially depolarize the primary beam and thus give rise to a signal at the detector.

The first operational prototype ocean profiling PIC sensor (Figure 3a) was deployed during the 2003 CLIVAR repeat-hydrography transect, A16N, in the North Atlantic. It rode the CLIVAR conductivity-temperature-depth (CTD) rosette from the surface to the ocean floor hundreds of times. In Iceland Basin waters where PIC levels were as high as several µM, its data replicated shipboard birefringence analyses of rosette-collected water samples (Guay and Bishop, 2002) and replicated PIC distributions determined from chemical analysis of particulates filtered from parallel water samples. This first profiling sensor, however, had major thermal and pressure hysteresis effects and was not sufficiently stable for use in oligotrophic waters and much of the deep water where PIC levels are low. The PIC sensor was subsequently re-engineered and redeployed multiple times: from pole to equator and surface to bottom during the 2005 CLIVAR transect A16S in the South Atlantic and in the Oyashio Current (2005), San Clemente Basin (2007), and near Bermuda and in the Atlantic Slope Water (2008). The current fourth generation of this sensor is capable of 5–10 nM precision in the deep ocean (Figure 3c).

Two neutrally buoyant PIC sensors for the Explorer were also developed in 2003. One deployed on a CE in the Atlantic suffered a mechanical failure of its polarizing cell mounts but remained operating for the float's year-long mission. The second sensor remains in hand.

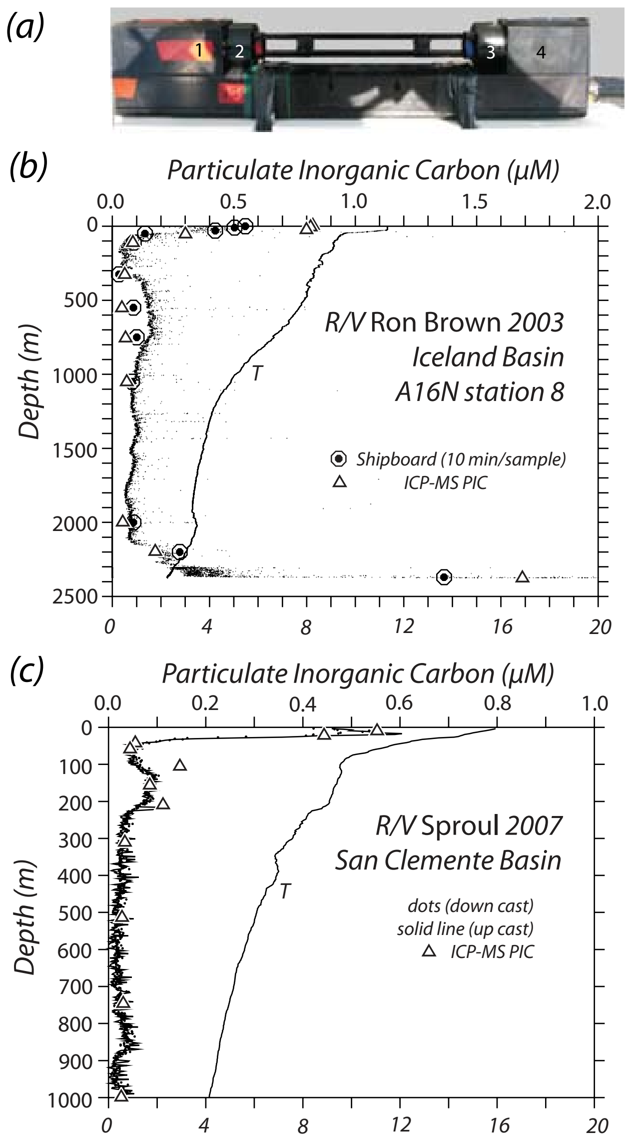

Figure 3. (a) Sensor for particulate inorganic carbon (PIC) capable of full water-column profiles based on a WET Labs Inc. 25 cm C-Star transmissometer. (1) LED laser light source. (2) First in-line polarizer, which filters laser light into the horizontal plane. (3) Second "guard" polarizer over the detector window, oriented to pass only vertical plane polarized light. (4) Detector. Birefringent calcium carbonate particles in the open 25-cm water path depolarize the primary beam and thus lead to photons passing the guard polarizer to the detector. (b) PIC sensor profile from the Iceland Basin in 2003 (A16N Station 8). Circles indicate shipboard birefringence analysis of filtered water samples, and triangles indicate PIC concentrations determined by inductively coupled plasma mass-spectrometer (ICP-MS) analysis of particulates filtered from rosette-collected water samples. The sensor used in 2003, which had a precision of only ~ 0.1 to 0.2 μM PIC, has been modified multiple times since. (c) Down and up cast profiles from the fourth-generation PIC sensor and ICP-MS-determined PIC from water samples obtained during a 2007 CTD-rosette cast in the San Clemente Basin. The agreement of up and down casts is of the order of 0.005 μM in deep water. The PIC sensor is capable of detecting PIC over the entire oceanic range (~ 0.005 μM to 40 μM). Minor work remains to commercialize this sensor.

One final round of engineering will render the PIC sensor fully ready for transfer to the commercial sector. What once required ship-collected samples and labor-intensive ship- or shore-based analysis now can be achieved at 24 Hz using a 0.2 W profiling sensor.

Optical Sedimentation Recorder and the Carbon Flux Explorer

Observations of carbon sedimentation in the upper kilometer of the ocean remain dependent on ships and are necessarily of short duration. This zone, which some refer to as the "forbidden zone" for carbon flux observations, is where substantial biological consumption (remineralization) of sinking organic particles occurs. We summarize below the development of the Optical Sedimentation Recorder (OSR) and the integration of OSR with a highly modified SOLO float to produce a first prototype Carbon Flux Explorer (CFE; Figure 4 and title page photo).

The instrumental CFE approach to observing POC and PIC sedimentation is a logical, but substantially more challenging, high pay-off extension of the simpler CE and PIC sensor concept described above. It melds the concept of a neutrally buoyant sediment trap (NBST; Buesseler et al., 2000, 2007a; Stanley et al., 2004) with the concept of a camera that images particles as they are deposited in a sediment trap (Asper, 1986). The power of the NBST approach is that it appears to avoid the hydrodynamic biases suffered by traditional surface-tethered arrays of sediment traps (e.g., Gardner, 2000; Buesseler et al., 2007b). The strength of our present approach is that it enables high-frequency (hourly to diel) observation of particle sedimentation variations using modern digital cameras and electronics; the current CFE design goal is sustained, high-frequency observation of sedimentation processes for seasons to years. Together with satellite communications, CFE has the potential to provide carbon sedimentation data in real time and operate in an experimental context absent ships.

CFE is aimed at providing mechanistic insight into carbon sedimentation as well as providing carbon flux quantification. CFE, for example, is capable of exploring the biological mechanisms and processes giving rise to the short-term pulsing of sedimentation seen in CFI records (Figure 2b).

OSR (Figure 4b), like all sediment traps, intercepts sinking particles. In our case, a funnel is used to concentrate particles onto a horizontal (flat) optical window. A digital camera operating in macro focus mode looks upward at the particles on the window. A 15 µm spatial image resolution is achieved over the entire sample collection area. The camera is outfitted with a motor-rotated, high-efficiency polarizer. A stabilized, low-power, white-light source with a fixed polarizer attached is suspended in the funnel and provides downward illumination so that particles can be imaged by the camera under transmitted parallel polarized light and transmitted cross-polarized light. As mentioned above, cross-polarized transmitted light is effective for detecting highly birefringent calcium carbonate particles. An annular ring light surrounding the sample collection area is used to achieve dark field illumination. Because all lighting systems are stabilized, raw RGB pixel counts in images can be reduced in terms of absolute reflectance/optical density.

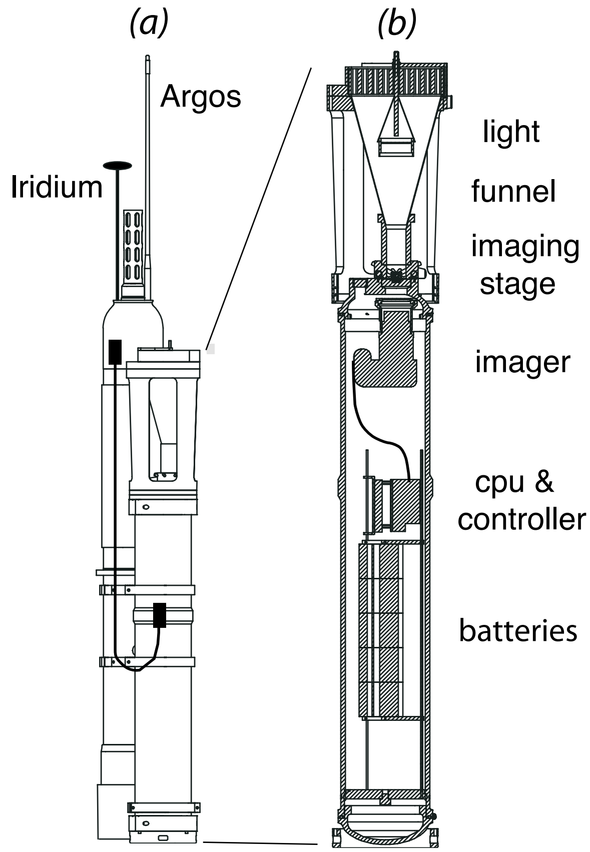

Figure 4. (a) Schematic of the Carbon Flux Explorer (CFE). CFE represents the integration of the Optical Sedimentation Recorder (OSR, engineered at Berkeley Lab) and the Sounding Oceanographic Lagrangian Observer (SOLO; Scripps) profiling float. (b) Optical Sedimentation Recorder (OSR). This instrument was designed to quantify carbon sedimentation on hourly time scales for seasons. SOLO communicates its dive status and pending actions to OSR and OSR communicates reduced data to SOLO for relay to Iridium satellites.

Camera parameters are selected to match specific illumination modes. Three sets of images are taken sequentially, separated in time by tens of seconds. Data are stored in memory external to the camera. Image cycles are typically separated in time by 30 minutes. Periodically, after a number of image cycles (usually several hours), particles are removed from the sample area (in the case of surface-buoy-tethered versions of OSR, the discharge is directed into sample bottles; in the case of CFE, the particles are discharged into the environment). An image cycle immediately following each cleaning provides a reference for subsequent images.

Control of camera, image transfers, and storage, lighting, cleaning, and sampling systems is achieved by a combination of microcontroller and single board computer (SBC). Onboard batteries are currently capable of providing power to drive the OSR for one to two months. The OSR system developed for CFE is also able to respond to event signals from the profiling SOLO (dive pending, surfacing pending, at depth, abort) and provides simple reduced image data, image thumbnails, and OSR engineering parameters for real-time transmission to shore and ship. Figure 5 illustrates how the three OSR imaging modes are used to separate and identify particle components and phases.

CFE's ability to operate in a temporal domain, heretofore unobserved, yet able to sustain observations for months (current prototype) to seasons to years, gives promise of a leap in observational carbon cycle oceanography using autonomous, low-powered platforms.

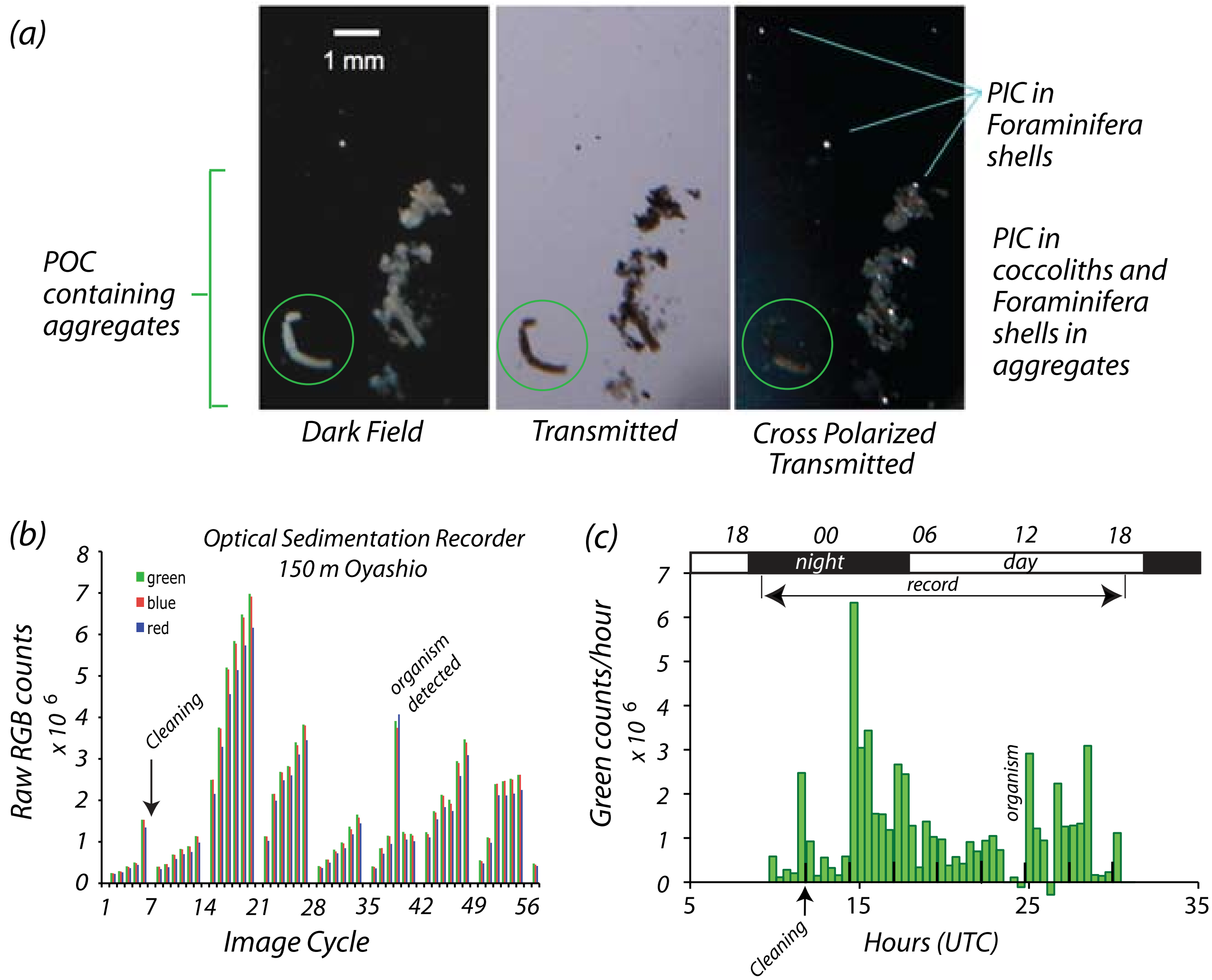

Figure 5. (a) Images of particles from the Carbon Flux Explorer deployment in 2007 in the San Clemente Basin, near San Diego, CA. The three modes of imaging, dark field (side illuminated), transmitted, and cross polarized (cross-polarized transmitted light) allow identification and separation of major particle phases. Shown is a "zoomed" area of one image set of particles collected at ~ 50 m. Right: Carbonates (small Foraminifera) indicated by blue lines are readily seen as bright spots in cross polarized images; the bright haze in the aggregate and in part of the fecal pellet is due to micron-sized calcium carbonate coccoliths. The green circle contrasts images of a fecal pellet. Note that either the carbonate has dissolved in part of the fecal pellet at the left of all images or the grazer had changed its diet. (b) Raw dark field RGB image counts integrated over the OSR sample collection area show particle accumulation in successive image cycles. Cleaning cycles (1,7,14,21...) occurred once every ~ 2.5 hours; images were taken at 25-minute intervals. A rarely photographed organism is present during cycle 39 in the fifth set of images; data from cycles 39–41 are excluded based on movement of particles and the sudden drop of integrated count after the organism departed. (c) Flux variability by first difference of charge-coupled device counts. Maximum sedimentation flux occurred at 0200 local time. Sedimentation varied by a factor of ten on an hour-to-hour basis.

CFE is currently an advanced engineering prototype that passed its first three-day sea trial in mid 2007 (Figure 4). OSR instruments have operated for 40 days underwater, and their subsystems are stable. We need to learn if biofouling effects are minor (as they are for optical sensors on CEs), and if they are not, how to control them. We further need to learn about other long-term operational CFE characteristics by challenging it to progressively longer deployments in increasingly challenging ocean environments. It is one to two years from transfer to the commercial sector and the oceanographic community.

SUMMARY AND PROSPECTS

There is a societal need to predict the ocean carbon cycle, particularly changes to the strength of the biological carbon pump. However, understanding the coupling between short-lived surface processes and carbon sedimentation is hugely limited by a lack of observations.

Particulate carbon pools are small and turn over rapidly compared to dissolved inorganic and organic carbon pools, and thus diurnal to seasonal variations of particulate carbon concentration and flux are readily observed to kilometer depths. For this reason, we focused on sensors for measuring POC and PIC pools and fluxes, and their integration with low-power, long-lived Lagrangian floats. We demonstrated two sensor approaches for Argo-style floats: (1) relatively small, neutrally buoyant sensors that draw power from and are read by the float's electronics, and (2) a fairly large and entirely autonomous and separate neutrally buoyant instrument package that listens to and communicates with the float when requested. Because our sensors were developed for low-power platforms, they can operate across all oceanographic platforms, from ship-lowered CTDs, to moorings, to high-powered AUVs, and finally, to CE cousins: buoyancy-driven gliders.

A Carbon Argo?

The prospects are excellent for observing the complete suite of carbon components from autonomous platforms over the next five to ten years. Ensemble deployment of CEs (possible now) and CFEs (possible in one to two years) in the biologically dynamic ocean would lead to a quantum gain in understanding of POC and PIC concentration and sedimentation variability, and thus lead to better parameterization of bio-carbon processes in model simulations. Such in-water systems will be invaluable for validation of satellite products such as those for PIC (e.g., Balch et al., 2005). Wider deployments of CEs and CFEs within an Argo-style array would permit real-time quantification and understanding of ocean carbon export.

Sensors for other carbon components are on the horizon. Dissolved inorganic carbon pools exceed particulate pools by greater than three orders of magnitude; consequently, sensors for detecting changes in dissolved inorganic carbon components must be parts-per-thousand accurate or better to be useful (Millero, 2007). This significant challenge is beginning to be met. For example, submersible sensors for CO_2 fugacity (fCO_2) have been deployed from moorings (DeGrandpre et al., 2006). These sensors currently have response times of about five minutes (as opposed to optical particle sensor response of fractions of a second), which are too long for efficient profiling of the fCO_2 gradients in the water column. Dissolved organic carbon (DOC) comprises the dominant (> 90%) fraction of the organic carbon pool in the ocean, and currently can only be determined by laboratory or shipboard analysis of water samples (Hansell et al., 2002). Preliminary experiments at Lawrence Berkeley National Laboratory suggest that low-power sensors for major components of the DOC pool are feasible.

Russ Davis (Scripps Institution of Oceanography, *pers. comm.*, December 2008) has pointed out that float profiling speeds (currently ~ 10 m min^{-1}) may be controlled in near-surface waters to match the response times of the current generation of slow CO_2 system sensors. At the same time, he says that it is important to recall that Argo floats were developed with the Argo mission in mind 10 to 15 years ago. Investment in float and sensor engineering to meet the needs of a Carbon Argo (C-Argo) mission is a logical expectation. In other words, floats built for the Argo mission are not optimized for biogeochemical sensors.

Although there is great focus on "wedge" strategies (e.g., conservation, nuclear, carbon sequestration; c.f. Pacala and Socolow, 2004) to offset or reduce CO_2 emissions (now at 8 Pg C y^{-1}) to the atmosphere, an integrated carbon management strategy must include monitoring and prediction of the 10 Pg C y^{-1} biological carbon pump. With a suite of fully integrated carbon sensors, it would be possible to determine the net carbon transfers from the atmosphere to the surface ocean, its distribution among time-varying carbon pools, and transfer efficiency to the deep sea in real time. With the right investment, and partnering among educational, governmental, and commercial sectors, a C-Argo program, combining multiple autonomous platform types and carbon sensors, could yield real-time assessment of global ocean carbon fluxes at a time when such data are desperately needed.

HISTORY OF THIS PARTNERSHIP

I was first captivated by the possibilities of autonomous ocean carbon observations by a World Ocean Circulation Experiment (WOCE) study that took place in the mid 1990s when 200 autonomous profiling floats were deployed in the Labrador Sea (Lavender et al., 2000) to observe the formation and transport of Labrador Sea Water (LSW). I recall attending the Labrador Sea session at the 1998 AGU Ocean Sciences Meeting and learning how the understanding of the formation and dynamics of LSW had just become "overturned" by this quantum jump in observational capability and saying to myself, "Imagine what we could learn if we could do this kind of experiment for the carbon cycle?" I rushed over to Russ Davis to broach the idea of carbon observations on floats—and the nucleation of our NOPP project began. The Scripps Instrument Development Group (IDG) was beginning work on the Spray Glider. Because this self-navigating autonomous vehicle required bi-directional satellite telemetry and IDG was investigating the ORBCOMM system, testing it using IDG's SOLO would speed development of the Spray Glider and exercise SOLO in a way that would increase its reliability for the upcoming Argo program. ORBCOMM telemetry would reduce the time at surface for data transmission from days to tens of minutes and thus enable deployment of optical sensors by minimizing exposure to biofouling conditions. WET Labs Inc. would work to stabilize transmissometer electronics and provide the company's transmissometer in a neutrally buoyant package capable of 2000 m. WET Labs would further provide several embodiments of a new sensor for particulate inorganic carbon. A successful proposal (leveraged with DOE projects and a NOAA postdoctoral fellowship grant) to the NOPP 1999 competition led to perhaps one of the most enjoyable projects of my career.

The partnership of Lawrence Berkeley National Labs, Scripps Institution of Oceanography (IDG), and WET Labs Inc. led to the eventual deployment of 12 CEs worldwide under the original NOPP (3 CEs), and new NOAA (5) and DOE (4) supported projects. This NOPP partnership was recognized with the 2006 R&D 100 Award for developing the Carbon Explorer. WET Labs Inc. has marketed the neutrally buoyant C-Rover transmissometer for floats, which was a direct outgrowth of our NOPP effort. US Patent #7,030,981 was awarded in 2006 to the Lawrence Berkeley National Laboratory for the PIC sensor concept.

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REFERENCES

Antoine D., J.-M. Andre, and A. Morel. 1996. Oceanic primary production. 2. Estimation at global scale from satellite (coastal zone color scanner) chlorophyll. *Global Biogeochemical Cycles* 10:57–69.

Armstrong, R.A., C. Lee, J.I. Hedges, S. Honjo, and S.G. Wakeham. 2002. A new mechanistic model for organic carbon fluxes in the ocean based on quantitative association of POC with ballast minerals. *Deep-Sea Research II* 49:219–236.

Asper, V.L. 1986. *Accelerated Settling of Marine Particulate Matter by Marine Snow Aggregates.* Ph.D. Thesis, MIT/WHOI Joint Program in Oceanography, WHOI-86-12, 189 pp.

Balch, W.M., D.T. Drapeau, J.J. Fritz, B.C. Bowler, and J. Nolan. 2002. Optical backscattering in the Arabian Sea: Continuous underway measurements of particulate inorganic and organic carbon. *Deep-Sea Research I* 48:2,423–2,452.

Balch, W.M., H.R. Gordon, B.C. Bowler, D.T. Drapeau, and E.S. Booth. 2005. Calcium carbonate measurements in the surface global ocean based on Moderate-Resolution Imaging Spectroradiometer data. *Journal of Geophysical Research* 110(C7): C07001, doi:10.1029/2004JC002560.

Berelson, W. M., W. M. Balch, R. Najjar, R.A.Feely, C. Sabine, and K. Lee. 2006. Relating estimates of $CaCO_3$ production, export, and dissolution in the water column to measurements of $CaCO_3$ rain into sediment traps and dissolution on the sea floor: A revised global carbonate budget. *Global Biogeochemical Cycles* 21, GB1024, doi:10.1029/2006GB002803.

Bishop, J.K.B., and T.J. Wood. 2008. Particulate matter chemistry and dynamics in the Twilight Zone at VERTIGO ALOHA and K2 sites. *Deep-Sea Research I* 55:1,684–1,706, doi:10.1016/j.dsr.2008.07.012.

Bishop, J.K.B., and T.J. Wood. In press. Year Round Observations of Carbon Biomass and FluxVariability in the Southern Ocean. *Global Biogeochemical Cycles.*

Bishop, J.K.B., R.E. Davis, and J.T. Sherman. 2002. Robotic Observations of dust storm enhancement of carbon biomass in the North Pacific. *Science* 298:817–821.

Bishop, J.K.B., T.J. Wood, R.E. Davis, and J.T. Sherman. 2004. Robotic observations of enhanced carbon biomass and export at 55°S During SOFeX. *Science* 304:417–420.

Broecker, W.S., and T.H. Peng. 1982. *Tracers in the Sea*. Eldigio Press, Lamont-Doherty Geological Observatory, NY, 690 pp, doi:10.1016/0016-7037(83)90075-3.

Buesseler, K.O., D.K. Steinberg, A.F. Michaels, R.J. Johnson, J.E. Andrews, J.R. Valdes, and J.F. Price. 2001. Comparison of the quantity and composition of material caught in a neutrally buoyant versus surface-tethered sediment trap. *Deep Sea Research I* 47(2):277–294, doi:10.1016/S0967-0637(99)00056-4.

Buesseler, K.O., C.H. Lamborg, P.W. Boyd, P.J. Lam, T.W. Trull, R.R. Bidigare, J.K.B. Bishop, K.L. Casciotti, F. Dehairs, M. Elskens, and others. 2007a. Revisiting carbon flux through the ocean's Twilight Zone. *Science* 316:567–570.

Buesseler, K.O., A.N. Antia, M. Chen, S.W. Fowler, W.D. Gardner, O. Gustafsson, K. Harada, A.F. Michaels, M. Rutgers van der Loeff, M. Sarin, and others. 2007b. An assessment of the use of sediment traps for estimating upper ocean particle fluxes. *Journal of Marine Research* 65:345–416.

CLIVAR. 1999. *The Design and Implementation of Argo: A Global Array of Profiling Floats*. Report 21, International CLIVAR Project Office, Southampton, UK, 35 pp.

Coale, K.H., K.S. Johnson, F.P. Chavez, K.O. Buesseler, R.T. Barber, M.A. Brzezinski, W.P. Cochlan, F.J. Millero, P.G. Falkowski, J.E. Bauer, and others. 2004. Southern Ocean iron enrichment experiment: Carbon cycling in high- and low-Si waters. *Science* 304:408, doi:10.1126/science.1089778.

DeGrandpre, M.D., A. Kortzinger, U. Send, D.W.R. Wallace, and R.G.J. Bellerby. 2006. Uptake and sequestration of atmospheric CO_2 in the Labrador Sea deep convection region. *Geophysical Research Letters* 33, L21S03, doi:10.1029/2006GL026881.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, and others. 2007. Couplings between changes in the climate system and biogeochemistry. Pp. 499–587 in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignorand, and H.L. Miller, eds, Cambridge University Press, Cambridge, UK, and NY, USA.

Dickey T., M.R. Lewis, and G.C. Chang. 2006. Optical oceanography: Recent advances and future directions using global remote sensing and in situ observations. *Reviews of Geophysics* 44, RG1001, doi:10.1029/2003RG000148.

Dunne, J.P., R.A. Armstrong, A. Gnanadesikan, and J.L. Sarmiento. 2005. Empirical and mechanistic models for the particle export ratio. *Global Biogeochemical Cycles* 19:4026, doi:10.1029/2004GB002390.

Fabry, V.J., B.A. Seibel, R.A. Feely, and J.C. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science* 65:414–432.

Falkowski, P.G., R. Barber, and V. Smetacek. 1998. Biogeochemical controls and feedbacks on ocean primary production. *Science* 281:200–206.

Field, C.B., M.J. Behrenfeld, J.T. Randerson, and P.G. Falkowski. 1998. Primary production of the biosphere: Integrating terrestrial and oceanic components. *Science* 281:237–240.

Feeley, R., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, and F. J. Millero. 2004. The impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science* 305:362–366.

Gardner, W.D. 2000. Sediment trap sampling in surface waters. Pp. 240–284 in *The Changing Ocean Carbon Cycle: A Midterm Synthesis of the Joint Global Ocean Flux Study*. R.B. Hanson, H.W. Ducklow, and J.G. Field, eds, Cambridge University Press, NY.

Gehlen, M., L. Bopp, N. Emprin, O. Aumont, C. Heinze, and O. Ragueneau. 2006. Reconciling surface ocean productivity, export fluxes and sediment composition in a global biogeochemical ocean model. *Biogeosciences* 3:521–537.

Guay C.K., and J.K.B. Bishop. 2002. A rapid birefringence method for measuring suspended $CaCO_3$ concentrations in water. *Deep-Sea Research I* 49:197–210.

Iglesias-Rodriguez, M.D., P.R. Halloran, R.E.M. Rickaby, I.R. Hall, E. Colmenero-Hidalgo, J.R. Gittins, D.R.H. Green, T. Tyrrell, S.J. Gibbs, P. von Dassow, and others. 2008a. Phytoplankton calcification in a high-CO_2 world. *Science* 320:336, doi:10.1126/science.1154122.

Iglesias-Rodriguez, M.D., E.T. Buitenhuis, J.A. Raven, O. Schofield, A.J. Poulton, S. Gibbs, P.R. Halloran, and H.J.W. de Baar. 2008b. Response to comment on "Phytoplankton calcification in a high-CO_2 world." *Science* 322:1466c, doi:10.1126/science.1161501.

Hansell D.A., C.A. Carlson, and Y. Suzuki. 2002. Dissolved organic carbon export with North Pacific Intermediate Water formation. *Global Biogeochemical Cycles* 16, Article 1007, doi:10.1029/2000GB001361.

Kleypas, J.A, R.A. Feeley, V.J. Fabry, C. Langdon, C.L. Sabine, and L.L. Robins. 2006. *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research*. Report of a workshop held April 18–20, 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the US Geological Survey, 88 pp.

Lam, P.J., and J.K.B. Bishop. 2007. High biomass, low export regimes in the Southern Ocean. *Deep-Sea Research II* 54:601–638, doi:10.1016/j.dsr2.2007.01.013.

Lavender, K., R.E. Davis, and B. Owens. 2000. Mid-depth recirculation observed in the interior Labrador and Irminger Seas by direct velocity measurements. *Nature* 407:66–69.

Lutz, M.J., K. Calderia, R.B. Dunbar, and M.J. Behrenfeld. 2007. Seasonal rhythms of net primary production and particulate organic carbon flux to depth describe the efficiency of biological pump in the global ocean. *Journal of Geophysical Research* 112, C10011, doi:10.1029/2006JC003706.

Martin, J.H., G.A. Knauer, D.M. Karl, and W.W. Broenkow. 1987. VERTEX: Carbon cycling in the northeast Pacific. *Deep-Sea Research* 34:267–285.

Millero, F.J. 2007. The marine inorganic carbon cycle. *Chemistry Reviews* 107:308–341.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feeley, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, and others. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437:681–686, doi:10.1038/nature04095.

Pacala, S.W., and R.H. Socolow. 2004. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science* 305(5686):968–972.

Riebesell, U., I. Zondervan, B. Rost, P.D. Tortell, R.E. Zebe, and F.M. Morel. 2000. Reduced calcification of marine plankton in response to increased atmospheric CO_2. *Nature* 407:364–367.

Riebesell, U., R.G.J. Bellerby, A. Engel, V.J. Fabry, D.A. Hutchins, T.B.H. Reusch, K.G. Schulz, and F.M.M. Morel. 2008. Comment on "Phytoplankton calcification in a high-CO_2 world." *Science* 322:1466b, doi:10.1126/science.1161096.

Sabine, C.L., R.A. Feely, N. Gruber, R.M. Key, K. Lee, J.L. Bullister, R. Wanninkhof, C.S. Wong, D.W.R. Wallace, B. Tilbrook, and others. 2004. The ocean sink for anthropogenic CO_2 in the ocean. *Science* 305:367–370.

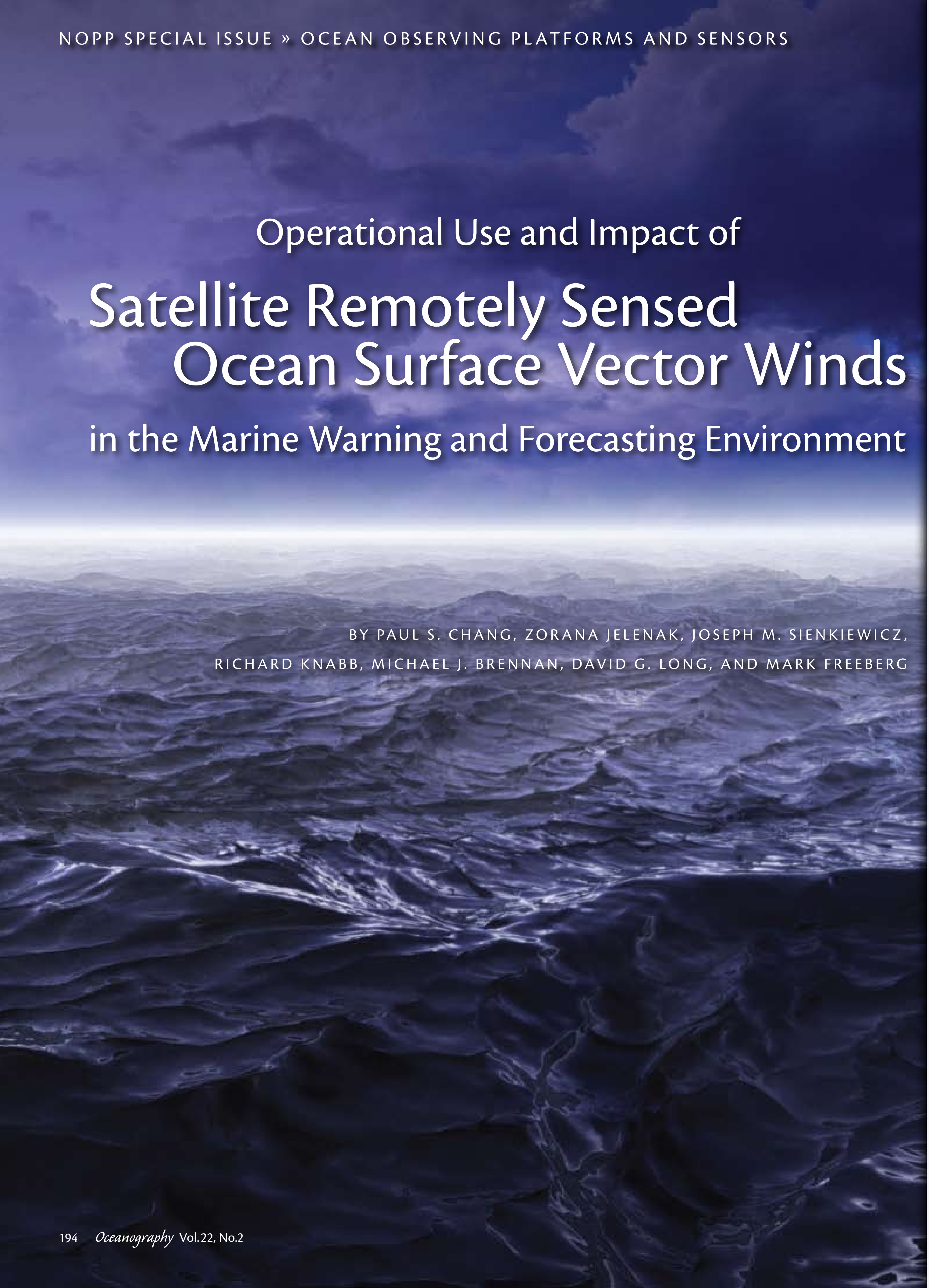
Siegenthaler, U., and J.L. Sarmiento. 1993. Atmospheric carbon dioxide and the ocean. *Nature* 365:119–125.

Sarmineto, J.L., and N. Gruber. 2006. *Ocean Biogeochemical Dynamics*. Princeton University Press, 503 pp.

Stanley, R.H.R., K.O. Buesseler, S.J. Manganini, D.K. Steinberg, and J.R. Valdes. 2004. A comparison of major and minor elemental fluxes collected in neutrally buoyant and surface-tethered sediment traps. *Deep-Sea Research I* 51:1,387–1,395.

Volk, T., and M.I. Hoffert. 1985. Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean-driven atmospheric CO_2 changes. Pp. 99–110 in *The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present*. E.T. Sunquist and W.S. Broecker, eds, Geophysical Monograph 32, American Geophysical Union, Washington, DC.

Westberry, T., M.J. Behrenfeld, D.A. Siegel, and E. Boss. 2008. Carbon-based primary productivity modeling with vertically resolved photo acclimation. *Global Biogeochemical Cycles* 22, GB2024, doi:10.1029/2007GB003078.



Operational Use and Impact of Satellite Remotely Sensed Ocean Surface Vector Winds in the Marine Warning and Forecasting Environment

BY PAUL S. CHANG, ZORANA JELENAK, JOSEPH M. SIENKIEWICZ, RICHARD KNABB, MICHAEL J. BRENNAN, DAVID G. LONG, AND MARK FREEBERG

ABSTRACT. In 2002, a National Oceanographic Partnership Program project was initiated with the ambitious objective of maximizing the use of currently and soon-to-be-available satellite ocean surface vector wind (OSVW) data, such as NASA's QuikSCAT scatterometer, in the operational weather forecasting and warning environment. This effort brought together people from the operational forecasting and satellite remote-sensing communities, academia, and the private sector. This diverse gathering of skill and experience yielded documentation of the impacts of these data in the operational short-term warning and forecasting environment of the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service, improvement in the use of these data in the public and private sectors, and the transition of promising research results into the operational environment. This project helped create momentum that has continued to grow long after the formal effort ended; today, NOAA uses QuikSCAT operationally and is investigating how to best establish a sustained satellite OSVW observing capability.

INTRODUCTION

The ocean comprises over 70% of Earth's surface, which makes satellite remote sensing a logical and significant component of an overall effort to meet societal needs for weather and water information; support commerce with information for safe, efficient, and environmentally sound transportation; and provide information for better coastal preparedness. Ocean surface vector winds (OSVW) are crucial pieces of information needed to understand and predict the short-term and longer-term processes that drive our planet's environment. As the largest source of momentum for the ocean surface, winds affect the full range of ocean movement, from individual surface waves to complete current systems. Winds along the ocean surface regulate interaction between the atmosphere and the ocean via modulation of air-sea exchanges of heat, moisture, gases, and particulates. With the ocean covering almost three quarters of Earth's surface, this interaction has significant influence on global and regional climate.

On June 19, 1999, the National Aeronautics and Space Administration (NASA) launched QuikSCAT, a microwave radar system known as a scatterometer, specifically designed to retrieve OSVW over the global ocean (Jet Propulsion Laboratory, 2006). Prior to launch, NASA's Jet Propulsion Laboratory (JPL) and the National Oceanic and Atmospheric Administration's (NOAA's) National Environmental Satellite, Data, and Information Service (NESDIS) worked together to implement a near-real-time OSVW processing and distribution system at NOAA to allow QuikSCAT data to be used by the operational weather forecasting and warning communities around the world. Although QuikSCAT was not the first scatterometer launched into space (Naderi et al., 1991; Stoffelen and Anderson, 1993; Gelsthorpe et al., 2000; Verhof and Stoffelen, 2008), its reliability, high quality, relatively fine spatial resolution, and large daily geographical coverage resulted in its having the largest impact of any scatterometry mission in the operational marine weather forecasting and warning world (Jelenak and Chang, 2008).

In 2002, a National Oceanographic Partnership Program (NOPP) project was initiated to exploit the currently and soon-to-be-available satellite OSVW data in the operational weather forecasting and warning environment. This effort had three main objectives: (1) to quantify the impacts of QuikSCAT OSVW data in the operational short-term warnings and forecasts issued by the National Weather Service (NWS) Ocean Prediction Center (OPC) and National Hurricane Center (NHC), (2) to improve the use of satellite OSVW data in the public and private sector, and (3) to transition promising research products toward operational use. This project brought together people from the federal government, private industry, and academia and initiated what has become one of the most successful transitions of a research data stream (QuikSCAT OSVW) into operational use, where it continues to have a profound impact on marine weather warning and forecasting.

OPERATIONAL USE

In the United States, NWS is responsible for providing marine weather warning and forecast information, and it has international obligations to provide the same within its areas of responsibility under the umbrella of the World Meteorological Organization. Additionally, the US military provides marine weather forecasting and warning services to support military operations. A combination of the NWS areas of responsibility with those of the military's Joint Typhoon Warning Center (JTWC) provides coverage of much of the world's ocean (Figure 1).

With only a very limited number of open-ocean buoy and ship reports available, remotely sensed satellite OSVW data are very important to accurate and systematic mapping of the global ocean wind field. QuikSCAT provides an almost complete OSVW map of the global ocean twice daily (Figure 2).

To be fully used by operational forecasters, experimental data sets such as QuikSCAT must be delivered in a timely fashion and made available for display on forecasters' operational workstations. QuikSCAT vector winds were first introduced to NOAA forecasters in late 1999 via the near-real-time (NRT) QuikSCAT Web portal (http://manati.star.nesdis.noaa.gov/quikscat). This site provided forecasters with initial access to scatterometer wind data; however, its utility was limited to determining wind-warning categories. In early 2000, QuikSCAT wind data were made available as image files on National Center for Environmental Prediction (NCEP) National Centers Advanced Weather Interactive Processing System (N-AWIPS) workstations. However, these images were static, with no capability to turn rain-flagged data on and off or to change the colors assigned to wind-speed ranges.

The opportunity provided by the NOPP project significantly advanced display capability as forecasters worked with developers to optimize QuikSCAT displays on the N-AWIPS workstations. Ocean forecasters at OPC, NHC, and the Weather Forecast Office (WFO) in Honolulu can now view both the QuikSCAT 25-km and 12.5-km

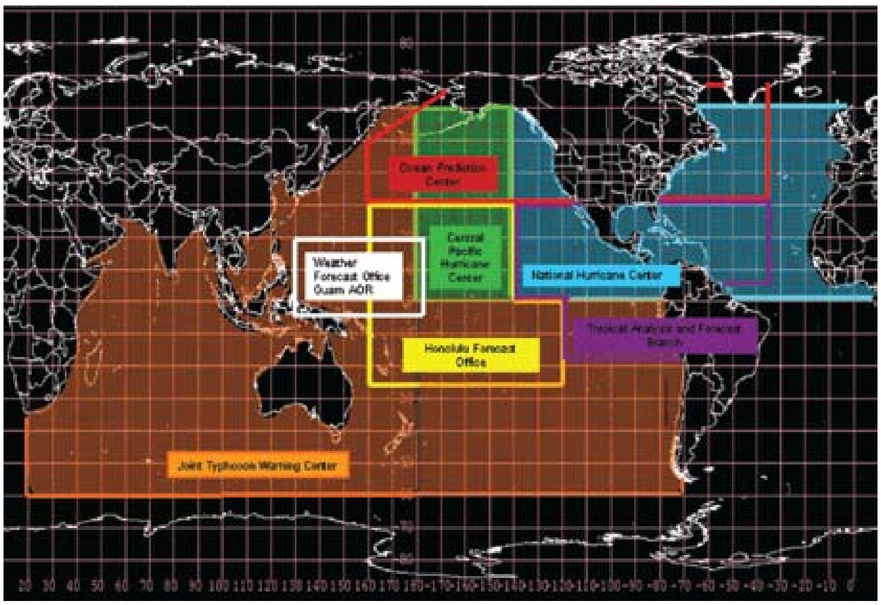


Figure 1. Map showing the combined areas of responsibility of all National Weather Service offices with marine warning and forecasting responsibilities, as well as the US military's Joint Typhoon Warning Center (JTWC). JTWC (orange), the National Hurricane Center (blue), and the Central Pacific Hurricane Center (green) share the warning responsibility for tropical cyclones.

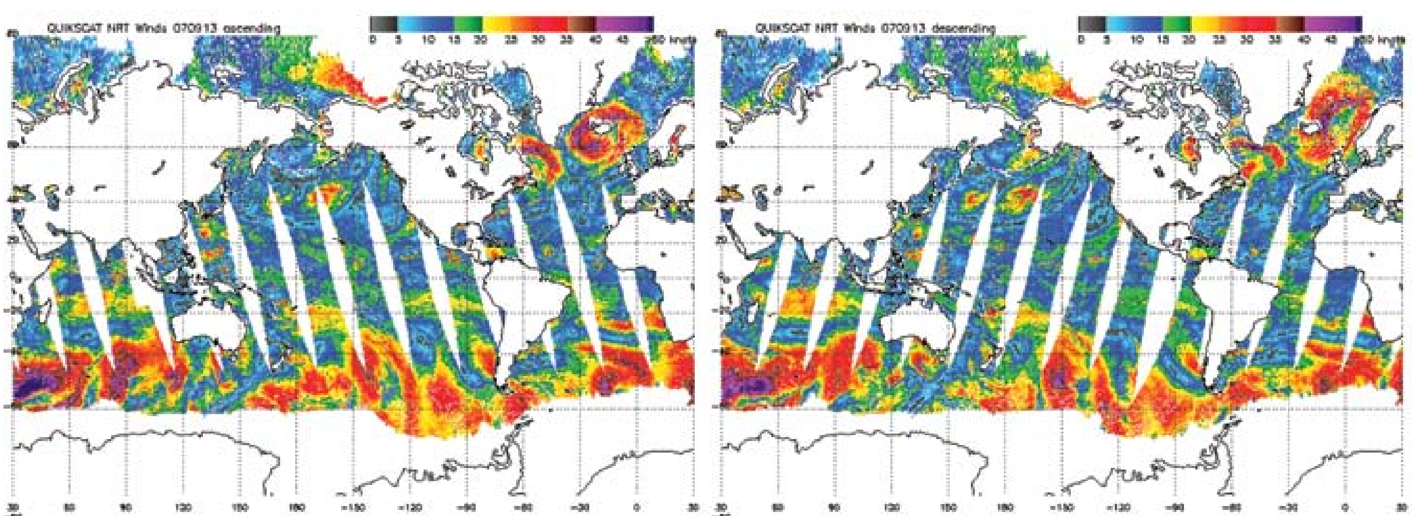


Figure 2. Typical daily coverage of ocean surface vector winds from NASA's QuikSCAT, resulting in 90% daily coverage of the world's ocean.

resolution wind fields, clearly display the data acquisition time, highlight potential areas of rain contamination, and customize the display to suit the forecaster and weather situation. Additionally, QuikSCAT vector winds have been provided through AWIPS to coastal WFOs in NWS's Western Region since 2000 and the rest of the WFOs since April 2005. This transition into AWIPS permitted the widest distribution of QuikSCAT data within NWS offices. The successful use of QuikSCAT by NOAA ocean forecasters is due in part to data quality but also to rapid data delivery and the comprehensive display capabilities built into the N-AWIPS software.

Our NOPP project provided an opportunity to place a person devoted solely to the transition of OSVW data from research to operations at both OPC and NHC. These unique positions created a bridge between the operational weather warning and forecasting world and the OSVW remote-sensing science/engineering world. Direct interaction with forecasters not only helped the remote-sensing specialists to understand the products forecasters were using and allow for more effective use of new data, but forecaster feedback also helped those processing the data to focus resources on the issues and products that would prove most useful to the operational community.

The critical point in achieving proper feedback loops and maximizing the effective use of QuikSCAT data in the operational environment was the development and implementation of end-user training tools. The training investment was minimal at best when the QuikSCAT OSVW data were first made available. Very early on, we realized that the lack of documentation and training material significantly limited use of the data, and thus their impact on weather forecasting and warning products. To improve use of the data, unique QuikSCAT training presentations were created by combining the forecasters' and remote-sensing specialists' different experiences and knowledge of the data tailored for specific weather phenomena, with emphasis on tropical and extratropical cyclones. The training material provided background information on microwave remote sensing with active sensors in general, and QuikSCAT specifics such as scanning strategy, viewing geometry, and its strengths and weakness for OSVW retrieval. The material also reviewed geographic coverage, orbits, and data latency issues. Training sessions were conducted at various NWS centers and offices, which resulted in significant increases in the understanding and use of the data. Our experience in transitioning QuikSCAT data from research to operations taught us that user training and education are keys to a successful outcome.

Today, QuikSCAT OSVW data are used in the daily operations of all NWS offices with marine warning and forecasting responsibilities. Their uses include aiding decisions to initiate, continue, and terminate marine warnings, including advisories for tropical cyclones; adjustment of short-term marine forecasts for the intensity and geographic coverage of winds; identification of swell-generation areas for longer-term wave forecasts; identification of lows, highs, fronts, and convergence zones and examination of their intensity and trends; and real-time verification of numerical weather prediction analyses for winds, waves, and feature intensity.

OPERATIONAL USE OF QUIKSCAT DATA FOR TROPICAL CYCLONE WARNING AND FORECASTING

QuikSCAT OSVW have several uses in the tropical cyclone (TC) warning and forecasting mission of NHC, Central Pacific Hurricane Center, and JTWC. These data are used to help estimate intensity (maximum wind), especially for tropical storms, because QuikSCAT

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has limitations in retrieving the very high winds in hurricanes and typhoons due to system design and resolution, and the impact of rain (Brennan et al., in press). However, in TCs undergoing extratropical transition (e.g., Jones et al., 2003), QuikSCAT can provide valuable information on both the cyclone's intensity and wind field size, as the coverage of heavy rainfall is typically reduced near the location of maximum winds. The broad geographic coverage of QuikSCAT OSVW often provides the only consistent source of information for the analysis of 34-kt and 50-kt wind radii in TCs that are not sampled by aircraft reconnaissance (Figure 3). These wind radii are critical for defining ship avoidance areas and helping to refine the placement of coastal warnings. Emergency management officials often require that evacuation preparations be completed by the time that the 34-kt winds reach the local coastline.

The detection and location of surface circulation centers is another important use of QuikSCAT data, which have been used as justification to both initiate advisories for incipient cyclones and declare cyclones that no longer have well-defined centers dissipated. However, errors in the automated QuikSCAT wind solution, particularly in TCs, often require manual analysis of directional ambiguities for operational center fixing applications (e.g., Brennan et al., in press). Accurate TC center fixes are critical to determining the TC's initial position and motion, which are important for accurate TC track forecasting. Additionally, information on the location of the TC surface center relative to the cyclone's organized thunderstorm activity is vital to accurate satellite-derived intensity estimates; QuikSCAT is useful in this

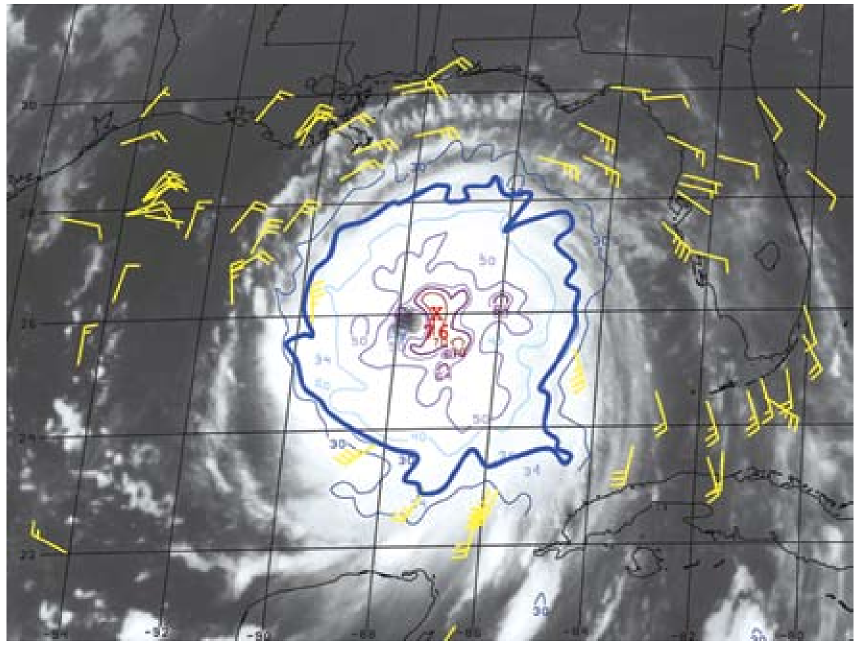

Figure 3. Thirty-four knot wind radii (blue line) as indicated by QuikSCAT in a pass over Hurricane Katrina (2005), with available ship and buoy observations (yellow barbs indicate wind speed in kt). The accuracy of the QuikSCAT analysis of the 34-kt radii in this situation provides forecasters with the confidence to use QuikSCAT for tropical cyclone 34-kt and sometimes 50-kt wind radii determination, especially in the open ocean where ship and buoy observations are sparse.

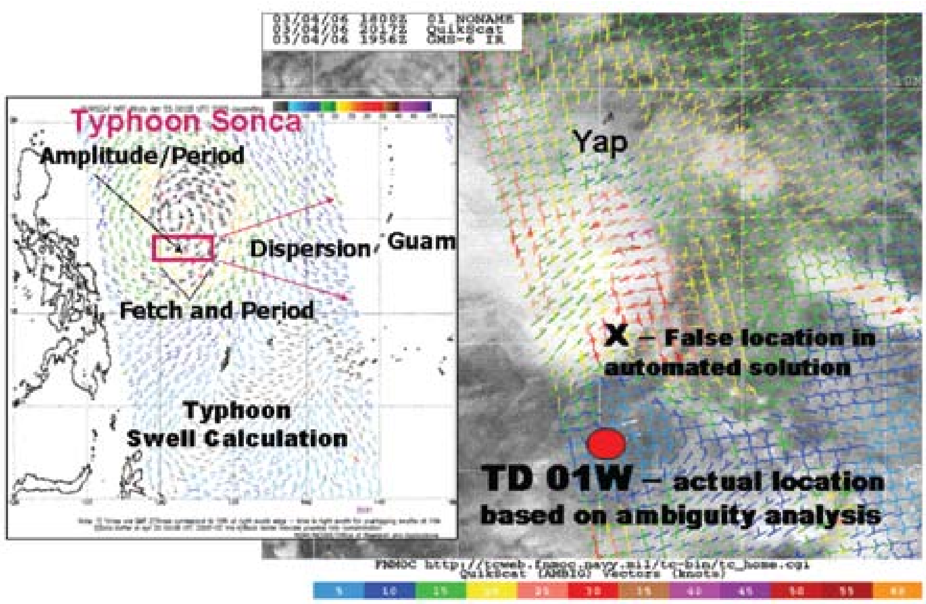

Figure 4. The broad swath of QuikSCAT winds allows forecasters to examine the character of swell generation regions in cyclones. Also, despite frequent errors in tropical cyclone (TC) center location in the automated QuikSCAT solution, manual analysis of directional ambiguities can be performed to locate the TC centers using all the possible QuikSCAT solutions. This tool has been essential for detection and center location of Pacific TCs not sampled by aircraft reconnaissance flights. *Courtesy of Roger Edson, Science and Operations Officer, NOAA/National Weather Service Office Guam*

application for TCs where the center is not easily seen in geostationary satellite imagery (Figure 4). Forecasters use QuikSCAT wind fields to determine potential swell generation associated with TCs as shown in the left image of Figure 4. In this example, forecasters can estimate fetch lengths, average wind speed, and dispersion pattern for swell.

The use of QuikSCAT at NHC has increased steadily since 2000, and has now reached the point where QuikSCAT is mentioned in 15–20% of NHC's tropical cyclone discussions in the Atlantic and East Pacific basins (Figure 5).

QuikSCAT winds are heavily used at NHC for daily marine analysis, forecasting, and warning activities. The best example of QuikSCAT's high impact is in the Gulf of Tehuantepec in the northeastern tropical Pacific, a region that is frequently impacted by strong, cold-season gap wind events that occasionally reach hurricane-force intensity (Figure 6). Prior to QuikSCAT, it was very difficult to obtain any information on wind intensity and coverage during these events. Using QuikSCAT data, a multi-year climatology of gale- and storm-force Tehuantepec events was constructed (Brennan et al., 2007), allowing NHC marine forecasters to identify forecast model biases and issue more accurate and timely warnings for these events.

OPERATIONAL USE OF QUIKSCAT DATA FOR THE DETECTION, WARNING, AND FORECASTING OF EXTRATROPICAL CYCLONES

Extratropical cyclones that reach hurricane force (HF) intensity are a significant threat to the safety of life at sea and a

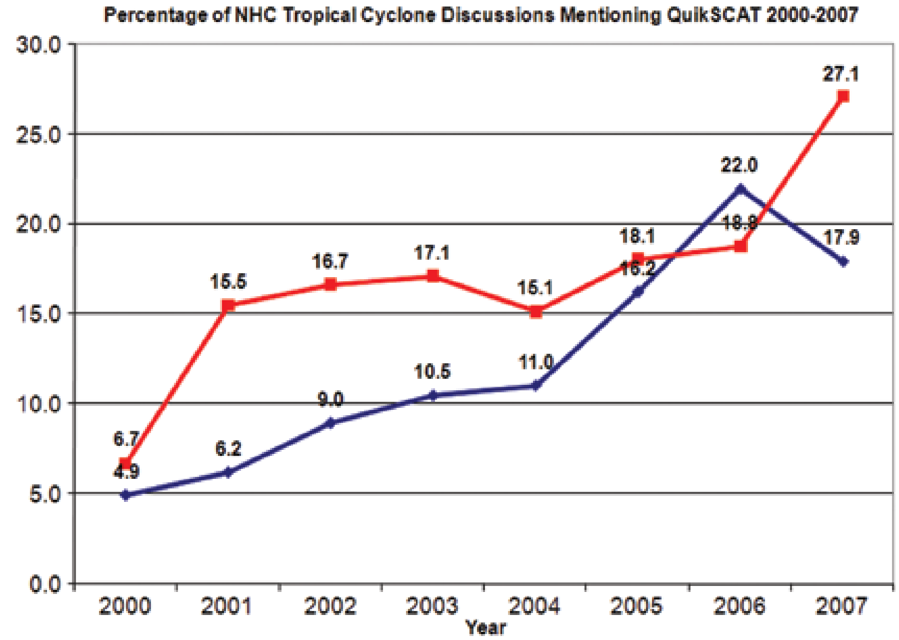

Figure 5. Percentage of Atlantic (blue) and East Pacific (red) tropical cyclone discussions issued by the National Hurricane Center that mention QuikSCAT (2000–2007).

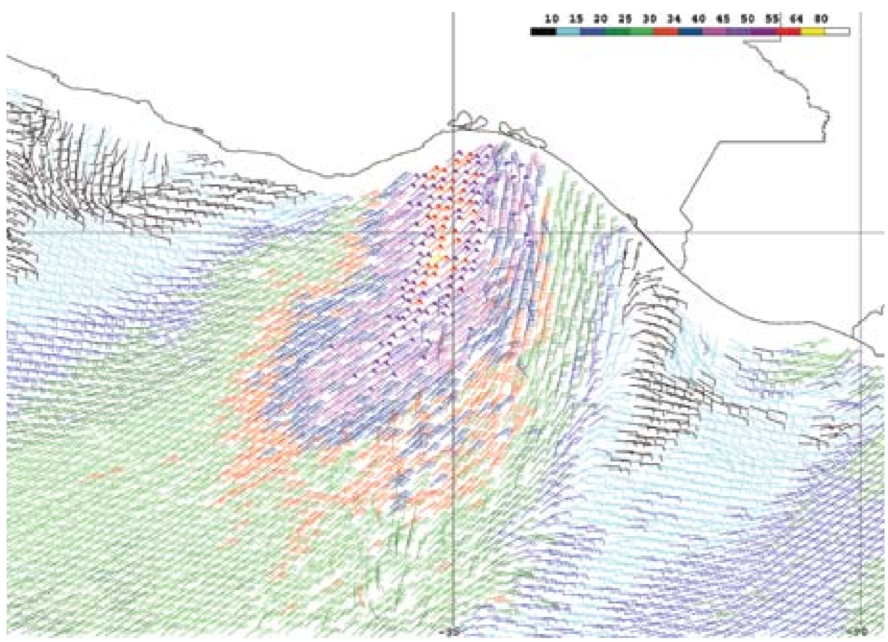

Figure 6. QuikSCAT 12.5-km-resolution wind retrievals in a hurricane-force Gulf of Tehuantepec gap wind event on November 22, 2006.

risk to cargo and vessels. Extratropical cyclones vary on scales from less than 100 km in diameter to 3,000 km or even 4,000 km in diameter and have an average life cycle of five days from genesis to death. These cyclones intensify explosively (see description in Sanders and Gyakum, 1980) and are called meteorological "bombs." Associated wind conditions can vary from only 10 to 20 kts to gale force (33 to 47 kts), storm force (48 to 63 kts), or hurricane force (> 63 kts). Winds of gale or greater force can extend over several million square kilometers of open ocean. At any given time, there can be as many as five to eight individual cyclones impacting the North Atlantic and North Pacific basins. In the main extratropical storm tracks of the North Pacific and the Atlantic, the forward speed of these cyclones during development can exceed 30 kts; the movement slows as the cyclones mature and the vortex deepens through the lower atmosphere.

OPC is responsible for issuing warnings and forecasts for the North Atlantic and North Pacific waters most frequented by these extreme ocean storms. OPC generates and issues marine warnings and forecasts, continually monitors and analyzes maritime data, and provides guidance on marine atmospheric variables for the purposes of protecting life and property, ensuring safety at sea, and enhancing economic opportunity. OPC warning bulletins are required to be received and monitored by all commercial vessels of 300 or more gross tons operating over the North Atlantic and North Pacific high seas and offshore waters. Customers include commercial mariners, fishermen, recreational sailors, the US Coast Guard, the NOAA Emergency Response Division (formerly Hazardous Materials Response Division or NOAA HAZMAT), and the US military.

QuikSCAT ocean vector winds have revolutionized short-term warning and forecasting over the expansive ocean areas for which OPC is responsible. The 1800-km wide swath, large retrievable wind speed range, and rapid delivery of QuikSCAT data have changed the way forecasters make short-term warning and forecast decisions, especially those concerning the higher and more dangerous wind warning categories (Von Ahn et al., 2006). In essence, OPC forecasters have never before had such a high degree of situational awareness of weather conditions over the ocean.

The most significant impact of QuikSCAT OSVW on NWS operations has been the ability to routinely and consistently observe winds of HF intensity in extratropical cyclones. This new capability gave forecasters at OPC and NWS the confidence to introduce a new wind-warning category for extratropical cyclones of HF intensity in December 2000 (see Figure 7). Prior to QuikSCAT, only two warning categories existed for extratropical wind sources: gale (33 to 47 kts) and storm (≥ 48 kts). Under the two-tier warning system, the most severe storms were included in the rather common storm warning category, making it difficult to highlight and adequately warn for their severity. OPC forecasters had long been uncomfortable with this two-tier warning system, but required a consistent observing capability to divide the common occurrence of winds of 48 to 63 kts and the less-common and more dangerous winds in excess of 63 kts; QuikSCAT winds provided that capability. The three warning categories are displayed on North Atlantic and North Pacific surface analyses that are broadcast via US Coast Guard radiofacsimile and are also available via the Internet at http://www.opc.ncep.noaa.gov/.

From fall 2006 through spring 2007, OPC identified and issued warnings for 115 separate extratropical cyclones that reached HF intensity (64 in the Atlantic and 51 in the Pacific; Figure 7). Although many of these cyclones spend their entire lives at sea, over the last several seasons, HF conditions produced by extratropical ocean storms have impacted the coasts of Alaska, the Pacific Northwest, and New England. For example, a mid-December 2006 extratropical cyclone caused widespread damage across Washington and Oregon and resulted in power outages to 1.5 million people (Figure 8). QuikSCAT winds have certainly raised the awareness of OPC forecasters as to the occurrence of HF intensity conditions. QuikSCAT has shown that HF winds in extratropical cyclones are: (1) much more frequent than thought; (2) occur most frequently in the late fall through winter months; (3) are short lived (on average 24 hours or less); (4) tend to occur in particular locations of the cyclone; and (5) can cover tens of thousands of square miles. HF cyclones occur across the heart of the North Atlantic and North Pacific great circle trade routes and can make landfall in areas such as Alaska, the Pacific Northwest, New England, and the mid-Atlantic coasts.

Prior to the QuikSCAT era, no additional warning category existed for the most damaging of extratropical cyclones. Figure 7 clearly shows forecaster reliance on QuikSCAT winds—as data

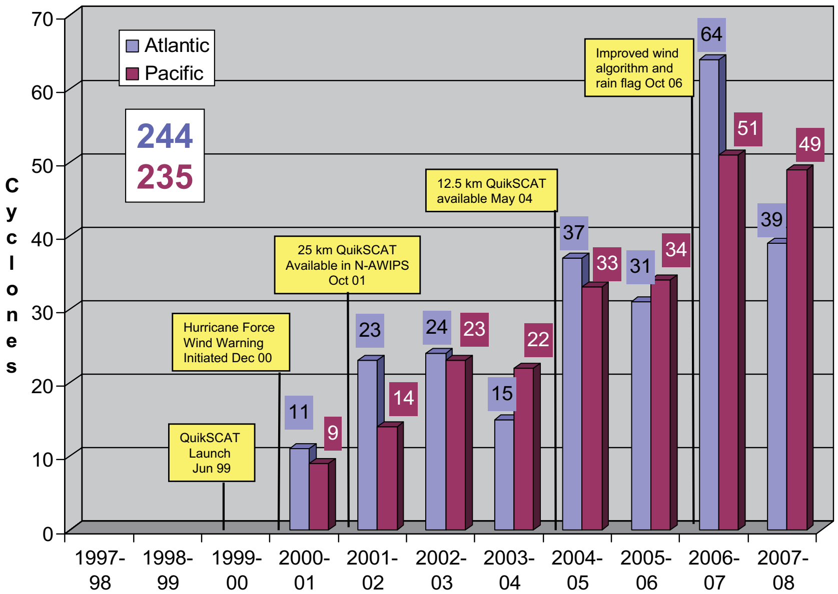

Figure 7. Bar graph showing the number of extratropical cyclones that reached hurricane force intensity for the eight cold seasons from December through May 2000–2001 and September through May 2001–2008. QuikSCAT winds are used heavily by forecasters to assess the wind conditions associated with extratropical cyclones. QuikSCAT milestones are shown by the yellow flags. Blue (maroon) bars show Atlantic (Pacific) cyclones. Total number of individual cyclones that reached hurricane force intensity is shown at left using the same color scheme.

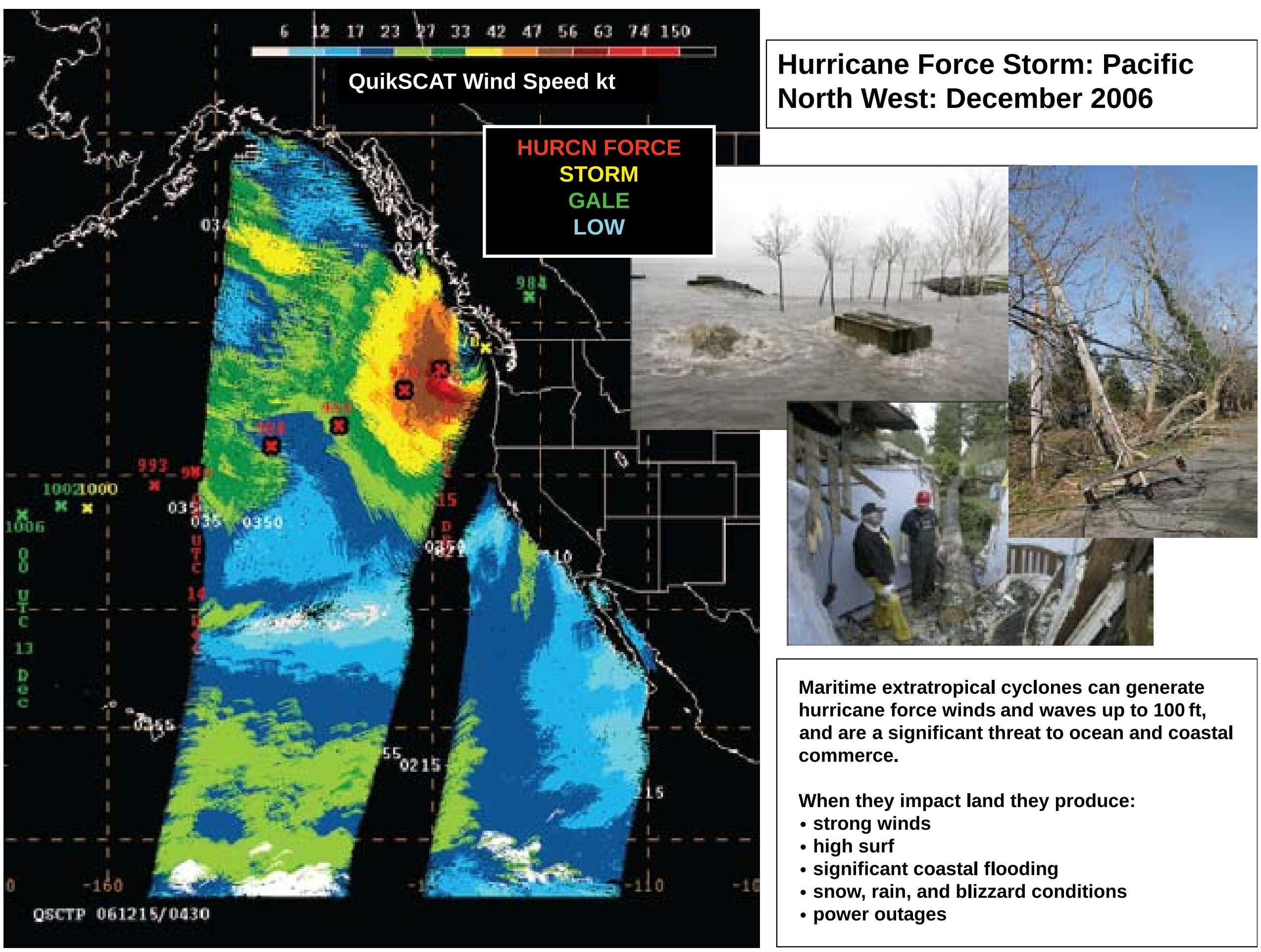

Figure 8. The 2006 "Hanukkah Eve" wind storm occurred on the evening of December 14 and extended into the morning of December 15. The storm blew down thousands of trees, knocked power out for close to 1.5 million customers, damaged hundreds of structures and homes, and injured dozens of people in the US Pacific Northwest and British Columbia, Canada. Hospitals treated 275 people for carbon monoxide poisoning following the storm.

availability increased, algorithms were improved, and higher resolution with less horizontal averaging was introduced, forecasters observed an increasing number of extratropical cyclones with HF conditions each season.

The loss of QuikSCAT would result in an 80% to 90% reduction in detection capability for HF winds from extratropical cyclones. To date, there is no other capability that provides the consistency in retrievable wind speed range and coverage for extreme winds as that available from QuikSCAT. Although the benefits of improved marine warning and forecasting for the coastal US regions seem clear, the need for accurate open-ocean warnings and forecasts might not be as obvious. However, ships sailing throughout the world's ocean transport more than 95% of US international trade by volume. During the last 50 years, commercial ships have doubled in size, waterborne commerce has tripled, and the number of small boats and recreational watercraft has increased. To keep ships on schedule and safe from dangerous ocean storms, the $200 billion global marine shipping industry increasingly relies on accurate marine warnings and forecasts (Kite-Powell, 2000). Accurate wind and wave information helps marine traffic avoid hazardous weather and keeps the costs of goods down, thus making products more affordable. Maritime commerce results in a contribution of $78.6 billion annually and generates nearly 16 million jobs; one out of six jobs in the United States is marine related (Year of the ocean: The U.S. marine transportation system, 1998).

As a result of QuikSCAT OSVW, today's marine warning and forecast services out to 48 hours (for HF cyclones) provide an estimated savings of $135 million annually to North Pacific and North Atlantic dry bulk and container shipping alone by minimizing storm exposure (Kite-Powell, 2008). In general, better information about the spatial and temporal occurrence of severe winds and waves allows adjustment of ships' routes to reduce exposure. In making decisions about route changes, ship operators must balance longer voyage times against expected (potential) losses due to storm exposure; more accurate forecast information can lead to better decision making.

Knowledge of the winds and waves over the ocean is important not only for maritime transportation but also for the fishing industry, offshore energy industries, search and rescue (SAR) efforts, and the accurate tracking and management of marine hazards such as oil spills. The two SAR events detailed below were supported by OPC, and illustrate how important QuikSCAT is considered for situational awareness of the ocean surface wind field:

First event: "On March 20 [2006], the OPC received a call from the US Coast Guard, Program Coordinator, Rescue & SARSAT [Search And Rescue Satellite Aided Tracking] Operations asking for assistance in determining the weather situation in the Red Sea where the *Al Salaam* ferry sank in Egyptian waters on February 2, 2006. The Coast Guard was responding to the International Maritime Organization, which asked the U.S. Government to conduct an investigation and produce a report on the chain of events leading up to the sinking. The Coast Guard noted that they had tried to obtain the information from several federal agencies but with no success. Although OPC does not analyze or forecast for that area, Dave Feit was able to pull together a combination of ship observations, QuikSCAT wind retrievals [Figure 9], and appropriate model data to provide the necessary information. The Coast Guard expressed appreciation for OPC's efforts." (Ocean Prediction Center, 2006)

Second event: "On February 16 [2007] the OPC received a call from NOAA HAZMAT requesting weather support for a factory ship for the Japanese whaling fleet, the *Nisshin Maru*, off Antarctica near 73.38 S and S 175.56 E. The support was requested to help the United States Coast Guard (USCG) assess the risk from an oil spill should it happen. OPC prepared a seven-day forecast for winds and seas at this location which was sent to NOAA HAZMAT. In addition, Joe Sienkiewicz, OPC Science and Operations Officer (SOO), provided QuikSCAT data and maps for the incident area to OPC forecasters. A total of two sets of forecasts were provided to HAZMAT who asked that OPC be prepared to continue to provide support, if needed. No further support to NOAA HAZMAT was required." (Ocean Prediction Center, 2007)

DEVELOPMENT OF NEW QUIKSCAT PRODUCTS AND THEIR TRANSITION TO OPERATIONS

This NOPP project also transitioned into the operational processing system a sophisticated enhanced resolution processing scheme developed by the Microwave Earth Remote Sensing Laboratory (MERS) at Brigham Young University. The MERS processing

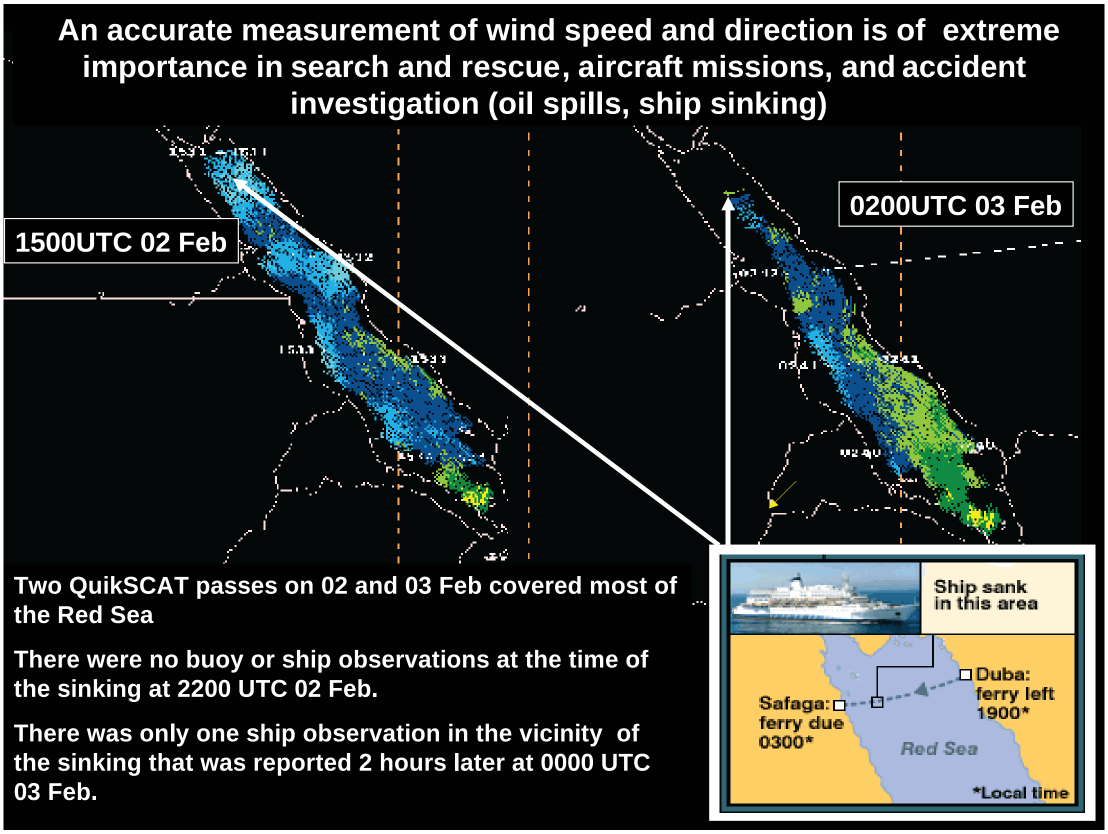

Figure 9. QuikSCAT provided measurements of wind speed and direction to help determine the cause for the sinking of a vessel in the Red Sea on February 2, 2006.

scheme produces ultra-fine- or ultra-high-resolution (UHR) wind speed and normalized radar-cross section (NRCS) images of Earth's surface from QuikSCAT (Long, 2004). These ultra-fine-resolution NRCS images reveal details of the wind structure in tropical cyclones, and together with the OSVW measurements have become an important tool in TC forecasting and warning, especially where aircraft reconnaissance is not available (Edson et al., 2002). The NOAA QuikSCAT NRT processing system now produces refined UHR, storm-centered, "postage-stamp" wind and NRCS products, which are posted to the NRT QuikSCAT storm page (http://manati.orbit.nesdis.noaa.gov/cgi-bin/qscat_storm.pl) (see Figure 10, where a land distance flag was recently added; Owen and Long, 2008a; Plagge et al., 2008). A careful study of eight years of QuikSCAT data revealed that UHR wind retrieval can accurately locate hurricane centers compared with best track locations, even in early stages of development (Said and Long, 2008). MERS has developed an experimental UHR simultaneous wind/rain wind retrieval algorithm along with a new wind direction ambiguity removal algorithm, both of which are currently undergoing validation experiments (Williams and Long, 2006, 2008a,b; Owen and Long, 2008b).

USE IN THE PRIVATE SECTOR

In addition to government agencies exploiting QuikSCAT OSVW, there are also a surprising number of users in the private sector and the general public. We have received emails from a wide range of folks, including the meteorologist aboard an aircraft carrier, the surfing community, recreational and racing vessels, and the offshore wind farm industry. Through its WeatherNet system, OCENS Inc. (a participant in this NOPP-funded effort) made QuikSCAT OSVW data available to its market base, which includes sail and power cruising, ocean racing, commercial and sport fishing, tug and barge operations, and shipping.

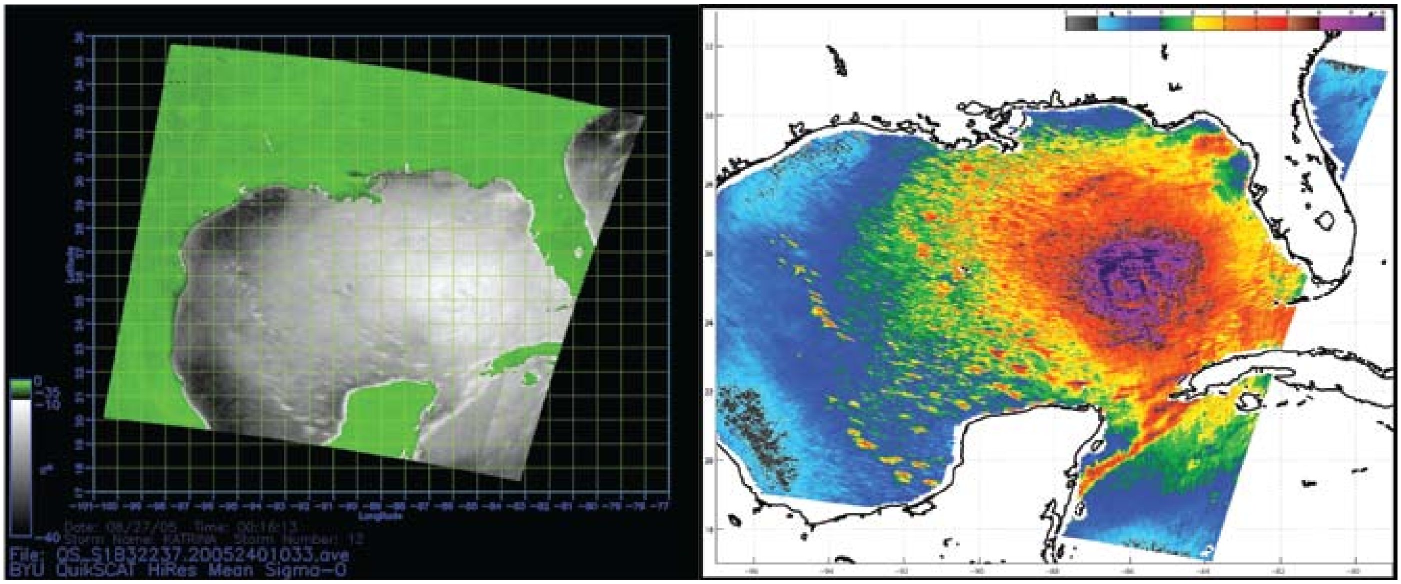

Figure 10. Early examples of ultra-high-resolution (UHR) processing of QuikSCAT data for Hurricane Katrina on August 27, 2005. (Left) UHR radar h-pol normalized radar-cross section image. High winds show up as lighter values, and lower wind speeds are darker. Land is colored green. (Right) QuikSCAT UHR wind speeds. Mesoscale structure and convective events are clearly visible.

Surveys conducted by OCENS found most user feedback was very positive. A broad set of their users found that the QuikSCAT data are most beneficial in areas where the weather is generally stable and the data are used to locate slight variations in wind patterns to enable optimum vessel routing. More advanced users have taken advantage of the availability of the QuikSCAT data to "tune" GRIB (GRIdded Binary) wind forecasts produced by the NWS Global Forecast System model and/or WaveWatch III models. Most notably, this practice was employed to startling success by the *Spirit of Sark*, a racing yacht participating in the Global Challenge Around-the-World Race, which is detailed in the following quote from an email received from Simon Bell, *Sark's* navigator:

Cold-Front Dissection: I have attached a GRIB-Explorer Screen-Shot for our first Brazilian-cold front (CF) [shown in Figure 11].

Using GRIB-Explorer we were able to calibrate our GFS Grib-file vs QuikSCAT and determine how far ahead/behind the GFS-Forecast was. From this, we could estimate our ETA at the Cold-Front. We were also able to "see" inside the Cold-Front and understand the structure of the Front and what conditions we could expect. We were able to see from the Screen-Shots that we could expect the wind to drop & back as we approached the CF and then jump to 30 kts from the SW at the Front. Using this info we flew our Spinnaker to ***within 30 seconds*** *before the SW-Wind hit...and WOW did it hit.*

We were also able to understand the dynamics of the Cold-Front. The weather-forecasts reported a Cold-Front at Location XY heading SE and moving NE at 10knts. By observing the QuikSCAT Data over time, we understood that the situation was MUCH more complicated! The N-side of the CF is driven by the NW-Wind and features on the N-Side therefore drift SE along the Cold-Front with this Wind. Then the whole Cold-Front does indeed Track NE...and combining this with the Drift we understood that features drift West! On the S-Side of the CF the opposite is true...features on the S-Side are driven by SE-Wind and therefore drift NW along the CF. Then with the whole Cold-Front Tracking NE...and combining this with the Drift we understood that features drift North! This helped us understand (too late) how to line-up on Gates thru the Cold-Front when one presented itself.

Spirit of Sark subsequently won the rugged Buenos Aires to Wellington Third Leg of the Global Challenge while making extensive use of QuikSCAT data acquired through WeatherNet and displayed in GRIB Explorer. Similar tuning techniques were employed by racers participating in

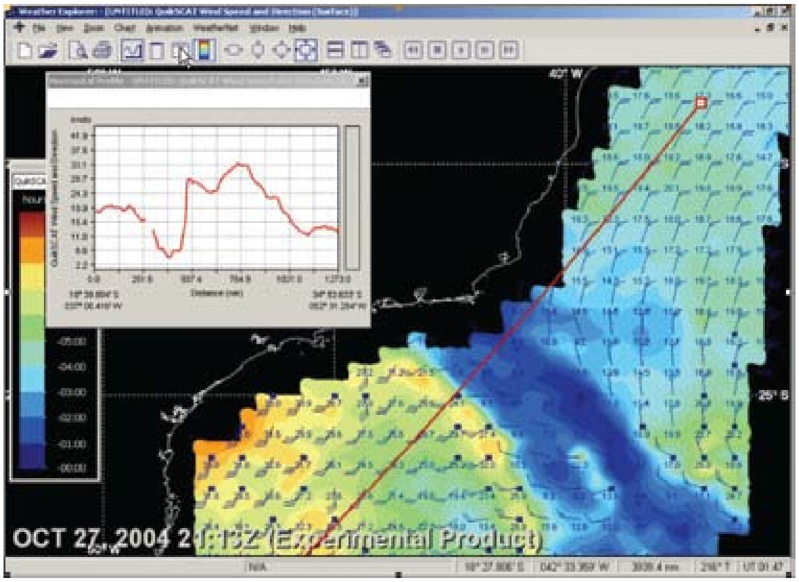

Figure 11. The GRIB-Explorer display of QuikSCAT wind vectors and wind speeds (color coded), depicting a cold front off the coast of Brazil on October 27, 2004.

the Newport–Bermuda, Annapolis–Bermuda, Pacific Cup, and Vic–Maui races during the summer of 2004. Better testimony to the benefits and utility of QuikSCAT data to the marine market would be difficult to find. Creating a means of enabling less technically proficient users to tune their wind forecasts en route with QuikSCAT information is an area of clear development opportunity.

LIFE AFTER NOPP FUNDING

The three years of NOPP support resulted in improved use of QuikSCAT OSVW data in the NWS operational environment, a measure of QuikSCAT impacts at the National Hurricane Center (NHC) and OPC. These years have also seen the transition of new QuikSCAT research products into operations and exploitation of these products by a commercial weather services company, which brought satellite OSVW data to individual users. An equally important outcome of this project was the development of partnerships among the participants that continue to this day, and these partnerships have played a critical role in NOAA's pursuit of a QuikSCAT follow-on mission. Fortunately, we were able to sustain and build upon this effort with support from NOAA's Ocean Remote Sensing Program and Research to Operations (R2O) Program. Through the R2O program, the QuikSCAT OSVW impacts at local NWS Weather Forecast Offices were also captured (Millif and Stamus, 2008). With satellite OSVW data from QuikSCAT becoming such a well-used NWS tool, a workshop to define NOAA's operational OSVW requirements was held at NHC in Miami, Florida, in June 2006 (Chang and Jelenak, 2006). The primary goals of this meeting were to: (1) document the use and impact of presently available satellite OSVW data in operational marine weather analysis, forecast, and warning activities at NOAA, (2) define the OSVW operational requirements within NOAA based on actual experience and phenomena observed, and (3) explore sensor/mission concepts capable of meeting the requirements. The desired outcome of the workshop was to help NOAA determine a course of action because there were no plans for a QuikSCAT follow-on mission.

Over the following year, the National Research Council (NRC) conducted a decadal survey of satellite observations in support of climate change monitoring, and listed as one of their recommendations the need for an advanced OSVW mission to replace the aging NASA QuikSCAT in order to provide key insights into ocean circulation and global heat transfer, and their impacts on Earth's climate (National Research Council, 2007). The NRC study also recommended that NOAA undertake this extended ocean vector wind mission (XOVWM) as a sustained operational capability.

In 2007, NOAA initiated an Analysis of Alternatives (AOA) type study to assess observing system options to mitigate or replace the current NASA QuikSCAT OSVW capability. OSVW AOA concluded that a sustained operational satellite OSVW capability should be designed to better address the operational weather forecasting and warning requirements through a more advanced observing system such as XOVWM identified in the 2007 NRC decadal survey described above.

Also in 2007, NOAA asked NASA JPL to conduct a NASA QuikSCAT follow-on mission study. The study showed that technology is currently available to improve scientific and operational

OSVW retrieval capability by an order of magnitude over that provided by QuikSCAT (Gaston and Rodriguez, 2008). The primary improvements are: finer horizontal resolution of surface wind estimates, decreased sensitivity to the effects of rain in the wind estimates, the ability to retrieve much higher wind estimates (> 50 m s^{-1}), and the ability to provide winds to within 5 km of the coast. In parallel, NOAA conducted a study assessing the impacts of both a QuikSCAT-equivalent and an improved OSVW capability, which resulted in the document *QuikSCAT Follow-On Mission: User Impact Study Report* (Jelenak and Chang, 2008).

Finally, NOAA is working with international partners to leverage scatterometry data from foreign satellites in an attempt to provide uninterrupted continuity of these data. Currently, the European Organisation for the Exploitation of Meteorological Satellites is flying an operational Advanced Scatterometer that will provide some OSVW data continuity, although it only provides approximately 55% of the coverage and twice as coarse spatial resolution wind retrievals as those provided by QuikSCAT. NOAA is also exploring access to data from Indian and Chinese satellites that will be launched in the next few years, as well as a partnership with the Japanese Exploration Space Agency (JAXA) to fly a QuikSCAT follow-on instrument as part of JAXA's Global Climate Observation Mission program.

CONCLUSION

Our NOPP project established personnel resources at OPC, NHC, and NESDIS that significantly strengthened existing collaborations. Because of this enhanced partnership, QuikSCAT OSVW data were transitioned in an optimal and efficient manner into the operational NWS environment. Quantifying the impacts of these data allowed us to better understand the value of this observing system capability. Additionally, we were able to determine and justify the actual operational weather warning and forecasting requirements for satellite OSVW, which will be important for the design of a QuikSCAT follow-on mission to continue this now routinely used OSVW capability. Academic and private sector partnerships were also enabled by our NOPP project. Working with Brigham Young University, we transitioned new QuikSCAT products into operations, and we expanded the use of QuikSCAT OSVW products in collaboration with OCENS Inc. The partnerships enabled by this NOPP opportunity had a significant role in the successful transition of QuikSCAT OSVW data into the operational environment at NOAA and beyond.

Ocean surface vector wind data received from NASA QuikSCAT have revolutionized operational marine weather warnings, analyses, and forecasting. QuikSCAT data give forecasters the ability to see the detailed wind field over vast ocean areas, to see the inner structure of ocean storms, and to identify areas of ocean wind wave generation. When issuing marine wind forecasts and warnings, these surface wind data give forecasters a higher level of situational awareness, providing a rich data source in areas not sampled by buoys and other wind platforms, ultimately resulting in improved forecasts and warnings. An impact study in the fall of 2002 by Von Ahn et al. (2006) demonstrated that the number of wind warnings issued for extratropical cyclones by OPC increased by 30% in the North Atlantic and 22% in the North Pacific when QuikSCAT winds were used in the forecast process. Based on this improved detection capability, OPC introduced a new warning category for hurricane-force winds in nontropical ocean storms in late 2000. For tropical cyclones, QuikSCAT data have become an important analysis tool at the National Hurricane Center, the Central Pacific Hurricane Center, and the Joint Typhoon Warning Center, providing information on the intensity of tropical depressions and tropical storms; improving the identification and analysis of TC center locations, especially in developing systems; and providing critical information on TC wind field structure, especially in data-sparse open ocean areas (e.g., Brennan et al., in press).

Today, QuikSCAT data are used around the world to help provide accurate marine weather warnings and forecasts. Users span government agencies, commercial companies (ship routing, offshore wind farms, weather information providers), and individual users (surfers, sailboat racers, recreational boaters). Satellite OSVW data from QuikSCAT impact many facets of daily life in marine and coastal communities. QuikSCAT OSVW data have successfully been transitioned to use in the operational environment. The next challenge will be to establish a sustained satellite OSVW observing capability that builds upon the knowledge gained from over nine years of QuikSCAT OSVW.

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REFERENCES

Brennan, M.J., H.D. Cobb, III, and R.D. Knabb. 2007. Observations of Gulf of Tehuantepec gap wind events from QuikSCAT: An updated event climatology and operational model evaluation, 22nd Conference on Weather Analysis and Forecasting/18th Conference on Numerical Weather Prediction, Park City, UT, American Meteorological Society. Available online at: http://ams.confex.com/ams/pdfpapers/124096.pdf (accessed March 21, 2009).

Brennan, M.J., C.C. Hennon, and R.D. Knabb. In press. The operational use of QuikSCAT ocean surface vector winds at the National Hurricane Center. *Weather and Forecasting*.

Chang, P.S., and Z. Jelenek. 2006. NOAA Operational Ocean Surface Vector Winds Requirements Workshop Report, 52 pp. Available online at: http://manati.orbit.nesdis.noaa.gov/SVW_nextgen/SVW_workshop_report_final.pdf (accessed March 21, 2009).

Edson, R.T., M.A. Lander, C.E. Cantrell, J.L. Franklin, P.S. Chang, and J.D. Hawkins. 2002. Operational use of QuikSCAT over tropical cyclones. Twenty-fifth Conference on Hurricanes and Tropical Meteorology, San Diego, CA, American Meteorological Society.

Gaston, R., and E. Rodriguez. 2008. *QuikSCAT Follow-On Concept Study*. JPL Publication 08-18, 66 pp. Available online at: http://winds.jpl.nasa.gov/publications/index.cfm (accessed March 25, 2009).

Gelsthorpe, R., E. Schied, and J. Wilson. 2000. ASCAT-METOP's advanced scatterometer. *ESA Bulletin* 102:19–27.

Jelenak, Z., and P. S. Chang. 2008. *NOAA Operational Satellite Ocean Surface Vector Winds - QuikSCAT Follow-On Mission*. User Impact Study Report, 90 pp. Available online at: http://manati.orbit.nesdis.noaa.gov/SVW_nextgen/QFO_user_impact_study_final.pdf (accessed March 21, 2009).

Jet Propulsion Laboratory. 2006. *QuikSCAT Science Data Product User's Manual.* JPL Publication D-18053-RevA, 91 pp. Available online at: ftp://podaac.jpl.nasa.gov/ocean_wind/quikscat/L2B/doc/QSUG_v3.pdf (accessed March 25, 2009).

Jones, S.C., P.A. Harr, J. Abraham, L.F. Bosart, P.J. Bowyer, J.L. Evans, D.E. Hanley, B.N. Hanstrum, R.E. Hart, F. Lalaurette, and others. 2003. The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. *Weather and Forecasting* 18:1,052–1,092.

Kite-Powell, H. 2000. *Benefits of NPOESS for Commercial Ship Routing: Travel Time Savings*. Report to the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office, Washington, DC. Available from the Woods Hole Oceanographic Institution Marine Policy Center.

Kite-Powell, H. 2008. *Benefits to Maritime Commerce from Ocean Surface Vector Wind Observations and Forecasts*.15 pp. Available online at: http://manati.orbit.nesdis.noaa.gov/SVW_nextgen/QuikSCAT_maritime_report_final.pdf (accessed March 21, 2009).

Long, D.G. 2004. Reconstruction of high resolution ocean wind vectors from low resolution scatterometer measurements. Pp. 196–207 in *Proceedings of SPIE Volume 5562 Image Reconstruction from Incomplete Data III*. P.J. Bones, M.A. Fiddy, and R.P. Millane, eds, SPIE, Bellingham, WA.

Milliff, R.F., and P.A. Stamus. 2008. QuikSCAT impacts on coastal forecasts and warnings: Operational utility of satellite ocean surface vector wind data. *Weather And Forecasting* 23:878–890.

Naderi, F., M.H. Freilich, and D.G. Long. 1991. Spaceborne radar measurement of wind velocity over the ocean—An overview of the NSCAT scatterometer system. *Proceedings of the IEEE* 79(6):850–866.

National Research Council. 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond.* The National Academies Press, Washington, DC, 456 pp. Available online at: http://www.nap.edu/catalog.php?record_id=11820#toc (accessed March 21, 2009).

Ocean Prediction Center. 2006. 2006 Accomplishments. Available at: www.opc.ncep.noaa.gov/Accomplishments/2006.pdf (accessed March 25, 2009).

Ocean Prediction Center. 2007. 2007 Accomplishments. Available at: www.opc.ncep.noaa.gov/Accomplishments/2007.pdf (accessed March 25, 2009).

Owen, M.P., and D.G. Long. 2008a. Land Contamination Compensation for QuikSCAT Near-Coastal Wind Retrieval. Paper presented at the International Geoscience and Remote Sensing Symposium, July 6–11, 2008, Boston, MA.

Owen, M.P., and D.G. Long. 2008b. Progress toward validation of QuikSCAT ultra-high-resolution rain rates using TRMM PR. Paper presented at the International Geoscience and Remote Sensing Symposium, July 6–11, 2008, Boston, MA.

Plagge, A., D. Vandemark, and D. Long. 2008. Validation and evaluation of QuikSCAT ultra-high resolution wind retrieval in the Gulf of Maine. Paper presented at the International Geoscience and Remote Sensing Symposium, July 6–11, 2008, Boston, MA.

Said, F., and D.G. Long. 2008. Effectiveness of QuikSCAT's ultra high resolution Images in determining tropical storm eye location. Paper presented at the International Geoscience and Remote Sensing Symposium, July 6–11, 2008, Boston, MA.

Sanders, F., and J.R. Gyakum. 1980. Synoptic–dynamic climatology of the "bomb." *Monthly Weather Review* 108:1,590–1,606.

Stoffelen, A., and D. Anderson.1993. ERS-1 scatterometer data characteristics and wind retrieval skill. Pp. 41–47 in *Proceedings of the First ERS-1 Symposium*, Cannes, France, European Space Agency Special Publication, ESA SP-359.

Verhoef, A., and A. Stoffelen. 2008. ERS Scatterometer Product User Manual version 1.6 Document external project, KNMI publication, 212f, EUMETSAT.

Von Ahn, J.M., J.M. Sienkiewicz, and P.S. Chang. 2006. Operational impact of QuikSCAT winds at the NOAA Ocean Prediction Center. *Weather and Forecasting* 21:523–539.

Williams, B.A., and D.G. Long. 2008a. Estimation of hurricane winds from SeaWinds at ultra high resolution. *IEEE Transactions on Geoscience and Remote Sensing* 46(10):2,924–2,935.

Williams, B.A., and D.G. Long. 2008b. Rain and wind estimation from SeaWinds in hurricanes at ultra high resolution. Paper presented at the International Geoscience and Remote Sensing Symposium, July 6–11, 2008, Boston, MA.

Williams, B. A., and D.G. Long. 2006. An Improved High Resolution Wind Ambiguity Removal Procedure for SeaWinds. Pp. 2,643–2,646 in *Proceedings of the International Geoscience and Remote Sensing Symposium*, July 31–August 4, 2006. Denver, CO.

Year of the ocean: The U.S. marine transportation system. 1998. *Year of the Ocean Discussion Papers*, Office of the Chief Scientist, NOAA. 1998. Available online at: http://www.yoto98.noaa.gov/papers.htm (accessed March 21, 2009).