Comparison of Early Model Forecasts With Satellite Data

The evaluation of hurricane forecast skill requires ensembles of historical forecasts. The purpose of this article is not to undertake such an evaluation, but rather to demonstrate the current status of satellite physical retrievals and their potential to provide valuable information for such evaluations and contribute to model improvements. Figure 3 shows a pictorial example of the 120-hour accumulated surface rainfall from satellite retrievals, and from single high-resolution forecasts from ECMWF and NASA models.

Predictions of Hurricane Katrina were statistically better than the historical forecast skill [e.g., *Knabb et al.*, 2005]. Similarly, ECMWF as well as NASA high-resolution global forecasts performed remarkably well during the first two days, with the forecast tracks closely matching what was observed for Katrina, and only small displacement errors. In the model, the heaviest rainfall during the first 48 hours was not near the storm center, but rather was about 80–120 kilometers to the south of the hurricane track, similar to what was observed. This interesting feature cannot be identified by examining the dynamical fields alone. Overall, the amplitude of the model accumulated rain amount is similar to satellite microwave retrievals, although the GEOS model shows a slightly lower amount while the ECMWF model shows a slightly higher amount. Track displacements start to amplify in the 96–120 hour forecasts, but the errors are still in line with the mean errors of the NOAA National Hurricane Center (NHC) official forecasts.

The simulated Katrina in the NASA model tends to move more slowly and remains over the Gulf of Mexico. The forecasted track deviates by two to three degrees west of the best track. The hurricane in the ECMWF forecast, though, deviates by two to three degrees east of the best track, and makes landfall between Alabama and Florida about 12 hours late. These differences in the hurricane track and accumulated precipitation may reflect inadequacies in the large-scale circulation provided in the initial conditions, or imperfect model physical parameterizations, but also may be due to the system's lack of predictability.

Developments in Hurricane Forecasts

Advances in spaceborne observations and numerical weather prediction (NWP) models provide new opportunities for improving hurricane forecasts. Apart from their importance for NWP, global atmospheric models of hurricanes and their forecasts represent an important and unique test bed of model formulations.

Recent developments that include moving from synoptic-scale-resolving to mesoscale-resolving global models show some very encouraging results. In addition to increasing resolution and including more physically based parameterizations on mesoscale effects in conventional general circulation models, cloud-scale-resolving global models—in which the cloud dynamics and mesoscale processes are explicitly resolved—also are being developed and could be used as a parallel approach to more realistically simulate hurricanes in global models in the future.

Better resolution of the hurricane structure and larger-scale steering circulation, along with improved initial conditions provided by high-resolution satellite data and sophisticated data assimilation systems, could lead to better detection, monitoring, understanding, and prediction of the genesis and development of hurricanes that have such a devastating impact on society.

Acknowledgments

The TRMM TMI, SSM/I, and MODIS data were provided by the NASA Goddard Space Flight Center Data Archive and Distribution Center. The AQUA AMSR-E data were provided by the National Snow and Ice Data Center Distributed Active Archive Center. The QuikSCAT data were obtained from the Physical Oceanography Distributed Active Archive Center at the NASA Jet Propulsion Laboratory. Constructive comments from Naomi Surgi (NOAA/NCEP) and two anonymous reviewers are gratefully acknowledged.

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Ice-Tethered Profilers Sample the Upper Arctic Ocean

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Studies conducted over the past decade indicate that the Arctic may be both a sensitive indicator of climate change and an active agent in climate variability. Although progress has been made in understanding the Arctic's coupled atmosphere-ice-ocean system, documentation of its evolution is hindered by a sparse data archive. This observational gap represents a critical shortcoming of the 'global' ocean observing system's ability to quantify the complex interrelated atmospheric, oceanic, and terrestrial changes now under way throughout the Arctic and that have demonstrated repercussions for society [*Symon et al.*, 2005].

Motivated by the Argo float program, an international effort to maintain an ensemble of approximately 3000 autonomous profiling instruments throughout the temperate oceans (see http://w3.jcommops.org), a new instrument, the 'Ice-Tethered Profiler' (ITP) was conceived to repeatedly sample the properties of the ice-covered Arctic Ocean at high vertical resolution over time periods of up to three years.

Several prototype ITPs have now been deployed within the Beaufort Gyre system of the Canada Basin. The two systems installed in August 2005 returned temperature and salinity profiles every six hours between a 10- and 760-meter depth for more than a year, revealing interesting spatial and temporal variations in the regional water masses.

On the basis of these results, five new ITP systems were constructed. Three of these were deployed in the Canada Basin in August/September 2006; the two remaining will be installed in spring 2007 about the North Pole. Plans are being developed internationally to deploy a basin-scale array of profiling instruments during the upcoming International Polar Year (March 2007 to March 2009).

Technology

The ITP represents the marriage of two related technologies: the profiling Argo float [*Gould et al.*, 2004] and the moored profiler [*Doherty et al.*, 1999]. The ITP system consists of three components: a surface instrument package that sits atop an ice floe; a weighted, plastic-jacketed wire rope tether of arbitrary length (up to 800 meters) suspended from the surface package; and an instrumented underwater unit that travels up and down the wire tether [*Krishfield et al.*, 2006].

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The surface unit houses a controller, inductive modem electronics, a GPS receiver, and an Iridium satellite phone with associated antennae and batteries within a watertight housing. The upper five meters of the wire tether are cast within a thick protective urethane jacket that also houses an electrical ground lead for the inductive modem. The profiling underwater unit is similar in shape and dimension to an Argo float except that the float's variable-buoyancy system is replaced with a traction drive unit (similar to that used on the commercially produced McLane Moored Profiler; see http://www.mclanelabs.com) that achieves nominal profile speeds of 25 centimeters per second. The assembled underwater unit has an overall diameter of approximately 23 centimeters and thus is able to fit through an 11-inch-diameter ice hole.

Profile start times and depth limits are specified by the user. Sensor data are acquired continuously at one hertz during both up-going and down-going profiles. At the end of each profile, full-resolution sensor and engineering data are transmitted from the underwater unit to the surface controller via the inductive modem link, and subsequently relayed to a shore-based data server using the Iridium telemetry system.

The raw data and preliminary pressure-gridded profiles are made available immediately from the program Web page (http://www.whoi.edu/itp) along with various plots of the observations. Calibrated, edited profile data will be produced at one- to two-month intervals and also will be made available from the Web site as well as from national data archives.

To date, the Sea-Bird Electronics, Inc. conductivity-temperature-depth (CTD) sensor (model 41-CP) has been interfaced to the ITP, and one of the newly-deployed systems also carries an oxygen sensor. Plans are being developed to add chlorophyll fluorescence, turbidity, and photosynthetically available radiation (PAR) sensors to future systems.

Prototype Performance

On 19 August 2004, during an expedition of the Canadian Coast Guard icebreaker *Louis S. St-Laurent*, the first prototype ITP (serial number 2) was deployed on a multi-year ice floe in the Arctic Ocean near 77°N, 141°W. The profiler was programmed with an accelerated sampling schedule of six profiles per day in order to more quickly evaluate endurance and component fatigue. After 40 days of operation, this first prototype ITP stopped transmitting; one possible explanation for its premature demise is that the supporting ice floe fractured and the system sank. By design, the surface package buoyancy of this first unit was not adequate to float the tether and ballast weight; subsequent systems are equipped with sufficient buoyancy. The following year, two improved ITP systems were deployed in the Canada Basin, again from the *St-Laurent*. ITP 1 was installed at 78.8°N, 150.3°W on 15 August; ITP 3 was deployed 8 days later at 77.6° N, 142.2°W. As of this writing, ITPs 1 and 3 have both returned more than 1500 CTD profiles.

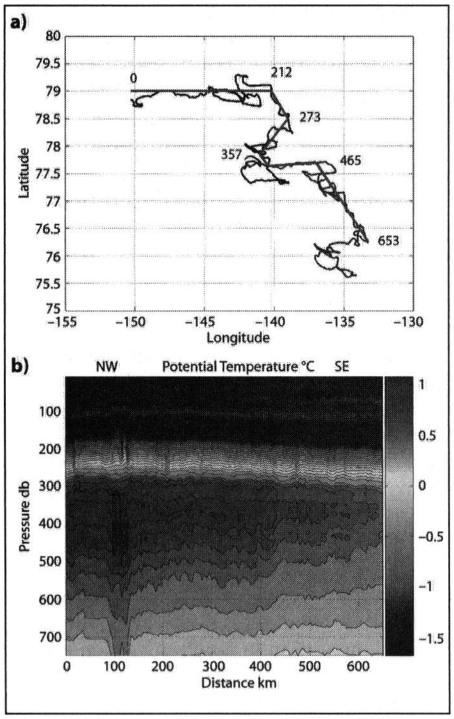

Fig. 1. (a) Drift tracks of Ice-Tethered Profiler (ITP) 1 (black) and 3 (blue) and a broken-line track (red) manually drawn through them. (b) A pressure- (nearly equivalent to depth in meters) distance contour plot of potential temperature constructed by mapping individual ITP profiles onto the broken line track shown in Figure 1a. The color scale for temperature is described to the right of this plot. The numbers in Figure 1a at the line break points indicate distance in kilometers along the broken-line track. This distance coordinate corresponds to the x-axis in Figure 1b. The Atlantic Water front noted in the text appears around a distance of 400 kilometers, while the Atlantic water eddy was sampled around a distance of 100 kilometers. A total of 421 up-going vertical profiles went into this figure, yielding a nominal spatial resolution for this analysis of 1.6 kilometers. Given that the typical ice drift speed of around 10 centimeters per second is an order of magnitude larger than the typical upper ocean current speed in this area of the Arctic, the ITP data may be interpreted as a near-synoptic spatial survey. Original color image appears at the back of this volume.

The recovered profile data reveal interesting variations in the water masses of the Beaufort Gyre, an area within the Canada Basin that houses a vast, variable reservoir of freshwater within the Arctic Ocean. Water properties allow discrimination between the layers originating in the Pacific and Atlantic Oceans and assessment of the changes experienced by those waters while traveling to, or while resident within the Arctic. Most notable of the Beaufort Gyre water masses are the Pacific Halocline Waters between approximately 40- and 180-meter depth and the Atlantic Water layer centered around 350 meters in depth. The former is characterized by multiple, thin temperature extrema in the vertical within a strong vertical salinity gradient. These Halocline layers are thought to manifest the summer and winter Bering Strait waters and alternate flow pathways through the Chukchi Sea and shelf areas [*Shimada et al.*, 2001; 2005]. The Atlantic Water layer is indicated by a broader temperature maximum in the vertical. Temperatures at the layer core are much lower in the Beaufort Gyre than at the Atlantic entrance to the Arctic due to mixing with the much colder waters that surround the Atlantic Water layer.

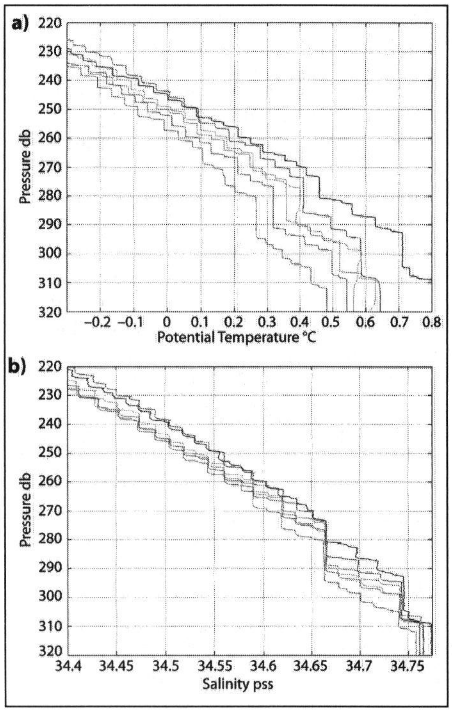

Fig. 2. Expanded views of selected (a) potential temperature and (b) salinity profiles from ITP 2 along ~75°N showing the double-diffusive thermohaline staircase that lies above the warm, salty Atlantic Layer. These one-hertz data have been adjusted for sensor responses but have otherwise not been filtered. Original color image appears at the back of this volume.

Data from the ITPs reveal a front in the Atlantic Water properties within the Beaufort Gyre near 140°W with warmer, saltier waters to the west. This front is nicely depicted by a composite depth-distance section constructed by mapping the profile data from ITPs 1 and 3 onto a broken-line track (Figure 1). Also revealed in Figure 1 are the remarkably long spatial scales of the thin Halocline Water layers. Research is ongoing to diagnose the circulation patterns responsible for these water property distributions.

Observations of temporal change in the ocean stratification may be used to help quantify variations in the supplies of Pacific and Atlantic waters to the Arctic and/or modulations of the processes responsible for water property modifications within this ocean. In turn, improved understanding of the Arctic fresh water budget, and climate system as a whole, should result. For example, marked changes in the temperature, salinity and stratification of the upper 30 m of the Beaufort Gyre were sampled by the ITPs. Importantly, the ice floes supporting the ITPs move relative to the upper ocean. Thus, these variations reflect a mixture of seasonal forcing (cooling, ice formation and brine rejection; solar warming, ice melting and freshening) and regional spatial gradients associated with river runoff and the patterns of precipitation and ice growth/decay. Information from a spatial network of sensors is required to decompose the spatial and temporal variability.

Poorly represented in the mapped section are several eddies that were sampled by the ITPs. These features are better visualized by the depth-time contour plots given on the ITP Web page. Eddies are believed to stir water properties horizontally in the ocean. In the Arctic, they may be an important agent for spreading water mass anomalies from the boundaries to the interior. The most striking eddy so far observed by ITPs is a warm-core feature in the Atlantic Water responsible for the large contour distortions around a distance of 100 kilometers (Figure 1). The rather broad depiction of this feature here is a mapping artifact caused by the meandering of the supporting ice floe, resulting in multiple encounters with the eddy. Numerous smaller, cold-core eddy features within the Halocline Waters also have been sampled. The source of these eddies is currently under investigation.

At smaller vertical scale, the raw one-hertz CTD data resolve fairly well the thermohaline staircase stratification above the Atlantic Water layer, thought to be caused by double diffusion (Figure 2), and also the 'nested' intrusive structures that incise the Atlantic Water as discussed by *Walsh and Carmack* [2003]. Both have been implicated in enhanced transport of heat anomalies within the Arctic Ocean (vertically through the staircase and laterally by the intrusions). Better understanding of these features and their effects is required to properly parameterize them in numerical ocean models (that presently cannot resolve such structures).

Future Plans

While they are effective at returning water column observations, ITPs currently do not sample ocean currents, properties of the sea ice, or surface layer meteorology. These fields may be sampled with complementary instrument systems such as the air temperature and atmospheric pressure sensors deployed under the International Arctic Buoy Program (http://iabp.apl.washington.edu/), the Ice Mass Balance Buoy system developed by the Cold Regions Research and Engineering Laboratory (http://www.crrel.usace.army.mil/sid/IMB/), and under-ice current meters and/or acoustic Doppler current profilers (see, for example, the Autonomous Ocean Flux Buoy System; http://www.oc.nps.navy.mil/~stanton/fluxbuoy/). Clusters of such instrument systems, termed ice-based observatories [*Proshutinsky et al.*, 2004] as epitomized by the North Pole Environmental Observatory (http://psc.apl.washington.edu/northpole), hold promise for advancing understanding of the Arctic climate and ecological systems.

Not well represented by the prototype ITP deployments are the possible large-scale analyses that could be conducted with a long-term, broad-scale array of under-ice profiling instruments, such as documenting the positions and intensities of baroclinic gyres within the Arctic and the variations in fresh water content. Toward that end, coordination discussions have been had with investigators from Europe (in particular the participants in the DAMOCLES—Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies—program; http://www.damocles-eu.org/), Japan (see the Polar Ocean Profiling System article on the Argo Web page), and North America to initiate and maintain such an array throughout the International Polar Year period.

While holding great promise for returning information about the ice-covered domains of the Arctic, ice-based instrument systems, by definition, cannot sample all of the Arctic; alternate technologies also are needed. Promising approaches include ice-capable profiling floats, gliders, and autonomous underwater vehicles as well as conventional bottom-anchored moorings. Clearly a mix of technology will be required to support the Integrated Arctic Observing Network envisioned in a recent U.S. National Academy of Sciences report [*Committee on Designing an Arctic Observing Network*, 2006]. The Ice-Tethered Profiler holds promise for contributing significantly to such an effort.

Acknowledgments

The engineering design work for the ITP was initiated by the Cecil H. and Ida M. Green Technology Innovation Program (an internal program at the Woods Hole Oceanographic Institution (WHOI)). Prototype development and construction was funded jointly by the U.S. National Science Foundation (NSF) Oceanographic Technology and Interdisciplinary Coordination Program and Office of Polar Programs (OPP) under award OCE-0324233. Continued support has been provided by the OPP Arctic Sciences Section under award ARC-0519899 and internal WHOI funding. Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of NSF.

We thank the officers and crew of the *CCGS Louis S. St-Laurent* and members of the science parties for their assistance in deploying the prototype instruments, as well as Eddy Carmack, Fiona McLaughlin, Sarah Zimmermann, and Koji Shimada for including our ITP activities in the collaborative Beaufort Gyre field program. We also acknowledge the technical assistance provided by McLane Research Laboratories, Inc., Sea-Bird Electronics, Inc., and Webb Research Corporation during the ITP development effort.

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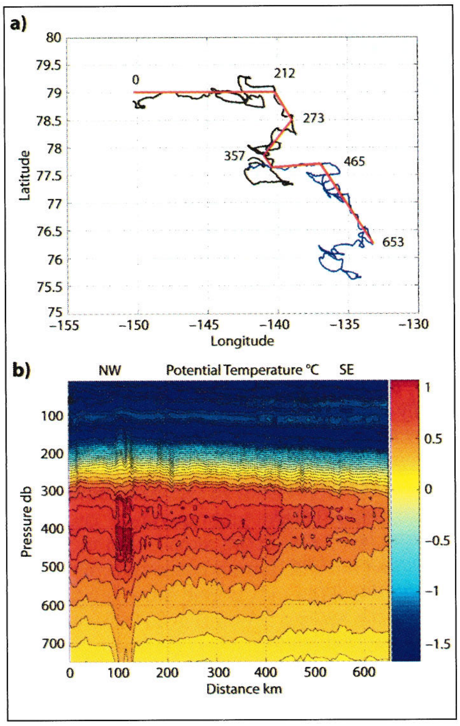

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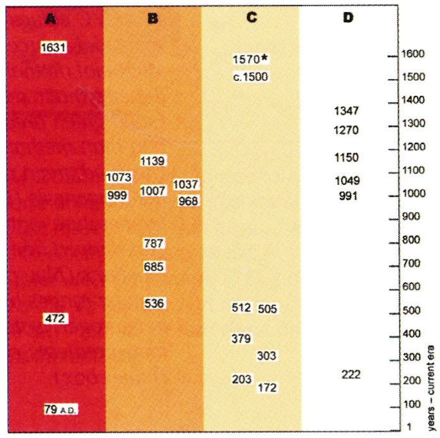

Fig. 2. Vesuvius activity between 79 A.D. and 1631 from historical data (after Principe et al. [2004], integrated from Smithsonian Institution Global Volcanism Program and this paper). A, B, and C use the Walker [1973] classification. (A) Plinian and small-scale Plinian eruptions. (B) Subplinian and violent Strombolian eruptions, the latter in which liquid magma fountains from the vent. (C) Activity with eruptions spanning from the violent Strombolian to Strombolian; this includes eruptions of ashes and a new event that is described in this paper (marked with an asterisk). (D) 'Doubtful' or uncertain events (events supported by written accounts that have yet to be verified by specialist historical research) in the Smithsonian Institution Global Volcanism Program (see http://www.volcano.si.edu/world).