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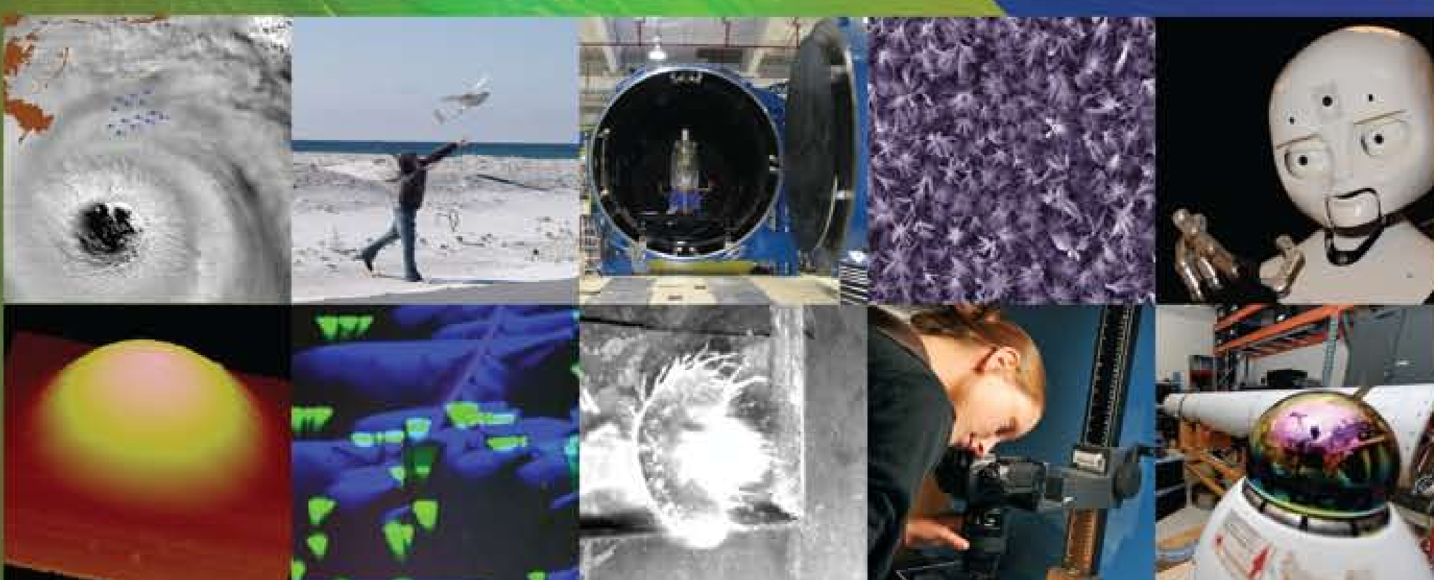

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A Thinning Arctic Ice Cap as Simulated by the Polar Ice Prediction System (PIPS): 2000–2008

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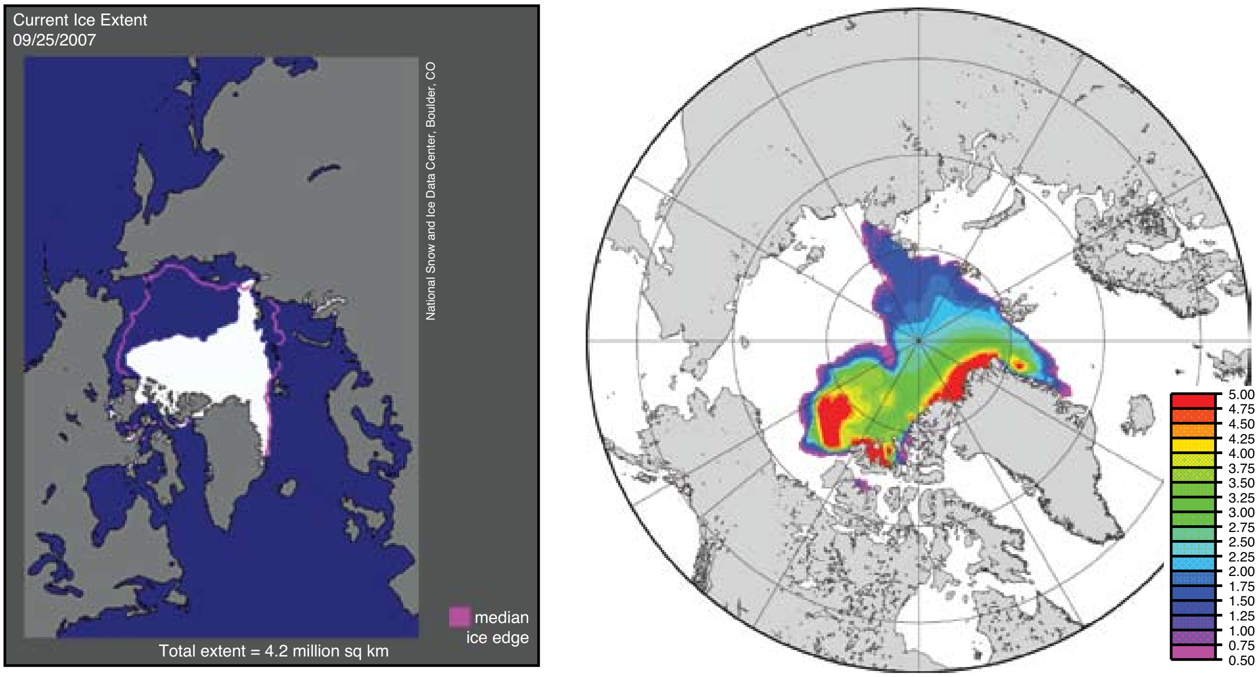
Introduction: Even though the Arctic is one of the most hostile operational environments in the world, numerous vessels transit the Arctic regularly in summer when coastal melting opens the shortest connection between much of the North Atlantic and North Pacific. Free drifting icebergs, 24-hour seasonal darkness, sub-zero temperatures, and a lack of dependable logistical support can make Arctic operations extremely challenging for ships, aircraft, and submarines. Accurate forecasts of changing ice conditions can be applied to anticipate changing conditions and mitigate operational challenges. Applications of the second- and third-generation Polar Ice Prediction System (PIPS) are used to model and diagnose continuing thinning of Arctic ice and larger summertime ice-free areas. A significant decrease in overall ice cover has been observed in relation to the anticipated median ice extent. In 2007, the summer minimum sea ice extent in the Arctic was 40% below the minimum sea ice extents of the 1980s and more than 20% below the previous record minimum of 2005. Forecasts from the second-generation ice prediction system, PIPS 2.0, agree well with documented observations concerning the current diminishing ice cap (Fig. 1).

Current Forecasting Capabilities: The Naval Research Laboratory (NRL) is continuing to develop increasingly capable ice forecast systems tailored to fit the needs of their Navy customers. PIPS 2.0 has been producing operational Arctic forecasts for the Navy since 1996. PIPS 2.0 couples the Hibler dynamic/thermodynamic ice model[1] to the Bryan and Cox ocean model[2] to cover all sea ice areas in the northern hemisphere. The model uses a rotated 0.28° spherical coordinate system to avoid the problem of a numerical singularity at the pole, such that grid spacing varies from 17 to 33 km over the domain. PIPS 2.0 provides operational 72-hour forecasts of ice drift, ice thickness, and ice concentration to the National Ice Center (NIC).

PIPS Results 2000 to 2008: Evaluation of PIPS 2.0 forecasts from 2000 to 2008 reveal a slow overall decrease in Arctic ice with a minimum during the summers of 2007 and 2008. This decrease is occurring both in area of ice coverage and total ice volume. For example, in the central Arctic, ice exhibits a seasonal cycle with minimum volume in September. PIPS 2.0 indicates that this annual minimum in ice volume has undergone a 35% loss from 0.59×10^9 m^3 in 2000 to a low of 0.38×10^9 m^3 in 2008 (Table 1). A similar decreasing pattern also occurs in both the western and eastern Arctic regions during the same time period. PIPS 2.0 monthly ice thickness fields from September (Fig. 2) show how "ice free" the coastal regions have become each summer during the past few years (2007–2008) and how the overall pattern of ice thickness varies. Since open ocean areas absorb more solar heating than ice covered areas, the reduction of ice extent in the summer creates an overall warmer ocean that slows winter regrowth of the ice cover. This leads to thinner wintertime ice and decreases in overall ice volume during the yearly cycle as periods of cooling are not able to restore ice thickness to previously observed levels. Even though extremely low temperatures in the northern hemisphere during the winter of 2007 helped to increase the ice area visible from satellite data to a more "normal" level, especially along the northern Greenland coast, the overall Arctic ice volume was lower in 2008 due to thinner ice than in past years.

Future Capabilities in Ice Forecasting: Sufficient measurements of sea ice conditions, effective assimilation of these observations, and thorough evaluation of forecast skill and error trends are critical to improving the quality of operational models and forecasts. In continuing efforts to provide state-of-the-art capabilities for ice forecasts, NRL has developed the next-generation operational ice forecast system, PIPS 3.0. This new capability couples the Los Alamos Sea Ice Model (CICE)[3] to the global Navy Coastal Ocean Model (NCOM),[4] taking advantage of developments in modeling and assimilation over the last ten years to predict ice conditions, ice currents, temperature, and salinity at a higher resolution (5–9 km in the Arctic) and with greater accuracy. PIPS 3.0 is now producing daily 48-hour forecasts at the Naval Oceanographic Office (NAVOCEANO) and will have competed its validation tests by mid-2009.

Conclusions: The Arctic has been and will continue to be a region of strategic and operational interest. The dramatic changes seen during the last decade impact the traversal of the region by introducing changing conditions expected to increase shipping activity and thereby increase overall operational risks. A history of nowcasts and forecasts from the operational ice prediction systems developed by NRL can be used to construct a baseline of ice conditions, cycles, and trends to enable more robust assessment of the extent and environmental impacts of Arctic ice changes. As higher-resolution forecast systems are developed, more accurate and detailed forecasts will



(a) (b)

FIGURE 1
(a) September 2007 Arctic sea ice extent (white), compared to the September median ice extent (pink line) calculated from 1979 to 2000 (Source: National Snow and Ice Data Center) compared to (b) the PIPS 2.0 monthly mean September ice thickness (m) for 2007.

TABLE 1 — PIPS 2.0 Yearly Maximum and Minimum Values of Total Ice Volume for the Central Arctic

Total Central Arctic Ice Volume × 10^9 m^3				
	Maximum		Minimum	
Year	Month	Value	Month	Value
2000	May	0.90	Sep	0.59
2001	May	0.93	Sep	0.69
2002	May	0.99	Sep	0.75
2003	Apr	0.95	Sep	0.58
2004	May	0.91	Sep	0.58
2005	Apr	0.93	Sep	0.62
2006	May	0.85	Sep	0.52
2007	May	0.86	Sep	0.49
2008	Mar	0.67	Sep	0.38

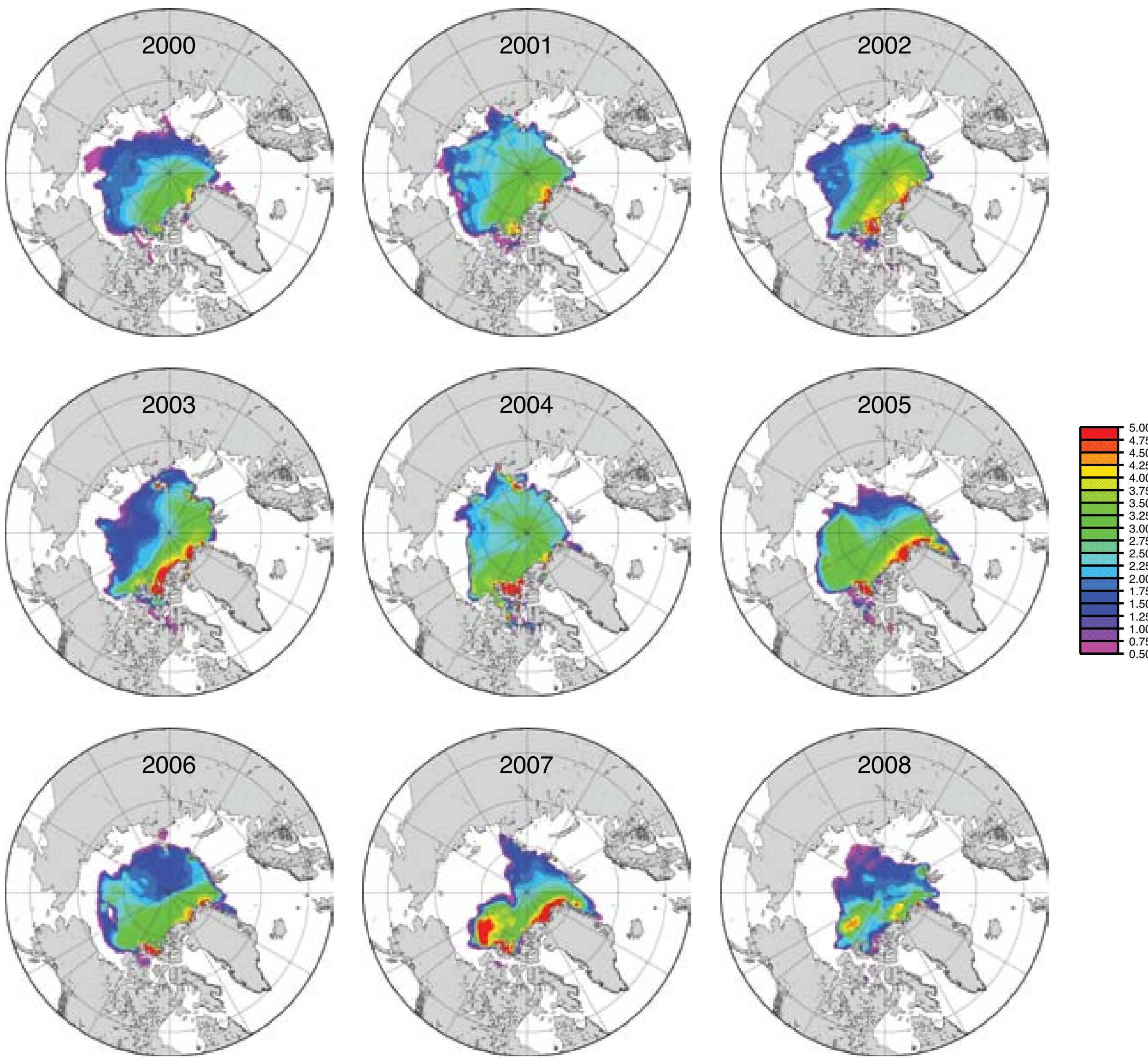


FIGURE 2
PIPS 2.0 September monthly mean ice thickness (m) from 2000 to 2008.

become available for use in predicting, understanding, and adapting to changing Arctic ice conditions.

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Predicting "Ocean Weather" Using the HYbrid Coordinate Ocean Model (HYCOM)

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Introduction: Development of an advanced global ocean prediction system has been a long-term Navy interest. Such a system must provide the capability to depict (nowcast) and predict (forecast) the oceanic "weather," some components of which include the 3D temperature, salinity, and current structure, the surface mixed layer, and the location of mesoscale features such as eddies, meandering currents, and fronts. The space scale of these eddies and meandering currents are typically ~100 km and current speeds can easily exceed 1 ms^{-1} in the Gulf Stream (Atlantic) and Kuroshio (Pacific). Numerical ocean models with sufficiently high horizontal and vertical resolution are needed to depict the 3D structure with accuracy superior to climatology and/or persistence (i.e., a forecast of no change). The existing two-model operational system, run daily at the Naval Oceanographic Office (NAVOCEANO), is based on the 1/32° Navy Layered Ocean Model (NLOM) and the 1/8° Navy Coastal Ocean Model (NCOM). Unlike NLOM, NCOM has high vertical resolution, but it has medium range horizontal resolution (15 km at mid-latitudes near 40°N) that is eddy-permitting. The next-generation system is based on a single model, the HYbrid Coordinate Ocean Model (HYCOM), that was developed as part of a multi-institutional consortium between academia, government, and private industry. At 2.2 times the horizontal resolution of NCOM, the HYCOM system is eddy-resolving, a distinction associated with important dynamical implications for both ocean model dynamical interpolation skill in the assimilation of ocean data and for ocean model forecast skill.[1] It represents the world's first eddy-resolving global ocean prediction system with both high horizontal and high vertical resolution and has been running daily in the operational queues at NAVOCEANO since 22 December 2006. The HYCOM system has been validated against observational data[2] and is scheduled for operational testing in 2009.

Prediction System Description: The ocean component of the nowcast/forecast system is 1/12° global HYCOM (mid-latitude resolution of ~7 km) with 32 hybrid vertical coordinate surfaces. The truly generalized vertical coordinate can be isopycnal (density tracking — often best in the deep stratified ocean), levels of equal pressure (nearly fixed depths — best used in the mixed layer and unstratified ocean), or sigma-levels (terrain-following — often the best choice in shallow water). HYCOM combines all three approaches by choosing the optimal distribution at every grid point and time step. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate models toward shallow coastal seas and unstratified parts of the world ocean. It maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics.

HYCOM employs the Navy Coupled Ocean Data Assimilation (NCODA), which is a fully 3D multivariate optimum interpolation scheme, to assimilate observational data. The data include surface observations from satellites, such as altimeter sea surface height (SSH) anomalies, sea surface temperature (SST), and sea ice concentration, plus in situ SST observations from ships and buoys and temperature and salinity profile data from XBTs, CTDs, and Argo floats. The 3D ocean environment can be more accurately nowcast and forecast by combining these diverse observational data types via data assimilation and using the dynamical interpolation skill of the model.

Real-time Results: Where possible, the real-time system is evaluated using independent observations; some examples follow. Figure 3 shows simulated SSH