Combining satellite altimetry, time-variable gravity, and hydrographic observations to understand the Arctic Ocean: A transformative opportunity

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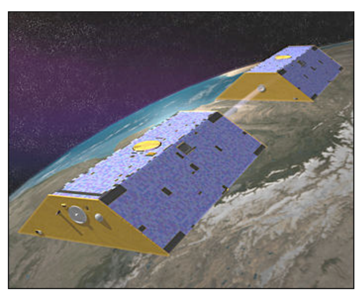
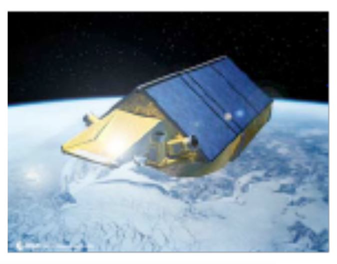
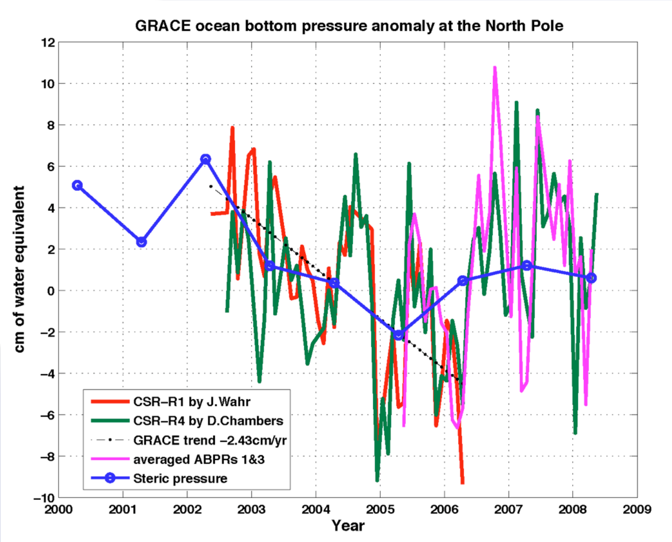




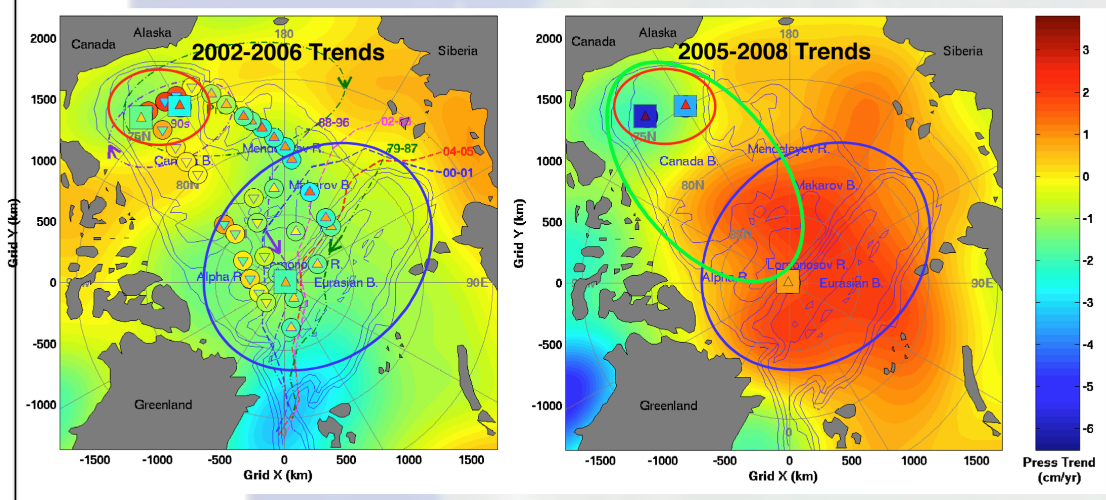
New developments in our observational capabilities present an unprecedented opportunity to make significant progress towards an integrated ability to address scientific issues of both the ocean and ice components of the Arctic Ocean system. In the coming decade, data from gravity satellites (GRACE and GOCE), and polar-orbiting altimeters (e.g., Envisat, ICESat, and upcoming CryoSat-2, ICESat-2, and SWOT) will provide basin-scale fields of *gravity* and *surface elevation*. Together with an optimally designed *in-situ* hydrographic observation network, these data sets will have the potential to significantly advance our understanding of the ice-ocean interactions, circulation and mass variations of the Arctic Ocean. Recent work has demonstrated the combined use of GRACE and bottom pressure recorder (BPR) data for understanding the Arctic circulation, and the use of high precision altimeters for documenting recent decline in sea ice thickness. We describe several topics of particular interest in the use of satellite and *in-situ* data, and the considerations for the design of an observational network for hydrographic sampling.

Time-variable gravity

GRACE and bottom pressure

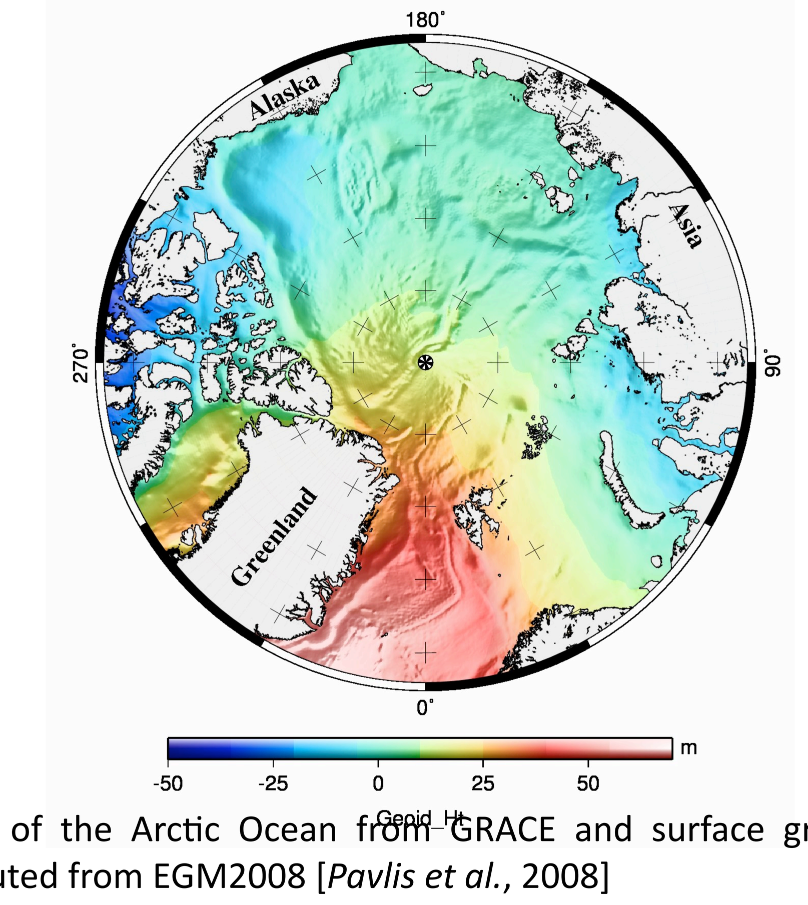


Bottom pressure (BP) from GRACE Releases 1 and 4 along with averages of ABPR records. Absolute values are arbitrary and have been set to zero for Release 4. Other record averages are matched to Release 4. The steric variation due to ocean mass changes from hydrographic observations in the top 200 m within 200 km of the Pole are also shown.



GRACE Release 4 BP trends, 2002-06 (left) and 2005-08 (right), in the Arctic Ocean. Colored circles (left) represent trends associated with a hypothesized return to climatology from conditions of the 1990s [Morison et al., 2007]. Also shown are the steric trends from hydrographic observations (colored squares) and the SSH trends (colored triangles) calculated as the difference between the bottom and steric pressure trends. The declining BP trend, 2002-06, in the central Arctic (blue ellipse) illustrates the anticyclonic advance of relatively fresh (light) Pacific-derived water across the basin, and the rising trend, 2005-08, is associated with a cyclonic advance of salty Atlantic-derived water. Declining trends in bottom pressure in the Beaufort Sea (red ellipses) due to declining salinity persist throughout and in 2007-08 accelerated to produce a growing lens of low salinity surface water in the eastern Canada Basin [Morison et al., 2007 & 2008].

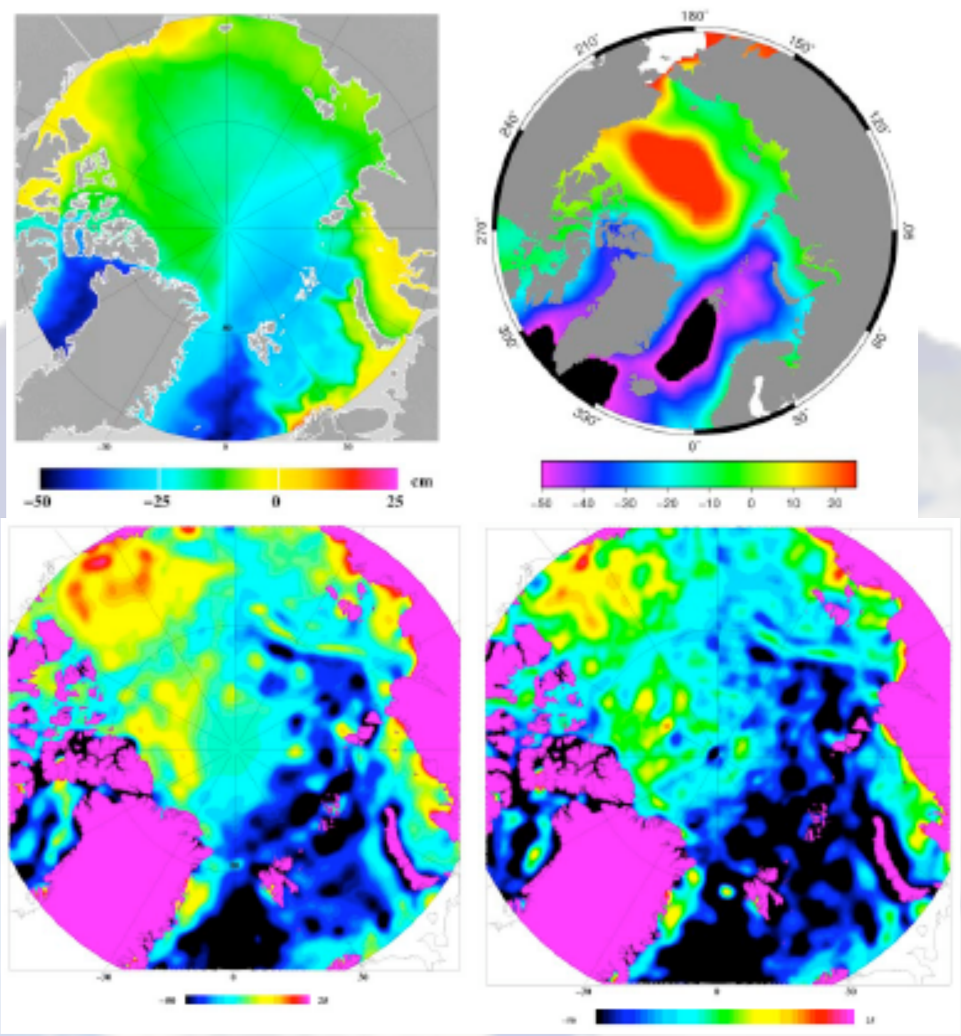
Improved Arctic Geoid



Geoid of the Arctic Ocean from GRACE and surface gravity data computed from EGM2008 [*Pavlis et al.*, 2008]

Satellite altimetry (sea/ice surface height)

Mean Dynamic Topography

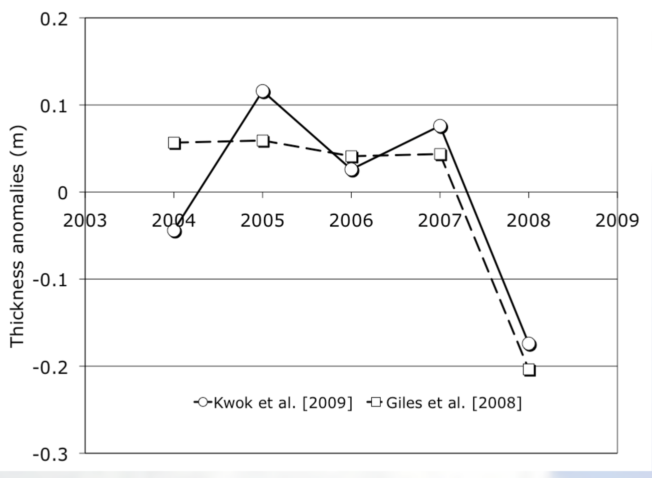


Comparison of modeled mean dynamic topography (MDT) with that derived from satellite altimetry. (Top) MDT from PIPS (left) and MICOM (right) for the period 1995-2003 (PIPS average is for March only). Unit: cm. (Bottom) Low-pass filtered MDT from remote sensing: MDT from MSS with ArcGP geoid (left) and EIGEN-GL4C (right). Unit: cm.

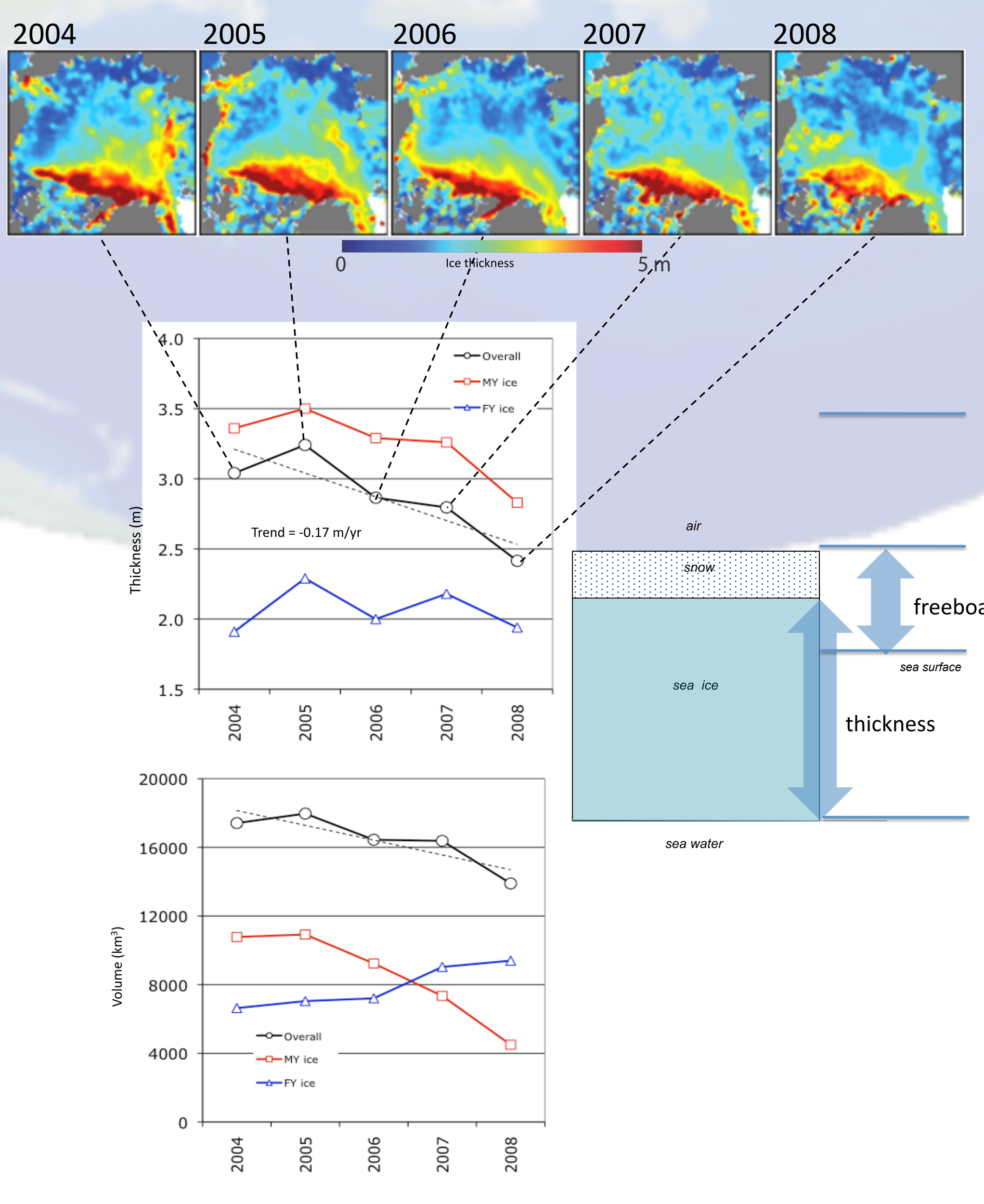
Improvement of Arctic Tide Models

Accurate models of tidal SSH and the IBE are required to remove high-frequency signals from undersampled satellite altimetry and gravity to reveal general circulation changes. RMS errors of current Arctic tide models are of order 10 cm.

Sea Ice Thickness from Freeboard



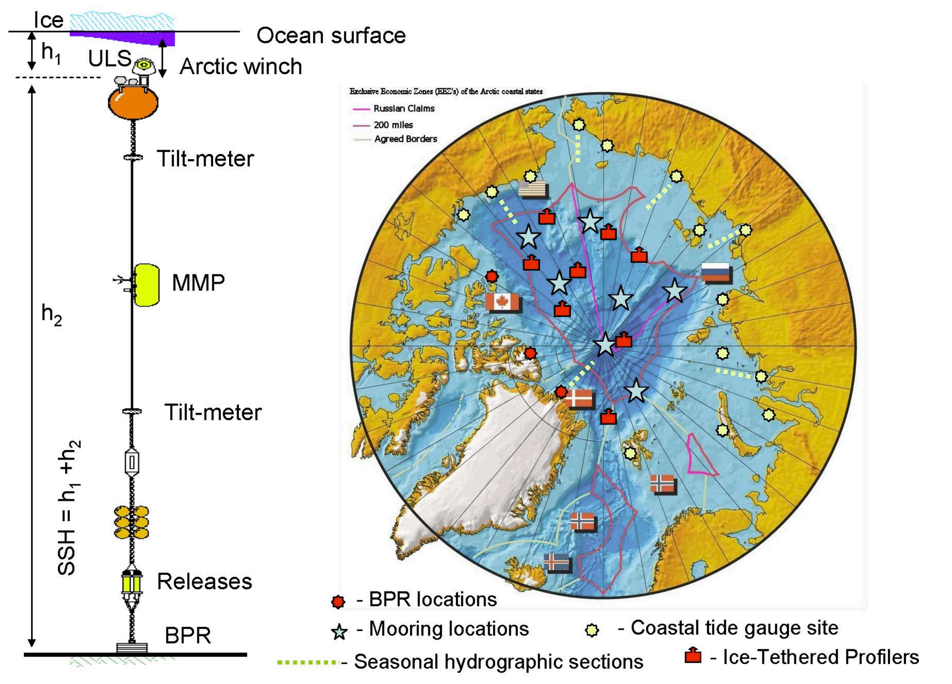
Comparison of the thickness anomalies derived from the Envisat radar altimeter [Giles et al., 2008] and the ICESat lidar. (after Kwok et al. [2009])



Decline in winter thickness and volume of the Arctic Ocean sea ice cover from ICESat (2004-2008). [Kwok et al., 2009]

Hydrographic sampling network

Sampling Array to complement spaceborne observations



Mooring components (left) and mooring, tide gauge and bottom pressure recorder (BPR) approximate locations to provide *in-situ* sustained observations in the Arctic Ocean to complement and validate space-borne measurements of ice thickness and sea surface heights in the Arctic Ocean.

Ideally, a network designed to systematically monitor sea level and ocean circulation should be guided by an objective strategy. For example, a set of Observing System Simulation Experiments (OSSE) could be employed to identify optimal in-situ observing site locations required measurement accuracy and frequency, and acceptable levels of uncertainty. The long-term goal of the combined Arctic in-situ and satellite monitoring system should address the need for sufficient data to validate Arctic GCMs so as to provide the interpolation of subsurface changes in the Arctic between the necessarily sparse elements of the in-situ arrays.

Time-variable gravity + Altimetry + Hydrography

Together with an optimally designed bottom pressure array for resolving shorter time scale processes, the steric (halosteric and thermosteric) and non-steric effects could be separated for quantifying changes in circulation and variability in Arctic sea level [Willis et al., 2008]. Furthermore, sea surface heights from altimetry when differenced with the mean Arctic satellite geopotential constrain the geostrophic circulation.

Conclusions

Results from current work that combines satellite and *in-situ* observations illustrate that significant improvements in our understanding of the Arctic Ocean are about to be realized with existing and forthcoming satellite data sets. Furthermore, the use of these data sets in conjunction with a well-designed *in-situ* hydrographic sampling network – with judiciously deployed ocean instrument technologies – would ensure the most accurate quantification of the sea level, circulation and mass changes of the Arctic Ocean. Together, an observational network that includes satellite remote sensing, *in-situ* data acquisition, and ice/ocean components considered in companion white papers [*Breivik et al.*, 2009; *Calder et al.*, 2009; *Lee et al.*, 2009], will undoubtedly contribute to a new understanding of the Arctic Ocean and its impact on global climate.

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