Vision for an Arctic Mass Change Program

A Short Letter for the Arctic Observing Summit
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by

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This letter advocates development of the Arctic Mass Change Program (AMCP), an integrated system of remote sensing, *in situ* observations, and data assimilation to measure Arctic terrestrial and ocean mass change and attendant freshwater and circulation changes. Mass and density variations are fundamental elements of environmental change in the Arctic. Changes in atmospheric circulation are mainly diagnosed as changes in atmospheric pressure. Similarly, ocean circulation is observed by measuring water density so that the fields of mass and pressure can be estimated. Measuring changes in average ocean density also tell us changes in freshwater distribution. The most fundamental observations of ice sheets and glaciers are mass balances. Tracking of the mass of terrestrial water is essential to hydrology. By making regular measurements of mass and volume, the Gravity Recovery and Climate Experiment (GRACE) and the satellite altimeters such as ICESat and CryoSat2 have ushered in a new era for high-latitude oceanography [*Kwok and Morison*, 2011; *Kwok et al.*, 2009; *Morison et al.*, 2007; *Morison et al.*, 2012; *Shum et al.*, 2009], hydrology [*Frappart et al.*, 2011; *Landerer et al.*, 2010], and the study of ice sheets [*Khan et al.*, 2010; *Van den Broeke et al.*, 2009; *Velicogna*, 2009; *Velicogna and Wahr*, 2005; 2006; *Wu et al.*, 2010] and glaciers [*Luthcke et al.*, 2008].

Given an accounting for atmospheric mass (i.e. surface atmospheric pressure, SAP), GRACE gravity measurements yield changes in ocean mass (ocean bottom pressure, OBP), ice sheet mass, and the mass of water stored on land. Satellite altimetry provides sea surface height (SSH) and, by subtracting the geoid elevation, dynamic ocean topography (DOT) from which the geostrophic circulation of the upper ocean can be inferred [*Kwok and Morison*, 2011]. The difference between OBP and DOT is the steric pressure anomaly, which in the salt-stratified Arctic waters is a measure of ocean freshwater content (FWC) [*Giles et al.*, 2012; *Morison et al.*, 2012]. Similarly, satellite altimetry measures the volume of ice sheets and glaciers and offers an independent estimate of ice mass changes. The power of these tools is that they extend sustained observations of mass, volume, and circulation over essentially all regions of the Arctic, including important areas where *in situ* measurements are practically impossible. However, realization of the full potential of the remote sensing observations requires repeated *in situ* measurements for validation, extension to higher frequencies, and the discrimination of hydrologic, ice sheet, and ocean mass change signals.

The need for intercomparisons with *in situ* measurements and models is particularly acute in near coastal regions where the hydrologic, ice sheet and ocean realms meet. It is near the coastal regions that ice sheet mass loss has been greatest[*Pritchard et al.*, 2009]. It is in nearshore regions where we find the boundary currents that are responsible for much of ocean mass transport. And it is the nearshore region where terrestrial freshwater seasonally accumulates in estuaries and deltas on its way to the sea. However, GRACE has a large footprint, and in the critical regions where land or ice sheets meet the ocean, the gravity signals of mass change in one environment leak into the mass signals of the other environment. As part of the de-aliasing process, ocean models are used to estimate and remove the leakage of ocean signal into the terrestrial realm, but the result is heavily model dependent in precisely the regions where we are most unsure of model performance and where their comparisons with *in situ* OBP measurements give mixed results [*Bonin and Chambers*, 2012; *Chambers and Bonin*, 2012; *Peralta-Ferriz*, 2012].

However, OBP from GRACE can be compared to OBP measured directly with *in situ* pressure sensors [*Morison et al*., 2007] or by the sum of DOT changes (measured *in situ* or by altimetry) and steric pressure anomaly changes measured by repeat hydrography. Ice sheet mass variations can be measured in near coastal regions by GPS surveying approaches and by altimetry [*Pritchard et al*., 2009; *Shepherd et al*., 2012]. Direct drainage basin-scale estimates of ground and surface water amounts serve the same purpose in the hydrologic sphere. Such comparisons among remote sensing and key repeat *in situ* measurements validate interpretations of satellite gravity and altimetry for mass, circulation, and freshwater changes over the whole Arctic. Such comparisons in near coast regions test and refine the discrimination of mass change signals from the ocean, ice sheets, and terrestrial water. High-frequency measurements provided by *in situ* OBP gauges can also be used to test the ocean models and the techniques used to de-alias GRACE gravity measurements for tides and other high-frequency ocean changes prior to monthly averaging.

Ultimately, we envision the AMCP to include a multi-environment data assimilation system that will form optimal estimates of ice sheet mass, terrestrial water, and ocean mass, freshwater content and circulation by optimal combination of remote sensing and *in situ* observations with ocean, ice sheet, and hydrologic models.

Planning for future gravimetry and altimetry satellite missions is ongoing (e.g., [*Watkins et al*., 2011]) and there is continuing progress in modeling the land, ice sheet and ocean environments. The two critical new steps to developing an Arctic-wide view of mass, freshwater, and circulation change are (a) establishment of a network of specific *in situ* repeat measurements, and (b) the development of assimilation techniques that incorporate models and observations from multiple environments. Many potential observing platforms already exist. The International Arctic Buoy Program already takes advantage of drifting buoys to measure atmospheric pressure over the Arctic Ocean. An example of comparable efforts contributing to coordinated measurement of Arctic mass change would be to equip all moorings with ocean bottom pressure gauges and all drifting buoys with dual-channel precision GPS that would measure SSH and also give precipitable atmospheric water vapor content. Similarly, work on data assimilation into individual models is ongoing (e.g., ECC2, [*Nguyen et al*., 2011]) and at least one attempt has been made to combine a data-assimilating an ocean model, GPS observations, and GRACE gravity measurements into predictions of ice sheet mass change [*Wu et al*., 2010].

What is needed most now is a shared vision of how greatly the whole of a coordinated AMCP could exceed the sum of its parts. With the availability of satellite gravimetry and altimetry plus multi-environment data assimilation, the information we obtain by combining these and *in situ* ocean, ice sheet, and hydrologic observations will be much better than what we could obtain examining each data source separately.

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