In response to the RFI of the NRC Decadal Survey for Earth Science and Applications from Space

Changing Arctic Climate System: Causes, Consequences, and Relationship to the Global Climate

Dmitry Dukhovskoy and Mark Bourassa

Florida State University

1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

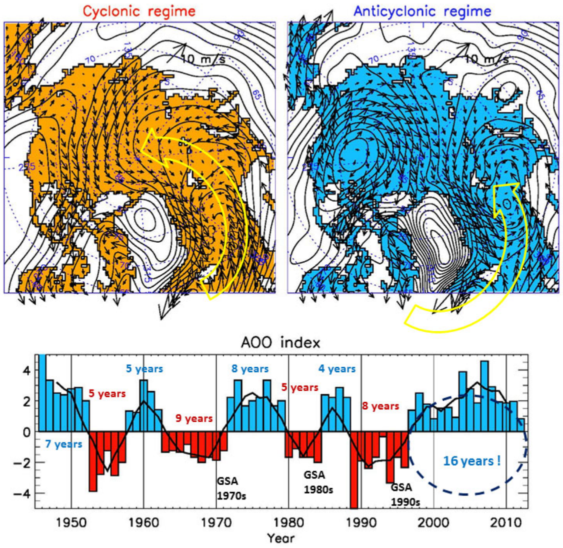

Figure 1: Top panels: sea level pressure (black lines, hPa) and wind typical cyclonic (left) and anticyclonic regimes (right). Yellow large arrows show prevailing storm tracks. Bottom panel: Bars show annual and black line depicts 5-year running mean AOO index (Proshutinsky and Johnson, 1997, updated) AOO alternates between anticyclonc (blue bars) and cyclonic regimes, (red bars) with a period of 10-14 years while since 1997 a strong anticyclonic regime has dominated over the Arctic Ocean (from Proshutinsky et al., 2015).

Observational data show that the Arctic system experiences dramatic change. Arctic change is manifest in the atypical behavior of the NAO (Hurrell & NSIDC, 2013), Arctic Ocean Oscillation (AOO, Proshutinsky and Johnson, 1997) and Arctic Oscillation (AO, Thompson and Wallace, 1998) indices in the 21st century (Proshutinsky et al., 2015). In the 20th century, these indices effectively characterized the quasi-decadal variability of the Arctic climate. In particular, 20th century climatology of the AOO has shown that anticyclonic and cyclonic regimes of the Arctic circulation alternate at 5 to 7 year intervals with a period of oscillation of 10-15 years. In a stark deviation from this pattern, the present, 21st century the anticyclonic regime has dominated in the Arctic since 1997 (Fig. 1).

The observed decadal changes in the Arctic climate were explained in terms of a feed-back mechanism that involves ocean-sea ice- atmosphere of the Arctic Ocean and sub-Arctic seas (Proshutinsky et al., 2002; Dukhovskoy, 2004; 2006a,b). In this conceptual model, regime shifts are controlled by atmospheric heat fluxes from the North Atlantic and freshwater fluxes from the Arctic Ocean.

Of essential importance to our understanding of the evolving Arctic system, and its impact on the global environment, is to discern the causes and consequences of the apparent break-down in the natural decadal variability of the Arctic climate. Why has the well pronounced decadal variability observed in the 20th century been replaced by relatively weak interannual changes under anticyclonic conditions in the 21st century?

Greenland discharge of meltwater and ice has been accelerating since the early 1990s (Bamber et al., 2012). Proshutinsky et al. (2015) hypothesized that excess Greenland meltwater advected into the sub-Arctic seas might have significant impact to deep convection (with subsequent atmospheric cooling and reduction of cyclonic activity). The authors assume that substantial volume of Greenland freshwater spreads into the convective sites of the interior sub-Arctic seas. The effect would be to impede the decadal oscillations that were a feature of the observations and well-represented by previous studies (Dukhovskoy et al., 2006a,b) prior to the 2000s. This mechanism explaining observed shift of Arctic climate variability into a different state, suggests different interaction between the Arctic climate system and the global climate. In the 21st century, global warming impacts the Arctic climate system through accelerated Greenland freshwater flux, which influences thermohaline processes in the sub-Arctic seas (similar to the Great Salinity Anomalies (Dickson et al., 1988), air-sea interaction and meridional heat flux to the Arctic, and ocean and atmospheric processes in the Arctic (Proshutinsky et al., 2015). this it has been speculated that excess Greenland freshwater flux will eventually disrupts thermohaline circulation in the sub-Arctic seas shifting Arctic climate system into cold state ("theromhaline catastrophe") (Stouffer et al., 2006; Proshutinsky et al., 2015). In addition to this, one of the consequences of the cessation of Arctic climate variability is persistent accumulation of freshwater in the Beaufort Gyre that has been shown by in situ hydrographic observations (Proshutinsky et al., 2009, 2013) and satellite measurements (Giles et al., 2012). Release of this excess freshwater from the Beaufort Gyre will cause another Great Salinity Anomaly observed in the 20s century (Dickson et al., 1988; Belkin et al., 2004). Thus, the Arctic climate system may feedback to the Global climate system mitigating or even reversing global warming. However, all suggested and hypothesized mechanisms of Arctic climate change in the 21st century as well as consequences of these changes for the Global climate need validation and more detailed analysis. Thus, the key challenges for Earth System Science are:

- **What physical processes in the Arctic Ocean – sub-Arctic seas ocean-ice-atmosphere system are responsible for the observed changes in Arctic climate variability?**
- **What are the driving mechanisms of climate regime shifts in the Arctic Ocean – GIN Sea system? Have these mechanisms changed in the 21st century?**
- **What will the consequences of the Arctic climate change be for the Global climate system?**

It is clear that we need a far greater understanding of the complex interactions between components of the Arctic system to predict the rate and magnitude of future Arctic change and its impact on the Global climate with some confidence. In order to address the above questions, changes in the components of the Arctic climate system have to be investigated. Some of them are listed as follows:

1) Ocean:• changes of thermohaline processes and water mass formation in the sub-Arctic seas and Arctic Ocean; • variability of characteristics of the North Atlantic current; • heat and freshwater/salt exchange between the Arctic Ocean and sub-Arctic seas.

2) Sea ice: • influence of decreasing sea ice cover on thermohaline processes in the Arctic Ocean (particularly shelf seas); • relation between deep convection and sea ice cover; • causes and physical mechanisms driving teleconnection in sea ice conditions in different Arctic and sub-Arctic regions; • role of deep ocean heat (stored in Atlantic and Pacific Waters) in ice change; • response of sea ice on changes in freshwater content in the upper mixed layer.

3) Atmosphere: • relation between deep convection and air-sea heat fluxes; • relation between atmospheric circulation and changes ice conditions; • impact of intensified ice melt and excess freshwater runoff from Greenland on the upper ocean and air-sea heat fluxes; • impact of change of ice conditions in the Arctic on air-sea heat fluxes and atmospheric heat transport to the Arctic Ocean.

2. Why are these challenge/questions timely to address now especially with respect to readiness?

Remote sensing has been provided detailed data about Arctic climate state and its variability, and new technologies can work with traditional observations to improve our understand or Arctic change and the impact on climate system. Recent changes in the remote sensing technology have improved quality and the range of information about sea ice - the key climate state variable of the Arctic climate. The combination of sea level and gravity (coupled with Argo) reflect changes in practically all dynamic and thermodynamic processes of terrestrial, oceanic, atmospheric, and cryospheric origin. There have been two changes in remote sensing technology that now make these questions feasible to answer. Furthermore, the rapid change in ice characteristics, and the related economic impacts (in commerce and local ocean warming followed by sea level rise) makes this topic highly relevant to society.

Key gaps in understanding are associated with transport of fresh water on the ocean surface, and air/sea exchanges of energy. New technology exists (space-based microwave Doppler radar scatterometry) to address transport. This question requires observations of ocean surface vector stress (what is commonly called surface vector winds, but is a better fit to stress) and surface current. Surface turbulent fluxes are not measured from space, but the capability to measure the bulk variables (stress, sea surface temperature, near surface moisture, and near surface air temperature) have been improved to the point where these fluxes can be accurately calculated from these observations. The measurement of stress (from scatterometers) removes the need to know sea state, which in this context is a poorly observed variable (and will likely continue to be so). Microwave SST observations are needed to penetrate the cloud cover that is sometimes common in this region. The great breakthroughs are in the measurements of near surface air temperature and humidity from radiometers (fig. 2).

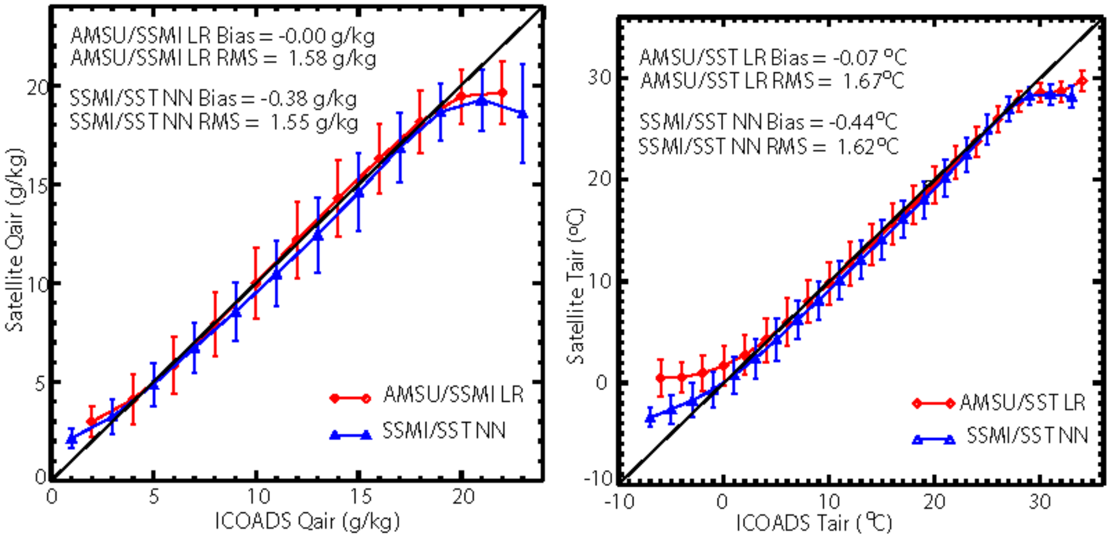

Figure 2. Validation of satellite retrievals (Bourassa et al. 2010) of humidity at a height of 10 m above the water surface (left) and air temperature at the same height (right). The red line is the Jackson and Wick (2010) retrievals, and the red is the Roberts et al. (2010) retrievals. Both are compared to in situ data from the ICOADS data set. These retrievals use different input data and very different techniques, yet they are quite similar.

International contributions to improvements in the in situ observing system (Argo floats) are also expected to improve sub-surface observations in this region, but they are not expected to be sufficient to address the above issues. However, they will aid in understanding the impact of the observed transports and surface energy fluxes on the sub-surface ocean. Observations of runoff will be useful, as will satellite estimates (from gravity observations) of the change in mass of the Greenland ice sheet, SST, sea ice, salinity, vector surface stress, and surface currents.

International contributions to scatterometer observations are expected to aid in stress observations, but fine resolution (~5km grid spacing; 10km resolution) are needed to resolve the coastal processes and calculate the derivative fields needed to determine ocean upwelling. The region has highly variable weather conditions, therefore coincident observations of winds (stress) and currents are highly desirable, such as could be provided by a Doppler scatterometer using Ka-band to achieve more accurate currents (a factor of 2.7 reduction in uncertainty) relative to Ku-band) and to achieve the fine resolution needed for the ocean vector stress. The only plan for a microwave radiometer suitable for measuring SST (which is important for the air temperature and humidity retrievals) is the Japanese AMSR series, for which there is currently no funded plan for putting such an instrument in space.

3. Why are space-based observations fundamental to addressing these challenges/questions?

Space-based observations are the most effective and are currently the only practical way to obtain these observations with sufficient spatial and temporal coverage. This is a very harsh region for surface in situ observations. Satellite observations provide necessary information to monitor and study changes in the state climate variables (sea ice, sea level, ocean wind stress, surface salinity). Additionally, remote observations of other variables allows one to derive other crucial information such as air-sea heat fluxes.

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