Fully Coupled and Process Resolving Arctic Climate Simulations – Luxury or Necessity?

Wieslaw Maslowski[1], Samy Kamal[1], Robert Osinski[2], Jaclyn Clement Kinney[1], Andrew Roberts[1], Anthony Craig[3]

[1]Naval Postgraduate School, [2]Institute of Oceanology, Polish Academy of Sciences, [3]NPS Contractor

Abstract: The Arctic is a complex and integral part of the Earth system, influencing the global surface energy and moisture budgets, atmospheric and oceanic circulations, and geosphere-biosphere feedbacks. Some key influences and teleconnections are linked to the recent changes in the multiyear sea ice cover. The ice cover is particularly important because it buffers air-sea heat fluxes and through ice-albedo feedback strongly influences Earth's absorption of solar radiation, especially by the ocean. Global warming has been most visibly manifested in the Arctic through a declining perennial sea ice cover, which has intensified during the late 1990s and in the 2000s.

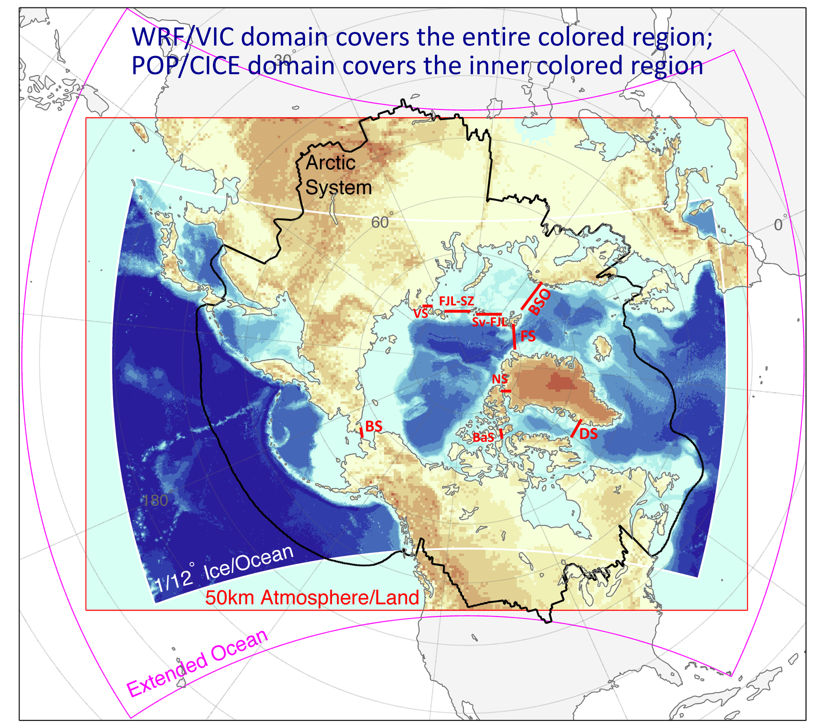
However, while historical reconstructions of arctic climate from Earth System models (ESMs) are in broad agreement with these changes, the rate of change in ESMs remains outpaced by observations. There are a number of reasons why models may not be able to simulate rapid ice change in the Arctic, which stem from a combination of inadequate parameterizations, unrepresented processes, coarse model resolution, and a limited knowledge of physical, real world interactions. Stand-alone global atmosphere-land or ocean-ice models do not include fundamental surface feedbacks at the marine interface, which negates strongly non-linear coupling known to be temporally and spatially sensitive and important in polar regions. Finally, a few fully coupled Arctic regional models exist that represent such processes and resulting coupling across the interface.

The Regional Arctic System Model (RASM) has been developed to better understand the past and present operation of Arctic System at process scale and ultimately to predict its change at time scales from days to decades. RASM is a fully coupled ice-ocean-atmosphere-land model that includes: the Weather Research and Forecasting (WRF) model, the LANL Parallel Ocean Program (POP) and Community Ice Model (CICE), the Variable Infiltration Capacity (VIC) land hydrology model and a streamflow routing (RVIC) model to transport the freshwater flux from the land surface to the ocean. The model domain is configured at an eddy-permitting resolution of 1/12° (or ~9km) for the ice-ocean and 50 km for the atmosphere-land model components. In addition, a 1/48° (or ~2.4km) grid for the ice-ocean model components has been recently configured. All RASM components are coupled at high frequency (i.e. 20-minute intervals) to allow realistic representation of inertial interactions among the model components.

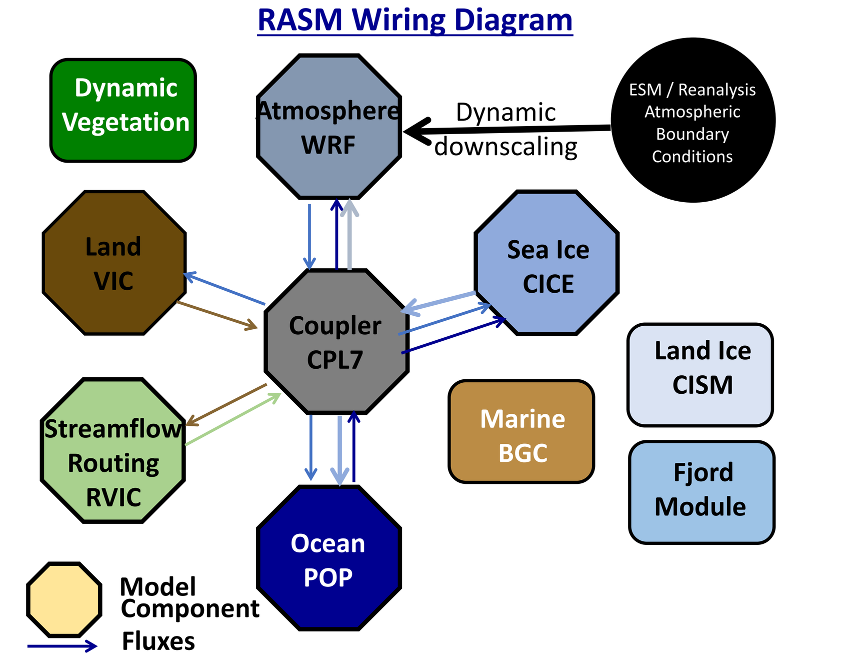
We demonstrate the capability of RASM in simulating observed seasonal to decadal variability and trends in Arctic climate. Selected physical processes and resulting feedbacks are discussed to emphasize the need for fully coupled climate model simulations, high model resolution and fine-tuning of many present parameterizations of sub-grid physical processes when changing model spatial resolution.

Regional Arctic System Model (RASM) - Overview

RASM Domains



RASM Wiring Diagram



RASM Configuration

RASM 1.0	Code	Configuration / Domain: Pan-Arctic including all sea ice covered ocean in the NH, Arctic river drainage, critical inter-ocean exchange and transport, as well as large-scale atmospheric weather patterns (AO, NAO, PDO)
Atmosphere	WRF3	50km, 40 levels, 2.5 minute time step.
Land	VIC	50km, 3 Soil Layers, 20 minute time step.
Ocean	POP2	1/12˚ & 1/48°, 45/60 levels (20m@5m/100m@5m),10 timesteps / 20 minute flux exchange.
Sea ice	CICE5	1/12˚ & 1/48°, 5 thickness categories,20/10minute thermodynamics, Anisotropic(EAP)/Isotropic(EVP) rheology
Coupler	CPL7x	Flux exchange every 20 minutes for all components, inertial resolving with minimized lags.

RASM Rationale

Overarching Science Hypothesis: Mesoscale processes and resulting feedbacks across ocean – sea ice – atmosphere interface are critical to improved model representation of the Arctic climate state, prediction of polar amplification and teleconnection to lower latitudes.

Arctic Climate Predictive Models need to:

- ❑ Resolve critical processes (e.g. ocean mesoscale eddies, sea ice deformation) and resulting feedbacks (e.g. air-ice-ocean coupling);
- ❑ Understand space dependence & optimize parameter space;
- ❑ Expand validation data (e.g. fluxes across the air-ice-ocean interface);
- ❑ Reduce computational cost / guide requirements of future high-resolution coupled climate simulations

RASM - a tool toward a climate model hierarchy to:

(i) Resolve / understand Arctic processes and feedbacks,
(ii) Guide Future Field Campaigns and Model (ESM) Development,
(iii) Reduce uncertainty and
(iv) Improve prediction

Arctic Ocean Exchange Gateways

Main: BS = Bering Strait, BSO = Barents Sea Opening, DS = Davis Strait, FS = Fram Strait
Secondary: BaS = Barrow Strait, FJL-SZ = Frans Josef Land-Severnaya Zemlya, NS = Nares Strait, Sv-FJL = Svalbard-Frans Josef Land, VS = Vilkitsky Strait

References:
Maslowski, W., J. Clement Kinney, M. Higgins, and A. Roberts, 2012: The Future of Arctic Sea Ice. Ann. Rev. Earth Plant. Sci. Vol. 40: 625-654, DOI: 10.1146/annurev-earth-042711-105345.
Roberts et al. 2015: Simulating transient ice-ocean Ekman transport in the Regional Arctic System Model and Community Earth System Model, Annals Glac. 56(69), p. 211-228.
DuVivier, A.K., J. Cassano, A. Craig, J. Hamman, W. Maslowski, B. Nijssen, R. Osinski, and A. Roberts, 2016: Winter atmospheric buoyancy forcing and oceanic response during strong wind events around southeastern Greenland in the Regional Arctic System Model (RASM) for 1990- 2010. J. Clim.,doi:10.1175/JCLI-D-15-0592.1.
Hamman, J., B. Nijssen, M. Brunke, J. Cassano, A. Craig, A. DuVivier, M. Hughes, D.P. Lettenmaier, W. Maslowski, R. Osinski, A. Roberts, and X. Zeng, 2016: Land surface climate in the Regional Arctic System Model. J. Clim., doi:10.1175/JCL-D-15-0415.1

Main Research Thesis

Atmospheric Forcing of Sea Ice

"*Atmospheric circulation trends are weak over the record as a whole, suggesting that the long-term retreat of Arctic sea ice since 1979 in all seasons is due to factors other than wind-driven atmospheric thermal advection*." - Deser and Teng, J. Clim. 2008

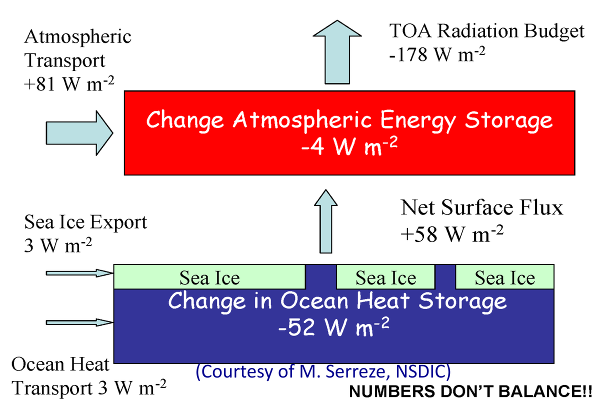
Oceanic forcing of sea ice and atmosphere can locally play a critical role via:

- ➢ Horizontal advection of warm Pacific / Atlantic water into/under the sea ice cover (Stroeve and Maslowski 2007; Maslowski et al. 2014)
- ➢ Accumulation of heat due to increased solar insulation under a diminishing sea ice cover in summer (e.g. Jackson et al. 2010)
- ➢ Locally induced (upwelling, topographically controlled flow, eddies) upward heat flux into the mixed layer and atmosphere (Maslowski et al. 2014)

RASM Analyses of Oceanic Budgets and Fluxes

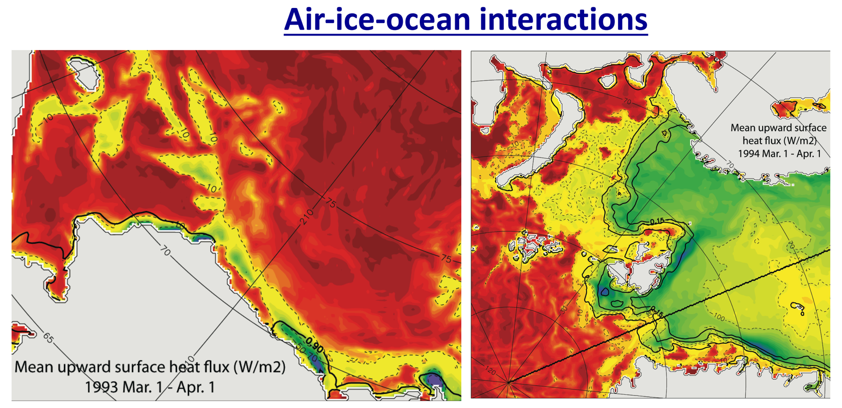
- ➢ In order to investigate the role of oceanic forcing, models need to realistically represent Arctic-Subarctic exchanges and Arctic Ocean budgets;
- ➢ Observational constraints are limited and highly depend on estimates of volume fluxes in / out of the Arctic Ocean
- ➢ One of the goals of this research is to understand model sensitivity to spatio/temporal resolution and resolving processes and feedbacks in representing the oceanic heat convergence, mechanisms of air-ice-sea exchanges and their role in climate change
- ➢ Six RASM simulations for 1980-2009 are analyzed:
  3 fully coupled RASM: **RBR9** = baseline (C_f=17), **RBR1** = C_f=34, **RBR2** = C_f=8.5 and
  3 RASM-G (POP+CICE+CPL7+CORE2): **G9** (1/12°&45), **GV9** (1/12°&60) and **G2** (1/48°&45)
- ➢ The presented analyses are work-in-progress and include:
  - ❑ Means and time series of oceanic heat convergence
  - ❑ Air-sea exchanges under changing sea ice cover (area and thickness)
  - ❑ Preliminary diagnostics of their impact on the atmospheric conditions
- ➢ Ultimately, these analyses are intended as guidance to the development of next generation climate and Earth system models

January Energy Budget of the Arctic Oceanic

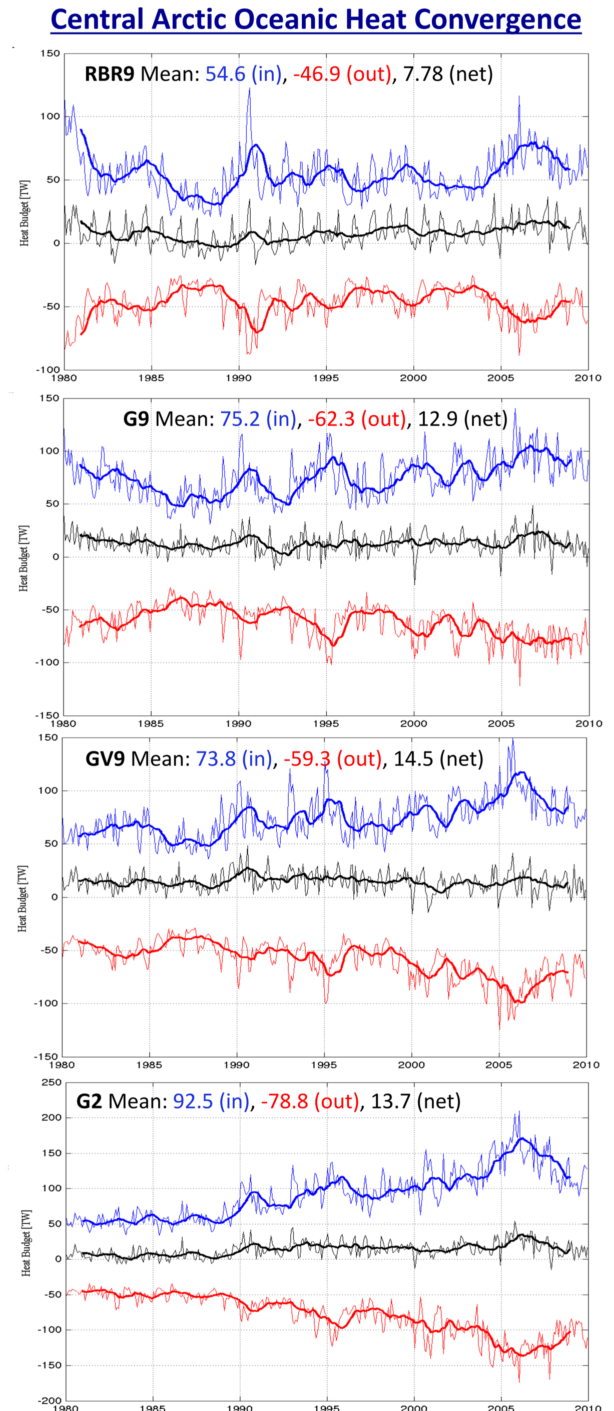


(Courtesy of M. Serreze, NSDIC)
NUMBERS DON'T BALANCE!!

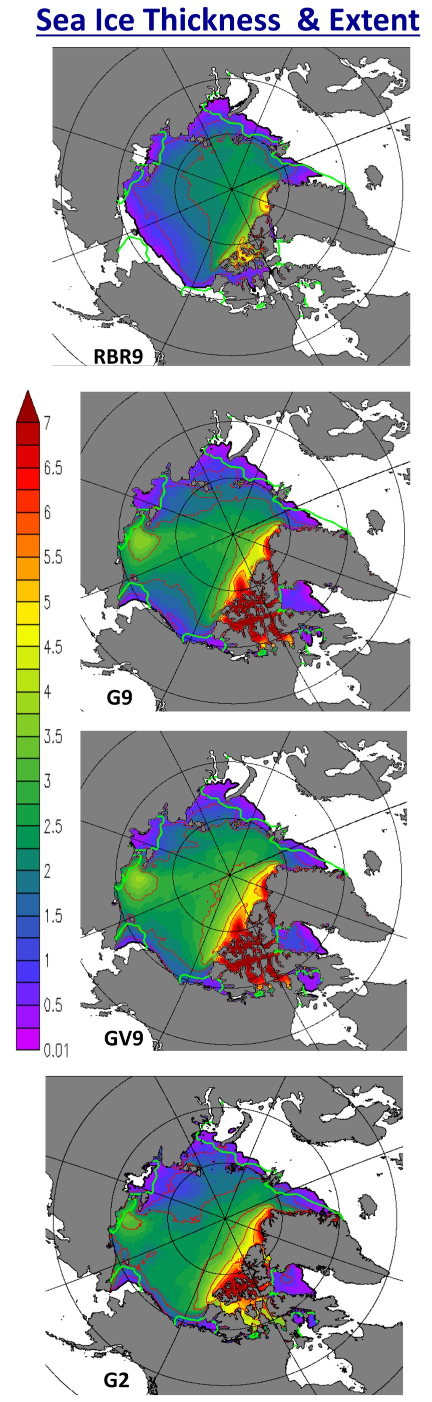
Air-ice-ocean interactions



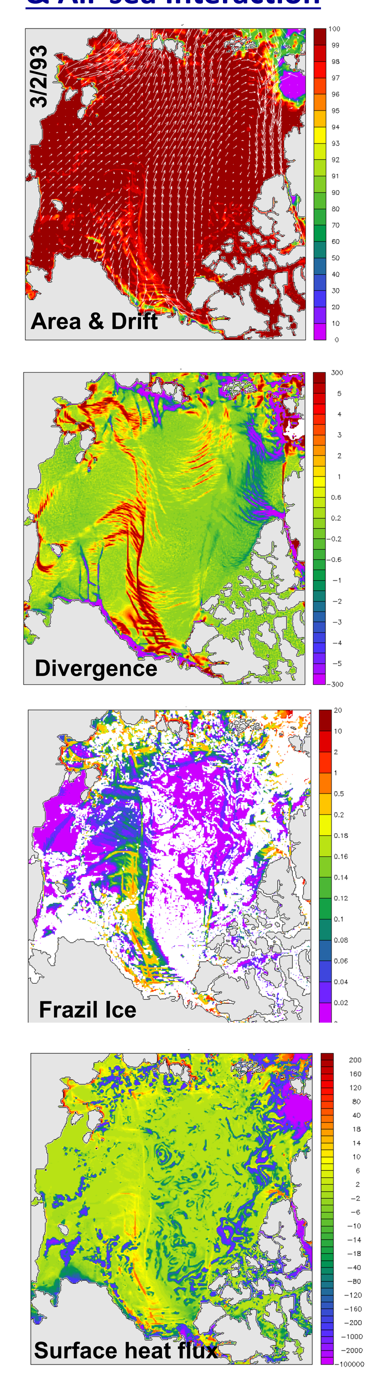
Central Arctic Oceanic Heat Convergence



Mean (1980-1989) September Sea Ice Thickness & Extent

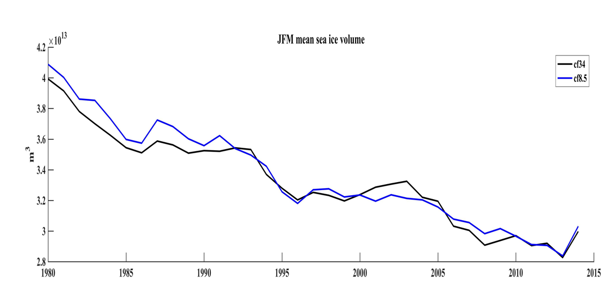


Sea Ice Deformation & Air-sea Interaction

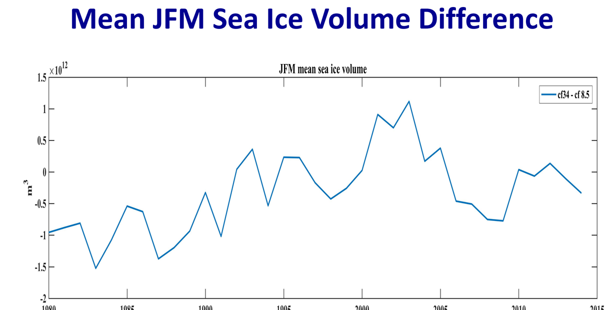


Comparison of RBR1 & RBR2

Mean JFM Sea Ice Volume

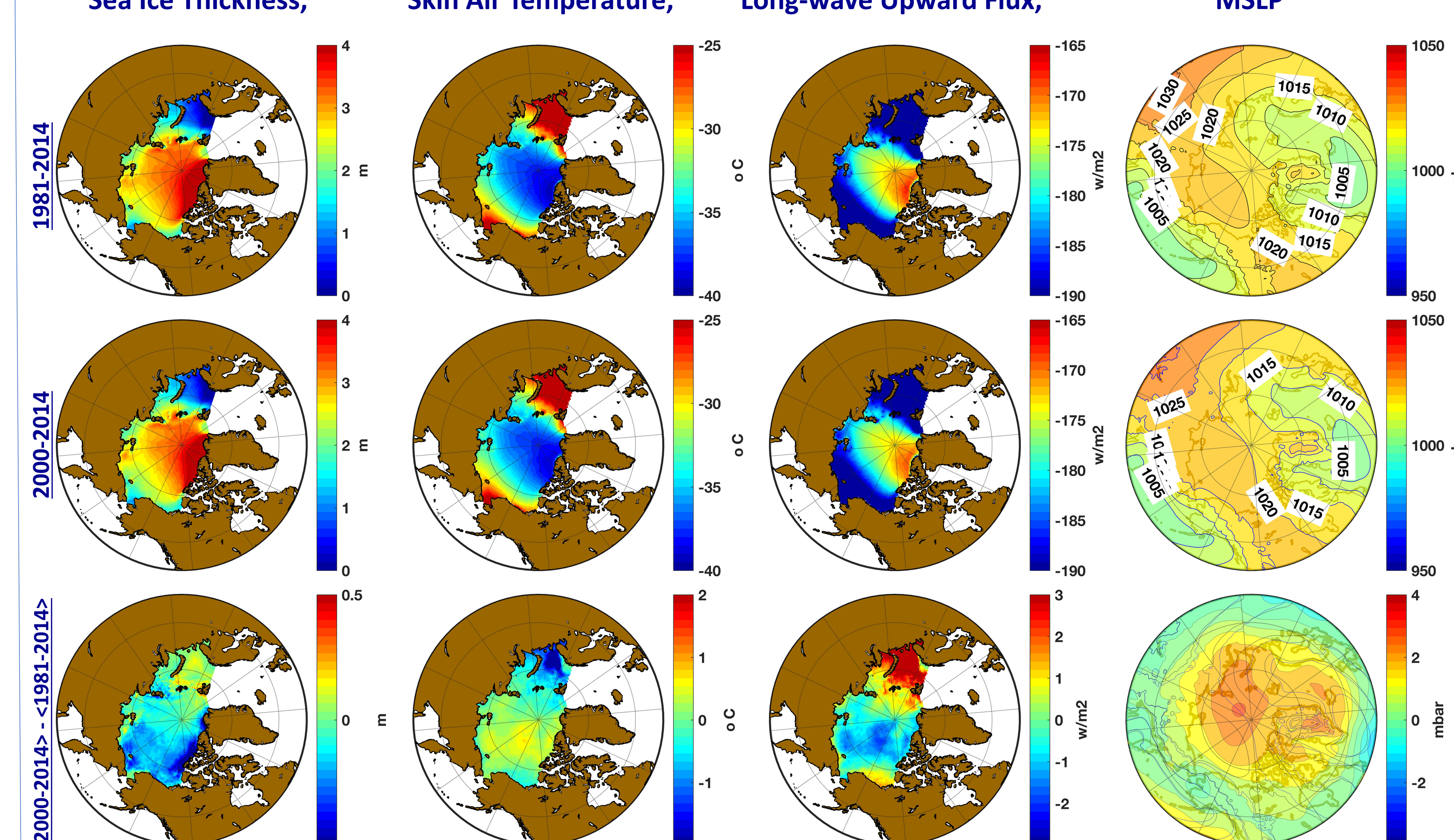


Mean JFM Sea Ice Volume Difference



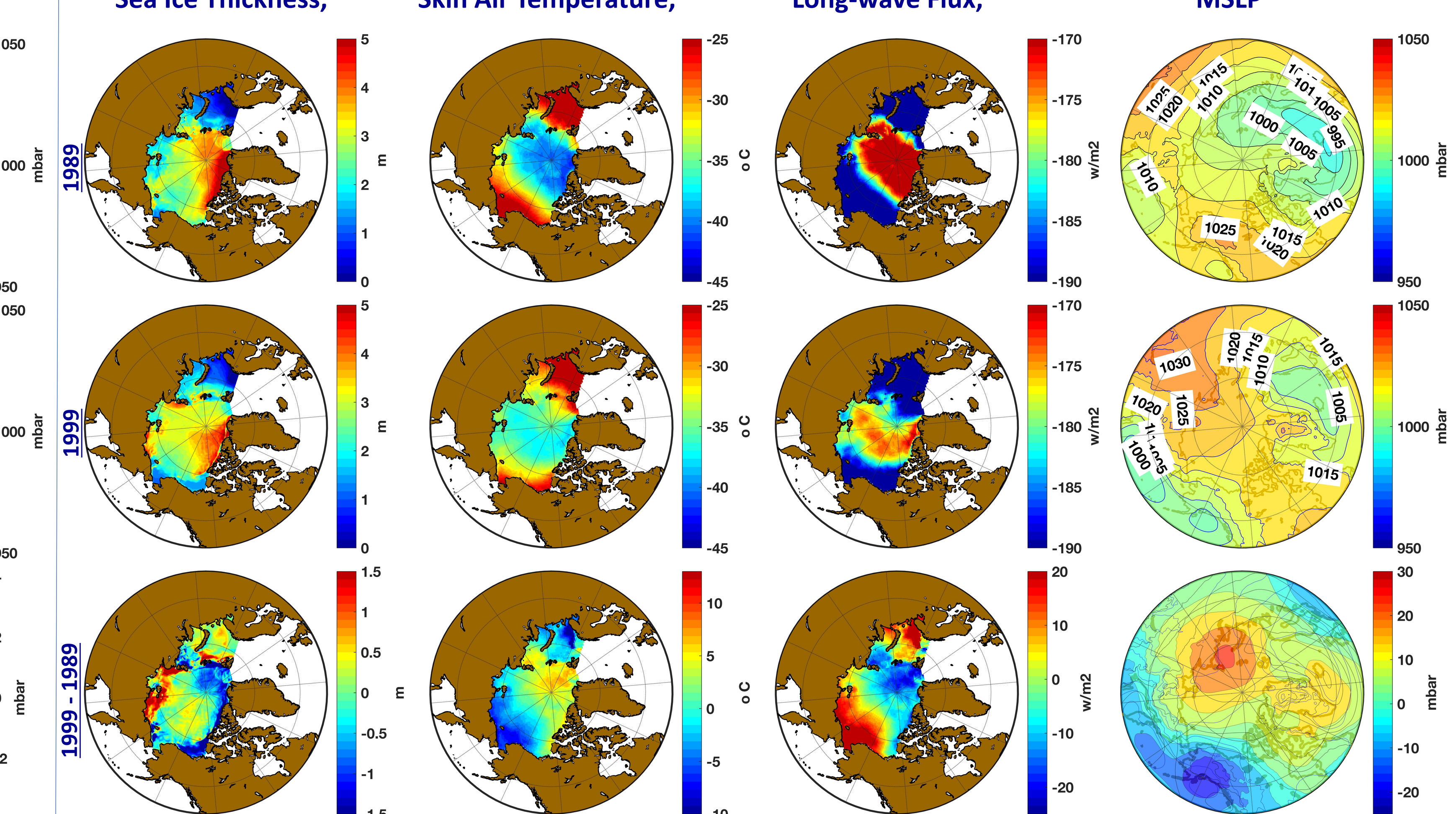
RBR1 Mean (1981-2014: top; 2000-2014: middle) Winter (JFM) and Difference (<2000-2014> - <1981-2014>; bottom)

Sea Ice Thickness, Skin Air Temperature, Long-wave Upward Flux, MSLP

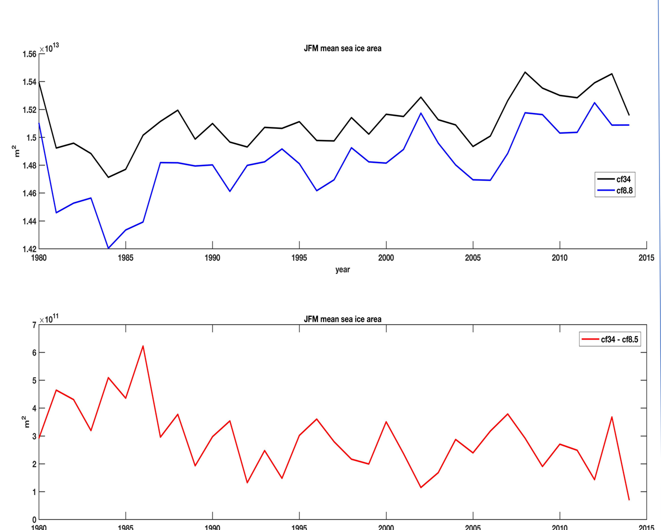


RBR Mean (1989: top; 1999: middle) Winter (JFM) and Difference (1999-1989; bottom)

Sea Ice Thickness, Skin Air Temperature, Long-wave Flux, MSLP

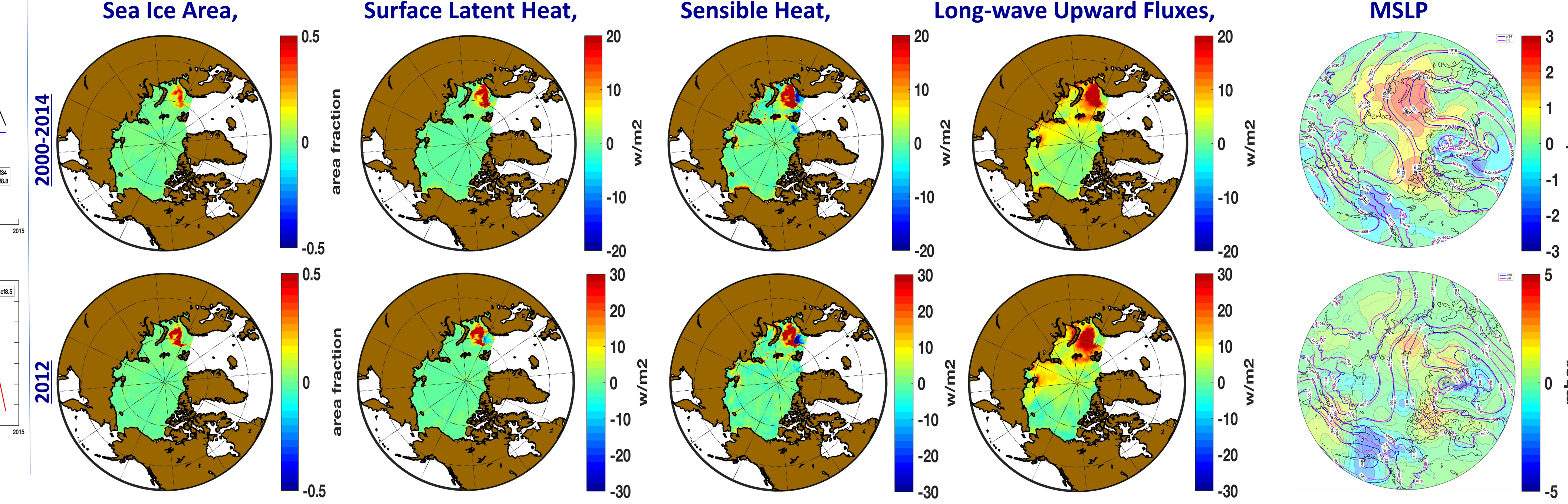


Sea Ice Area (top) & Difference (bottom)



Differences Between Two Cases (RBR1 – RBR 2) Mean (2000-2014: top; 2012: bottom) Winter (JFM)

Sea Ice Area, Surface Latent Heat, Sensible Heat, Long-wave Upward Fluxes, MSLP



Summary

- ➢ Fully coupled Arctic climate models are needed to investigate coupling channels across the air-sea interface under a changing sea ice cover
- ➢ Climate model components require spatio-temporal configurations sufficient to resolve critical physical processes and resulting feedbacks across coupling interfaces
- ➢ Sea ice thickness distribution, deformations and ice-edge dynamics, in addition to sea ice area, impose significant control of air-sea fluxes in winter
- ➢ Resulting local air-sea fluxes are not accurately represented in state-of-the-art atmospheric reanalyses nor in stand-alone atmospheric simulations
- ➢ Regional impacts of locally and seasonally enhanced air-sea fluxes are yet to be determined, as well as their possible linkage to lower latitudes
- ➢ Global climate models with regionally refined grids over the Arctic might provide important, new insights into Arctic / mid-latitude teleconnections