Evolution of the Arctic Climate System Simulated by Pan-Arctic WRF as Sea Ice Changes

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Pan-Arctic WRF

Background

Introduction

Efforts to develop a coupled atmosphere – ocean – sea ice – land Arctic regional model, known as the Regional Arctic Climate Model (RACM), are on-going. The atmospheric model in RACM is a version of the National Center for Atmospheric Research (NCAR) Weather Research and Forecasting (WRF) model that has been optimized for the polar regions. In the fully coupled RACM, the NCAR CCSM flux coupler CPL7 links the WRF atmosphere to the POP/CICE ocean and VIC land models. Here we present tests of stand-alone WRF done for two purposes:

- To develop a baseline version suitable for the pan-Arctic domain
- To assess couplings between the surface and atmosphere in initial one-way simulations in which ocean and ice properties are specified.

For these simulations, we use WRF 3.1 with WRF's built in NOAH land model.

Domains

1. RACM

The simulation domain of RACM covers the entire pan-Arctic region and includes all sea ice-covered regions in the Northern Hemisphere and all terrestrial drainage basins that flow into the Arctic Ocean. The ocean and sea ice models use a horizontal grid spacing of less than 10 km, while the atmosphere and land models use a horizontal grid spacing of 50 km or less.

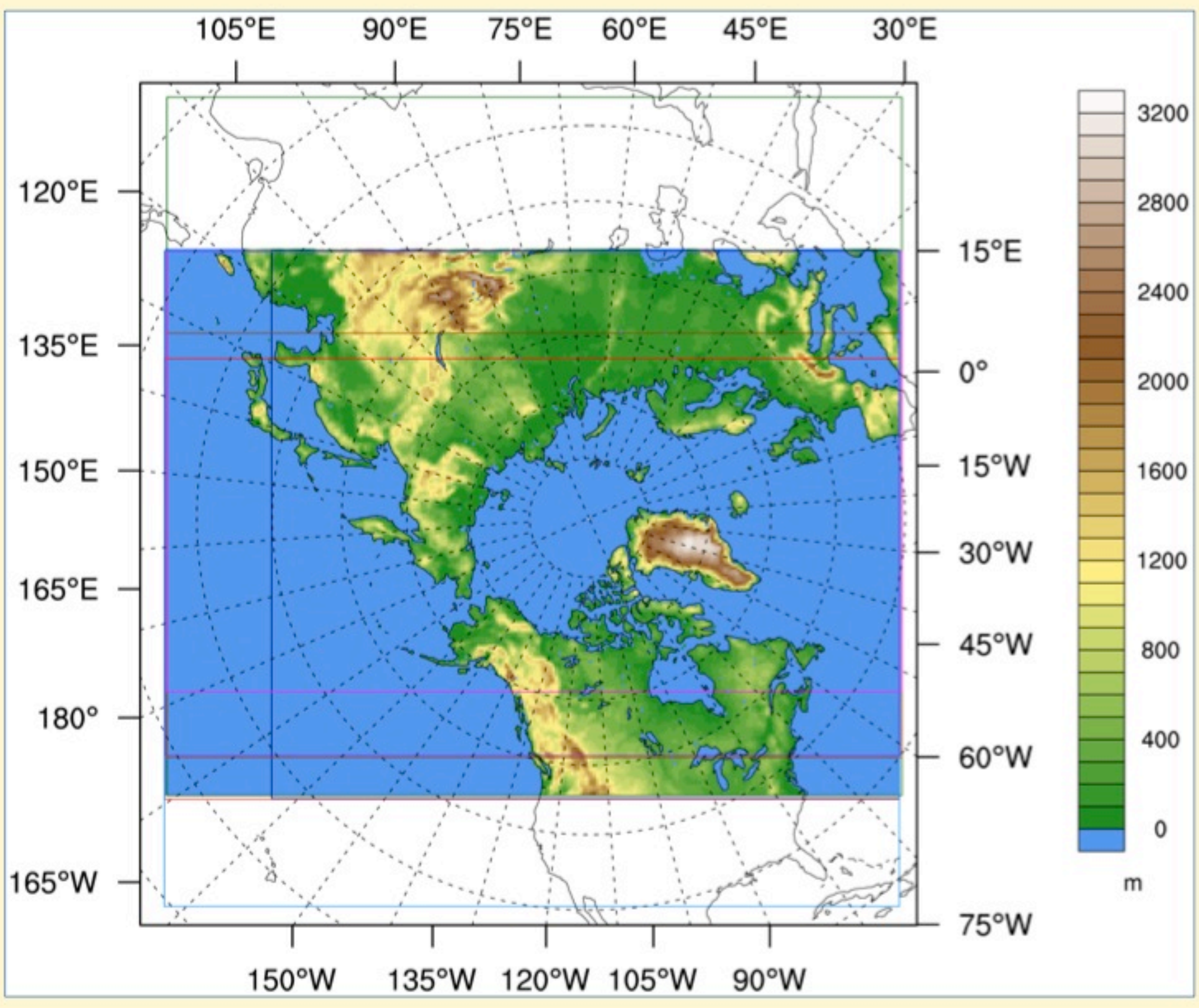


Figure: Model domains used in evaluating WRF for RACM pan-Arctic simulations. The domain indicated with the shaded topography is the model domain that will be used for fully coupled regional Arctic climate system model simulations. Colored outlines represent boundaries for the other model domains used when evaluating WRF.

2. CORDEX

We are also contributing to the WCRP Coordinated Regional Downscaling Experiment (CORDEX). The baseline CORDEX simulation uses the pan-Arctic domain below, with a 50-km grid.

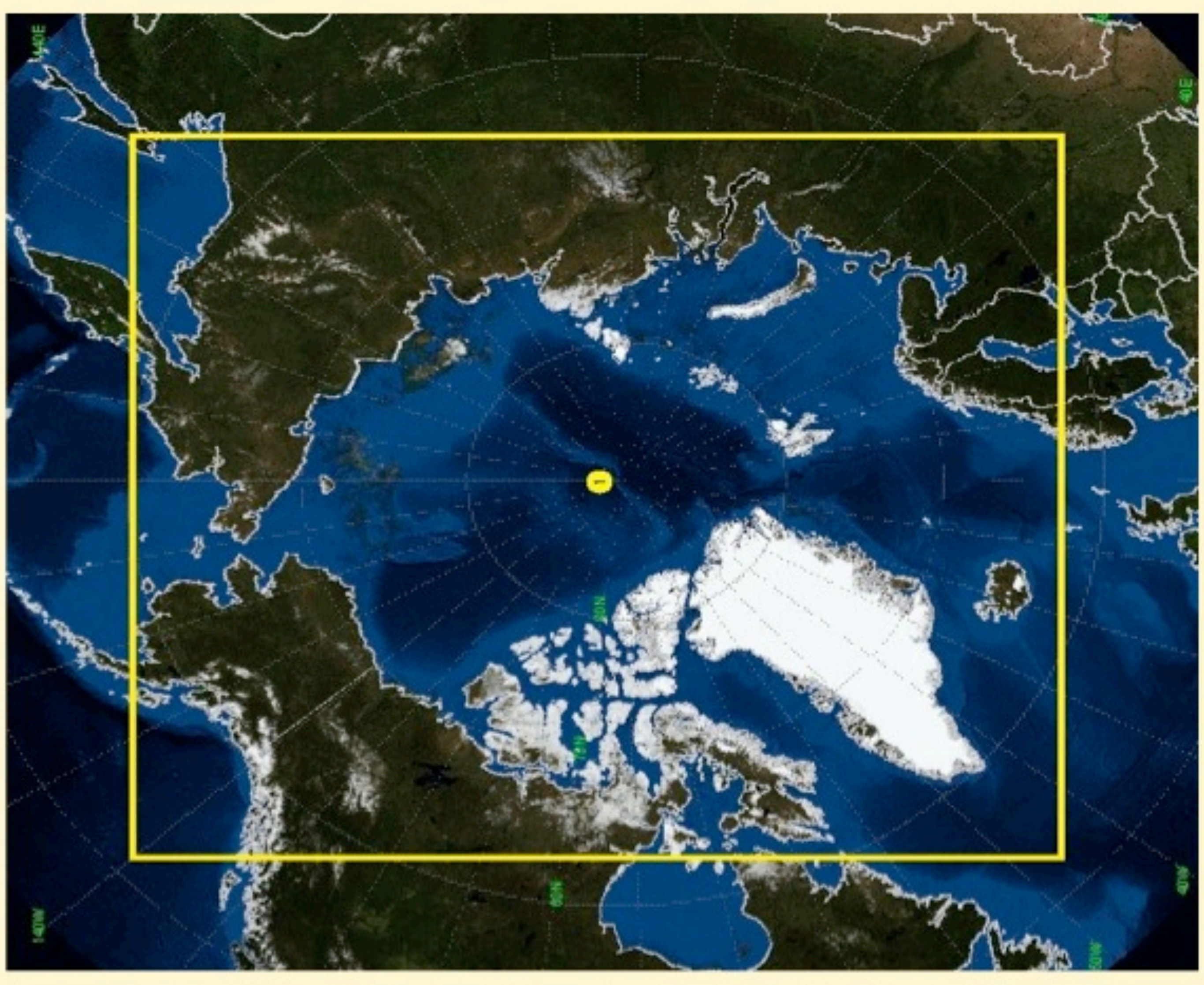


Figure: The CORDEX pan-Arctic domain. The region interior to the "sponge zone" is outlined by the yellow box.

Pan-Arctic WRF

RACM Domain Evaluation

An extensive suite of simulations with WRF were conducted to determine biases in the WRF simulated atmospheric state. 3-member ensembles were run for the months of January, April, July, and October 2007 using a variety of model physics options and pan-Arctic domains. The basline domain is the RACM domain appearing on the previous panel. All simulations were compared to NCEP reanalysis fields of pressure, temperature, humidity, and geopotential height at several levels in the atmosphere.

Bias Problem

After completing 24 different sets of simulations using a range of radiation, cloud microphysics, boundary layer, and land parameterizations it became obvious that WRF, when run on a large pan-Arctic domain, develops significant circulation biases in the North Pacific, and occasionally in the North Atlantic, storm track regions. The figure below shows results from the WRF simulation that has the smallest errors of all parameterization combinations evaluated.

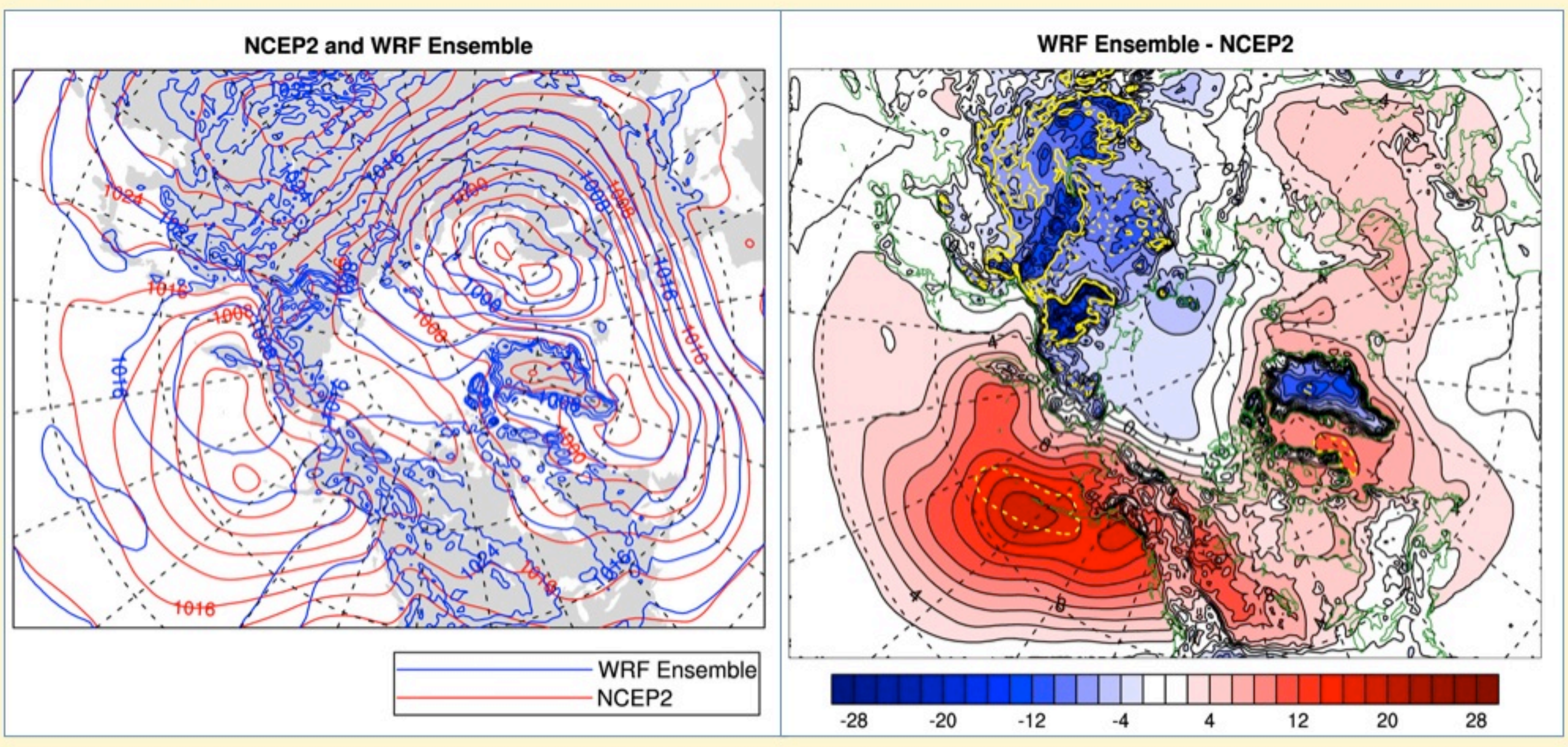


Figure: Overlay of monthly mean sea level pressure (SLP) contours from the NCEP reanalysis (red lines) and 3-member WRF ensemble (blue lines) (left panel) and difference between the monthly mean SLP (WRF ensemble minus NCEP reanalysis) (right panel) for January 2007. Large positive biases in SLP are present in the North Pacific and to a lesser extent in the North Atlantic.

Problem Solution

In order to determine if the large errors illustrated in the figure above were specific to the model domain being used, several simulations were run using smaller or larger domains than the RACM domain. In these simulations the large errors evident above persisted with slight changes in location and/or intensity. Only simulations run on much smaller pan-Arctic domains (e.g., CORDEX domain) had small errors.

Given the large errors that occur in long-duration climate-type simulations with WRF on a large pan-Arctic model domain additional simulations using a variety of data assimilation techniques were evaluated. The use of data assimilation to constrain the large-scale atmospheric features to be consistent with lateral boundary conditions is common for many regional climate models and was viewed as critical for conducting fully coupled simulations with RACM in the future. Results from a WRF simulation that used the same model physics options as was used for the simulations shown above, but that also used spectral nudging of wind and temperature for wave numbers 1 and 2 showed drastically reduced errors across the entire domain (below). For this simulation spectral nudging was applied in the top 20 (out of 40 total) vertical levels in WRF, with the strength of nudging linearly increased from zero at level 20 to full value at level 30.

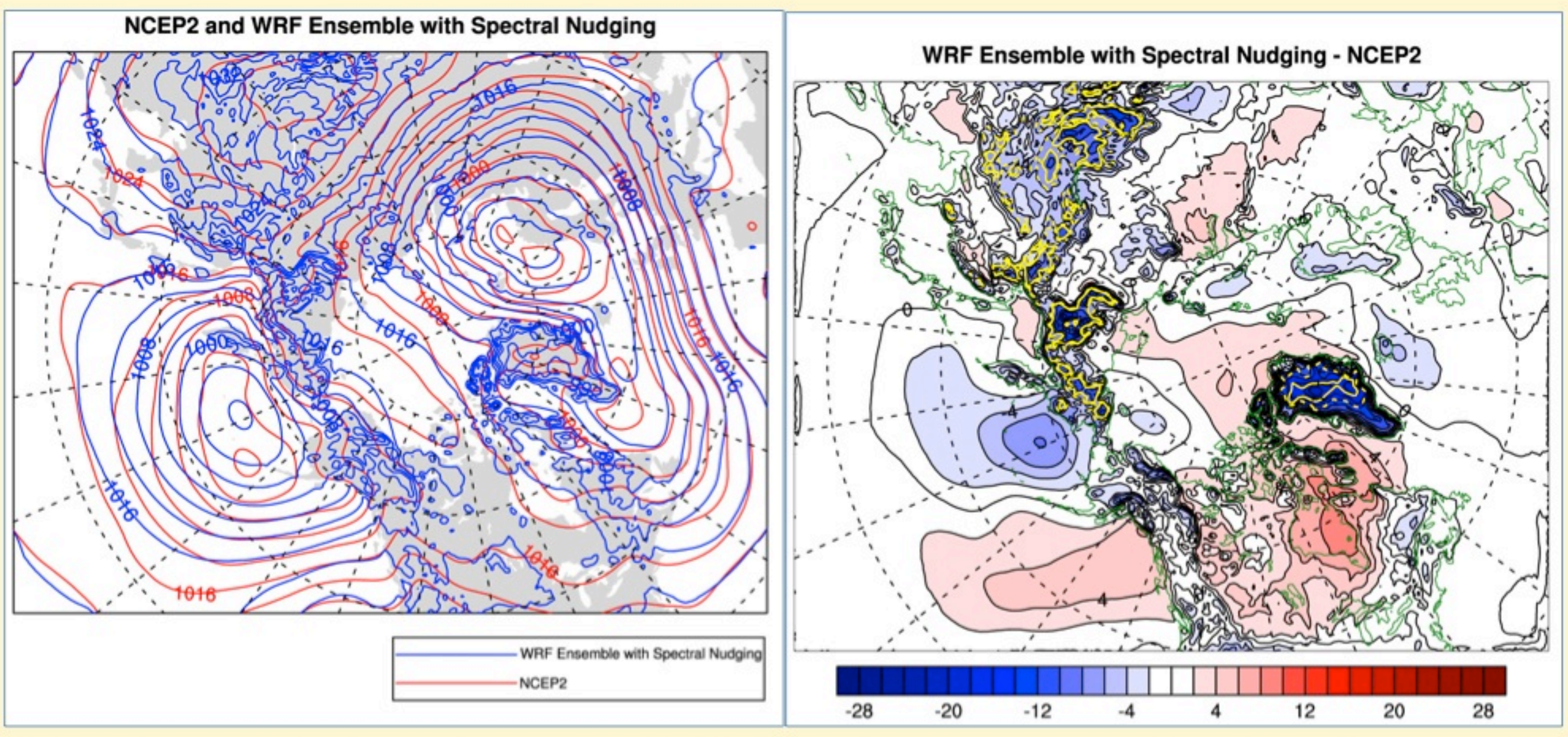
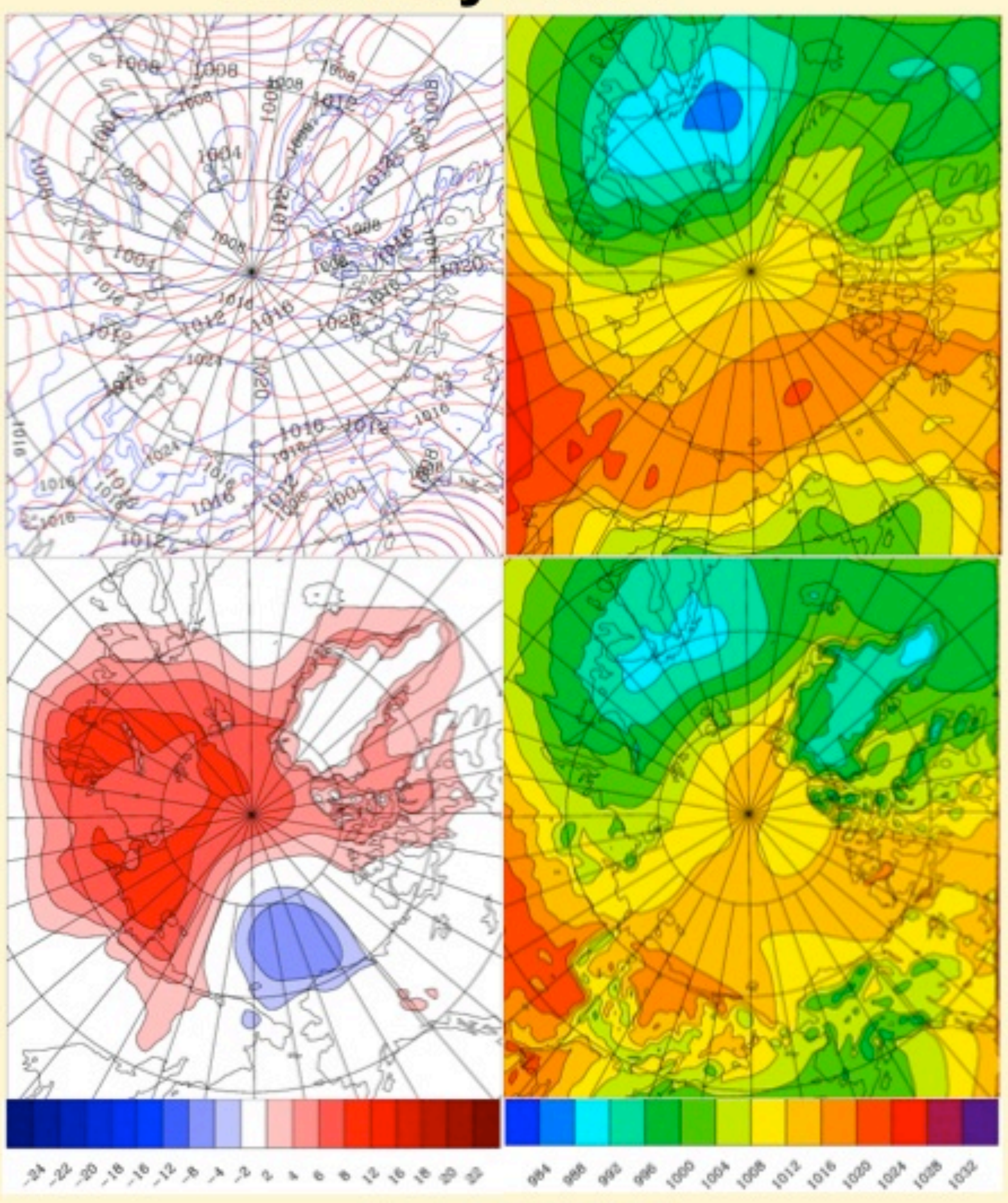


Figure: Same as the figure above except for WRF simulation using spectral nudging of wave numbers 1 and 2.

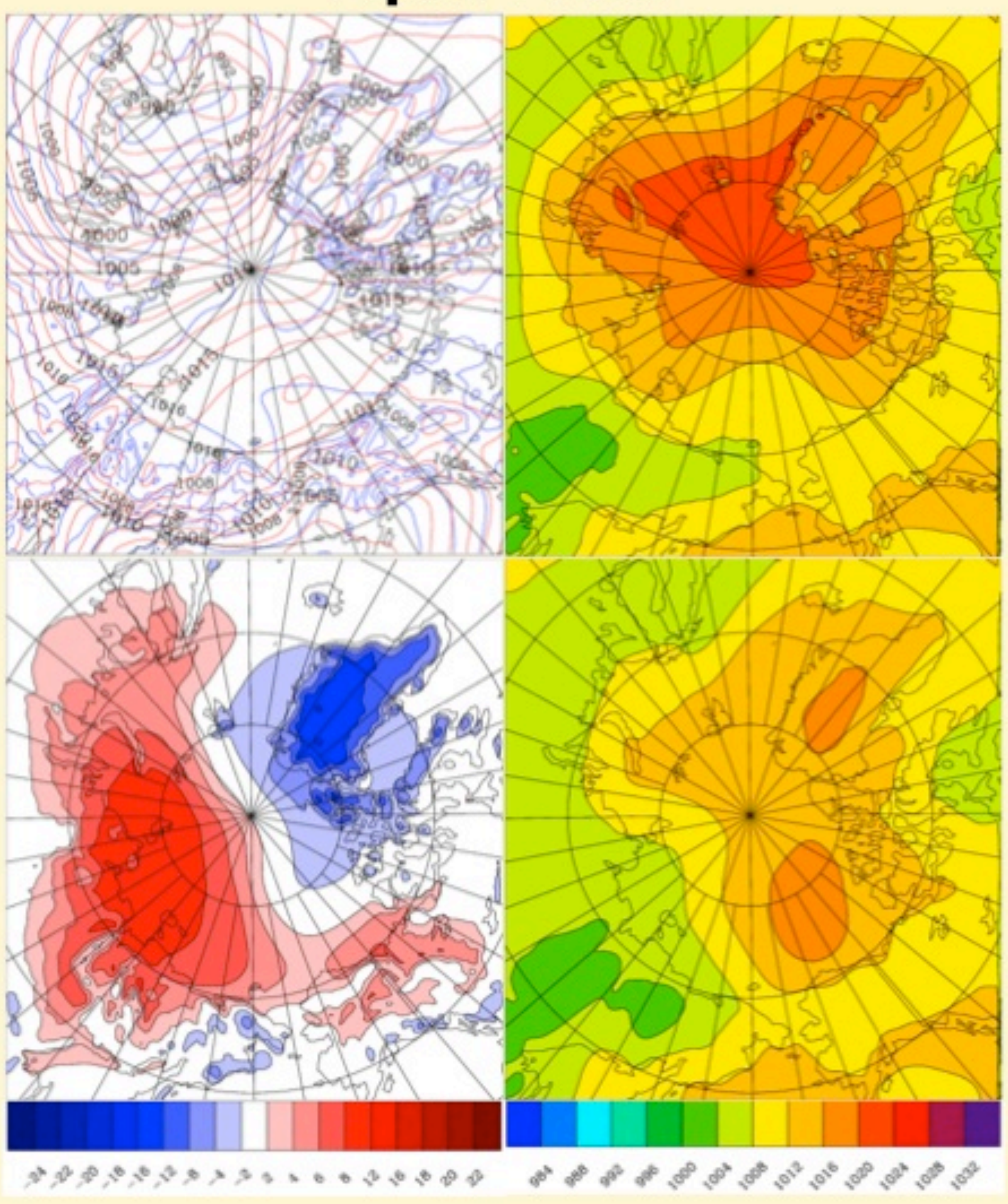
Pan-Arctic WRF
CORDEX Arctic Domain
January – August 2007

Simulations using ERA-Interim Reanalysis and NSIDC Fractional Sea Ice

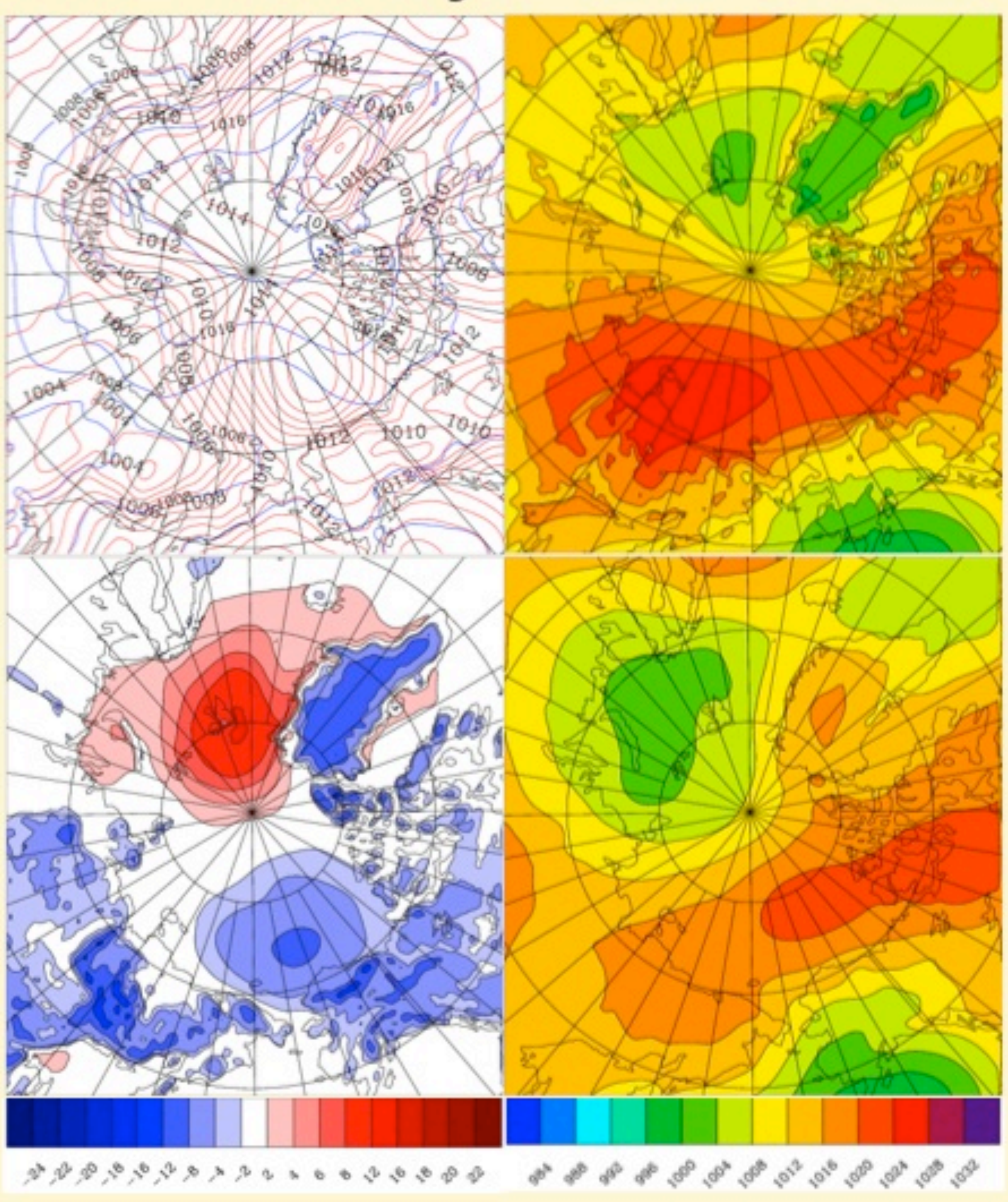
January 2007



April 2007



July 2007



Each of the first three plot groups contain:

top left: Pan-Arctic WRF (PAW) monthly MSLP contours (blue) plotted against Era-Interim monthly MSLP (red).

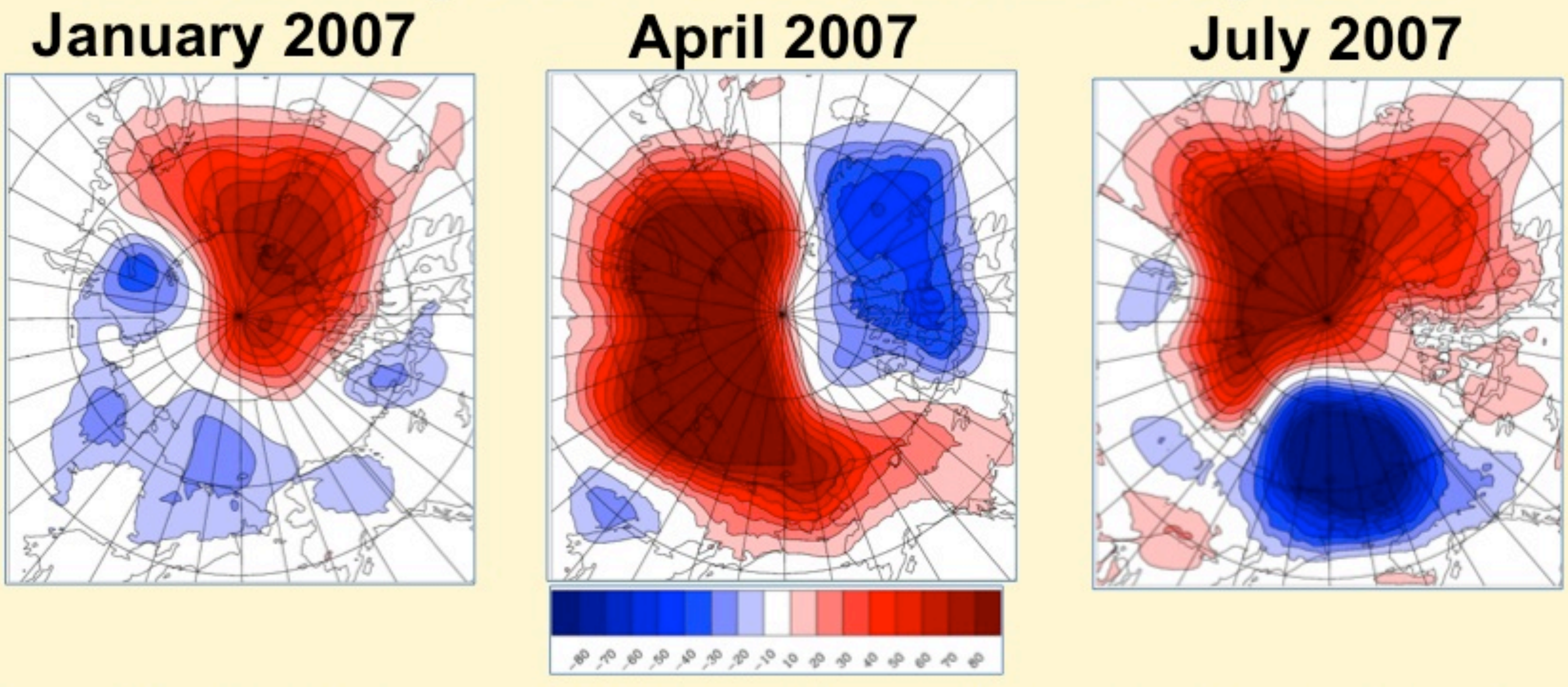
top right: PAW Monthly MSLP.

bottom left: PAW - Era-Interim Monthly MSLP bias. Large MSLP anomalies over regions of high topography are as a result of the different algorithms (WRF vs Era-Interim used to convert station pressure to SLP.

bottom right: Pan-Arctic WRF Monthly MSLP.

Mean Monthly 500-hPa Geopotential Height Bias

January 2007 **April 2007** **July 2007**



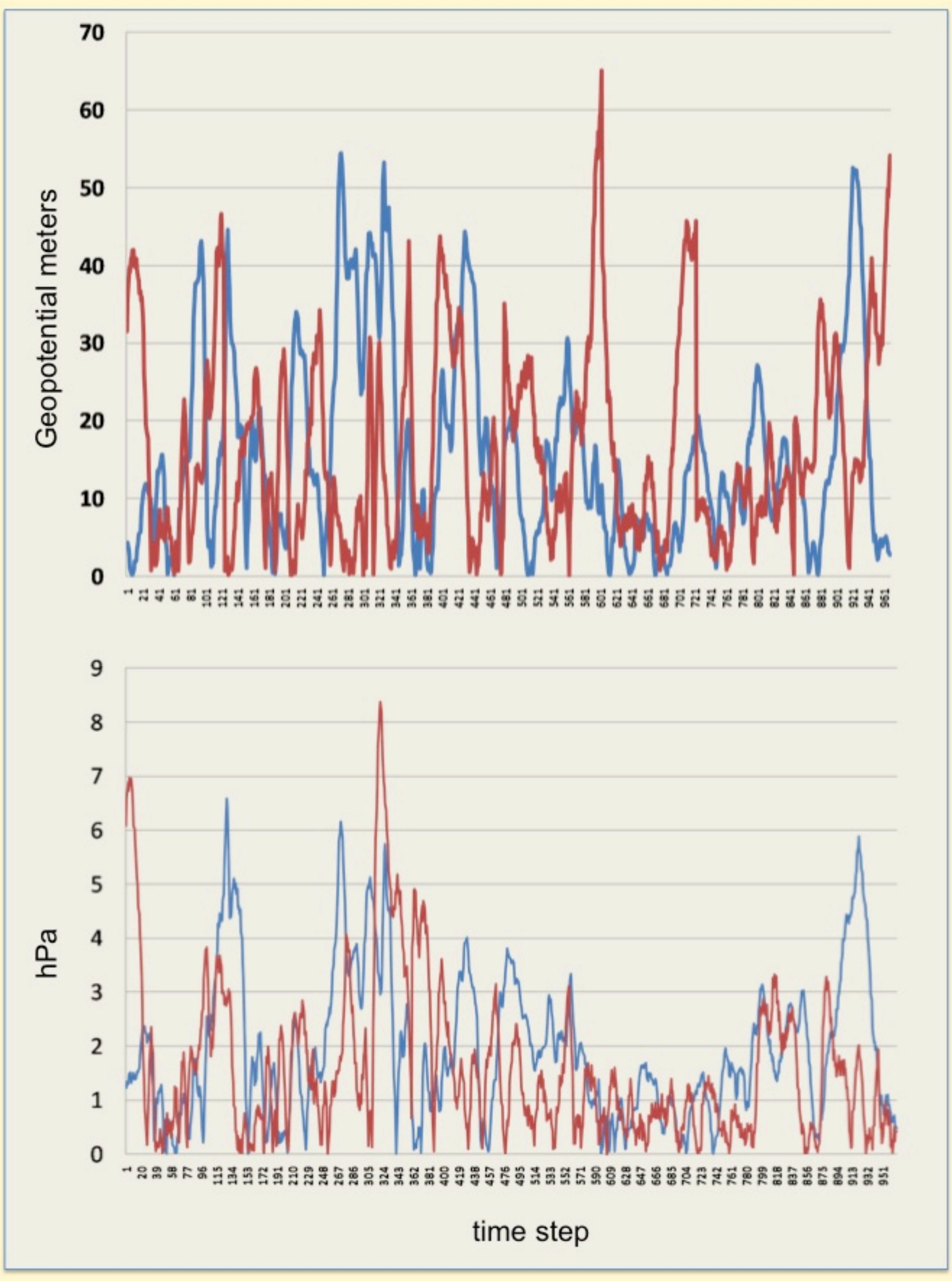
above: Monthly plots of mean 500-hPa height biases. The weakest bias couplet is found in January while the strongest exists in April.

right top: Plotted 500-hPa geopotential height root mean square difference (RMSD) between Pan-Arctic WRF and ERA-Interim Reanalysis (blue line) For comparison, observation RMSD (red line) is plotted

right bottom: Plotted MSLP root mean square difference (RMSD) between Pan-Arctic WRF and ERA-Interim Reanalysis (blue line) For comparison, observation RMSD (red line) is plotted.

Reanalysis RMSD is computed by taking the RMS difference between the ERA-Interim daily MSLP and corresponding monthly mean values of the reanalysis.

Reanalysis RMSD is useful in determining the amount of internal variability in the atmosphere. Magnitudes of both RMSD curves correspond to a high degree. Thus, the model versus reanalysis RMSD may have a considerable dependence on unforced, quasi-random internal variability.

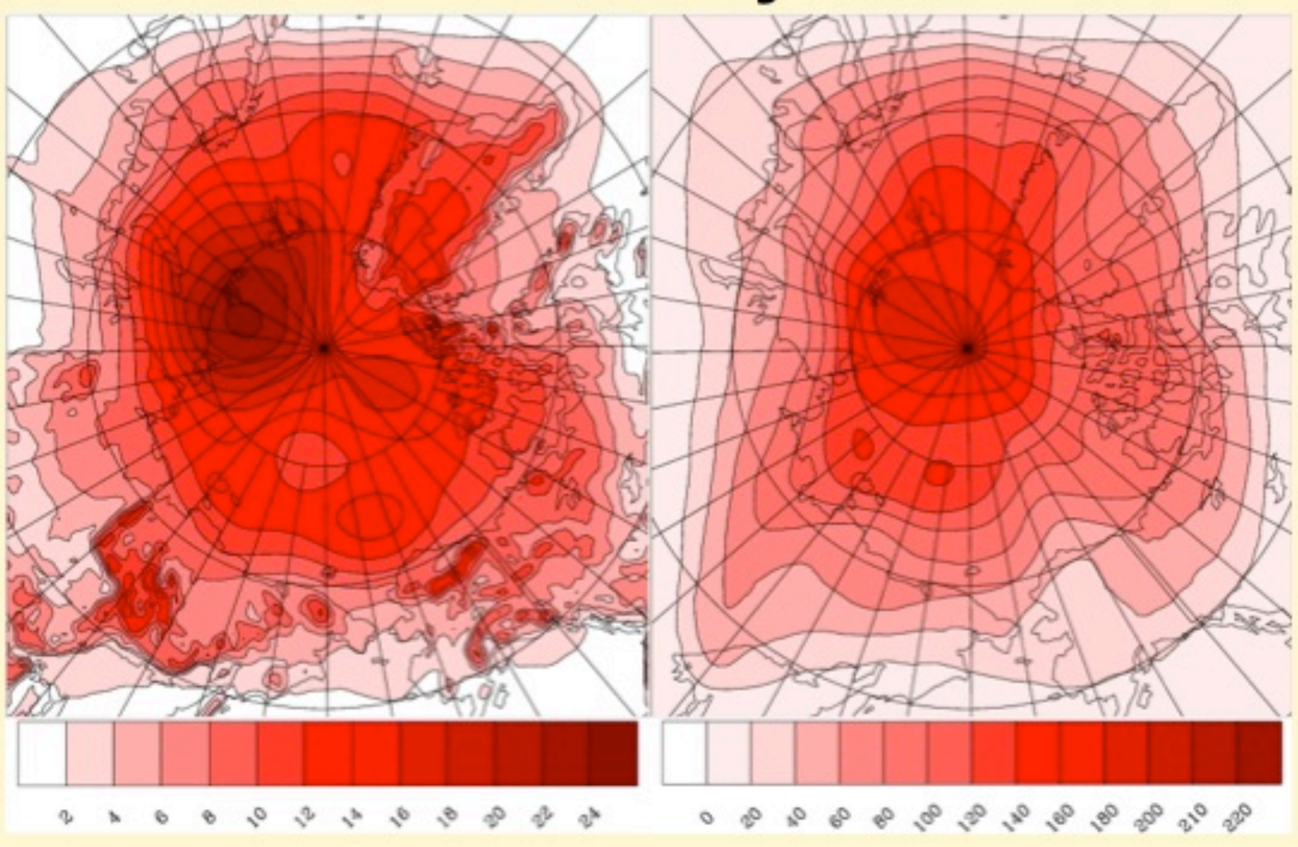


Pan-Arctic WRF

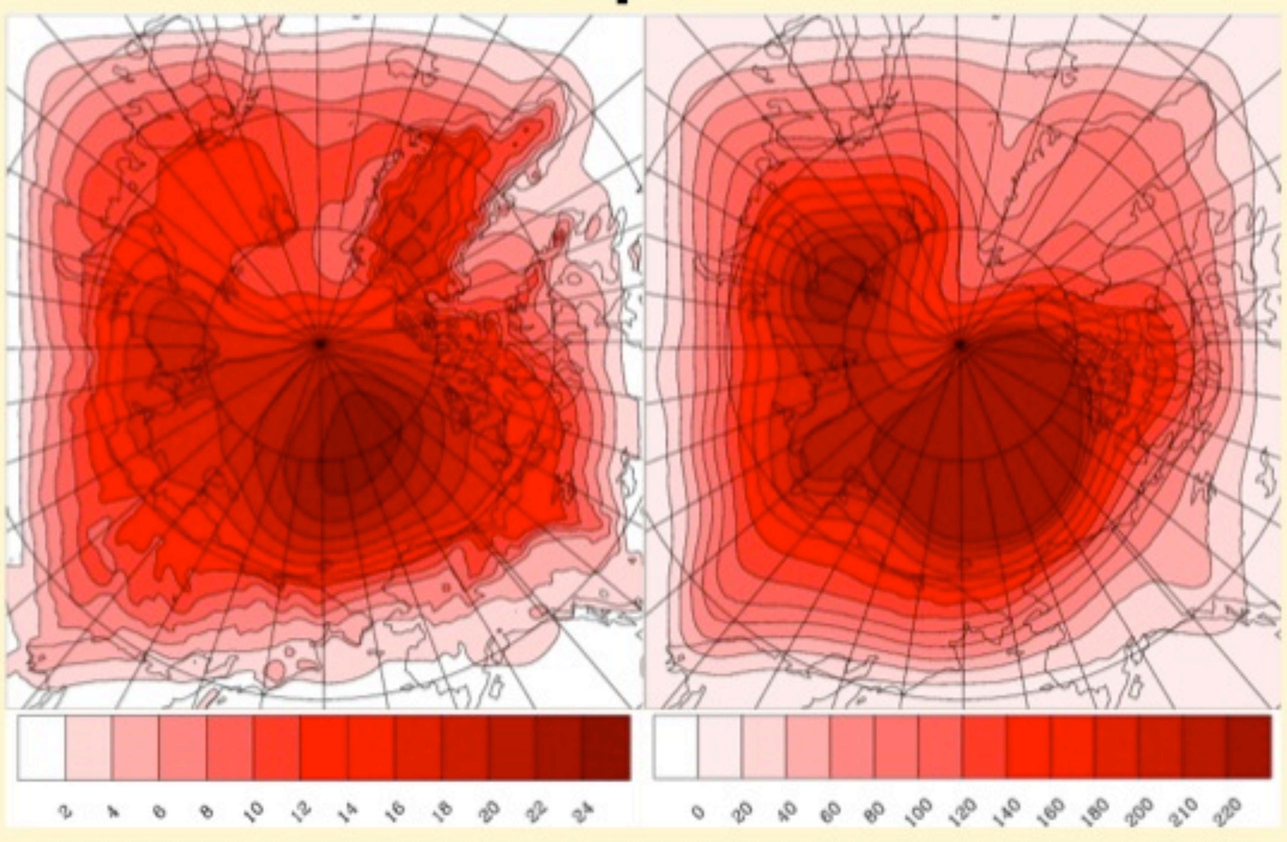
CORDEX Arctic Domain

January – August 2007

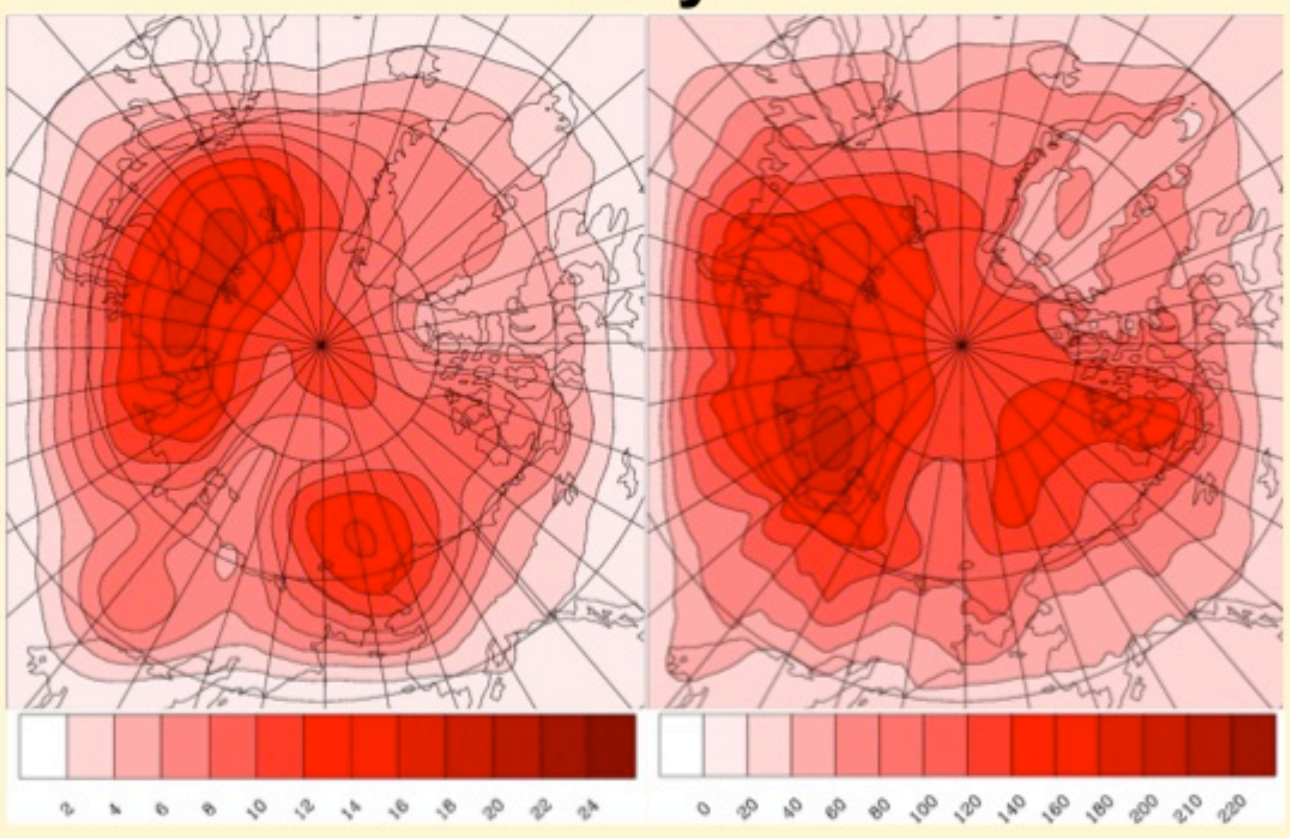
January



April



July



Each of the first three plot groups contain:

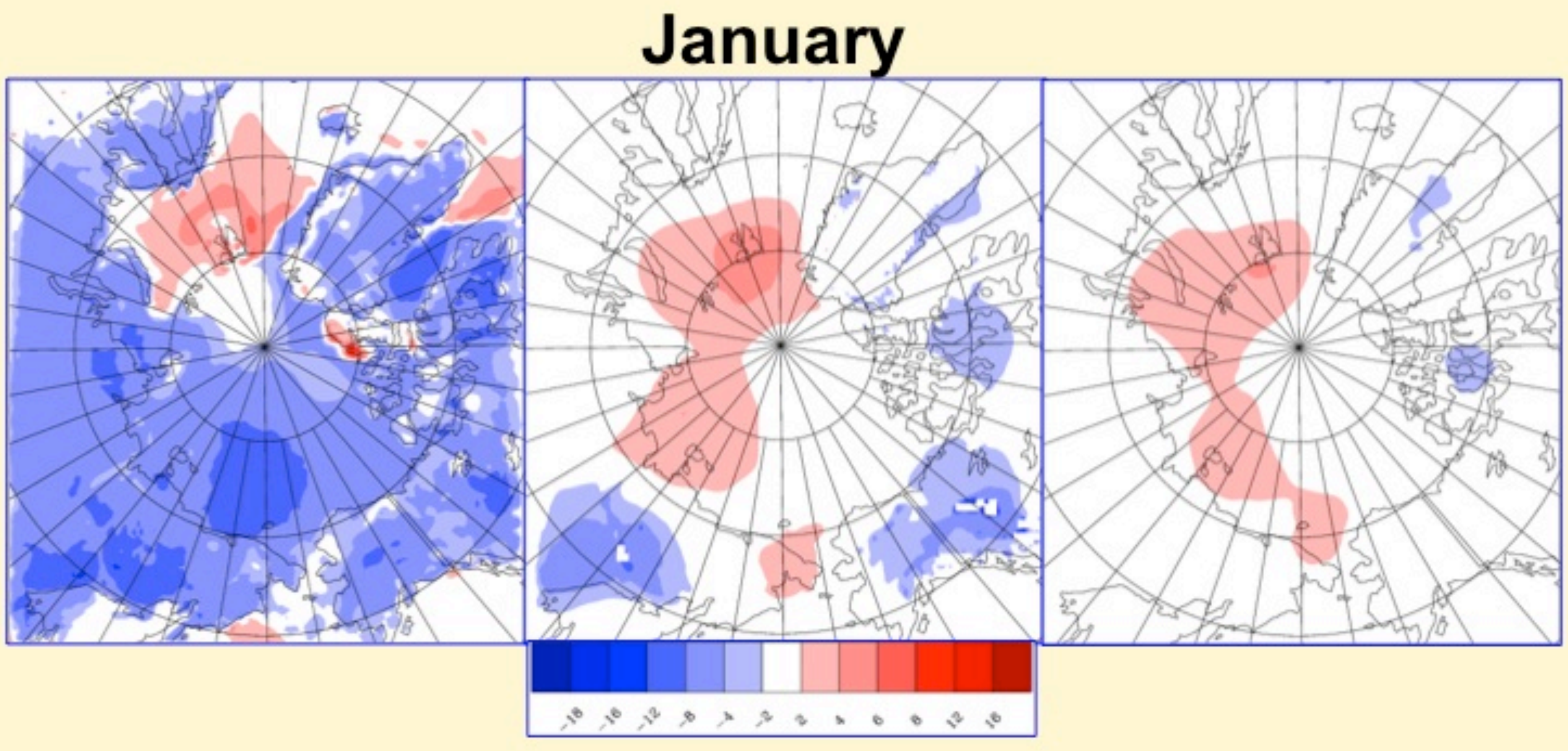
left: Monthly mean RMSD sea-level pressure

right: Monthly mean RMSD 500-hPa geopotential heights.

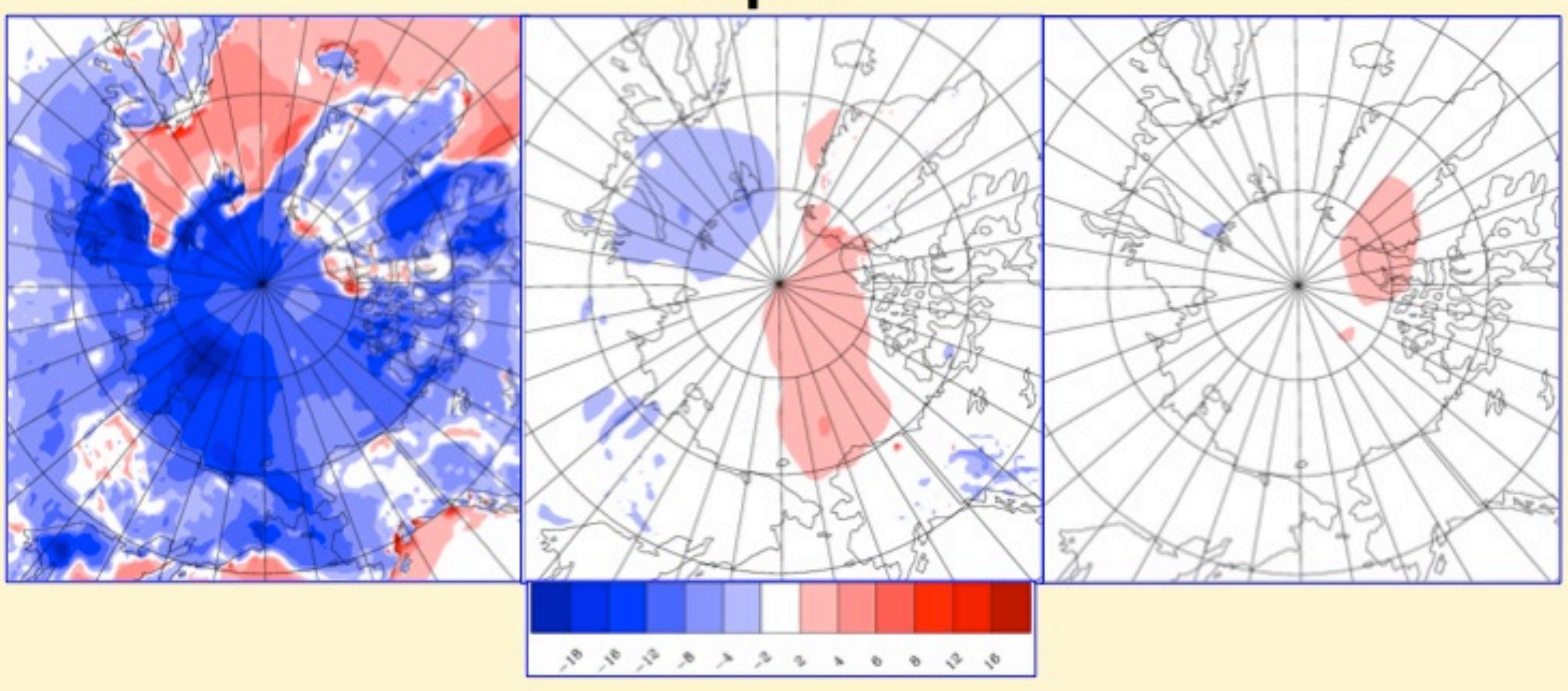
The largest RMS differences appear in April. However, when compared with RMSD time series on the previous panel, a considerable amount of variability can be attributed to model/reanalysis; both RMSD curves are comparable in magnitude to their respective reanalysis RMSD curves.

Two-meter, 850-hPa, and 500-hPa Temperature

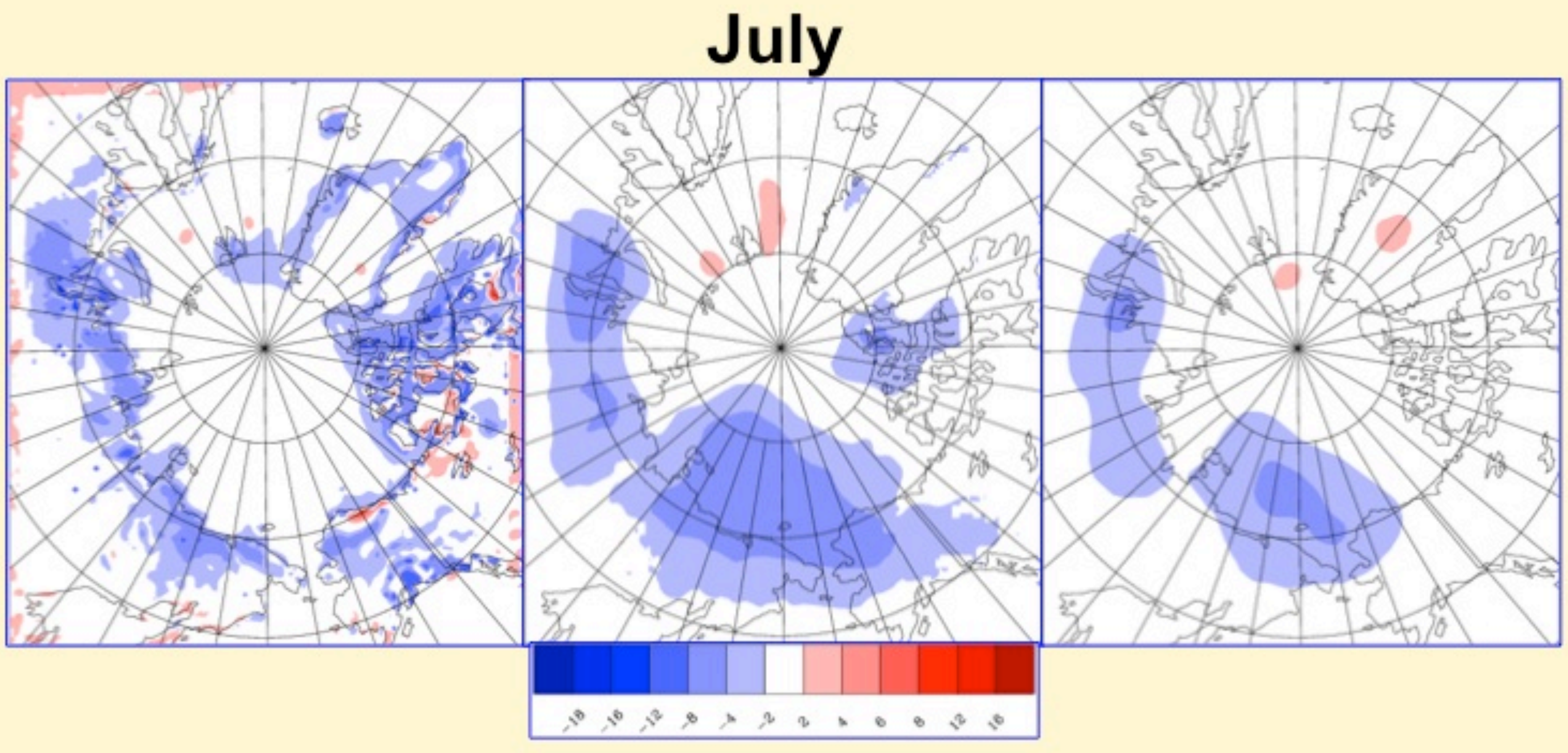
January



April



July



Each temperature bias plot set contains: 2-m (left), 850-hPa (center), and 500-hPa (right).

top: Monthly mean temperature bias for January 2007. Surface anomalies are largest over regions of sea ice and snow cover. Aloft, there is good agreement between PAW and Era-Interim, thus biases are minimal.

center : Monthly mean temperature bias for April 2007. The surface plot shows the largest negative bias over the East Siberian Sea into the Barents Sea. Large cold biases may be a result of the treatment of sea ice and snow in PAW.

bottom: Monthly mean temperature bias plots July 2007. All three plots show good agreement between the model output and reanalysis.

Pan-Arctic WRF

CORDEX Arctic Domain

Sea-Ice Treatment

In this study, we examine effects of ice treatment in PAW, comparing simulations allowing *fractional sea ice* in each 50-km grid box versus those using the original WRF treatment allowing only 0% or 100% ice cover in a grid box *(binary sea ice*).

WRF used ERA-Interim to simulate June-Dec 2007, encompassing a period when there was substantial fractional sea ice in the Chukchi/Beaufort Sea region. Two four-member ensembles were simulated: one using binary sea ice everywhere and the other using fractional sea-ice in the Chukchi/Beaufort Sea region and binary elsewhere. Start times for each member were staggered by one day, from late May 2007.

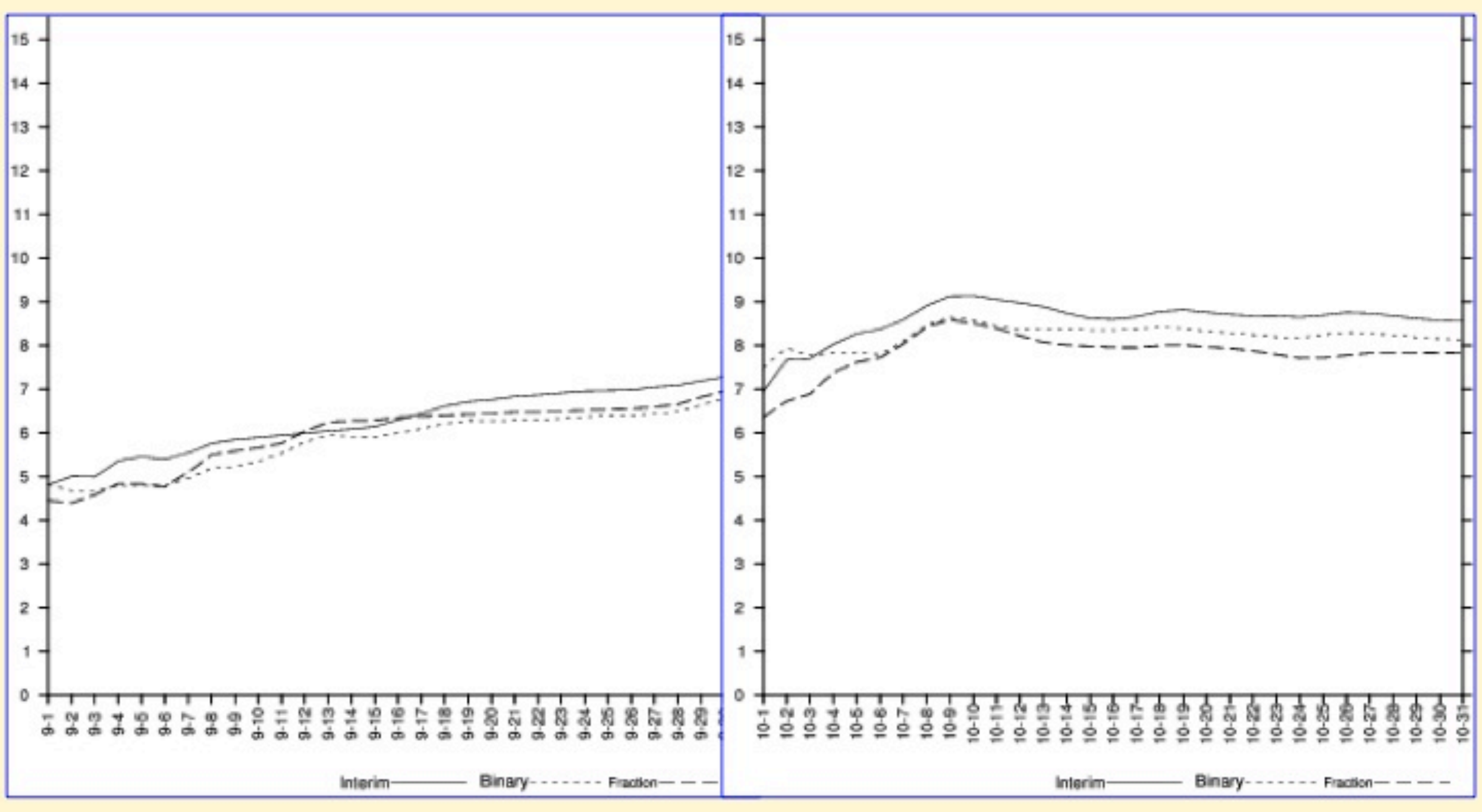
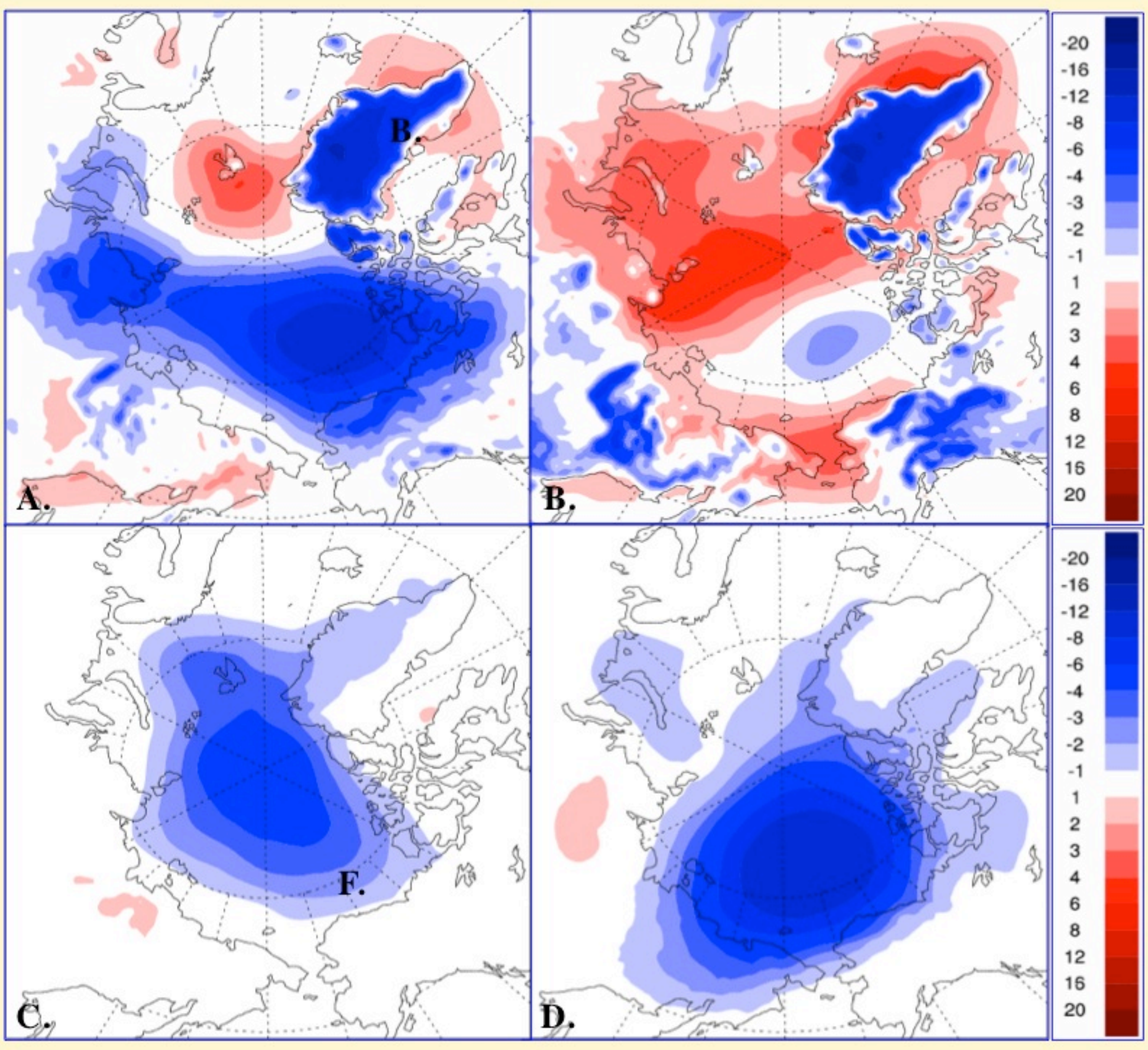


Figure: RMS differences (hPa) between daily mean sea-level pressure (MSLP) and the monthly average MSLP from the same source (ERA-Interim, WRF-binary,WRF-fractional) **A.** September, **B.** October. The simulations reproduce well the observed behavior. The RMSDs collectively give a measure of unpredictable internal variability or "noise".

Figure: WRF-binary ensemble minus ERA-Interim MSLP (hPa) for **A.** September and **B.** October. Differences are relatively small vs. RMSD above, except for land areas, where differences occur between WRF and ERA MSLP algorithms.

WRF-fractional minus WRF-binary ensemble MSLP differences (hPa) for **C.** September and **D.** October. Differences are largest in October, a month with relatively warm sea-surface temperature, cooling atmospheric temperatures, and relatively large fractions of open ocean..



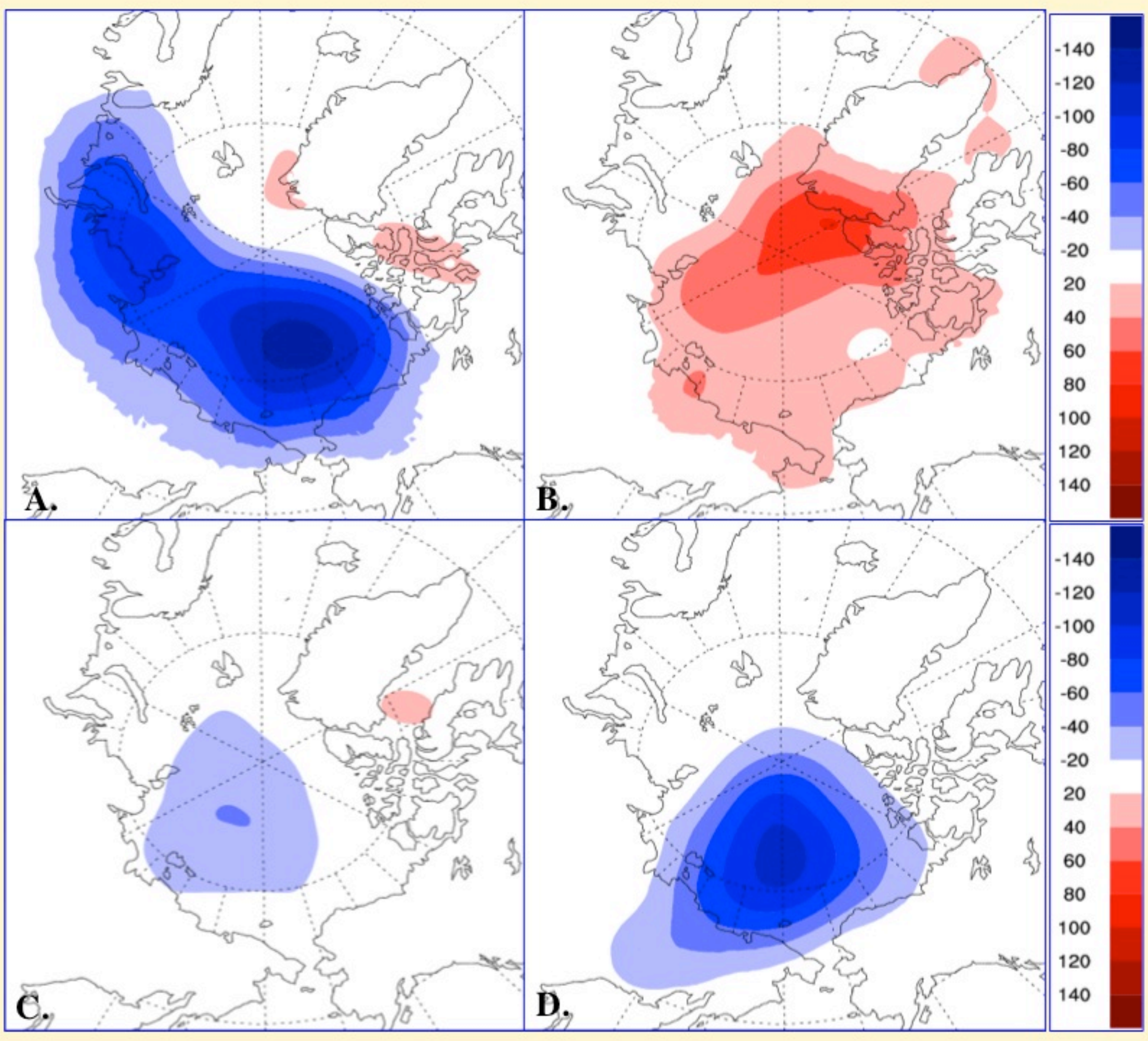


Figure: Same as the panels above, but for 500 hPa heights (m).

Differences from the reanalysis are a little larger than the internal variability (see previous panel), though less so in October.

Differences due to ice treatment are deeper in the atmosphere in October than September.

Pan-Arctic WRF

CORDEX Arctic Domain

Sea-Ice Treatment & Summary

These figures are also from the fractional versus binary sea-ice study described in the previous panel.

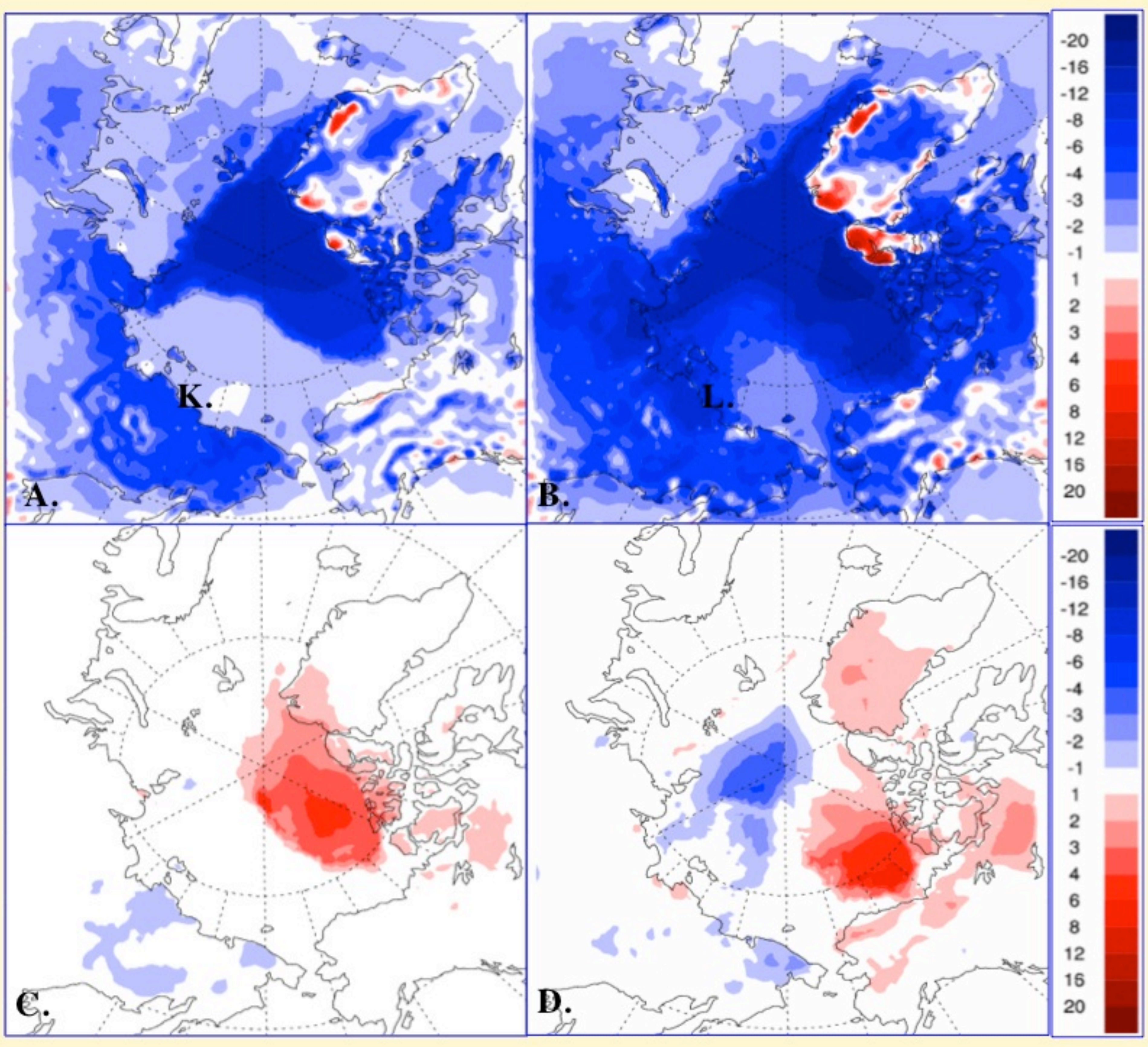


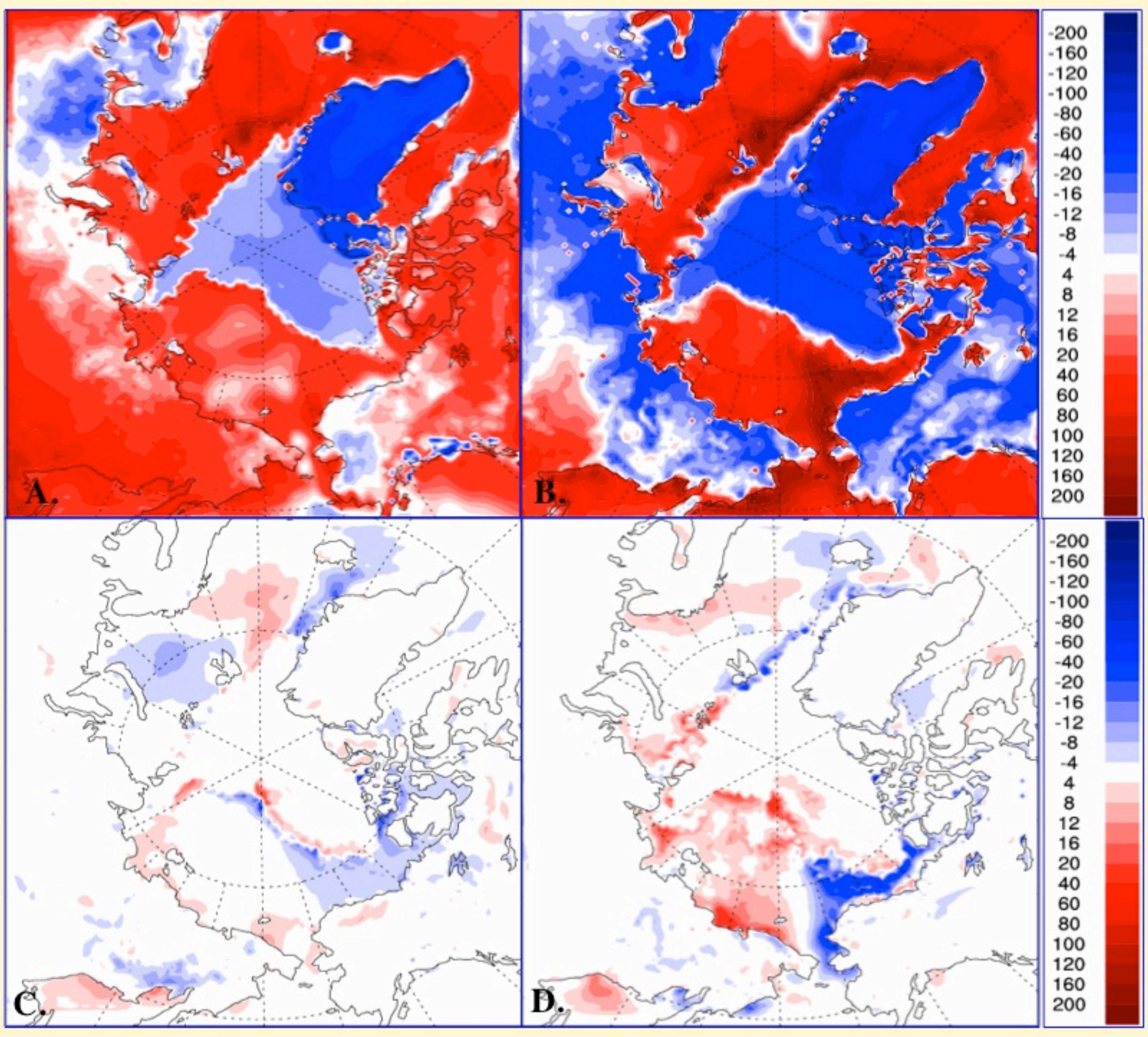
Figure: WRF-binary ensemble minus ERA-Interim 2-m temperature (˚C) for **A.** September and **B.** October. Differences partly reflect WRF difficulties in simulating snow-covered sea ice.

WRF-fractional minus WRF-binary ensemble 2-m temperature differences (˚C) for **C.** September and **D.** October.

Differences do not align with surface sensible heat flux differences (below) due to advection of heat by the anomaly circulation (previous panel).

Figure: Same as the panels above, but for surface sensible heat flux (W/m^2), positive downward.

Region of largest differences occurs where there are differences in sea-ice treatment between the two ensembles.



Summary

1. Pan-Arctic WRF simulations on the large RACM domain perform well when using spectral nudging in the upper half of the model atmosphere. Without nudging, substantial bias appears in monthly sea-level pressure.

2. Pan-Arctic WRF simulations on the smaller CORDEX domain perform well without need for nudging.

3. Substantial differences appear between an ensemble of simulations that allow fractional sea ice and an ensemble that does not. The largest differences occur in October when the ocean is relatively warm, the atmosphere is cooling, and fractional ice cover covers a relatively large area.