A Synthesis of Arctic Climate Change*

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Outline

- Primer on Arctic Climate Change
- Global Reanalysis Performance in the Arctic
- Outline of Arctic Regional Reanalysis
- Polar WRF
- Atmospheric Data Assimilation
- Land Surface Data Assimilation
Figure 3: September ice extent from 1979 to 2007 shows an obvious decline. The September rate of sea ice decline since 1979 is now approximately 10 percent per decade, or 72,000 square kilometers (28,000 square miles) per year.

NSIDC Press Release: Models Underestimate Loss of Arctic Sea Ice
30 April 2007


Figure 1. Actual observations of September Arctic sea ice (red) show a more severe decline than any of the eighteen computer models (average, dashed line) that the 2007 IPCC reports reference.
Greenland Melt Extent 2005

Konrad Steffen and Russell Huff

Cooperative Institute for Research in Environmental Sciences (CIRES)
University of Colorado at Boulder, CO 80309-0216
http://cires.colorado.edu/science/groups/steffen/greenland/melt2005/

Greenland melt extent for 1992 and 2005

Total melt extent area that experiences 1+ melt day April – September. 2005 melt extent exceeds the previous 2002 record. (Steffen et al. 2004; Hanna et al. 2005)
Permafrost Melting in the Arctic? (NOAA Arctic Change)

Mean annual ground temperatures in Yakust, Siberia (62.1°N, 129.8°E), from 1833-2003. [From V. Romanovsky]

Permafrost distribution in the Arctic. Pink is continuous, blue is discontinuous, green is sporadic. [Romanovsky et. al., 2002, Fig. 1]

Mean annual ground temperatures at Fairbanks, Alaska, for 1930-2003. The temperature 1 meter below the surface has risen very close to 0°C. [From V. Romanovsky]

http://www.arctic.noaa.gov/detect/land-permafrost.shtml
What is Atmospheric Reanalysis?

- A detailed, quantitative history of the weather and climate achieved with a fixed analysis scheme.
- Combines in-situ and remote observations as input, and integrates with a numerical weather/climate prediction model for a physically realistic depiction of the atmosphere. Therefore, reanalysis is a synthesis of our efforts to observe and understand the Earth.
- Outputs fields for quantities that can be readily observed (such as pressure and temperature), quantities that are problematic to measure (such as precipitation), and quantities that cannot be directly measured (such as surface fluxes).
- While the fields within a given reanalysis are not sensitive to the assimilation methodology (as it does not change), the fields are sensitive to the availability and quality of observations (the better the observations, the better the reanalysis).
- The first 2 generations of atmospheric reanalyses are dominated by global projects (NCEP/NCAR, ERA-15, NCEP-2, ERA-40, JRA-25, ...).
- Reanalyses can also be performed over a limited area (NARR).
**FIGURE 1.** The vertical structure of the Arctic warming during the 1980s and 1990s, based on the ERA-40 reanalysis. Averaged temperature trends around latitude circles for 1979–2001 plotted versus latitude and height for the four seasons.

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**Vertical structure of recent Arctic warming**
Rune G. Graversen, Thorsten Mauritsen, Michael Tjernström, Erland Källén & Gunilla Svensson
Arctic System Reanalysis Motivation

1. Rapid climate change is observed in the Arctic, as illustrated by the all-time minimum of summer sea ice extent in September 2007. Comprehensive pictures of Arctic climate and Arctic physical processes are needed.

2. Previous global atmospheric reanalyses (NCEP/NCAR, ERA-15, NCEP-2, ERA-40, JRA-25) encounter many problems at high latitudes. The ASR would use the best available depiction of Arctic meteorological and climatological processes with improved temporal resolution and much higher spatial resolution.

3. The ASR would provide fields for which direct observation are sparse or problematic (precipitation, radiation, clouds, ...) at higher resolution than existing reanalyses.

4. The ASR would provide a convenient synthesis of field programs to observe the Arctic (SHEBA, LAII/ATLAS, ARM, FIRE, M-PACE, ...).
ASR Outline

A physically-consistent integration of Arctic data

Participants:
Ohio State University - Byrd Polar Research Center (BPRC)
- and Ohio Supercomputer Center (OSC)
National Center Atmospheric Research (NCAR)
University of Colorado
University of Illinois
University of Alaska Fairbanks

High resolution in space (~10 km) and time (3 hours)

Begin with years 2000-2010 (EOS coverage)

Supported by NSF as an IPY project
ASR Duty Roster

Polar WRF Model Development and Optimized Sea Ice Representation

OSU BPRC Polar Meteorology Group, PI

Mesoscale Atmospheric Data Assimilation

NCAR MMM (D. Barker + Y.-H. Kuo)

Land Surface Treatment and Data Assimilation

NCAR (F. Chen, developer of the Noah LSM)
University of Colorado (M. Serreze)

Data Ingest, Data Monitoring, and Quality Control

University of Illinois (J. Walsh) and U. Colorado Computing

Ohio Supercomputer Center
Arctic Regions Supercomputer Center?

Reanalysis Distribution to the Community

U. Illinois/ NOAA CDC?/ NCAR?
ASR High Resolution Domain

Outer Grid: 30 km resolution

Inner Grid: 10 km resolution

Vertical Grid: 71 levels

Inner Grid includes Arctic river basins
Weather Research and Forecasting Model (WRF)

Direct Interactions of Parameterizations

Clouds from resolvable storms
- Microphysics
  - Cloud effects
    - Cloud detrainment
  - Cumulus
    - Sub-grid scale clouds
      - Shallow Cu, downdrafts from deep Cu

Terrestrial infrared and solar shortwave
- Radiation
  - Surface fluxes
    - SH, LH
  - Downward
    - SW, LW
- Surface emission/albedo
- Surface
  - Soil, water, vegetation, snow and ice
Before Polar WRF: Polar MM5

1. Polar work began with Penn State/NCAR MM4

2. MM5 was also adapted for Arctic and Antarctic applications
   (1) Real-time forecasting/Operational uses
   (2) Synoptic meteorology studies
   (3) Regional Climate studies
   (4) Paleoclimate studies

3. Polar Optimizations to MM5 physics
   (1) Revised cloud / radiation interaction
   (2) Modified explicit ice phase microphysics
   (3) Optimized turbulence (boundary layer) parameterization
   (4) Implementation of a sea ice surface type
   (5) Improved treatment of heat transfer through snow/ice surfaces
   (6) Improved upper boundary treatment

4. Limited future support for MM5
Now there is Polar WRF

Polar Optimization:
Fractional sea ice (ice and water within the same grid box)
Sea ice albedo (specify to vary with time and latitude)
Morrison microphysics (2-moment)
Noah LSM modifications
Heat transfer for snow and ice
Surface energy balance
Testing of Polar WRF

1. **Permanent ice sheets**
   Start with Greenland (Follow Polar MM5 path)
   January 2002 (winter) and June 2001 (summer)
   Also Antarctic AMPS forecasts (NCAR MMM Division)
   Starting Antarctic climate simulations (Elad Shilo at BPRC)

2. **Polar pack ice**
   Use 1997/1998 Surface Heat Budget of the Arctic (SHEBA) observations on drifting sea ice
   Selected months: January, June, and August

3. **Arctic land**
   Soon to begin
Begin Polar WRF work with Greenland studies

North Atlantic Grid for Greenland Polar WRF Simulations

97 x 139
24 km spacing
28 vertical levels
Polar MM5 shows a deficit for incident longwave radiation.
Polar WRF is much improved and shows a small bias at Summit Greenland.

Both Polar MM5 and Polar WRF reasonably represent the diurnal cycle of incident shortwave radiation.
Summary of Greenland Simulations

- Following the path of development for Polar MM5, WRF has been optimized for polar applications beginning with Greenland domains.
- Polar WRF is at least as successful as Polar MM5 for simulations of the Greenland winter surface layer.
- Polar WRF simulations of the Greenland summer surface layer are comparable to those of Polar MM5 when verified with AWS observations, and surface energy balance for Polar WRF is better.
Test Polar WRF for Arctic Ocean/sea ice with selected SHEBA case studies (1997/1998)

SHEBA Location (from Perovich et al. 2007)
Noah LSM + MYJ PBL + Morrison et al. microphysics

Western Arctic Domain for Comparison with SHEBA observations

141 x 111 25 km spacing  28 levels
Temporal evolution of sea ice surface

Snow covered ice

Bare ice

Ponds

Snow, leads, bare ice constant – ponds always changing
Agreement between simulated and observed surface pressure demonstrates that Polar WRF is capturing the synoptic variability at Ice Station SHEBA during January 1998.

Similar results are seen for June and August 1998.
January Surface Temperature at Ice Station SHEBA

Correlation: 0.83
Bias: -2.20°C
RMSE: 4.29°C

June Surface Temperature at Ice Station SHEBA

Correlation: 0.38
Bias: 0.42°C
RMSE: 1.05°C

August Surface Temperature at Ice Station SHEBA

Correlation: 0.46
Bias: 0.20°C
RMSE: 1.15°C
Figure 9 10-m Wind speed (m s\(^{-1}\)) from observations and the Polar WRF simulation at Ice Station SHEBA for January, June and August 1998.
Polar WRF Summary/What is next?

- Polar WRF works well over the Greenland Ice Sheet
- Polar WRF captures the synoptic variability over the Arctic pack ice with small bias and high-frequency errors due to clouds.
- Test over Arctic land next to determine if there is a warm bias during winter.
  - Snow cover
  - Initial soil temperature and moisture
  - Stable boundary layer and topography
- Antarctic climate tests
- AMPS Antarctic real-time forecasts
Mesoscale Atmospheric Data Assimilation

Dale Barker
NCAR MMM
WRF-Var Observations for ASR

- **In-Situ:**
  - Surface (SYNOP, METAR, SHIP, BUOY).
  - Upper air (TEMP, PIBAL, AIREP, ACARS).

- **Remotely sensed retrievals:**
  - Atmospheric Motion Vectors (e.g. MODIS).
  - Ground-based GPS Total Precipitable Water.
  - SSM/I oceanic surface wind speed and TPW.
  - Scatterometer oceanic surface winds.
  - Wind Profiler.
  - Radar radial velocities and reflectivities.
  - Satellite temperature/humidities (e.g. TOVS, AIRS?).
  - GPS refractivity (e.g. COSMIC).

- **Radiance Assimilation:**
  - Microwave: AMSU, SSM/I, SSMI/S(?)
  - Infrared: HIRS, AIRS(?), IASI(?).
WRF-Var Radiance Assimilation Status

- BUFR 1b radiance ingest.
- RTM interface: RTTOV8.5 or CRTM
- NESDIS microwave surface emissivity model
- Range of monitoring diagnostics.
- Quality Control for HIRS, AMSU, AIRS, SSMI/S.
- Bias Correction (Adaptive, Variational in 2008)
- Variational observation error tuning
- Parallel: MPI
- Flexible design to easily add new satellite sensors
Testbed Configuration (from MMM/AMPS):

- **Model**: WRF-ARW, WRF-Var (version 2.2).
- **Namelists**: 60 km (165x217), 31 levels, 240 s timestep.
- **Period**: October 2006.
- **Suite**: NoDA, 3D-Var (6-hourly full cycling).
Land Component for Arctic System Reanalysis

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Research Applications Laboratory (RAL)
The Institute for Integrative and Multidisciplinary Earth Studies (TIIMES)
National Center for Atmospheric Research
Noah LSM includes

- Land ice (glacier)
- Sea ice
  - The above two will be treated by components in Polar-WRF.
- The routines in Noah to deal with these two processes will not be used for ASR
- Land-vegetation
- Land-bare soil
High-Resolution Land Data Assimilation System (HRLDAS) for ASR

- Blending atmospheric and land-surface observations and land surface model
- To provide land state variables for driving the coupled Polar WRF/Noah modeling system
  - Soil moisture (liquid and solid phase)
  - Soil temperature
  - Snow water equivalent and depth
  - Canopy water content
  - Vegetation characteristics
- To provide long-term evolution of the above variables plus surface hydrological cycle (runoff, evaporation) and energy cycle (surface heat flux, ground heat flux, upward long-wave radiation)
Satellite data - MODIS & AVHRR

- **fPAR/LAI**: MODIS 8-day, 1km, 2000-current
- **Albedo**: MODIS 8-day, 1km, 2000-current
- **Land Skin Temperature**: MODIS 8-day and daily, 1km and 6km, 2000-current
- **Green Vegetation Fraction**: MODIS-based, 1km, 16-day, 2000-current
- **Green Vegetation Fraction**: AVHRR, weekly, 0.144deg, 1982-2005
MODIS 1km Vegetation Data
June 18, 2002

MODIS fPAR 1 km

MODIS LAI 1 km
Summary of ASR Status

- ASR grew out of Antarctic NWP. Development of enhanced components are proceeding, and will soon be merged. Coupled atmosphere-land DA, but not atmosphere-ocean. Arctic ocean DA being done by others that offers the prospect of enhanced ocean conditions (e.g., sea ice thickness).

- WRF (and Noah LSM) physics are being optimized for polar applications beginning with Greenland and Arctic Ocean domains. Arctic land is next.

- Atmospheric data assimilation advances at NCAR. Start with 3DVAR, but transition to EnKF anticipated.

- HRLDAS will provide high-resolution land surface variables on the same grid as WRF-3DVAR.

- Timeline: Completion of 2000-2010 by 2011. Second phase is anticipated to cover 1985-present in a climate monitoring capacity with major NOAA participation likely.