Modeling the Arctic Climate System
General model types

• Single-column models: Processes in a single column
• Numerical Weather Prediction (NWP) models: Used for short-term weather forecasting and atmospheric “reanalyses”. NWP models employ data assimilation.
• Sea ice and ice-ocean models: Dynamic and thermodynamic interactions in the sea ice system
• Global Climate Models (GCMs): Used to understand global climate and climate change, these range atmospheric models (AGMs) with a “slab” ocean to fully coupled models (AOGCMs), coupling models of the atmosphere, ocean-ice, land surface and even the carbon cycle.
• Land Surface Models (LSMs): Interactions between the land surface, atmosphere and underlying surface. They are a components of NWP models and GCMs.
• Regional Climate Models: Applied to large or small regions, typically “nested” within GCMs
• Ecosystem models: Simulation of the functional and structural dynamics of ecosystems
Single column models
Time series (1 September 1998 to 31 December 2000) from a single-column active layer thickness model for model grid cells in (a) Siberia and (b) northern Canada. The top panels for each location show surface air temperature (including 31-day running mean), snow height $h_s$ (shaded) and snow density $\rho_s$ (thin dashed line). The middle panels show the depth of the thawed layer (shaded regions) and the development of thawing planes (solid line) and freezing planes (dashed lines). The bottom panels show the total thaw depth (with maximum values labeled). Also plotted on the middle and bottom panels by horizontal dash-dotted lines are the boundaries of the major soil layers at 0.3 and 0.8 m depth. Grid cell elevation $z$, latitude and longitude are also given [from Oelke et al., 2003, by permission of AGU].
Modeled depth of active layer (a) and the date of maximum thaw depth (b) for 1999 over the Arctic terrestrial drainage from the single-column active-layer thickness model. Areas with no permafrost in the drainage are indicated by dark grey shading [from Oelke et al., 2003, by permission of AGU].
Numerical weather prediction models
A NWP model is an atmospheric model used with data assimilation to forecast weather (out to 7 days or so), treating the forecast as an *initial value (or initial state)* problem.

The atmospheric model (whether it be a global or regional model) is based on a system of mathematical equations that describe the behavior of the atmosphere:

-- Newton's first law (principle of inertia) and second law \( F = ma \)
-- Ideal gas law (equation of state)
-- Conservation of energy, moisture and mass

The atmospheric variables are temperature, pressure, density, humidity and winds.

Forecasts are made by assimilating observations into a previous short-term forecast to get a 3-dimensional initial state of the atmosphere (known as an analysis), then running the atmospheric model forward from the initial state, then repeating to process:

1) At time \( t = 0 \), the 3-dimensional initial state of the atmosphere (the analysis) is constructed by assimilating observations into a previous forecast

2) A forecast out to (typically) 7 days or so (atmospheric circulation, precipitation, temperature, etc.) is obtained by repeatedly extrapolating time-derivatives; \( \Delta t \sim 10 \text{ min} \)

3) New data come in and are assimilated into another short-term forecast (e.g., a 12-hour forecast) to get a new initial state (analysis)

4) The model is then run forward from the new initial state (the new analysis) to get a new set of forecasts, and so on.
Numerical schemes and resolution

NWP models can be

1) grid-point models
2) spectral models
   -- variables represented as superpositions of waves
   -- shortest wavelength determines resolvable features

Model resolution is defined by the **horizontal** dimension of model grid cells (this can be determined by the number of waves in a spectral model) and by the **vertical** distance between levels (usually variable)
Global grid: Spectral T42 resolution (about 2.8° latitude-longitude). By modern standards, this is quite coarse.

Courtesy NCAR
60 vertical levels of the North American Model (NAM)
Data assimilation: The basics

The goal is to get the best 3-dimensional initial state of the atmosphere (an analysis) by assimilating data into the atmospheric state from a precious short-term forecast (e.g., 12 hours), from which the model is then run forward. Assimilation data include:

- Radiosonde profiles of temperature, humidity and winds
- Satellite retrievals of temperature, humidity and winds
  - Aircraft reports
  - Surface pressure

Surface data may also be assimilated.
NWP: The data assimilation process

1A. Short-range forecast

1B. Observations

Data Assimilation Process

- Raw data checks
- Observation increments
- Quality control (on increment)
- Objective analysis procedure
- Analysis increments or "corrections"

2. Observation increments

3. Analysis increments or "corrections"

4. Analysis

Cycling

Next short-range "guess"

Forecast model

Remainder of full-length forecast (Eta to 60 or 84 hours, AVN to 126 hours, etc.)

Red = Ob. to follow
Blue = RAOB
Purple = Aircraft
Gray shading = Wind Speed (5 kt inc.)

Schlatter / NOAA
The global radiosonde network. Radiosonde profiles (temperature, humidity, winds) are only one of many types of data assimilated in modern NWP systems. The radiosonde network in the high Arctic and much of the global ocean is fairly sparse. Satellite data are very important in these regions.

https://www.meted.ucar.edu/index.php
These drifting buoys provide data on surface pressure and air temperature that can be assimilated into NWP systems. The buoy program has been in operation since 1979.

http://iabp.apl.washington.edu/
Examples of analyses from a numerical weather prediction model, blending gridded fields from a short-term forecasts with observations. Left: Field of 500 hPa height for the Northern Hemisphere; Right: corresponding field of sea level pressure.
Example of forecasts: Precipitation

Observed precipitation
(actual example)

Model forecast – 33 km resolution

Model forecast – 81 km resolution

Courtesy of NOAA/NCEP
Practicalities of NWP models

• Sea surface temperatures, sea ice concentration and snow cover are not assimilated but are rather prescribed from observations (one generally plugs in fields derived from satellite or a combination of data from satellites and surface observations)

• The land surface simply parameterized (reflection absorption and conduction)

⇒ Forecast skill decays to near zero by 7-10 days
Atmospheric reanalysis

NWP systems are always evolving and being tweaked. Reanalysis provides more temporally consistent time series of analyses and forecast (such as of precipitation) by assimilating historical times series of observation into a “fixed” NWP system. Reanlyses are important tools of climate research.

Major reanalysis efforts

- **NCEP/NCAR**: The “original” from the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research, updated daily, still used but becoming obsolete (1958-present)
- **ERA-15**: First effort from the European Centre for Medium Range Weather Forecasts (ECMWF) (1979-1993)
- **ERA-40**: The next generation from ECMWF, generally better than NCEP/NCAR but it only covers the period 1957-2002
- **ERA-Interim**: The latest and greatest from ECMWF, 1979-present
- **MERRA**: Modern Era Retrospective Analysis for Research and Applications – a new reanalysis from NASA, 1979-present
- **NCEP CFSRR**: The Climate Forecast System Reanalysis is the latest from NCEP (1979-present)
- **ASR**: The Arctic System Reanalysis (in development), a reanalysis based on the Weather Research and Forecasting (WRF) regional model
Sea ice and ice-ocean models
Some key features

• Model complexity and the degree of coupling between the ocean ice and atmosphere ranges widely. Ice and ice-ocean models are variously run in “standalone” mode, driven by fields from an atmospheric reanalysis (winds, temperature, other fields depending on model complexity) or are part of fully coupled global climate models.

• Salinity replaces humidity as key variable (key variables are salinity, pressure, temperature and velocity)

• Continents limit the model domain

• Ocean model resolution in generally finer than for NWP models because ocean eddies have smaller scales than in atmosphere. Ocean models range from eddy-resolving (< 10 km) to eddy-permitting (~10 km) to no eddies.
Simulated mean ice velocity and mean annual sea level pressure from an ice-ocean model run in standalone mode (driven by inputs from an atmospheric reanalysis) for (a) 1979-1988; (b) 1989-1996; anomaly fields of ice velocity based on the difference (c) between the 1979-1988 mean and the 1979-1996 mean and (d) between the 1989-1996 mean and the 1979-1996 mean. Contours of sea level pressure are given at every 1 hPa [from Zhang et al., 2000, by permission of AMS]. Results document the differences in sea ice circulation between periods dominated by negative and positive phases of the NAO. When the NAO is negative (positive) the ice circulation anomaly is anticyclonic (cyclonic).
Results from the same model of simulated mean ice thickness for (a) 1979-1988 and (b) 1989-1996 and (c) their difference field (b-a). The contour interval is 0.5 m [from Zhang et al., 2000, by permission of AMS]. The difference field indicates that when the NAO was in a primarily positive phase (1989-1996), ice was thinner in the eastern Arctic (Siberian side) and thicker in the western Arctic (North American side).
U.S. Navy Polar Ice Prediction System (PIPS) sea ice concentration simulation. PIPS is run operationally by the Fleet Numerical Meteorology and Oceanography Center (FNMOC)

http://www.oc.nps.edu/~pips3/anim/ice_anim.html
U.S. Navy Polar Ice Prediction System (PIPS) sea ice thickness simulation. PIPS is run operationally by the Fleet Numerical Meteorology and Oceanography Center (FNMOC).
Simulated Arctic Ocean temperatures and velocities with a high-resolution (1/12°) ocean model (from Clement et al., 2007). The figure shows the depth-averaged (66-120 m) temperature difference compared to freezing along with velocity for April 2001. Note the fine-scale features of the circulation.
Daily snapshot of sea ice divergence and convergence from the 9-km resolution Los Alamos National Laboratories CICE model. Ice deformation must be accounted for in a model to properly simulate the effects of leads on winter air-sea energy exchange. CICE is designed to be a component of global climate models, although it can also be used in standalone mode for sea ice simulations such as in the above example.

http://climate.lanl.gov/Models/CICE/
The PIOMAS (Pan-Arctic Ice Ocean Modeling and Assimilation System) is a coupled ice-ocean model with the capacity for assimilating observations. For the ice volume hindcast simulations shown here, satellite-derived sea ice concentration data are assimilated into the model to improve ice thickness estimates. Atmospheric information to drive the model, specifically wind, surface air temperature, and cloud cover to compute solar and long wave radiation are specified from the NCEP/NCAR reanalysis. PIOMAS is forced with input from a global ocean model at its open boundaries. Results from PIOMAS indicate a pronounced downward trend in normalized ice volume (area x thickness).

http://psc.apl.washington.edu/wordpress/research/projects/arctic-sea-ice-volume-anomaly/
Global climate models
Global Climate Models (GCMs)

CGMs are of varying complexity, ranging from atmospheric models (AGCMs) with a “slab” ocean to fully coupled “earth system” models in which the atmosphere, ocean, land, vegetation and carbon cycles are fully interactive.

Simulations span decades to centuries rather than days as is the case with NWP models (to examine past, present and future climate states).

While specification of initial atmospheric conditions is key to getting a good weather forecast from an NWP model, the initial atmosphere state in GCMs is irrelevant (one is simulating climate, not weather). One can think of an AGCM as essentially a global NWP model run without data assimilation (although NWP models do not even have a slab ocean – sea surface temperature is simply specified)

Resolution is generally coarser than for NWP models
Schematic for Global Atmospheric Model

Horizontal Grid (Latitude-Longitude)

Vertical Grid (Height or Pressure)
The evolution of GCM complexity

Courtesy IPCC
State-of-the-art GCM: Sea surface salinity simulations

http://www.gfdl.noaa.gov/video/cm24sss.mov
Projected changes in winter (DJF) and summer (JJA) surface air temperature, precipitation and sea level pressure for the period 2080-2099, relative to 1980-1999 from an average of coupled global climate models participating in the IPCC-AR4. Results are based on the A1B emissions scenario (Source: IPCC 2007). While temperatures are expected to rise strongly in the Arctic, and precipitation will increase (but decrease on other areas), there will also be changes in patterns of atmospheric circulation. How credible are these projections? Looking as how well global models simulate the present-day climate provides some insight.
Surface air temperature biases (winter) of IPCC AR-4 models for present-day climate compared to observations (courtesy J. Walsh, Univ. IL Urbana Champaign). Biases can be quite large, reflecting, among other things, model-to-model scatter in patterns of atmospheric circulation, atmospheric heat transport, cloud cover and sea ice extent. These biases bear on interpretation of projected future conditions.
Ability of the IPCC-AR4 GCMs to capture major modes of atmospheric variability

From Stoner et al., 2009, J. Climate
The observed sea ice thickness distribution has the thickest ice north of the Canadian Arctic Archipelago and the thinnest ice along the Eurasian side of the Arctic Ocean. This pattern reflects the mean circulation of the atmosphere and upper ocean.

Key issue: if a GCM can’t get the mean atmospheric circulation of the Arctic correct, it won’t be able to get the correct thickness pattern, which will have cascading effects on other climate elements, such as the surface energy budget.
Ice thicknesses from sea ice models forced by AGCM winds, temperatures: if surface winds are off, ice thicknesses are off

(from Bitz et al., 2002)
End-of-summer sea ice extent is declining at a faster rate than expected from CMIP-3 climate model hindcasts (models participating in the IPCC AR-4 models). Why this is the case is still not entirely clear. CMIP-5 models seem to perform somewhat better.

From Stroeve et al., 2012
Present-day Arctic sea ice coverage (annual means and seasonal cycle) as simulated by the IPCC AR-4 models compared to observations (HadISST). There are some large biases compared to observations, which must be considered when interpreting simulated future conditions. (from Zhang and Walsh, 2006)
Land surface models (LSMs)
The community land model (CLM) is designed for use within the NCAR Community Climate System Model (CCSM) GCM, but is often used in standalone mode. The biogeophysics component addresses exchanges of energy, water, and momentum with the atmosphere. It concerns aspects of micrometeorology, canopy physiology, soil physics, radiative transfer, and hydrology. The hydrologic component addresses interception of water by plant foliage and wood, throughfall and stemflow, infiltration, runoff, soil water, and snow. These are directly linked to the biogeophysics and also affect temperature, precipitation, and runoff. Runoff (both surface and sub-surface) is routed downstream using a river routing model. A river transport model is coupled to CLM for hydrological applications as well as for improved land-ocean-sea ice-atmosphere coupling in CCSM. CLM also has biogeochemistry and dynamic vegetation components. Dynamic vegetation means that vegetation is not static, but can change.

http://www.cgd.ucar.edu/tss/clm/
Community Land Model subgrid structure

Land units:
- Glacier
- Wetland
- Vegetated
- Lake
- Urban

Columns:

Soil Type 1

PFTs:
- C3 Arctic Grass
- C3 non-Arctic Grass
- C4 Grass
- Crop

Plant Functional Types:
0. Bare

Tree:
1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

Herbaceous / Understorey:
9. Broadleaf Evergreen Shrub, Temperate
10. Broadleaf Deciduous Shrub, Temperate
11. Broadleaf Deciduous Shrub, Boreal
12. Crop

Lawrence et al., JGR, 2007
Soil thermodynamics: an important issue bearing on active layer depth and permafrost degradation that LSMs such as CLM can address.

Solve the heat diffusion equation for 15-layer soil and snow model:

\[
C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial T}{\partial z} \right)
\]

where \( C_p \) (heat capacity) and \( K \) (thermal conductivity) are functions of:

- temperature
- total soil moisture
- soil texture
- ice/liquid fractions

Courtesy J. Walsh, Univ. IL Urbana Champaign
Siberia (65°-70°N, 110°-120°E) soil simulation with CLM

No Soil Carbon

Soil Carbon

Porosity

Sat Hydraulic Cond

Volumetric Soil Water

Soil Temp

Thermal Conductivity

Soil Carbon

Porosity

Sat Hydraulic Cond

Volumetric Soil Water

Courtesy J. Walsh, Univ. IL Urbana Champaign
Mean annual evapotranspiration over the Arctic terrestrial drainage from five different LSMs driven with data from the ERA-40 reanalysis over the period 1980-2001. While each model shows the same basic spatial pattern, there are large differences in magnitude.

Compiled by D. Slater, NSIDC
The Torne-Kalix river system modeled under the PILPS 2e project and location of observation stations [from Bowling et al., 2003, by permission of Elsevier]. PILPS 2e was a model intercomparison project, comparing output from 21 different LSMs, each driven with the same data inputs.
Basin averaged snow water equivalent (SWE) for March (approximately the month of the annual maximum) for the Torne-Kalix watershed from the 21 PILPS 2e land surface models (listed as a–u) over the period 1989-1998 [from Bowling et al., 2003, by permission of Elsevier]. There is large scatter in depicted SWE between the different models. Models with a high latent heat flux and downward sensible heat flux (energy source to the surface) tend to have the lowest snow accumulation.
Total basin mean annual surface and subsurface runoff for the Torne-Kalix watershed from the 21 PILPS 2e land surface models (listed as a-u) over the period 1989-1998. The dashed horizontal line is the observed mean annual runoff at the mouths of the Torne and Kalix rivers combined [from Bowling et al., 2003, by permission of Elsevier]. For some models, subsurface runoff dominates, while for others, runoff is solely from the surface.
Regional models
In a typical application, a regional climate model (RCM) is nested within a GCM. The RCM is driven at its boundaries by GCM data, and generates its own climate within. The advantage is that the RCM can be run at high resolution, resolving features that would not be resolvable in a GCM. The use of a nested RCM is a form of “downscaling”. RCMs can be quite robust, with coupled atmospheric, land surface and ocean models. RCMs can also be nested within global NWP models like the NCEP/NCAR reanalysis.
In ten years, GCMs are likely to have resolutions comparable to the current generation of RCMs. RCM resolutions will also increase. Figure courtesy J. Walsh, Univ. IL Urbana Champaign.
Average September ice concentration from five sensitivity experiments using the ARCSyM regional climate model addressing development of the large negative sea ice extent anomaly observed for September 1990 [from Lynch et al., 2001a, by permission of AGU]. Ice concentrations in the control run are very similar to those in the NOLHF run (meaning that the extra moisture source from open water had little effect). Proper simulation of the anomaly requires proper initial ice thickness (PRECON experiment), ice dynamics (NODYN experiment) and albedo feedback (NOALB experiment) See text book for details of the different experiments.
Time series of 24-48 hour Polar MM5 forecasts (thick solid lines) and corresponding AWS observations from the Summit site on central Greenland (thin solid lines) for April and May, 1997. Time series are shown of surface pressure, near surface temperature, wind speed, wind direction and mixing ratio. Surface pressure in MM5 is interpolated from the height of the model grid point elevation to the height of the AWS station. The model wind speed is interpolated from the lowest model level to the height of the AWS station. The remaining modeled variables are given as the value of the lowest model level [from Bromwich et al., 2001, by permission of AMS]. The overall conclusion: MM5 generally performs well.
Application of the Modèle Atmosphérique Régional (MAR) to assess the record surface melt observed over the Greenland Ice Sheet in 2010. Panel (a) shows MODIS albedo anomalies for 2010, relative to 2004–2009 means for May–August. Panel (b) depicts MAR estimated standardized anomalies (relative to 1979–2009) of the number of days with bare ice exposed for the period May–September. Panel (c) shows May–September snowfall anomalies from MAR, relative to 1979–2009 means.
Ecosystem models
In (a), TEM includes (1) the environmental module, (2) the dynamic soil layer module (DSL), (3) the ecological module, and (4) the fire disturbance module. In (b), the dynamic soil layer module includes explicit simulation of soil carbon vertical distribution and change of the thicknesses of organic layers based on the soil carbon content. The thickness of the soil organic layer may change due to ecological processes or fire disturbance. Note that this module includes the explicit representation of permafrost dynamics. In (c), the ecological module of TEM includes a dynamic vegetation model (TEM-DVM) with multiple vegetation pools, including the leaf (L), wood (W) and root (R) pools. The example in (c) shows three plant functional types (PFTs) in a given ecosystem, although the number of PFTs in an ecosystem may be either more or less in model applications. The arrows with ‘light’ and ‘N’ between the PFTs illustrate that competition occurs between the PFTs. \( R_H \) = heterotrophic respiration; \( GPP \) = gross primary productivity; \( R_A \) = autotrophic respiration; \( C_V \) = carbon in living vegetation; \( L_C \) = litterfall carbon; \( N_V \) = nitrogen in living vegetation; \( N_{VS} \) = structural nitrogen in living vegetation; \( N_{RESORB} \) = nitrogen resorption; \( N_{MOBIL} \) = mobile nitrogen; \( N_{UPTAKE} \) = nitrogen uptake by the vegetation; \( C_S \) = soil carbon; \( N_S \) = soil nitrogen; \( NETNMIN \) = net nitrogen mineralization; \( N_{AV} \) = available nitrogen; \( N_{LOST} \) = nitrogen lost from the ecosystem.

Conceptual diagram of the Terrestrial Ecosystem Model (TEM) used to examine terrestrial Arctic ecosystem feedbacks.

http://www.sel.uaf.edu/projects/feedbacks.php
Historical and projected changes in (a) Net Primary Production (NPP), (b) heterotrophic respiration (HR), and (c) Net Ecosystem Production (NEP) for the entire Arctic tundra area (solid line) and the Kuparuk Basin (dotted line) as simulated by the Terrestrial Ecosystem Model (TEM) during the historical period (1921-1994) and projected period (1995-2100). The shading represents the standard deviation in carbon fluxes simulated by TEM across the entire tundra [from McGuire et al., 2000, by permission of Blackwell Publishing]. In this simulation, carbon storage in the tundra increases over the projection period (as seen in the time series of NEP). What will really happen is a matter of debate – many scientists think that thawing of permafrost will lead to a net release of carbon to the atmosphere.