Regional Climate Modeling

A Land Surface Modeling Perspective

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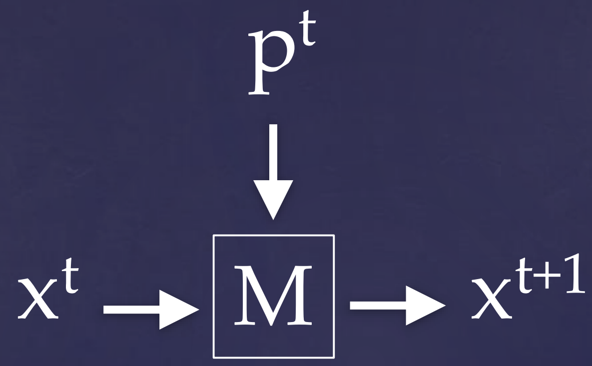
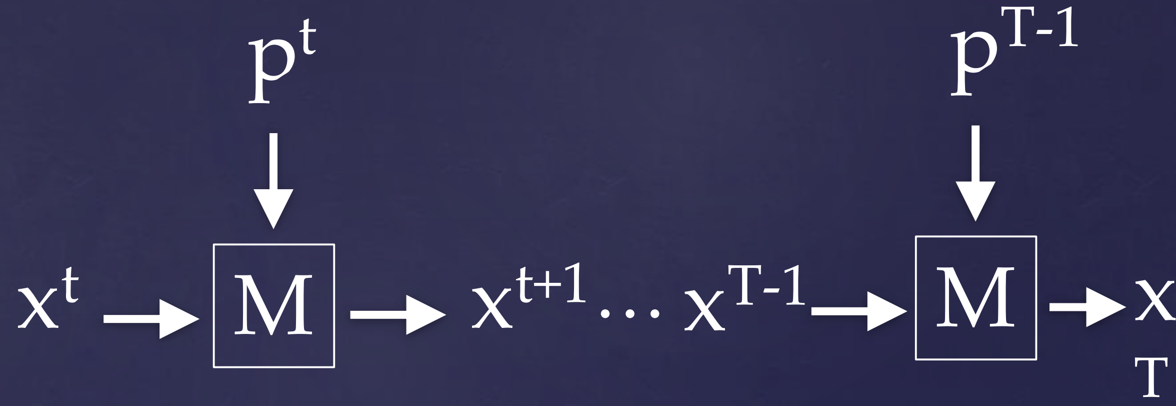
The *Model*



x^t : state variables at time t (e.g., temperature)
p^t : parameters/forcing at time t (e.g., leaf refl.)
M : the model
x^{t+1} : state variables at time t+1

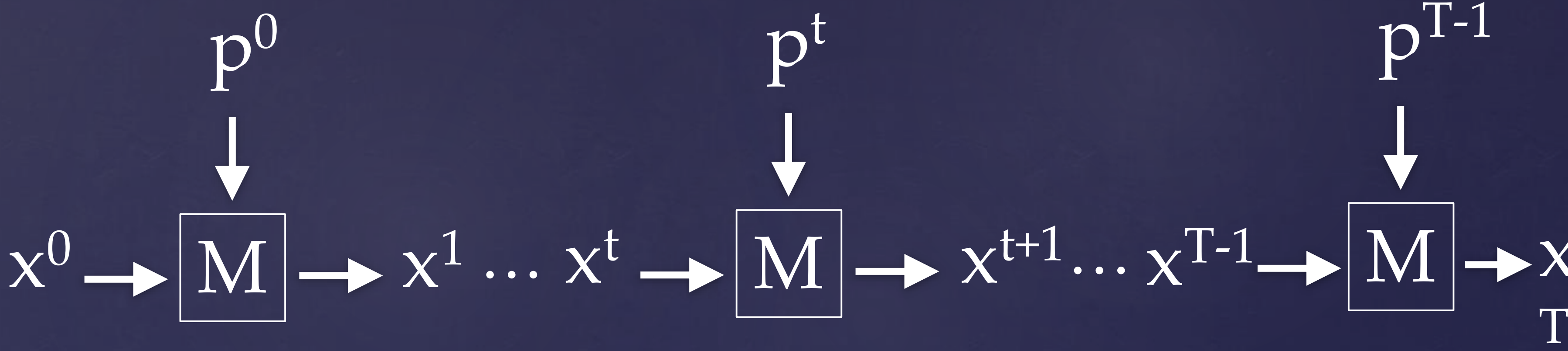
The *Model*



x^T : state variables at final time T

p^{T-1} : parameters/forcing at time T-1

The *Model*



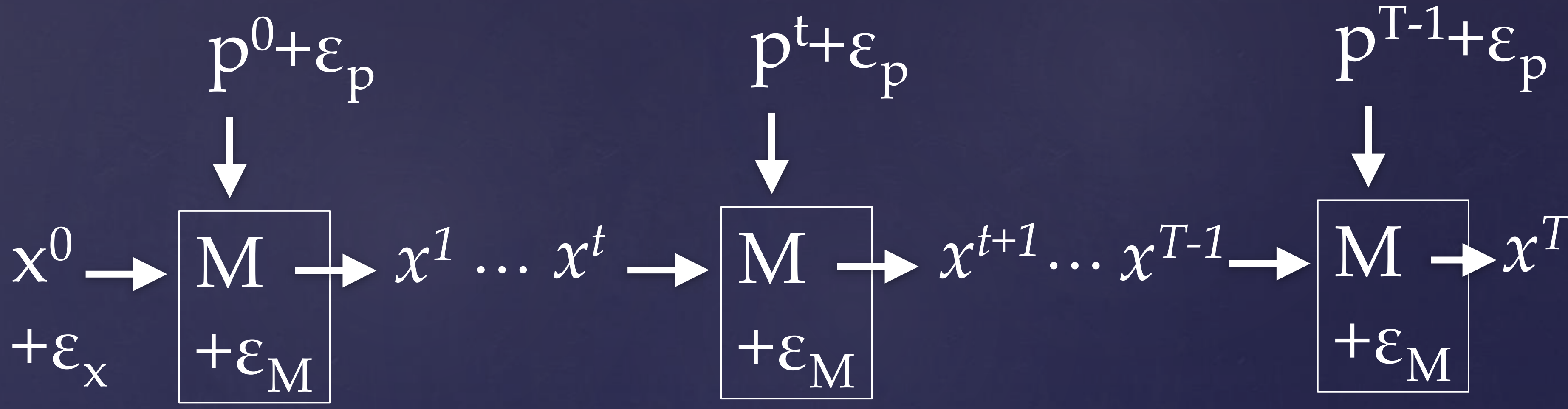
x^0 : state variables at initial time

p^0 : parameters/forcing at initial time

M : the model

x^1 : state variables at time 1

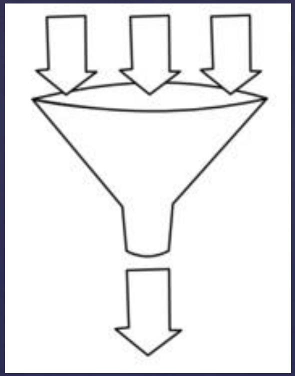
The *Model* with uncertainty



ε_x : initial state uncertainty
ε_M : model uncertainty
ε_p : parameter/forcing uncertainty
x^t : state variables with accumulated uncertainty

The Earth System Model

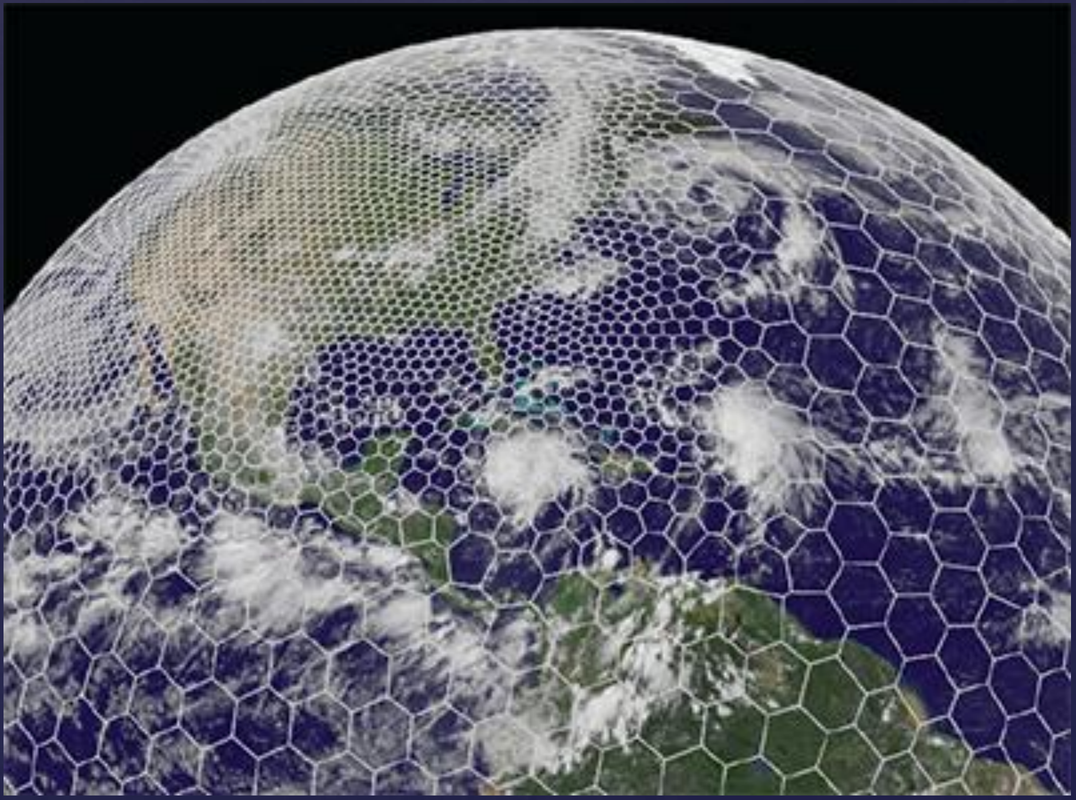
$$
\begin{aligned}
\partial_t U + (\nabla \cdot \mathbf{V} u)_\eta + \mu_d \alpha \partial_x p + (\alpha / \alpha_d) \partial_\eta p \partial_x \phi &= F_U \\
\partial_t V + (\nabla \cdot \mathbf{V} v)_\eta + \mu_d \alpha \partial_y p + (\alpha / \alpha_d) \partial_\eta p \partial_y \phi &= F_V \\
\partial_t W + (\nabla \cdot \mathbf{V} w)_\eta - g[(\alpha / \alpha_d) \partial_\eta p - \mu_d] &= F_W \\
\partial_t \Theta + (\nabla \cdot \mathbf{V} \theta)_\eta &= F_\Theta \\
\partial_t \mu_d + (\nabla \cdot \mathbf{V})_\eta &= 0 \\
\partial_t \phi + \mu_d^{-1} [(\mathbf{V} \cdot \nabla \phi)_\eta - gW] &= 0 \\
\partial_t Q_m + (\mathbf{V} \cdot \nabla q_m)_\eta &= F_{Q_m}
\end{aligned}
$$



M

Model Flavors

- Operational models typically come in two sizes:
  - global (NCAR CESM; NOAA GFS/CFS; ECMWF; etc.)
- Relatively low spatial resolution (~25 - 50km)
- Used to predict climate (seasonal to decadal) and medium range weather (~10days)

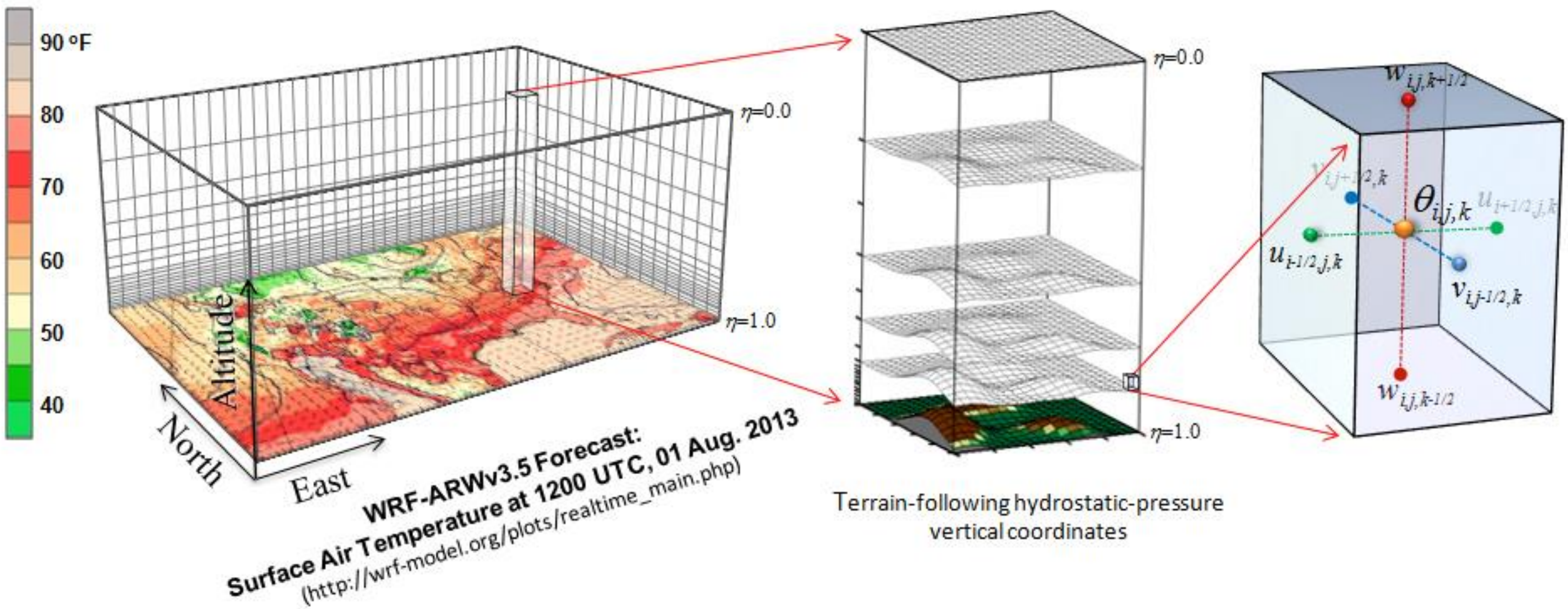


NCAR MPAS model using stretched grid

Model Flavors

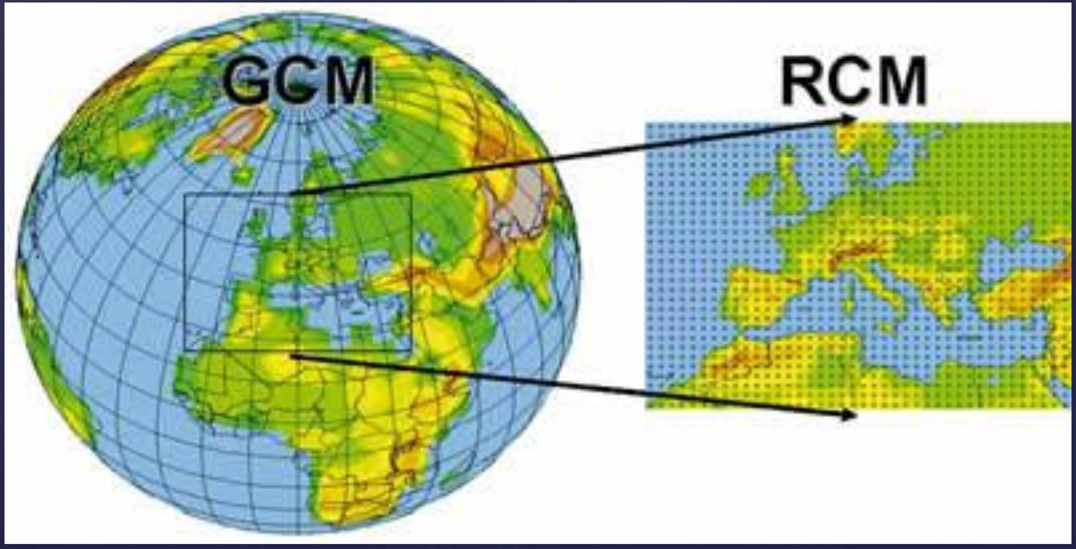
Operational models typically come in two sizes:
regional (NCAR WRF; NOAA NAM/RUC/HRRR)
Relatively high spatial resolution (~1km)
Used to predict weather and "downscale" climate models

NCAR WRF model



Global vs. Regional

- Global models have no lateral boundaries – they stretch around the planet
- Regional or limited-area models are spatial subsets of the planet – the easiest method for execution is to embed them in global models
- Why do regional climate modeling?
  - Increased spatial and temporal scales, output products



Dynamical vs. Statistical

- Dynamical models: physics-based models that may or may not have components inspired by statistics
- Statistical models: statistics-based models that may or may not be inspired by physics

$$
\begin{aligned}
\partial_t U + (\nabla \cdot \mathbf{V} u)_\eta + \mu_d \alpha \partial_x p + (\alpha/\alpha_d)\partial_\eta p \partial_x \phi &= F_U \\
\partial_t V + (\nabla \cdot \mathbf{V} v)_\eta + \mu_d \alpha \partial_y p + (\alpha/\alpha_d)\partial_\eta p \partial_y \phi &= F_V \\
\partial_t W + (\nabla \cdot \mathbf{V} w)_\eta - g[(\alpha/\alpha_d)\partial_\eta p - \mu_d] &= F_W \\
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\partial_t \mu_d + (\nabla \cdot \mathbf{V})_\eta &= 0 \\
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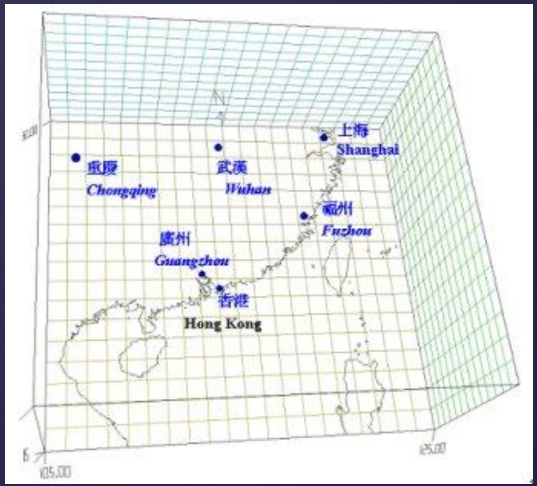
\partial_t Q_m + (\mathbf{V} \cdot \nabla q_m)_\eta &= F_{Q_m}
\end{aligned}
$$

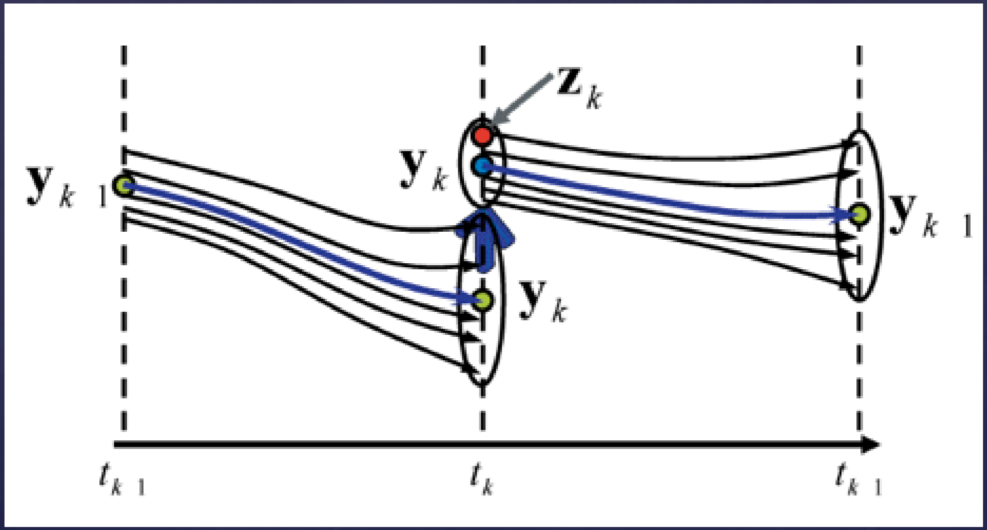
$\longrightarrow$

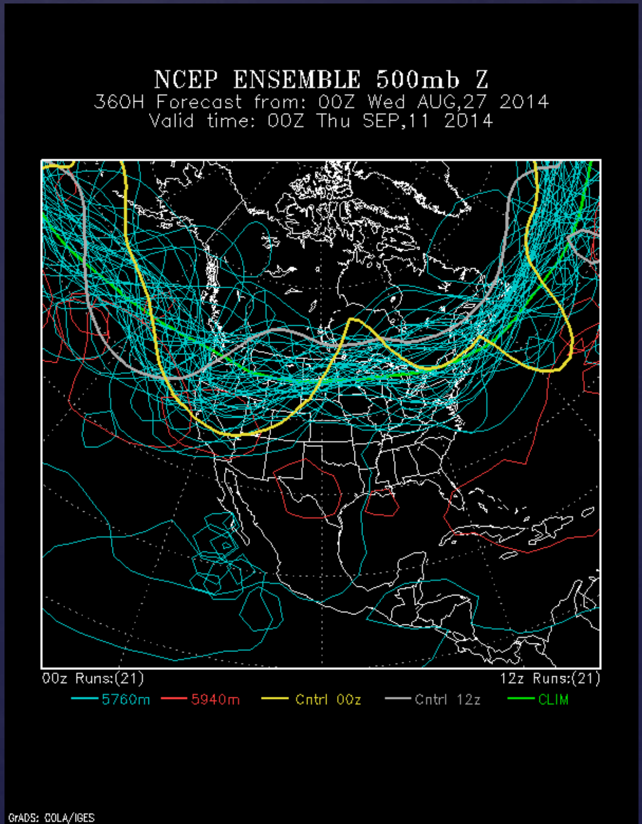


When physics-based models fail, it is not the fault of the physics, but the application of the physics or the statistics

Ensemble Models

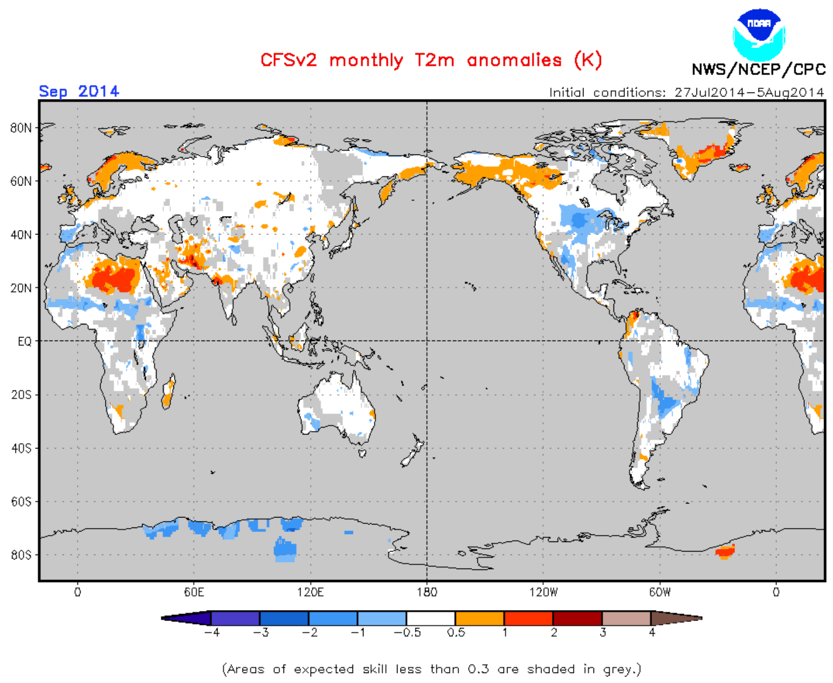
- Model results spread due to initialization, parameter and model uncertainty
- Done by many operational centers to create probability forecasts

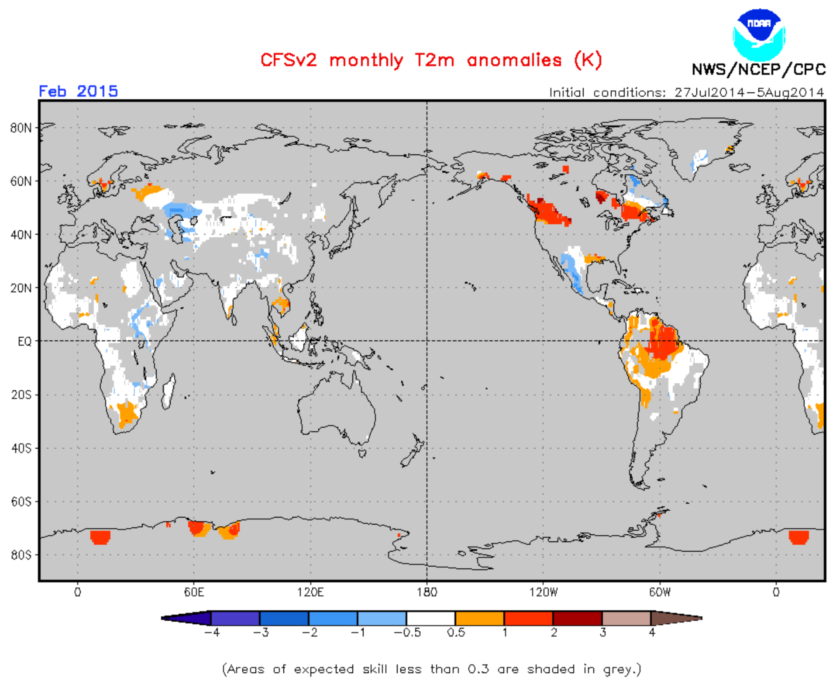




Ensemble Models

- Operation Climate Forecast System at NCEP uses a staggered initialization to produce an ensemble forecast (10-day lags)
- Shading implies lack of skill in the forecast



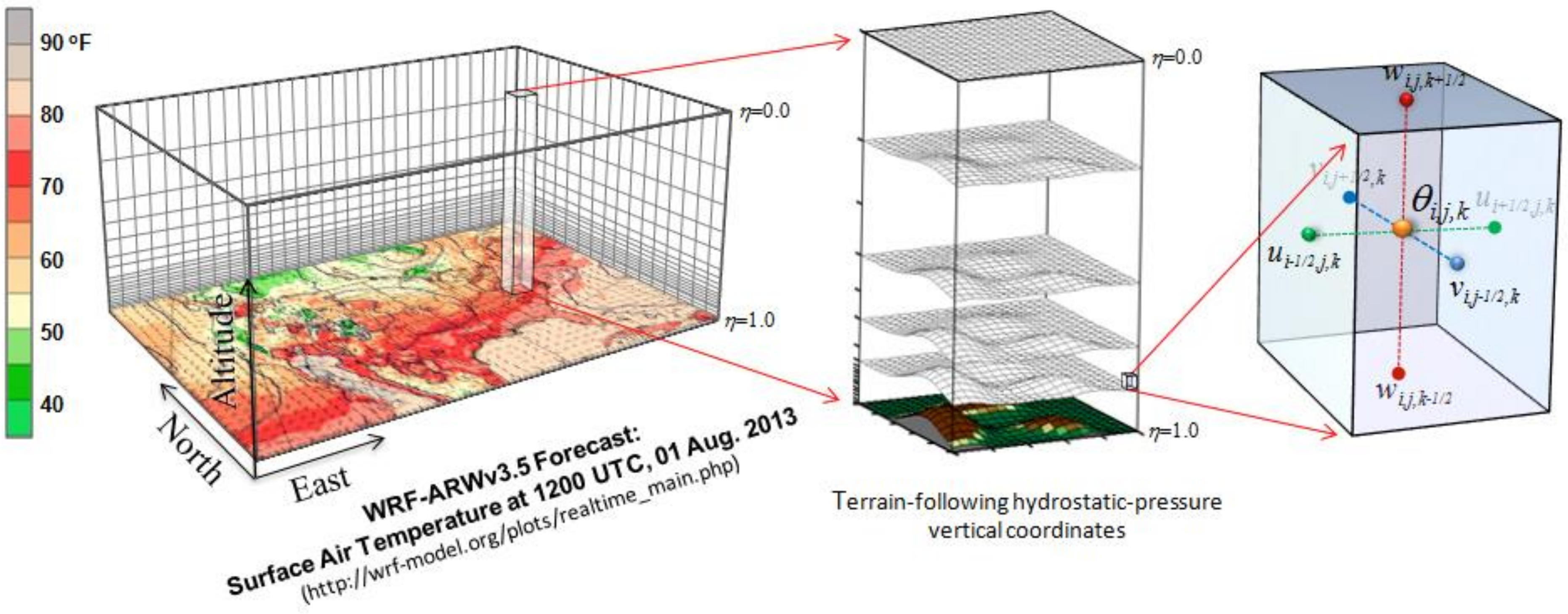


The Model Grid: Why a grid?

$$\frac{dT}{dz} = \frac{T(z_2) - T(z_1)}{z_2 - z_1}$$

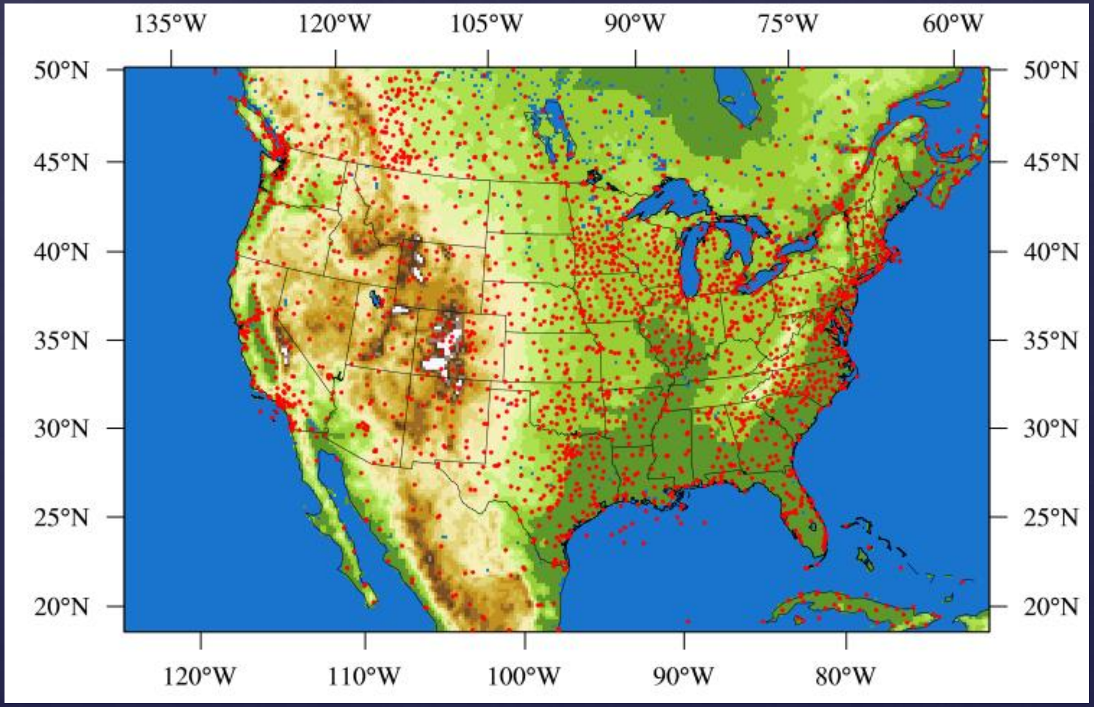
Discretization of the equations that solve for the future
Challenge: initialization

NCAR WRF model



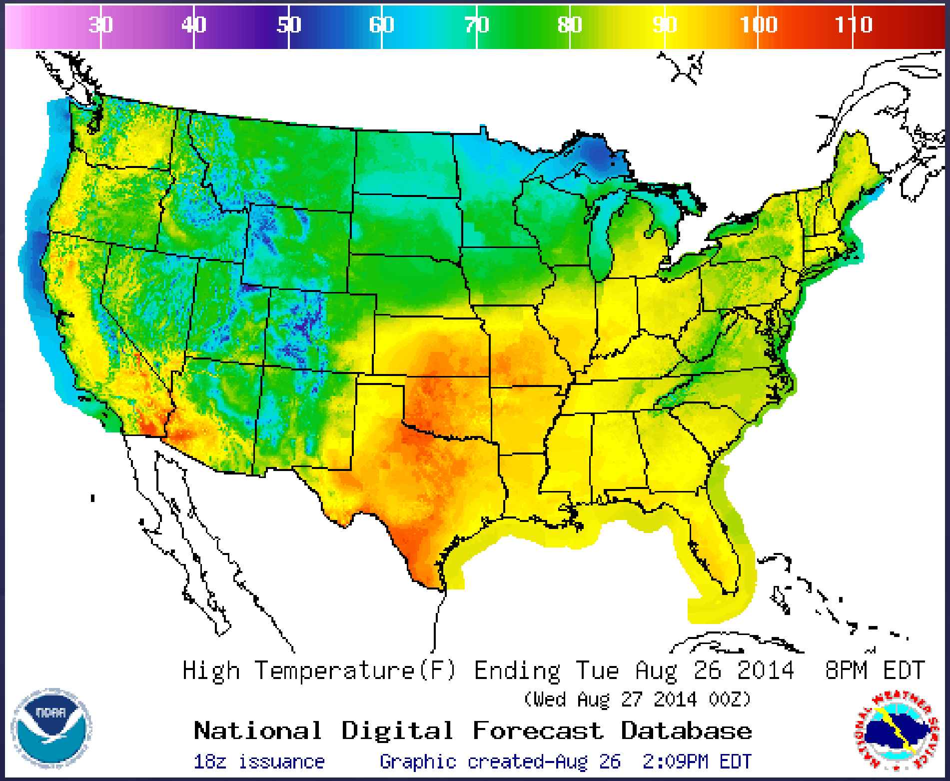
Initialization Uncertainty

- Initialization is usually done with
  - Observations
  - Previous model output
  - A blending of observations and model output
- Here is an example of surface reporting stations



Initialization Uncertainty

- Initialization is usually done with
  - Observations
  - Previous model output
  - A blending of observations and model output
- Here is an example of near-surface temperature



Where is the most variation?

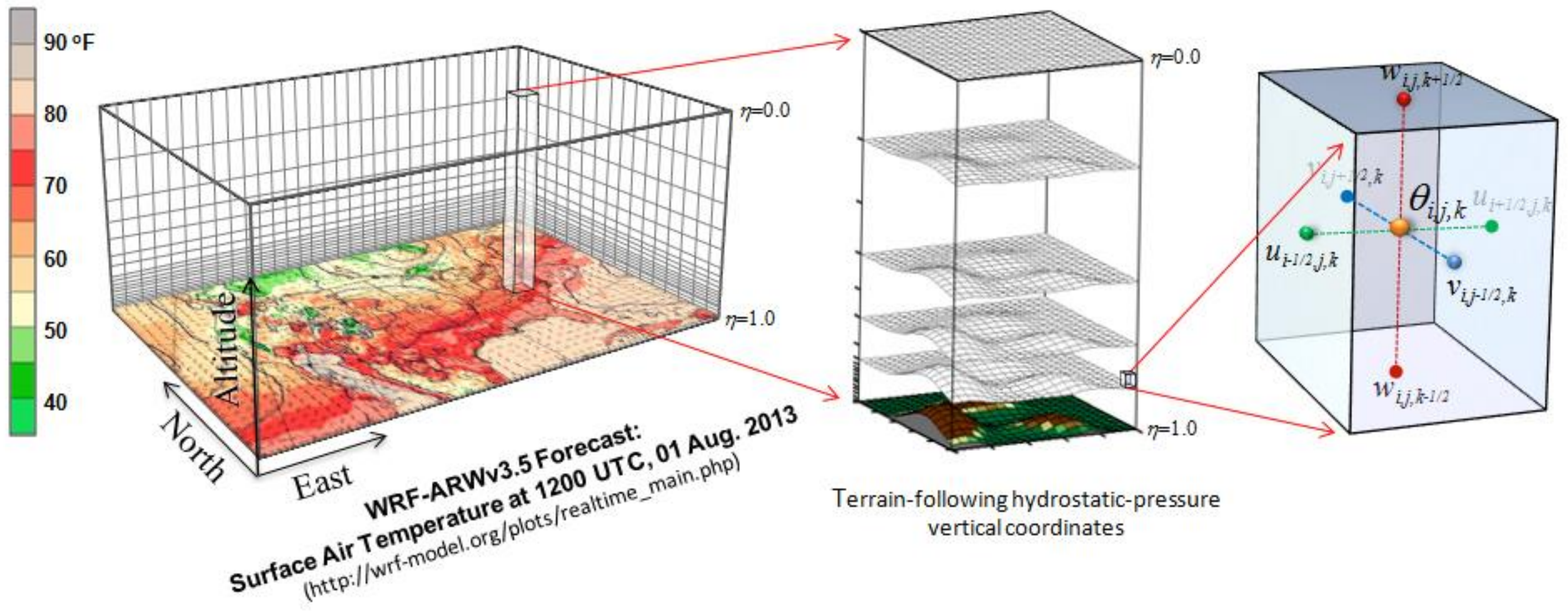
Initialization Uncertainty

- Initialization is usually done with
  - Observations
  - Previous model output
  - A blending of observations and model output
- Here is an example of atmospheric temperature locations

How to fill the gaps?

Sides of the Box

- Energy, mass, and water flow through the sides of the box and one must provide this information to the model running inside the box
- Typically, a global model or a larger-area regional model is used to supply this information across the lateral boundaries



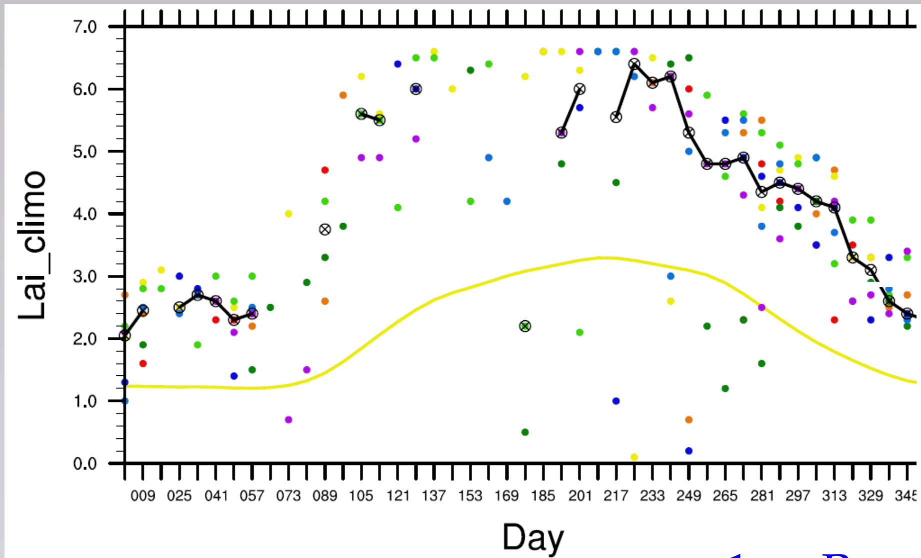
Parameterization

- What about the sub-grid scale?
- This is where one must use (physically-based) statistical relations to "parameterize" what is happening.
- What is parameterized?
  - Clouds – Microphysics – Precipitation
  - Convection
  - Radiation
  - Boundary Layer
  - Land Surface – plants, soil, snow
- The land surface in important for forecasts of all time scales. Why?
  - Memory – significant sources exist in soil (water and energy), snow and vegetation

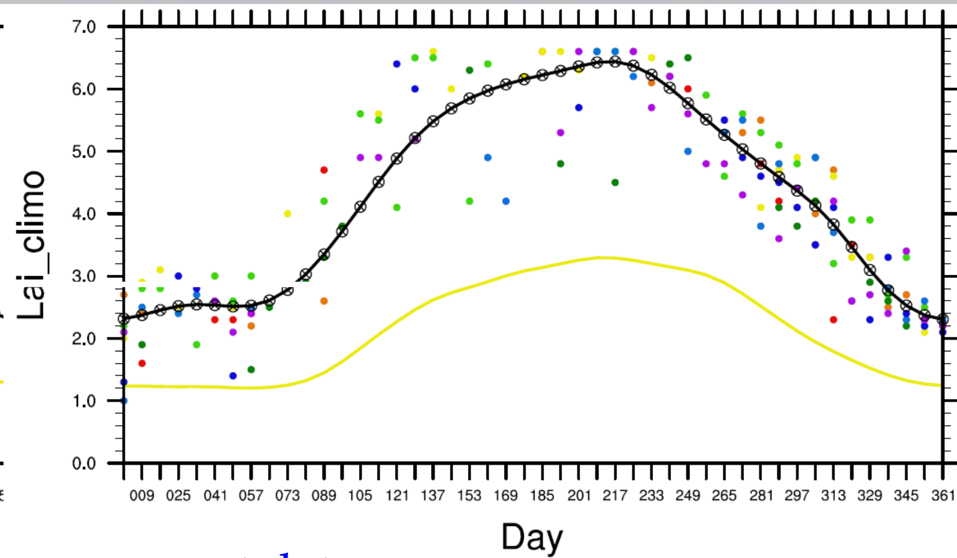
Challenge: parameter specification

Parameter Uncertainty: Vegetation

Original Pixel Data



Final Smooth Climatology



1. Remove suspect data
2. Fill missing data
3. Smooth

Marks

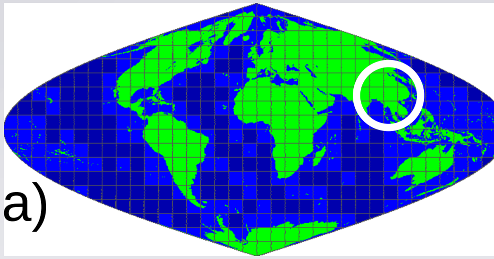
– Individual value of year

2001 2002 2003 2004 2005 2006 2007 2008

Lines

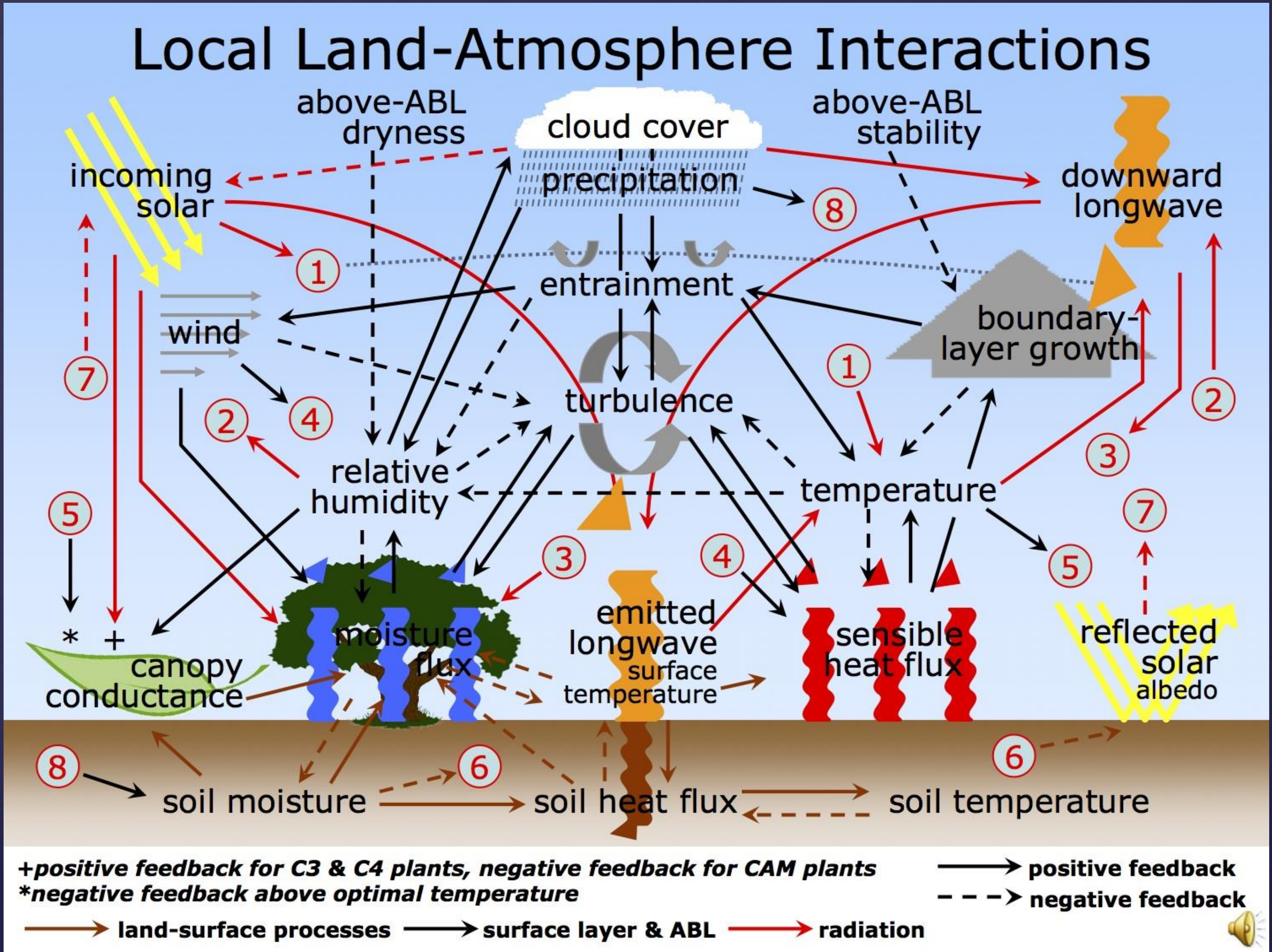
– black: median

– yellow: tile climo (Savanna)



The Bottom Boundary

- Where it all happens (land modeler's perspective)



Courtesy Mike Ek (NOAA)

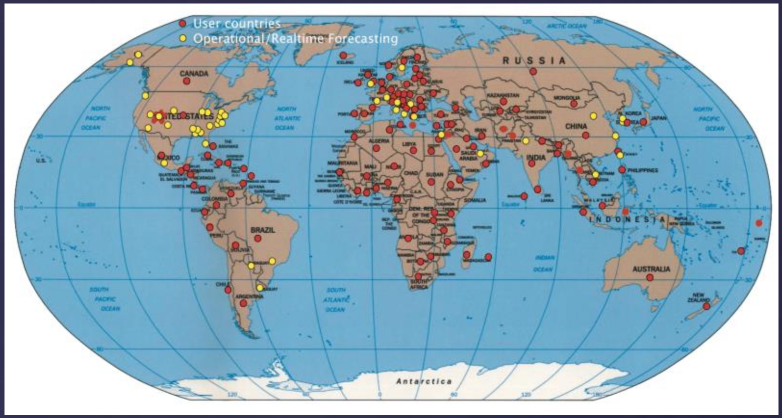
Parameterization

- Land surface modeling is moving beyond just being a source of energy and water fluxes to the atmosphere
- Land surface models now focus on a more process-based approach instead of a bulk representation
- Land surface models can now produce detailed surface states
  - Vegetation temperature
  - Soil layer temperature and moisture
  - Snow depth and water
  - Vegetation, including crop, growth
  - Upper soil – aquifer interactions

Weather Research and Forecasting (WRF) Model

Widely-used "community model" for both research and operational forecasting

- Academic scientists
- Forecast teams at operational centers
- Applications communities (e.g. Air Quality, Agriculture, Hydrology, regional climate, Utilities)

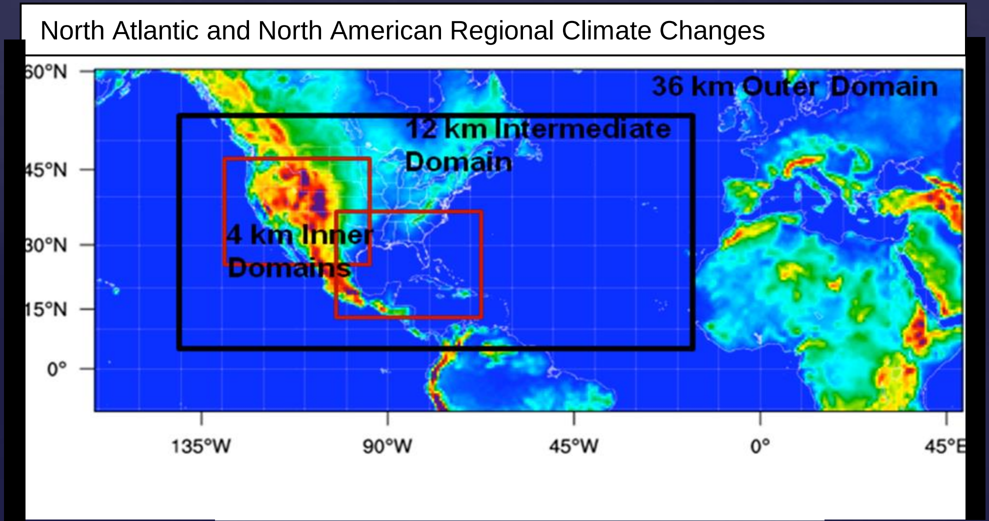


Registered Users 1/1/14

American universities, Govt. labs, Private sector	6782
Foreign users	14775

	21557

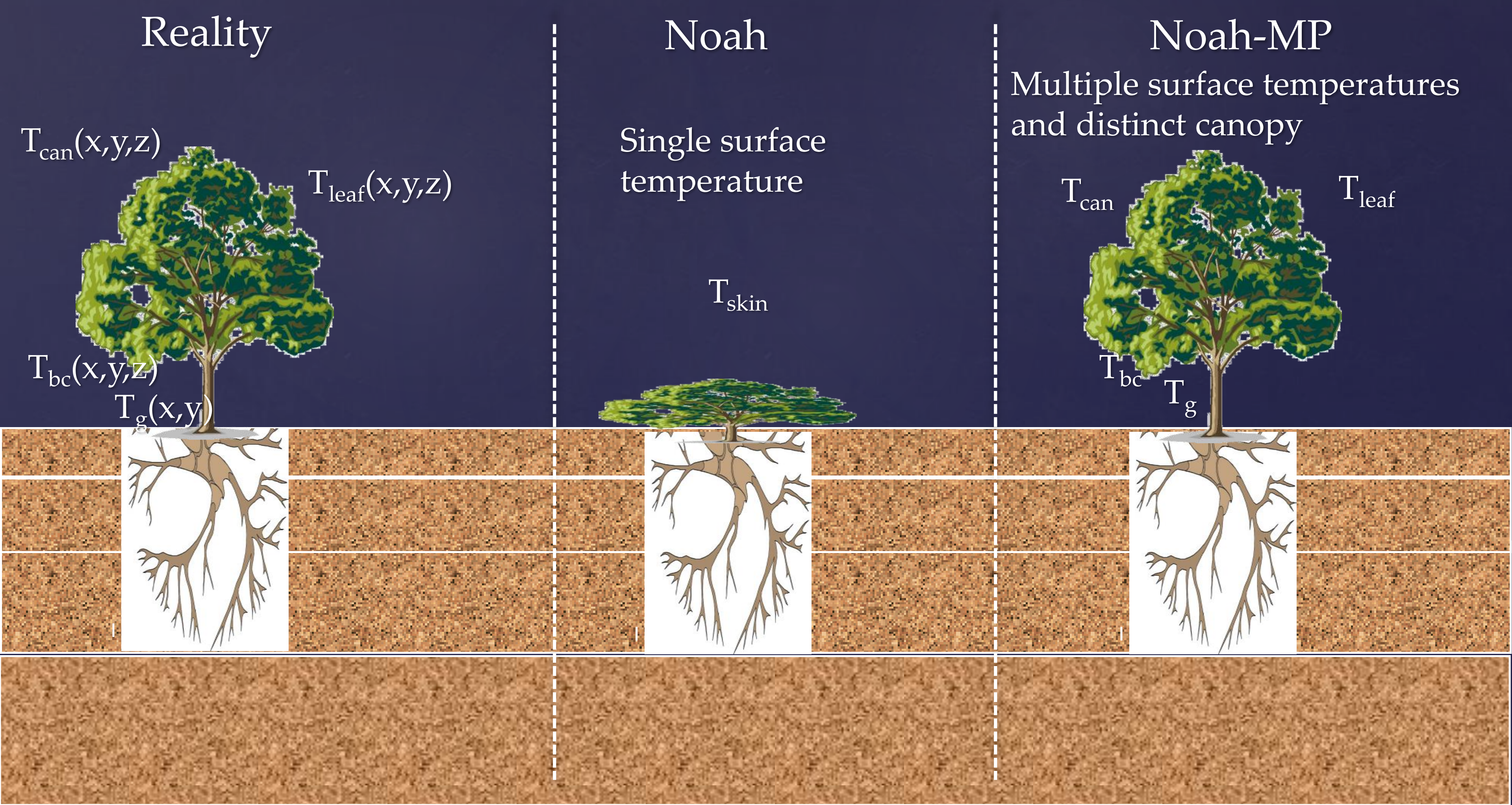
Countries represented: 152



Model Uncertainty: Land Surface Model Structure

Noah LSM in NOAA Eta, NAM, GFS, CFS, MM5 and WRF Models
(Pan and Mahrt 1987, Chen et al. 1996, Chen and Dudhia 2001,Ek et al., 2003)

Noah-MP LSM in WRF and NOAA GFS (Yang et al., 2011; Niu et al., 2011)



Noah-MP: a community land model

Parameterization → sub-grid → uncertainty

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, D12109, doi:10.1029/2010JD015139, 2011

The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements

Guo-Yue Niu,[1,2] Zong-Liang Yang,[1] Kenneth E. Mitchell,[3] Fei Chen,[4] Michael B. Ek,[3] Michael Barlage,[4] Anil Kumar,[5] Kevin Manning,[4] Dev Niyogi,[6] Enrique Rosero,[1,7] Mukul Tewari,[4] and Youlong Xia[3]

Received 4 October 2010; revised 3 February 2011; accepted 27 March 2011; published 24 June 2011.

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Noah-MP: a community land model

- Multiple parameterizations to treat key hydrology-snow-vegetation processes in a single land modeling framework
- In a broad sense,
  - Multi-physics ≡ Multi-hypothesis
- A modular & powerful framework for
  - Diagnosing differences in process representation
  - Identifying structural errors
  - Improving understanding of physical processes
  - Enhancing data/model fusion and data assimilation
  - Facilitating ensemble forecasts and uncertainty quantification

Noah-MP: a community land model

1. Leaf area index (prescribed; predicted)
2. Turbulent transfer (Noah; NCAR LSM)
3. Soil moisture stress factor for transpiration (Noah; SSiB; CLM)
4. Canopy stomatal resistance (Jarvis; Ball-Berry)
5. Snow surface albedo (BATS; CLASS)
6. Frozen soil permeability (Noah; Niu and Yang, 2006)
7. Supercooled liquid water (Noah; Niu and Yang, 2006)
8. Radiation transfer:
   Modified two-stream: Gap = f(3D structure; solar zenith angle; ...) ≤ 1-GVF
   Two-stream applied to the entire grid cell: Gap = 0
   Two-stream applied to fractional vegetated area: Gap = 1-GVF
9. Partitioning of precipitation to snowfall and rainfall (CLM; Noah)
10. Runoff and groundwater:
    TOPMODEL with groundwater
    TOPMODEL with an equilibrium water table (Chen&Kumar,2001)
    Original Noah scheme
    BATS surface runoff and free drainage

More to be added

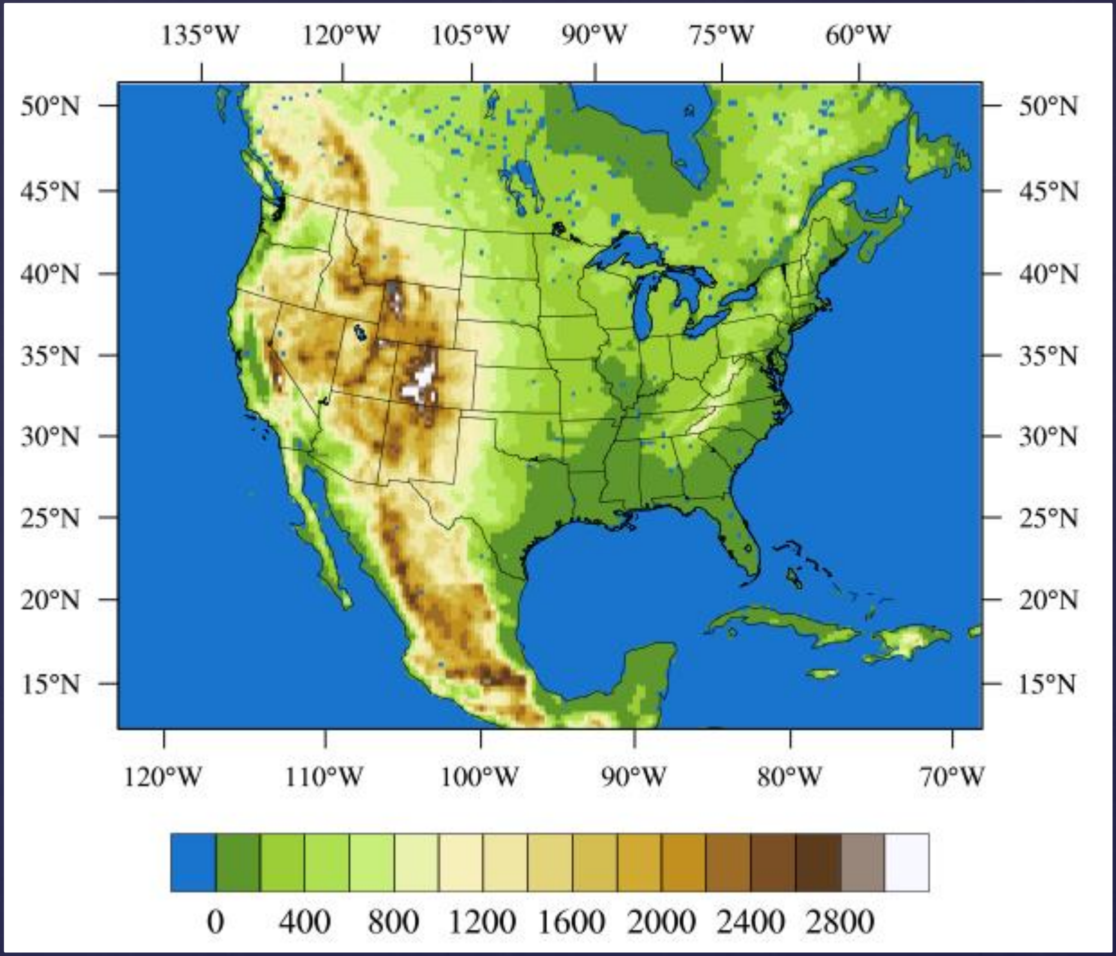
North American Regional Climate Simulations with WRF/Noah-MP: Validation and the effect of groundwater interaction

Michael Barlage
Mukul Tewari, Fei Chen, Kevin Manning (NCAR)
Gonzalo Miguez-Macho (U. Santiago)

14th WRF Users' Workshop

Domain and Setup

- Two six-month 30km simulations starting Feb 25
- 2002 and 2010
- Spin-up soil for one year using offline HRLDAS
- IC/BC from NARR
- CAM radiation; YSU; Thompson



Miguez-Macho & Fan water table dynamics in Noah-MP

Equations:

Mass balance in groundwater storage:

$$\frac{dS_g}{dt} = \Delta x \Delta y R + \sum_{1}^{8} Q_n - Q_r$$

Darcy's Law for groundwater – river exchange:

$$Q_r = rc \times (wtd - riverbed)$$

conductivity

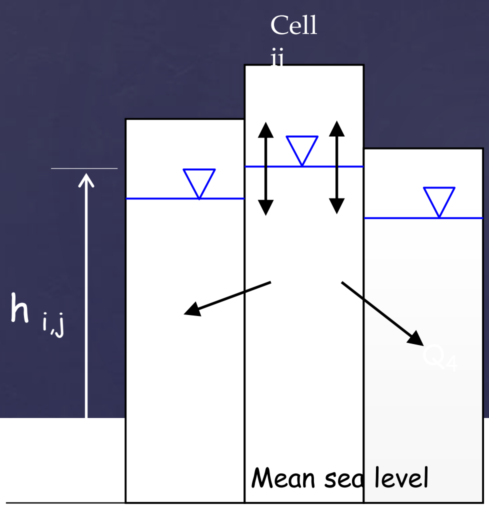
Darcy's Law for lateral groundwater flow:

$$Q_n = w \cdot \left(\frac{\int_{wtd_n}^{\infty} K_n \cdot dz + \int_{wtd}^{\infty} K \cdot dz}{2} \right) \left(\frac{h_n - h}{s} \right)$$

width of flow cross section

Transmisivity

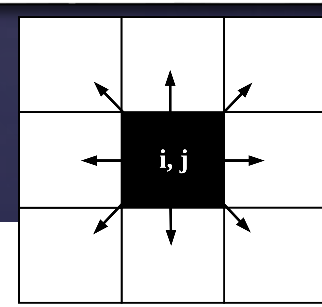
Head difference divided by distance (water table slope)

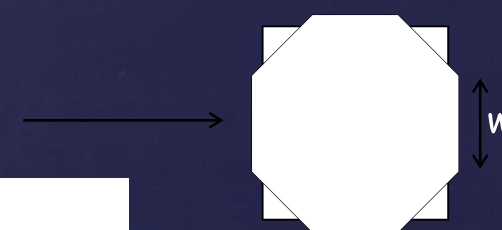


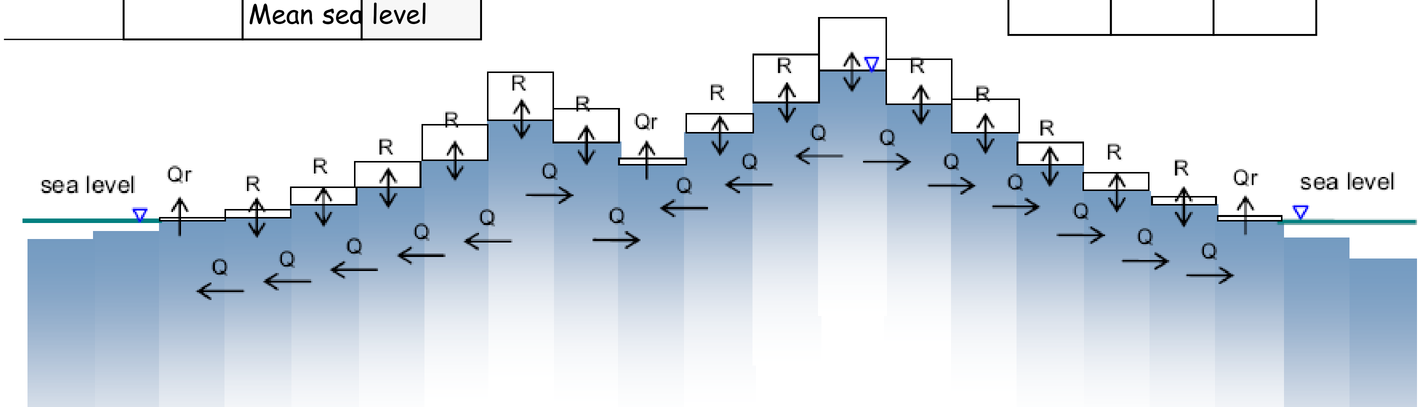
Water table depth (wtd)

Cross section view

Plan

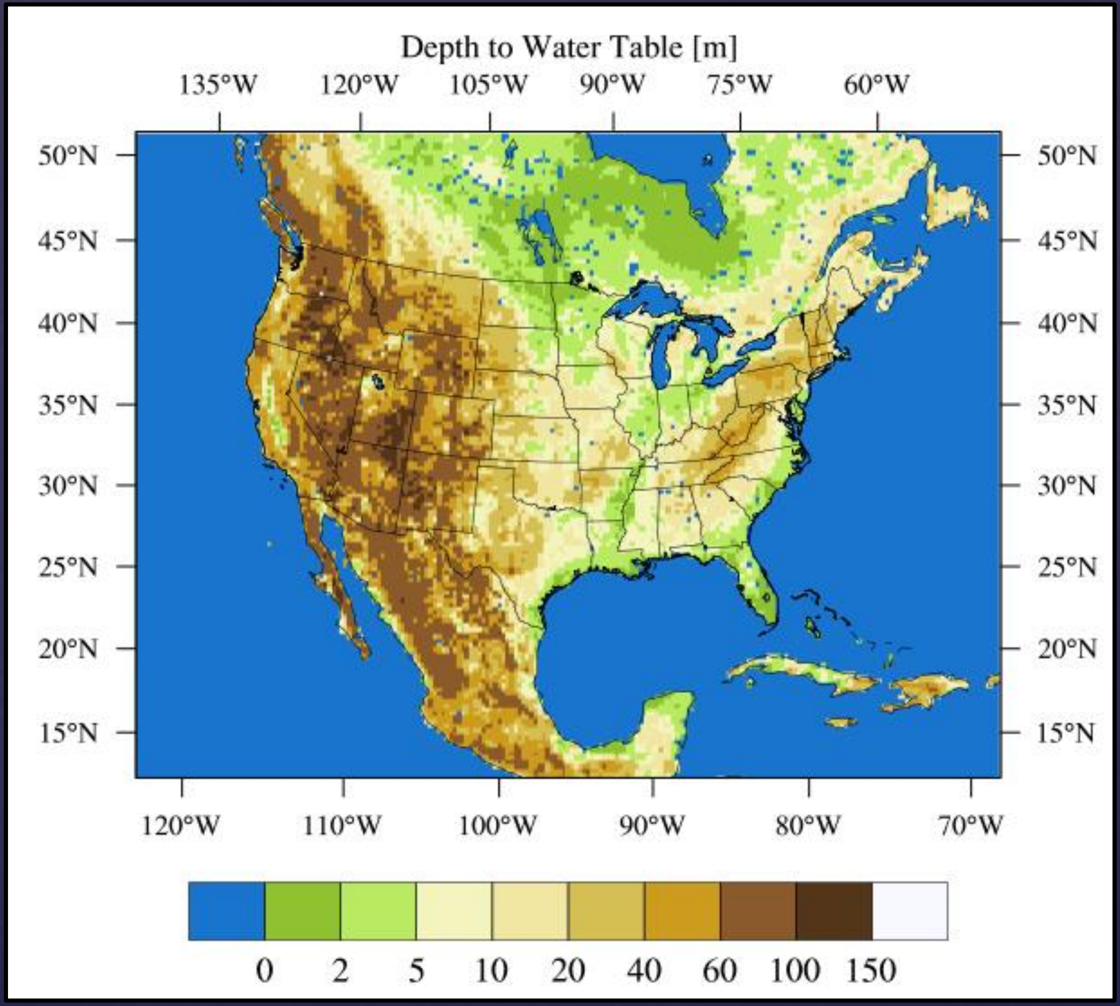






Fan et al, JGR 2007
Miguez-Macho et al., JGR 2007

Depth to Water Table

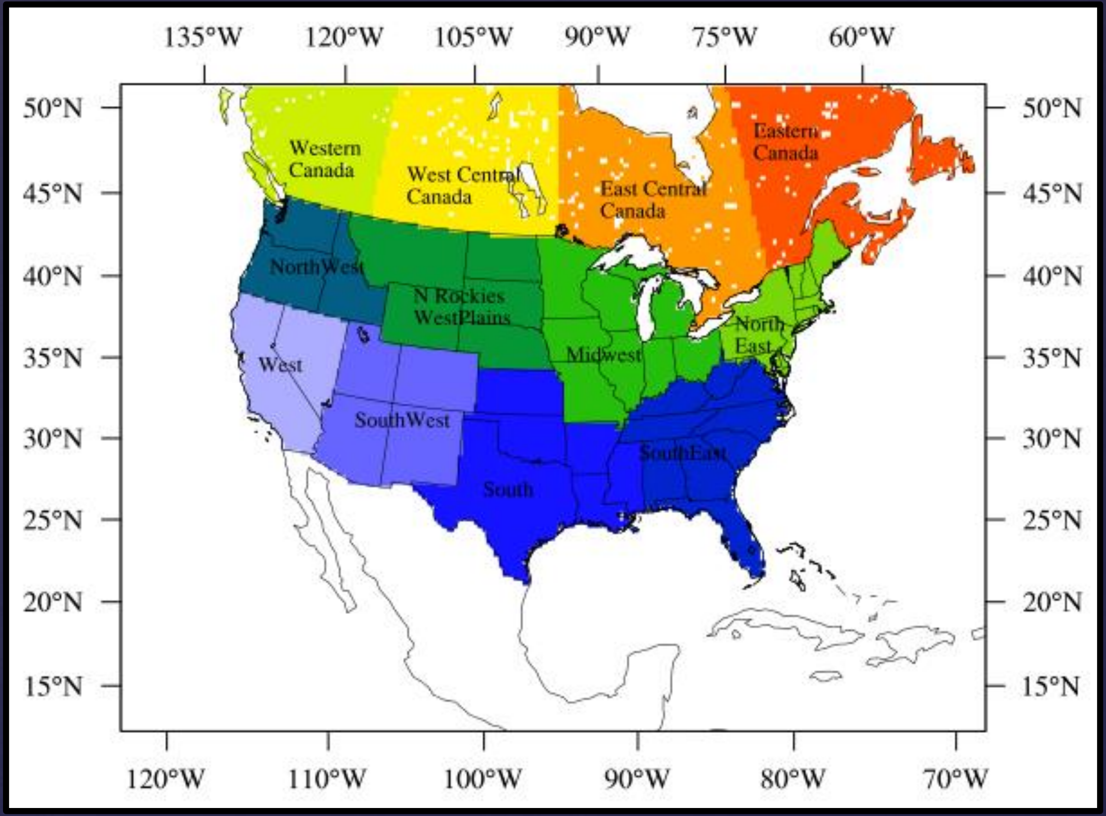


Looks similar to terrain

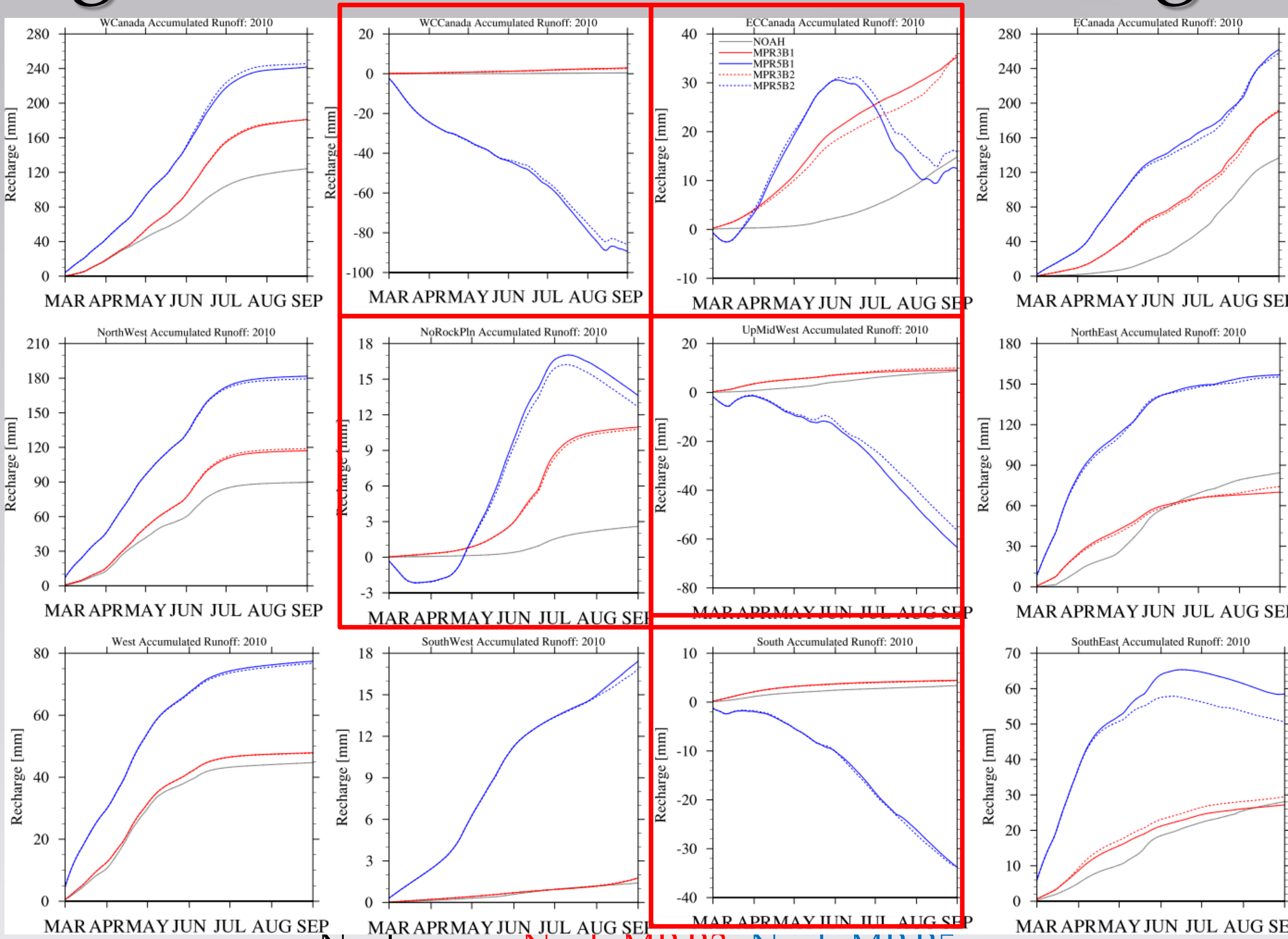
Focus of this presentation are locations with shallow water table

Analysis Regions

- Based on NCDC Regional Climate Zones
- Observations: METAR/SYNOP stations, NCDC daily gridded precip

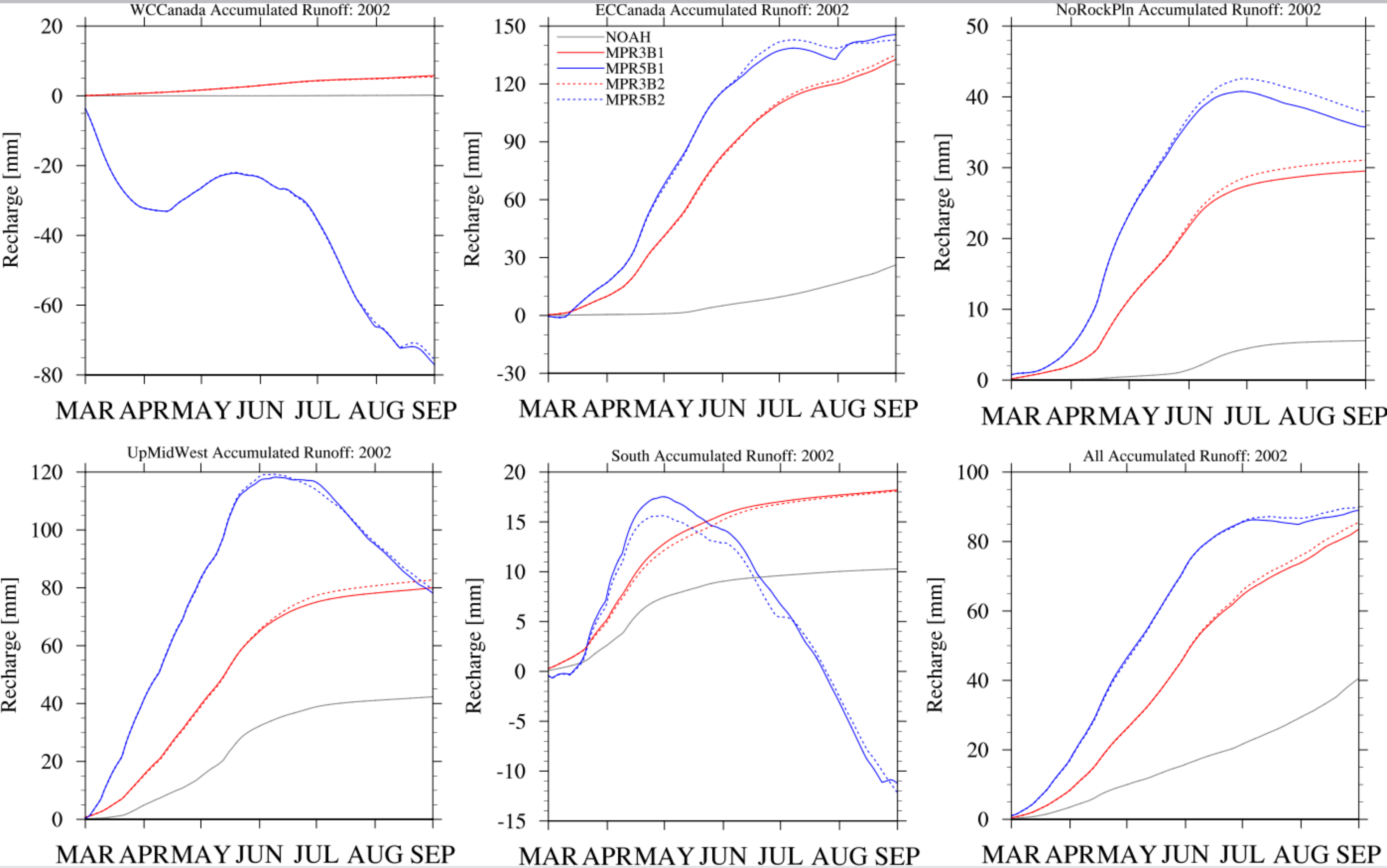


Regional Groundwater Recharge



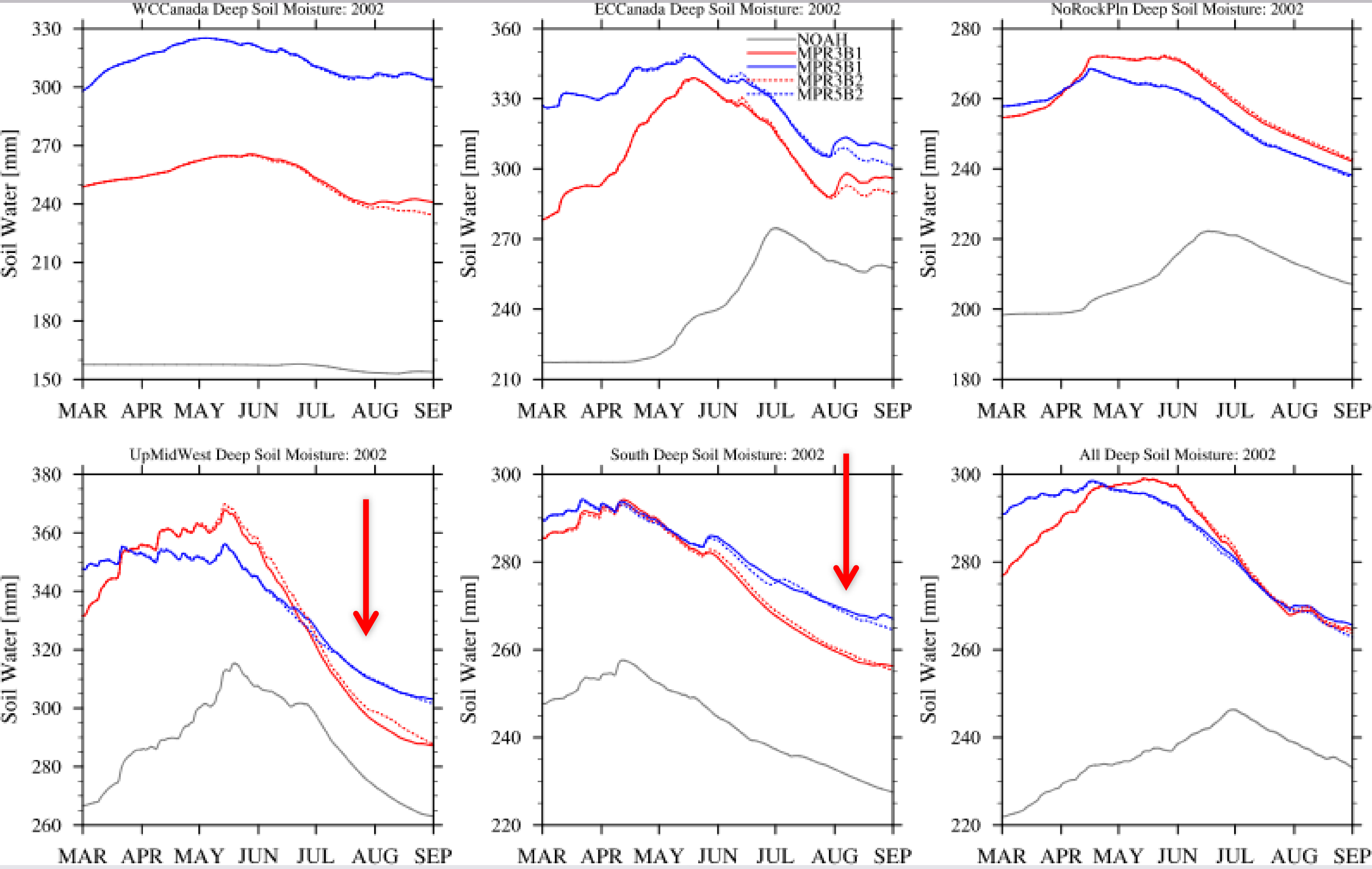
Noah Noah-MP R3 Noah-MP R5

Regional Groundwater Recharge: 2002



Noah Noah-MP R3 Noah-MP R5

Regional Deep Soil Moisture: 2002

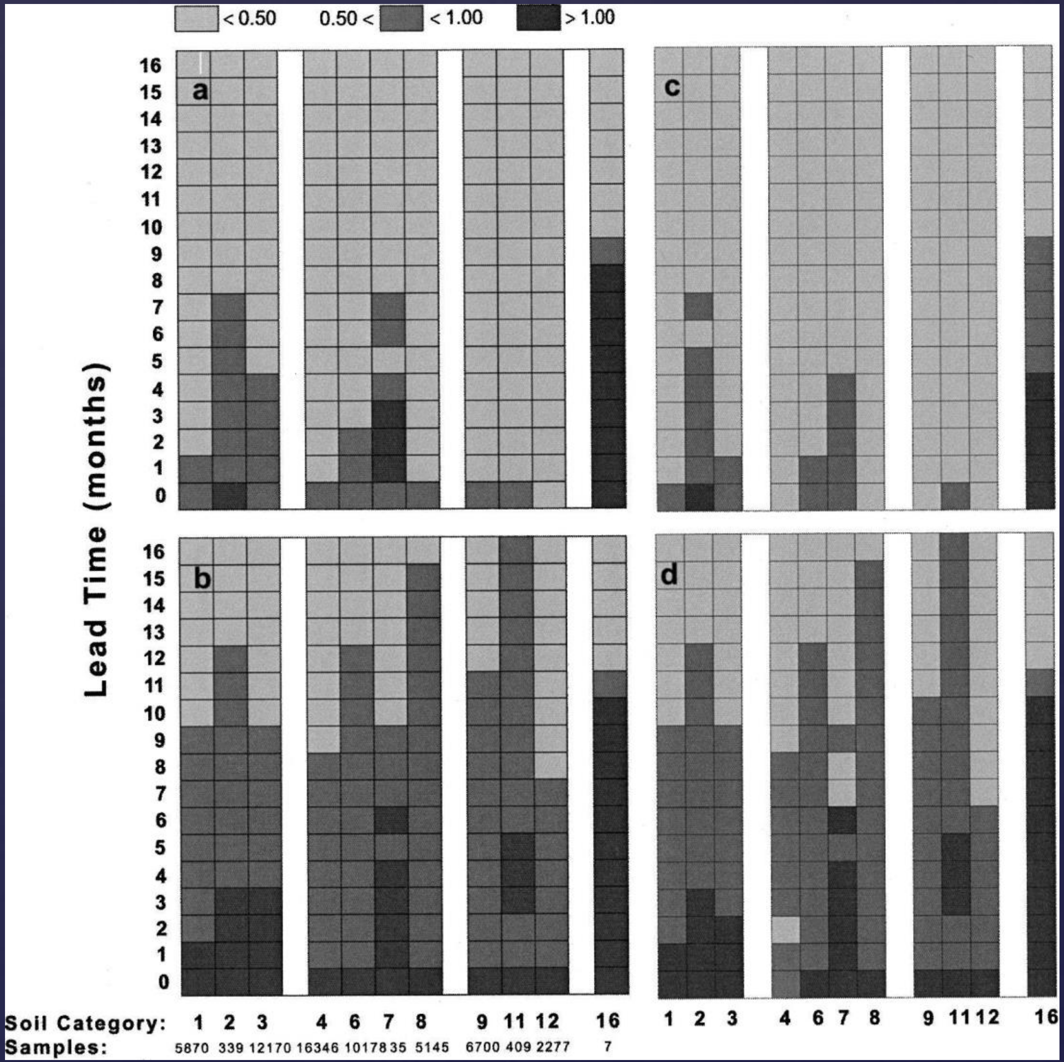


Noah Noah-MP R3 Noah-MP R5

Initialization Uncertainty

Importance of Initialization Consistency

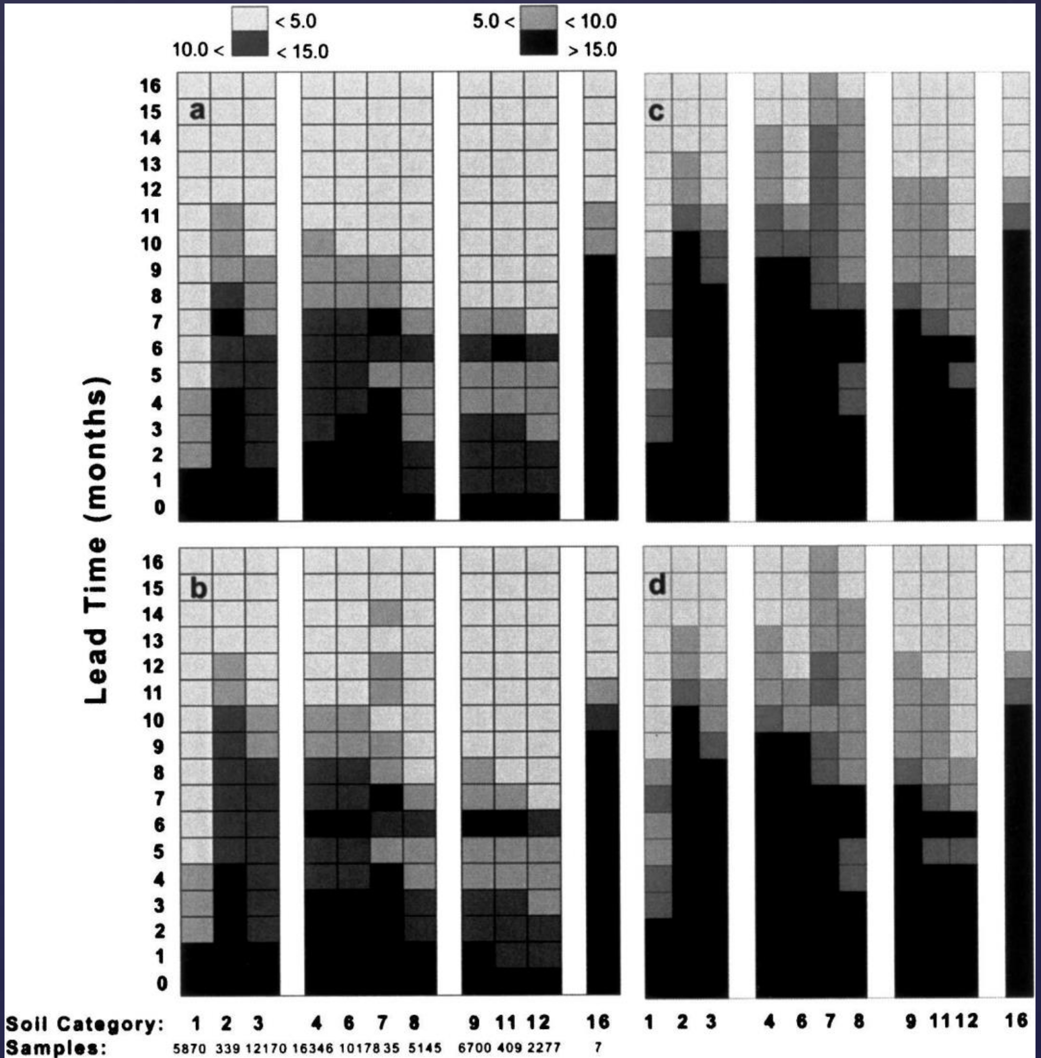
- Before running a model, significant spin-up is required to ensure initialization consistency
- For soil temperature, this can require a year or more



Initialization Uncertainty

Importance of Initialization Consistency

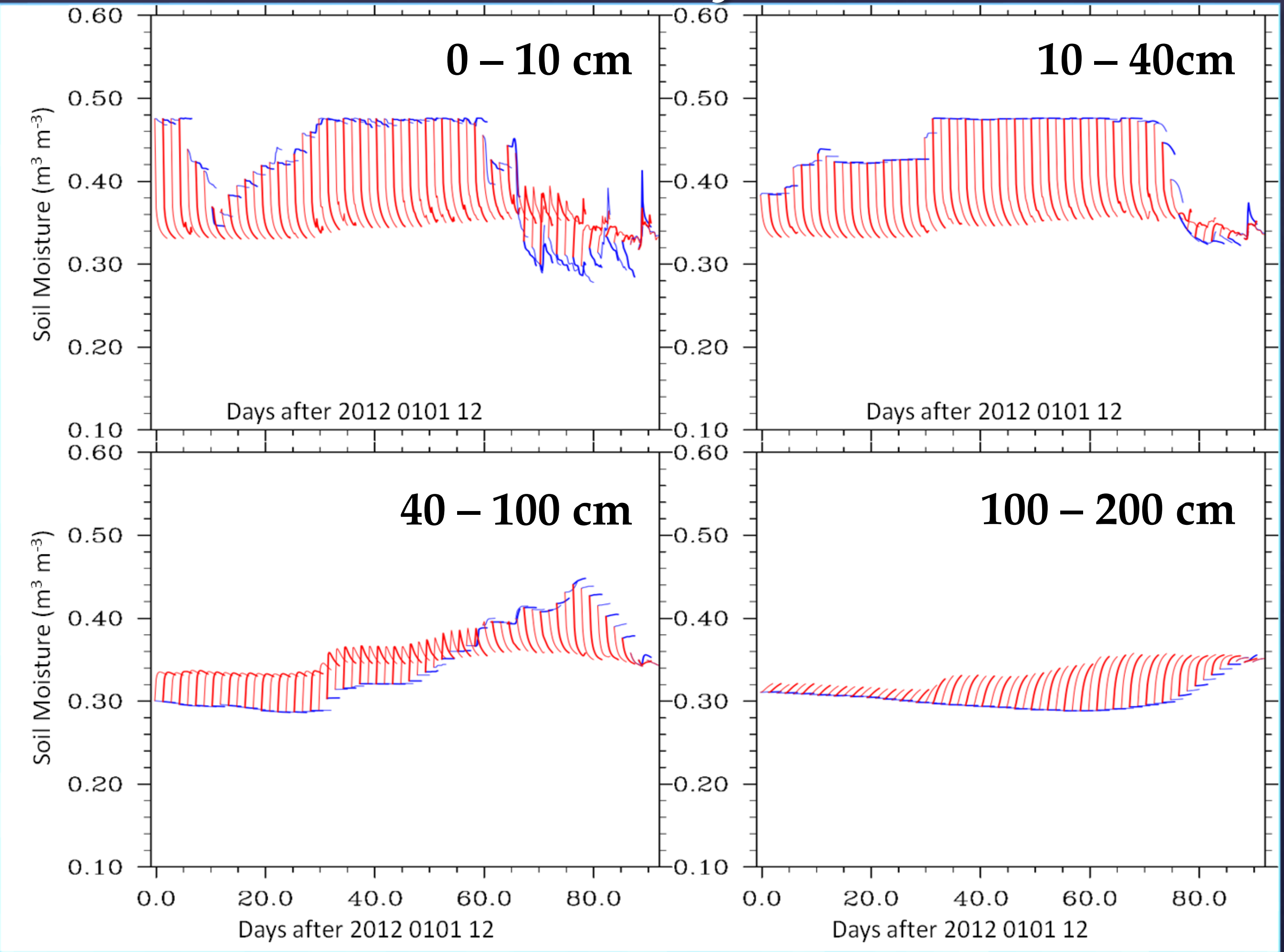
- Before running a model, significant spin-up is required to ensure initialization consistency
- For surface fluxes, this can require even more time



Initialization Uncertainty

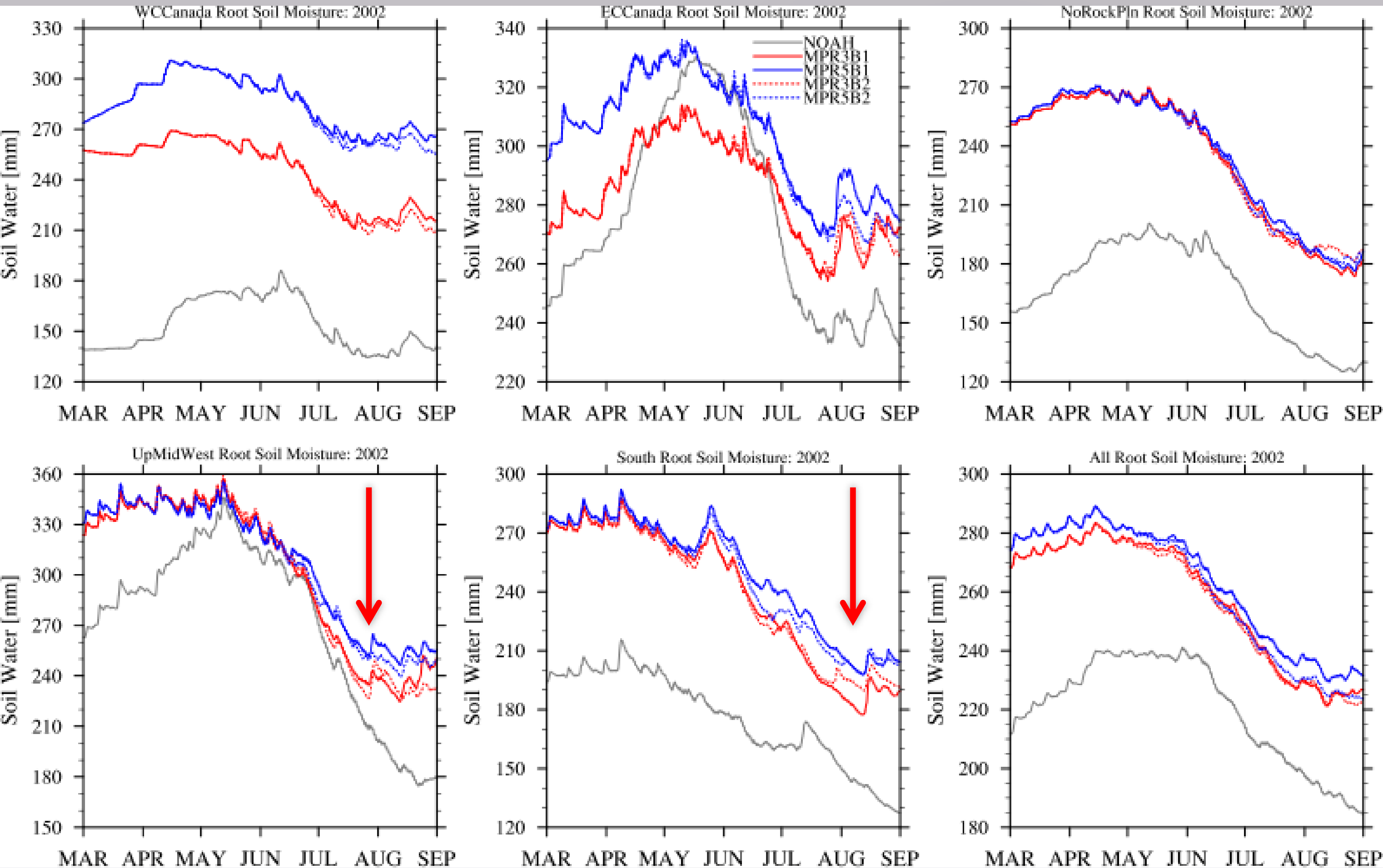
Importance of Initialization Consistency

Soil Moisture by Level



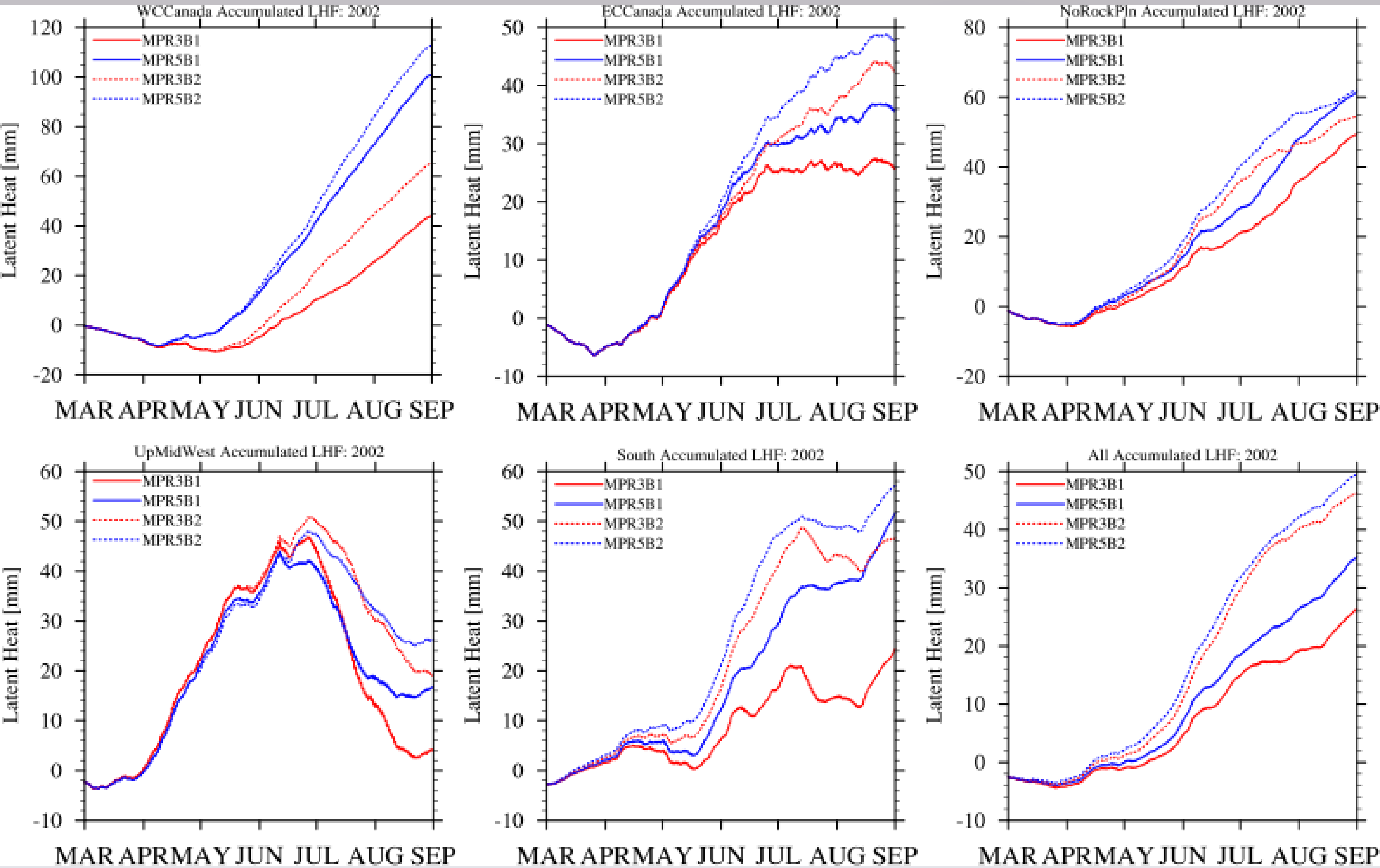
Noah in blue
Noah-MP in red

Regional Root Soil Moisture: 2002



Noah Noah-MP R3 Noah-MP R5

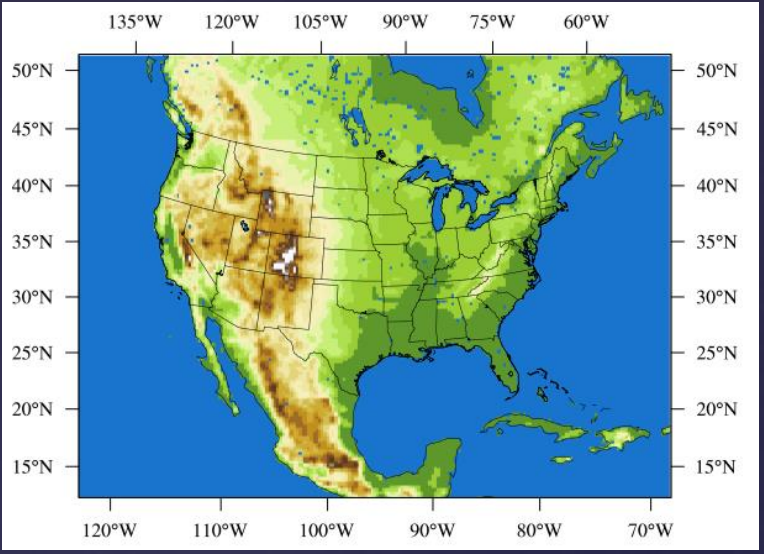
Regional Latent Heat Flux: 2002



Noah Noah-MP R3 Noah-MP R5

Noah vs. NoahMP
Surface Verification

- Six-month 30km WRF simulations - 2010
- Spin-up soil for one year using offline HRLDAS
- IC/BC from NARR
- Verification against ~2600 surface stations



Model	Season	Output field	Day bias	Day RMSE	Night bias	Night RMSE
Noah	MAM	T_{2m}	-2.79	3.18	-1.95	2.17
Noah-MP	MAM	T_{2m}	**0.17**	**0.92**	**-0.01**	**0.77**
Noah	JJA	T_{2m}	**-0.04**	**0.75**	-1.04	1.37
Noah-MP	JJA	T_{2m}	1.09	1.53	**0.13**	**0.94**
Noah	MAM	Td_{2m}	-0.48	1.16	-1.29	1.64
Noah-MP	MAM	Td_{2m}	**0.19**	**1.04**	**0.48**	**1.01**
Noah	JJA	Td_{2m}	**-0.98**	**1.53**	-1.73	2.08
Noah-MP	JJA	Td_{2m}	-1.18	1.84	**-1.00**	**1.57**

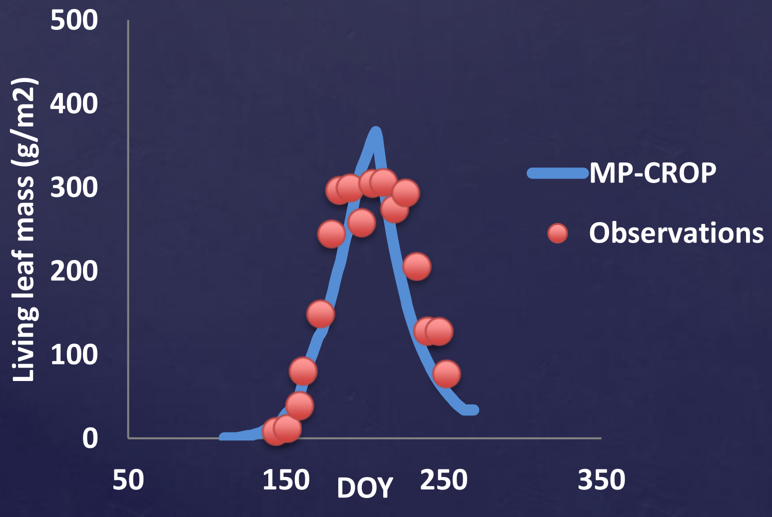
Green: Noah-MP improves Red: Noah-MP degrades

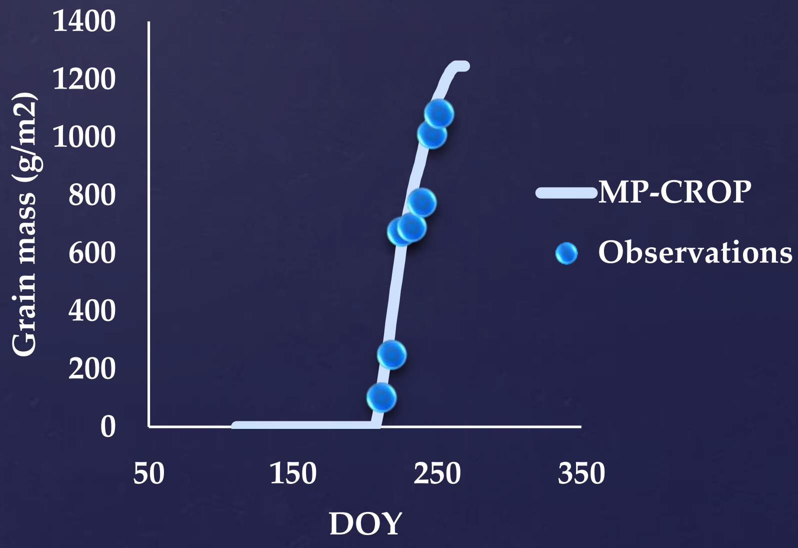
Development of WRF-Crop

- Built upon the WRF-Hydro and Noah-MP ensemble modeling framework
- Extend the dynamic vegetation model in Noah-MP to parameterize crop yield
  - Noah-MP photosynthesis-based dynamic vegetation allocates carbon to leaves, stems, grain, roots and wood as well as fast and slow soil carbon pools
  - Incorporate a whole suite of crop growth modules (rice, corn, wheat, sorghum, soybean, etc.)
- Extend WRF-Hydro to parameterize irrigation
  - A groundwater transfer and storage with dynamic water table depth
  - Aquifer water recharges lowest soil layers and can also added to surface water as irrigation

Development of WRF-Crop

Noah-MP predicted green leaf mass (left) and grain mass (right) at an Illinois site (corn)

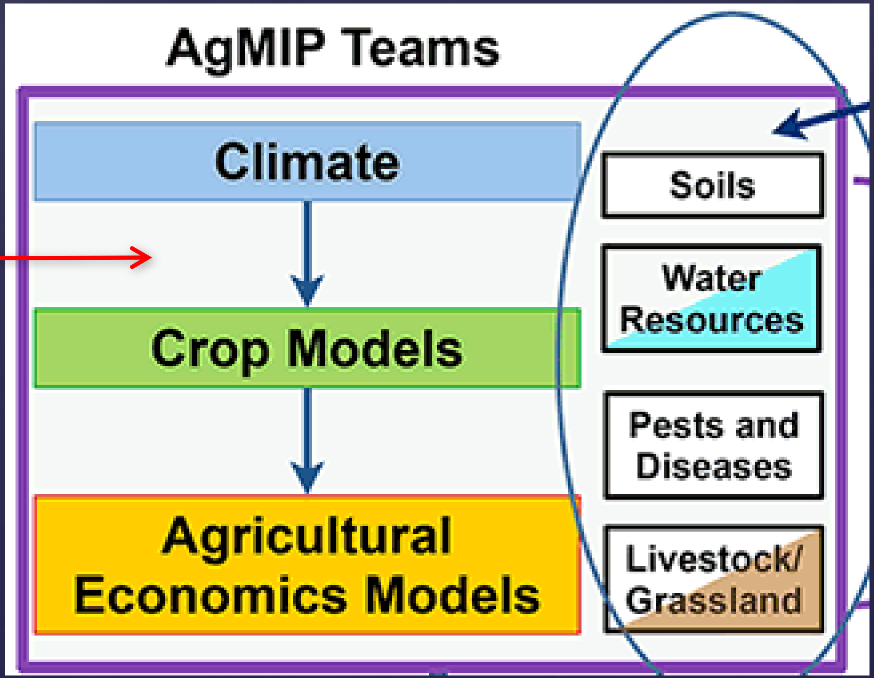




Model Intercomparison

- Land modelers like to do "intercomparison projects"
- This is essentially a method of "fair" performance evaluation.
- Yield modelers like to do this too: the Agricultural Model Intercomparison Project

Note the lack of two-way interaction



Rosenzweig et al. 2013

NARCCAP

North American Regional Climate Change Assessment Program

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  - MM5I+HadCM3 NEW!
  - RCM3+CGCM3
  - RCM3+GFDL
  - WRFG+CCSM
  - WRFG+CGCM3

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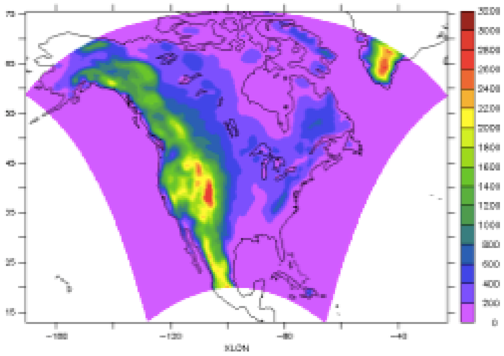
About the Program



The North American Regional Climate Change Assessment Program (NARCCAP) is an international program to produce high resolution climate change simulations in order to investigate uncertainties in regional scale projections of future climate and generate climate change scenarios for use in impacts research.

NARCCAP modelers are running a set of regional climate models (RCMs) driven by a set of atmosphere-ocean general circulation models (AOGCMs) over a domain covering the conterminous United States and most of Canada.

The AOGCMs have been forced with the SRES A2 emissions scenario for the 21st century. Simulations with these models were also produced for the current (historical) period. The RCMs are nested within the AOGCMs for the current period 1971-2000 and for the future period 2041-2070. As a preliminary step to evaluate the performance of the RCMs over North America, the RCMS are driven with NCEP Reanalysis II data for the period 1979-2004. All the RCMs are run at a spatial resolution of 50 km.

RCM Characteristics — AOGCM Characteristics — RCM/GCM combinations.

NARCCAP also includes two timeslice experiments at 50 km resolution using the GFDL atmospheric model (AM2.1) and the NCAR CCSM atmospheric model (CAM3). In a timeslice experiment, the atmospheric component of an AOGCM is run using observed sea surface temperatures and sea ice boundaries for the historical run, and those same observations combined with perturbations from the future AOGCM for the scenario run. Omitting the coupled ocean model saves considerable computation and allows the atmospheric model to be run at higher resolution.

Thoughts

- Regional climate models contain many sources of uncertainty
- We need to be able to assess and communicate the effect of these uncertainties on model output
- A good start is with ensemble multi-model, and perturbed parameter and initialization approaches
- Tools are being developed to address this (e.g., multi-model models)
- What information is useful?