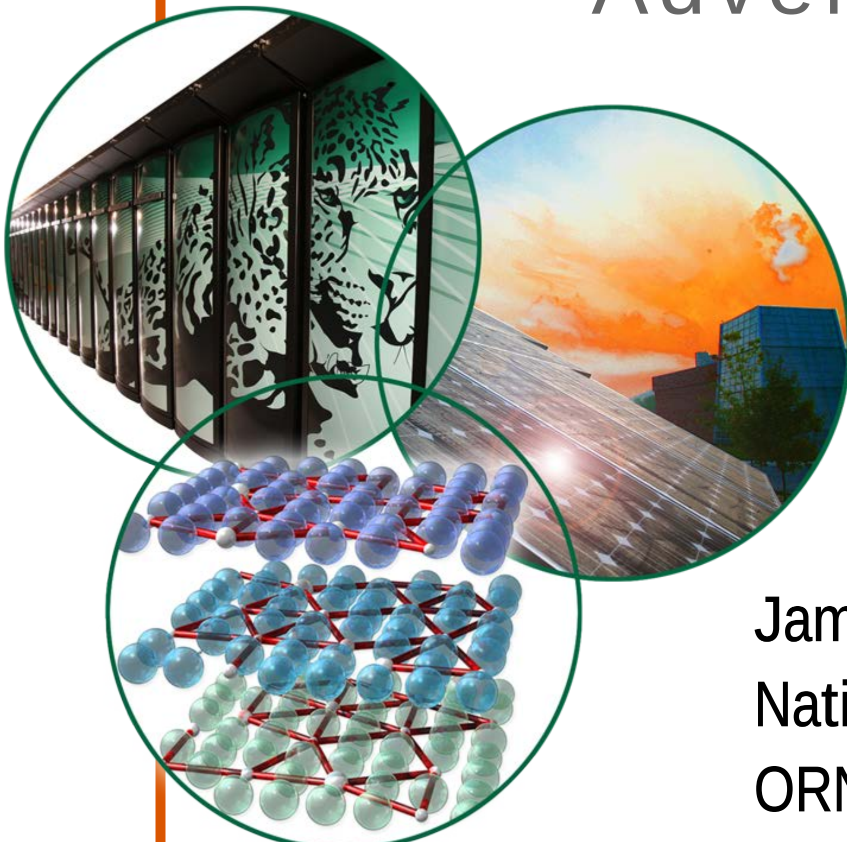
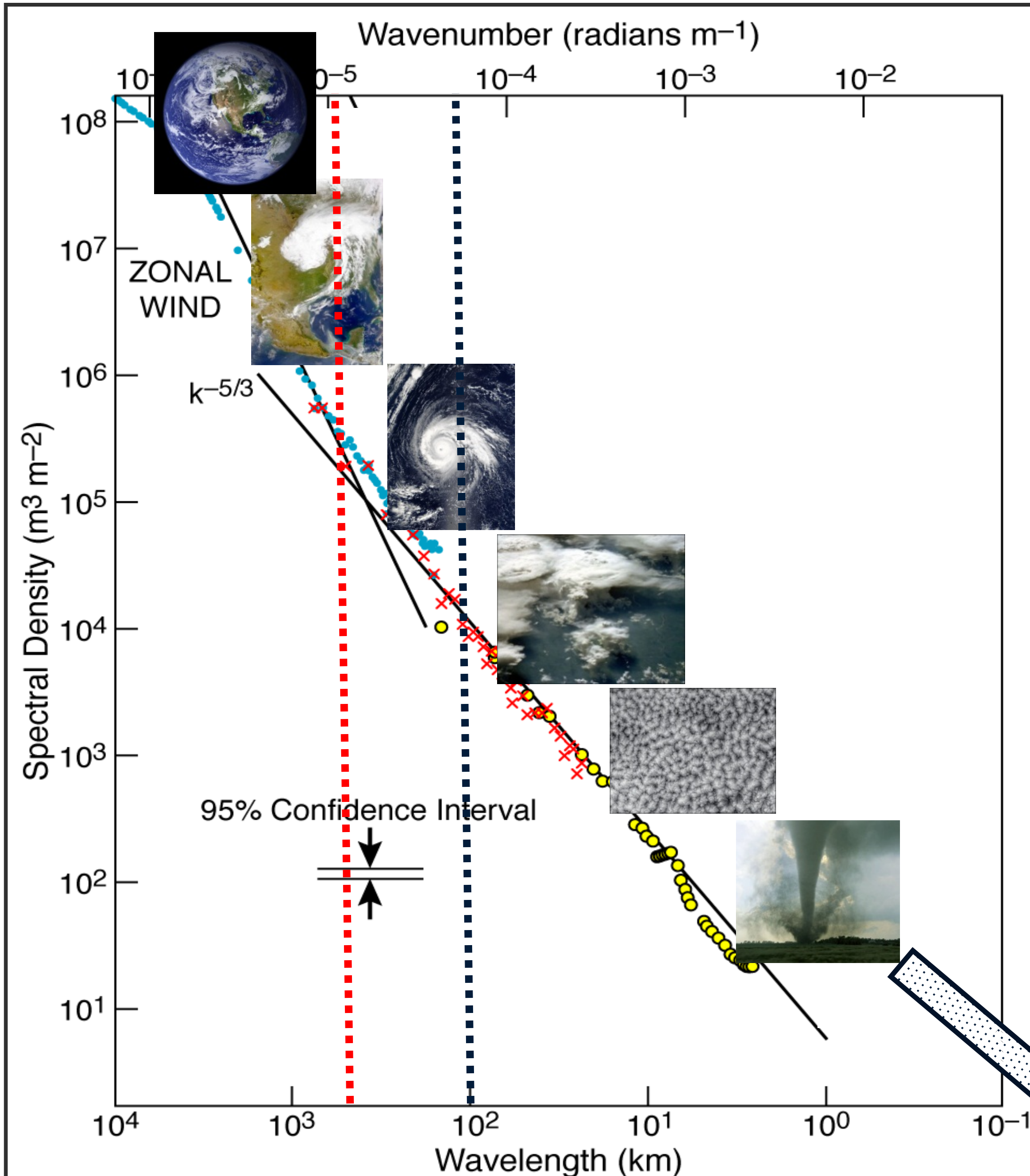
Adventures in “Tuning”



James J. Hack, Director
National Center for Computational Sciences
ORNL Climate Change Science Institute
Oak Ridge National Laboratory

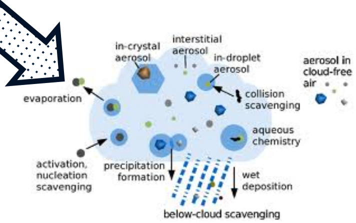
Kinetic energy spectra observations



Nastrom and Gage, 1985

Atmosphere and Ocean exhibit a continuum of motion scales

- Resolved scale treatment formulated on first principles conservation laws (energy, mass, momentum)
- Unresolved scales represented using parameterizations based on highly-detailed process models formulated in statistical equilibrium with resolved scale motion field



Meteorological Primitive Equations

- Applicable to selected motion scales; > 1hour, >20km

$$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \mathbf{F}, \qquad \textit{(horizontal momentum)}$$

$$d\overline{T}/dt - \kappa\overline{T}\omega/p = Q/c_p, \qquad \textit{(thermodynamic energy)}$$

$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0, \qquad \textit{(mass continuity)}$$

$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0, \qquad \textit{(hydrostatic equilibrium)}$$

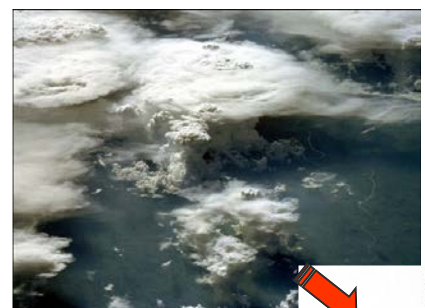
$$d\overline{q}/dt = S_q. \qquad \textit{(water vapor mass continuity)}$$

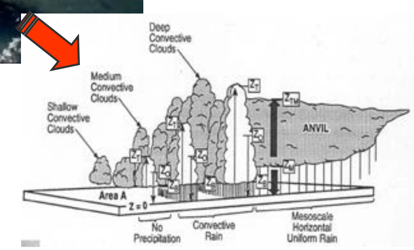
Parameterization

- dictionary.com
  - pa·ram·e·ter·ize: To describe in terms of parameters

Treatment of physical processes that occur on scales below the numerical truncation limit

- dry and moist convection
- cloud amount and optical properties
  - water, ice, particle size, phase, habit, overlap
- radiative transfer
- planetary boundary layer transports
- surface energy exchanges
- horizontal and vertical dissipation processes
- ...





Simulating multi-scale multi-physics geophysical systems (atmospheric models)

- **If you have built a numerical model you have been guilty of "tuning"**
  - fundamental element of all discrete approximations
- **Parameterized processes must be "tuned"**
  - historical constraint is mean statistical behavior
  - other constraints relate to behavior of individual processes
    - unfortunately quantitative observational constraints are limited
- **Parameterized physics behavior varies with resolution**
  - changes with horizontal resolution (difficult challenge)
    - time and space truncation properties
  - changes with vertical resolution (extremely difficult challenge)
- **Problem is not an engineering exercise**

A simple example from the distant past

$$\frac{\partial v}{\partial t} = K_{H_0}\left[\nabla^2 - \frac{1}{r^2}\right] v = K_{H_0}\left[\frac{\partial}{r\partial r}\left(r\frac{\partial v}{\partial r}\right) - \frac{v}{r^2}\right]$$

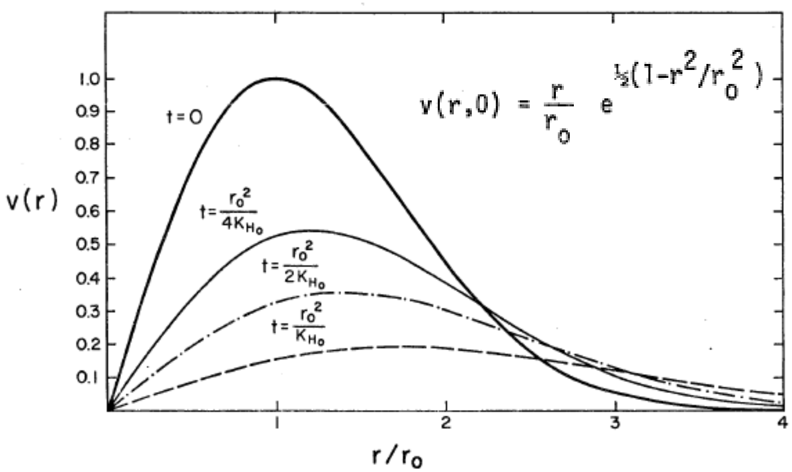
linearized tangential wind (axisymmetric vortex)

$$\frac{\partial \hat{v}}{\partial t} = K_{H_0}\int_0^\infty \left[\frac{\partial}{r\partial r}\left(r\frac{\partial v}{\partial r}\right) - \frac{v}{r^2}\right] J_1(kr)\, r\,dr$$

first order Hankel transform

Integrating by parts $\frac{\partial \hat{v}}{\partial t} = -K_{H_0}\int_0^\infty v k^2 J_1(kr)\, r\,dr = -K_{H_0} k^2 \hat{v}$ leading to the solution

$\hat{v}(k,t) = \hat{v}(k,0)\, e^{-K_{H_0} k^2 t}$ which can be transformed to give $v(r,t) = \int_0^\infty \hat{v}(k,0)\, e^{-K_{H_0} k^2 t} J_1(kr)\, k\,dk$



K_{H_0} (m^2/s)	r_0 (km)		
	50	100	200
10^3	5.993	23.971	95.883
10^4	0.599	2.397	9.588
10^5	0.060	0.240	0.959

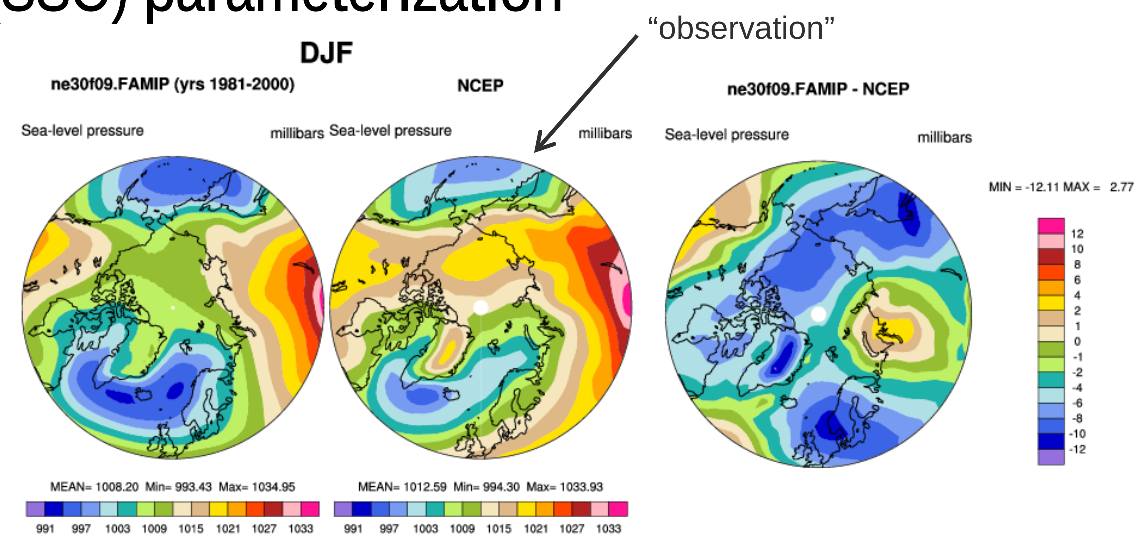
Time in days to halve initial total kinetic energy

Very elegant approach, but in the end the decision comes down to an educated guess

Example of momentum phenomena

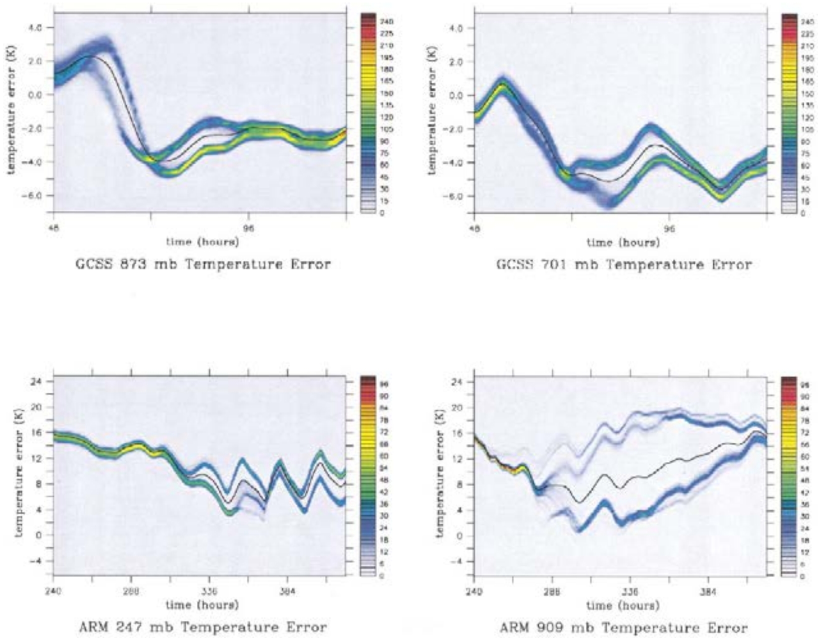
- Orographic form and gravity-wave drag in stably stratified flow
  - orography creates obstacles, i.e. *blocking drag*
  - orography generates vertically propagating waves → transport momentum between their source regions where they are dissipated or absorbed in regions of wave breaking, i.e. *gravity wave drag*
- Is of sufficient magnitude and horizontal extent to substantially modify the large scale mean flow
- Coarse resolution models require treatment in the form of a sub-grid scale orography (SSO) parameterization

Details of wave generation forcing field and associated wave breaking mechanisms critical to simulation of the resolved scale flow

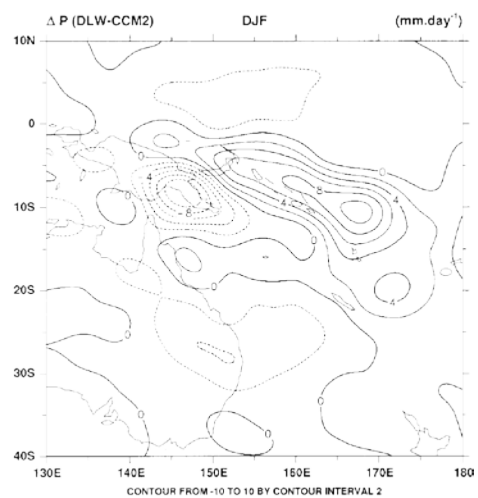


Growing list of parameterized processes

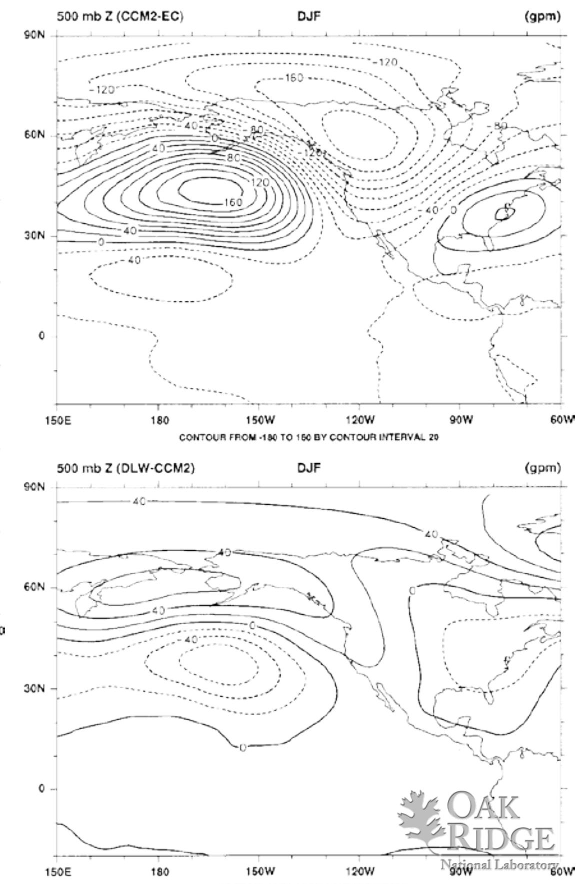
- Many based on linear theory
  - implementation in non-linear framework becomes long and incomplete process
- The collection of parameterized processes is highly coupled
  - non-linearities create a challenging environment for parameter evaluation
    - local and non-local



Hack and Pedretti (2000)

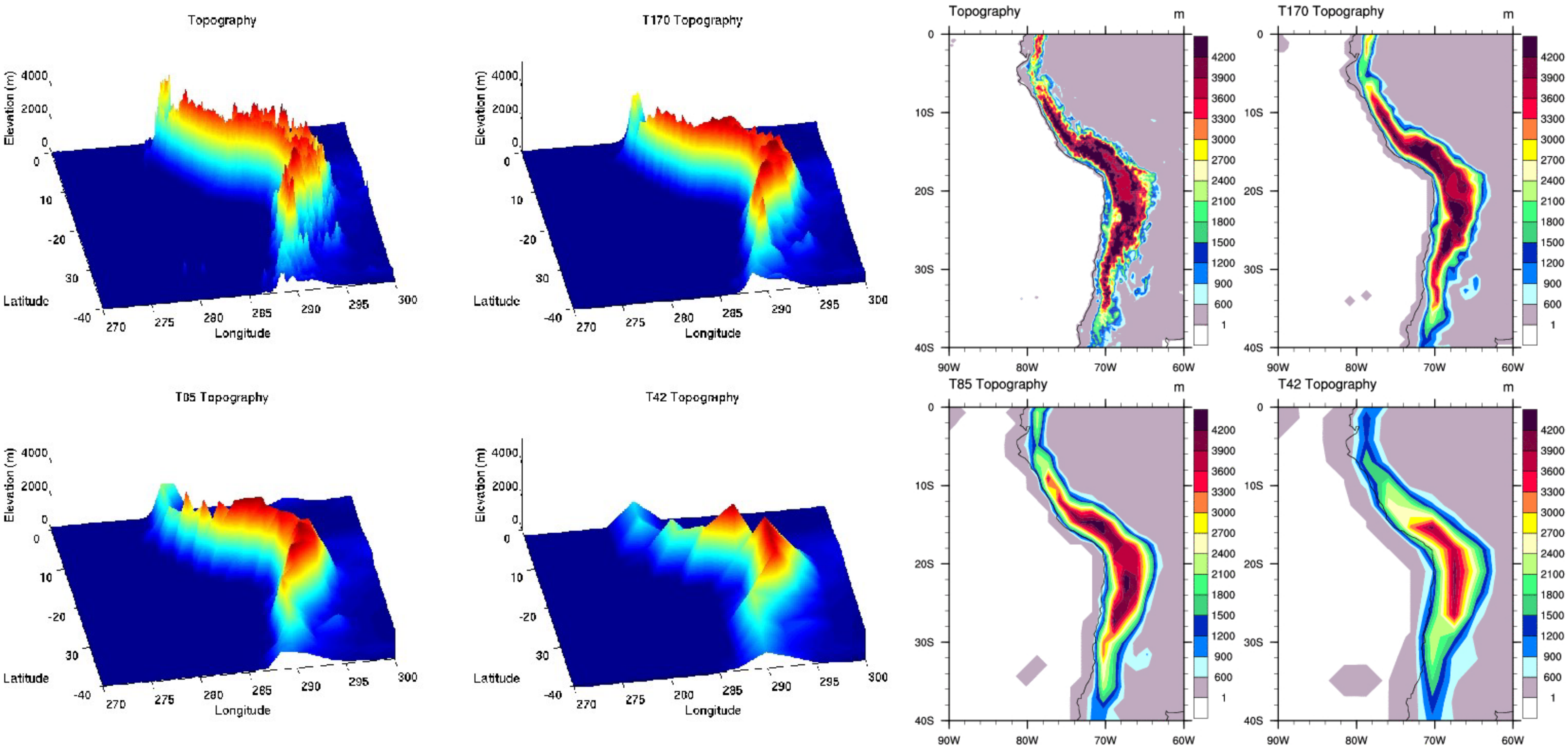


Hack (1998)



Oak Ridge National Laboratory

Global Modeling and Horizontal Resolution



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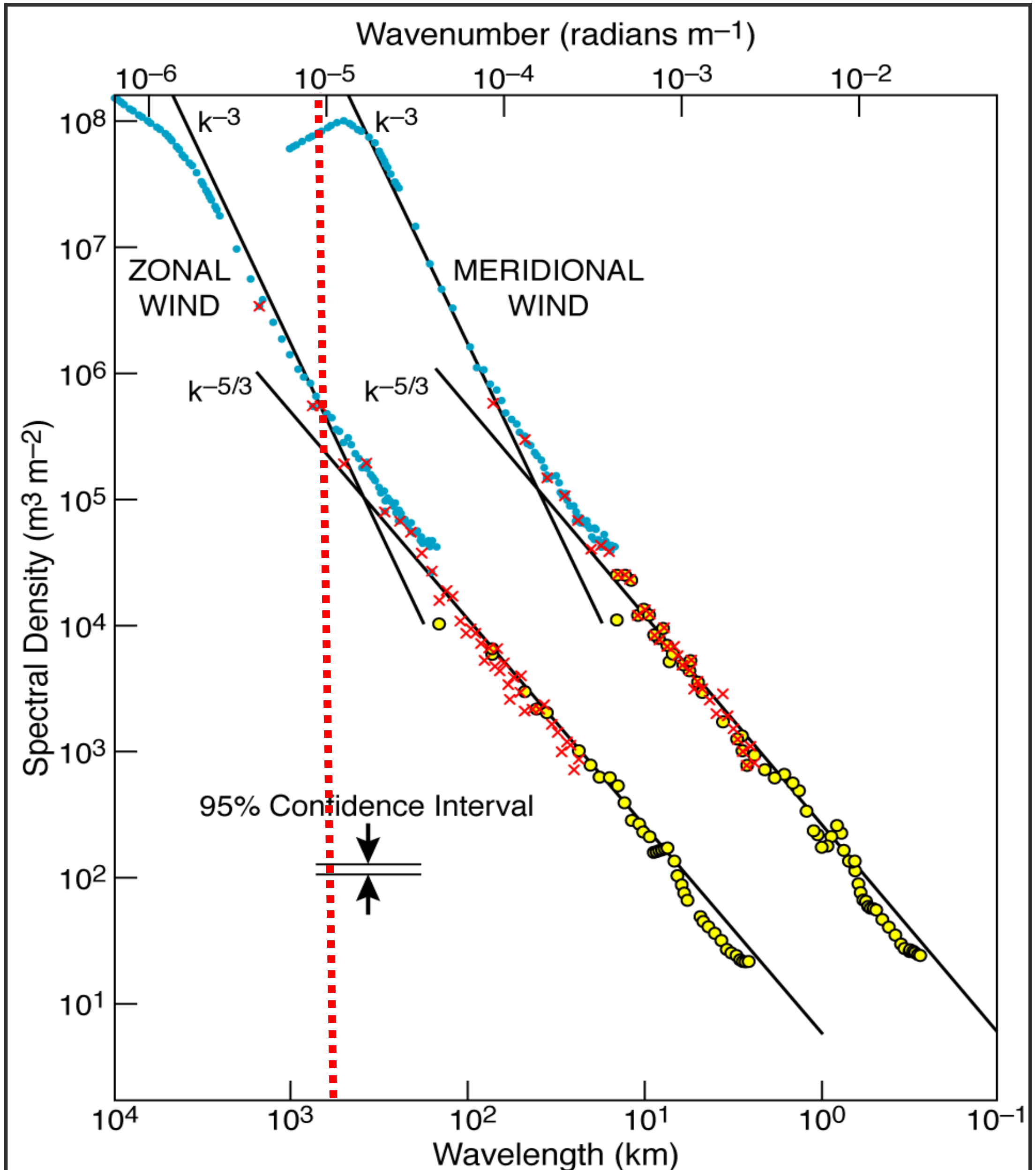
Kinetic energy spectra observations



Nastrom and Gage, 1985

Unresolved processes

- Traditionally assume that effects of unresolved scales can be represented through parameterizations based on bulk formulae.
- Inherently assumes that there is no coupling between dynamics and physics on these unresolved scales.
- Essentially ignores upscale energy cascades

Original image from Julia Slingo

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Documented resolution dependence (CAM4)

Resolution and dycore-dependent parameters

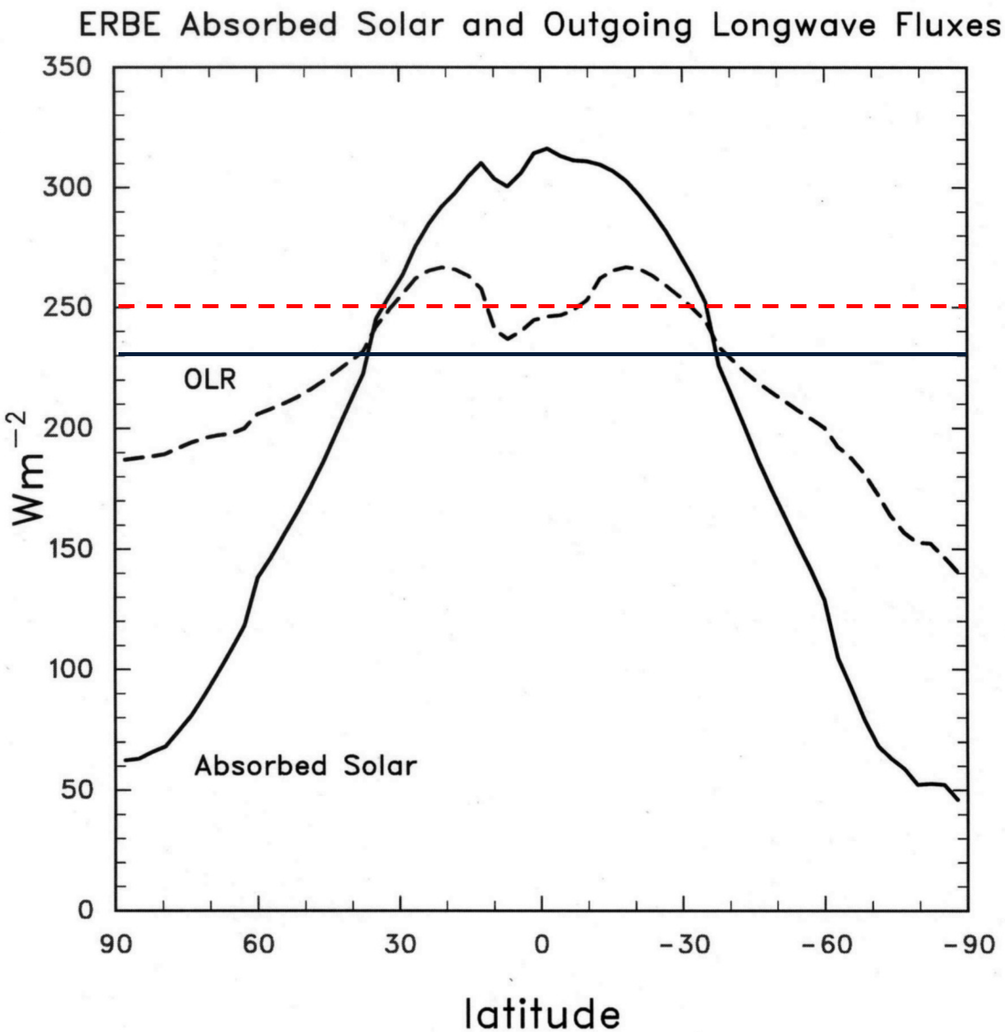
The following adjustable parameters differ between various finite volume resolutions in the CAM 4.0. Refer to the model code for parameters relevant to alternative dynamical cores.

Table C.1: Resolution-dependent parameters

Parameter	FV 1 deg	FV 2 deg	Description
$q_{ic,warm}$	2.e-4	2.e-4	threshold for autoconversion of warm ice
$q_{ic,cold}$	18.e-6	9.5e-6	threshold for autoconversion of cold ice
$k_{e,strat}$	5.e-6	5.e-6	stratiform precipitation evaporation efficiency parameter
RH_{min}^{low}	.92	.91	minimum RH threshold for low stable clouds
RH_{min}^{high}	.77	.80	minimum RH threshold for high stable clouds
$k_{1,shallow}$	0.04	0.04	parameter for shallow convection cloud fraction
$k_{1,deep}$	0.10	0.10	parameter for deep convection cloud fraction
p_{mid}	750.e2	750.e2	top of area defined to be mid-level cloud
$c_{0,shallow}$	1.0e-4	1.0e-4	shallow convection precip production efficiency parameter
$c_{0,deep}$	3.5E-3	3.5E-3	deep convection precipitation production efficiency parameter
$k_{e,conv}$	1.0E-6	1.0E-6	convective precipitation evaporation efficiency parameter
v_i	1.0	0.5	Stokes ice sedimentation fall speed (m/s)

Simple characterization of *the* tuning process

- Outgoing Longwave Radiation = Absorbed Solar Radiation

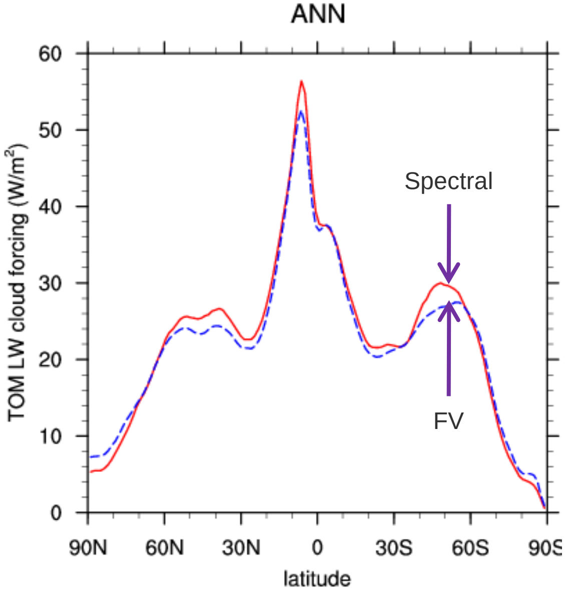


- Meridional structure of the component fluxes is strongly modulated by cloud processes
- One requirement is to accurately reproduce this structure as observed by Earth Radiation Budget observations by exploring sensitivities in the parameterizations of moist physical processes

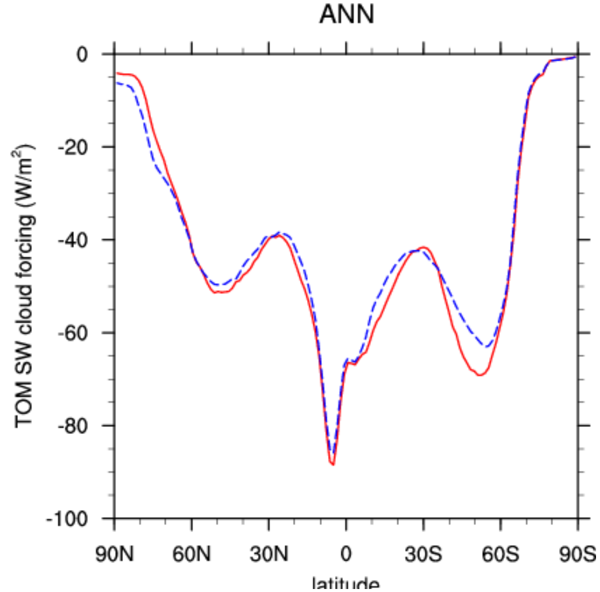
Creation of T85 CAM4 Configuration

- Simulation properties equal or superior to released Finite Volume configuration

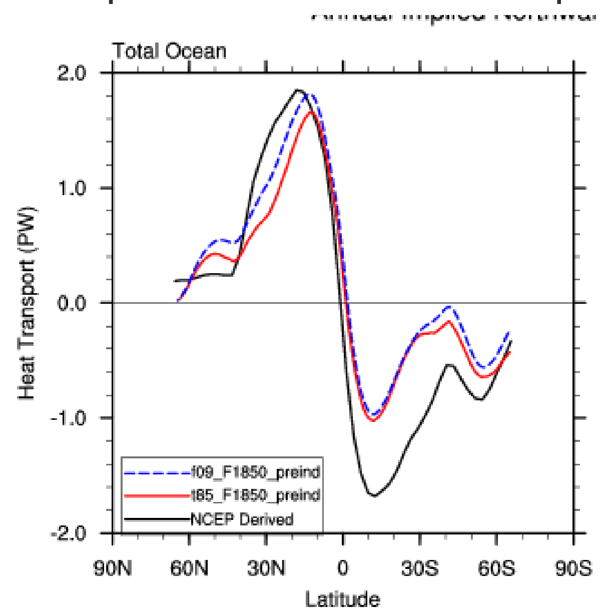
Long Wave Cloud Forcing



Short Wave Cloud Forcing

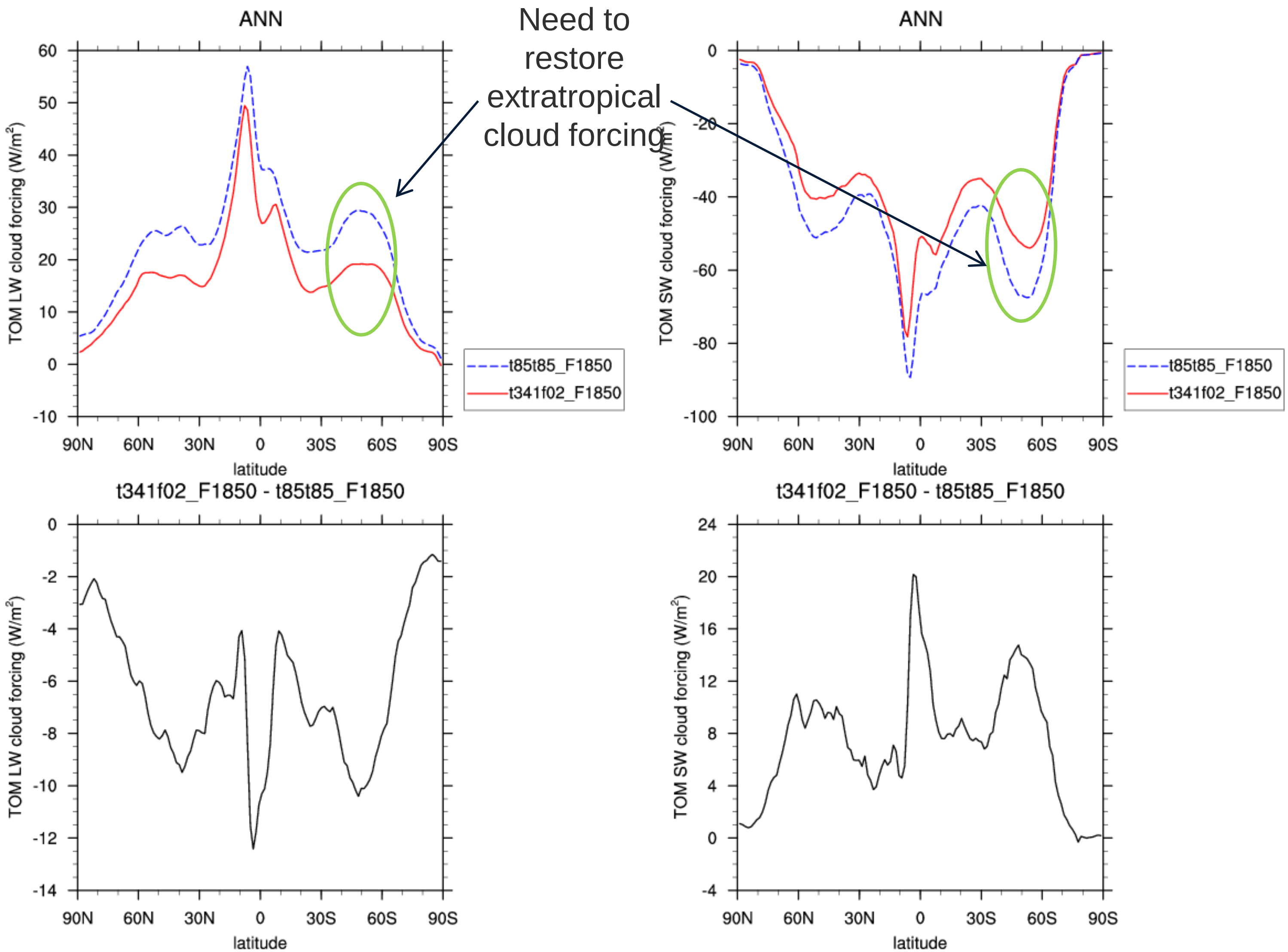


Implied Ocean Heat Transport



Creation of T341 CAM4 Configuration

- Simulation properties exhibit systematic deterioration of radiation budget



CCSM4 (CAM4) Tuning Parameter Perturbation Study T85T85.F1850

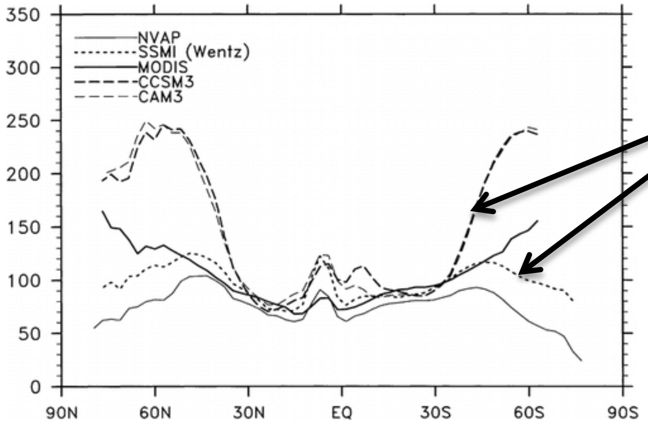
notes: all simulations run at Oak Ridge on Jaguar control simulation
(all default values) = isolated perturbaton simulations (value' per param)

Parameter	Default Value	Changed Value	Code Location	Parameter Function/Description
rhminl	.90	.45	namelist: cldfrc_rhminl (cloud_fraction.F90)	minimum rh for low stable clouds
rhminh	.77	.385	namelist: cldfrc_rhminh (cloud_fraction.F90)	minimum rh for high stable clouds
sh1	.04	.4	cloud_fraction.F90	parameter for shallow convection cloud fraction, code: shallowcu = max(0.0_r8,min(sh1*log(1.0_r8 +sh2*cmfmc2(i,k+1)),0.30_r8))
sh2	500	5000.	cloud_fraction.F90	parameter for shallow convection cloud fraction, " "
dp1	.1	1.0	cloud_fraction.F90	parameter for deep convection cloud fraction, code: deepcu = max(0.0_r8,min(dp1*log(1.0_r8+dp2*(cmfmc (i,k+1)-cmfmc2(i,k+1))),0.60_r8))
dp2	500.	5000.	cloud_fraction.F90	parameter for deep convection cloud fraction, " "
premit	250.	750.	cloud_fraction.F90	top pressure bound for mid level cloud
r3lcrit	10.0e-6	1.e-6	cldwat.F90	critical radius at which autoconverion becomes efficient
icritc	45.0e-6	4.5 e-6	cldwat.F90	threshold for autoconversion cold ice, code: icrit = icritc*wt + icritw*(1-wt)
icritw	2.e-4	.2 e-4	cldwat.F90	threshold for autoconversion warm ice, " "
conke	5. e-6	.5 e-6	cldwat.F90	tunable constant for evaporation of precip
capnw	400.	800.	cldwat.F90	warm continental cloud particles density /cm3
capnc	150.	75.	cldwat.F90	cold continental and oceanic cloud particles density / cm3
capnsi	75.	30.	cldwat.F90	sea ice cloud particles density /cm3
cmftau	1800.	3600.	hk_conv.F90	characteristic adjustment time scale for moist convection (time over which convection is assumed to act)
c0	5. e-5	5. e-6	hk_conv.F90	rain water autoconversion coefficient for moist convection
tau	3600.	7200.	zm_conv.F90	convection time scale
c0	3.5 e-3	3.5 e-4	zm_conv.F90	used for condensed liquid/rain production rate, tunable param
ke	1.e -6	1.e -5	zm_conv.F90	tunable evaporation efficieny
rliqocean	14.	7.	pkg_cldoptics.F90	liquid drop size over ocean (micron)
rliqland	8.	4.	pkg_cldoptics.F90	liquid drop size over land (micron)
rliqice	14.	7.	pkg_cldoptics.F90	liquid drop size over ice (micron)

Cloud problem not addressable with available degrees of freedom

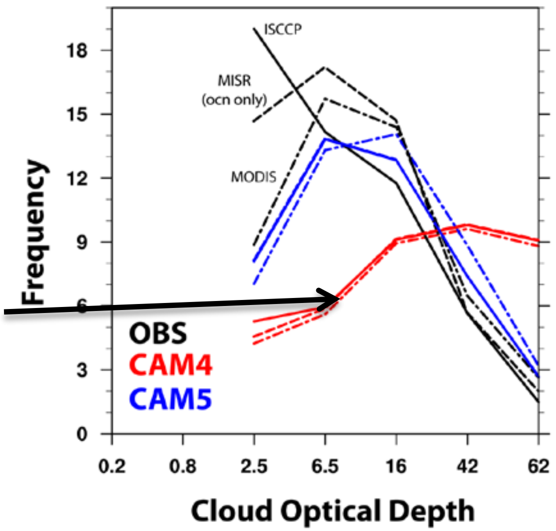
Creation of T341 CAM4 Configuration

- Treatment of clouds with increasing resolution remains 1st order problem



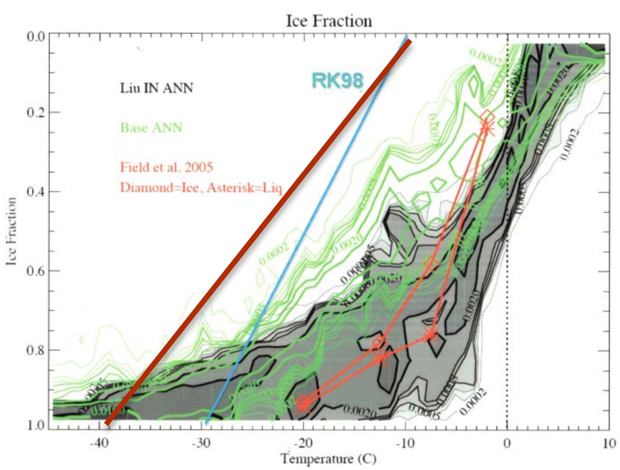
Apparent excessive liquid water path lengths (CAM3)

Hack et al. (2006)



Too many optically thick clouds

Jennifer Kay, NCAR (2011)



Diagnosed relationship between condensed water and ice inconsistent with newer observations and detailed microphysics simulations

Andrew Gettelman, NCAR (2010)

Creation of T341 CAM4 Configuration

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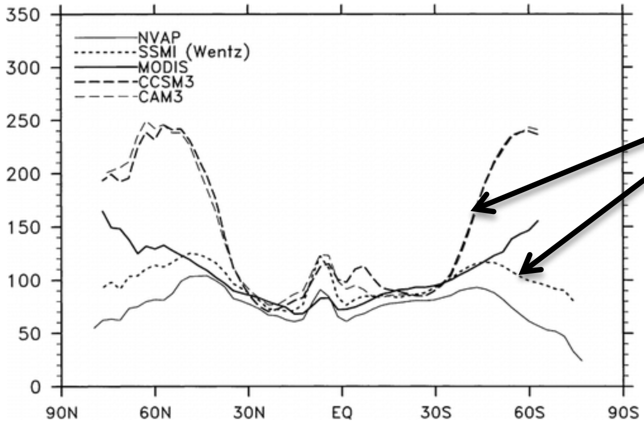

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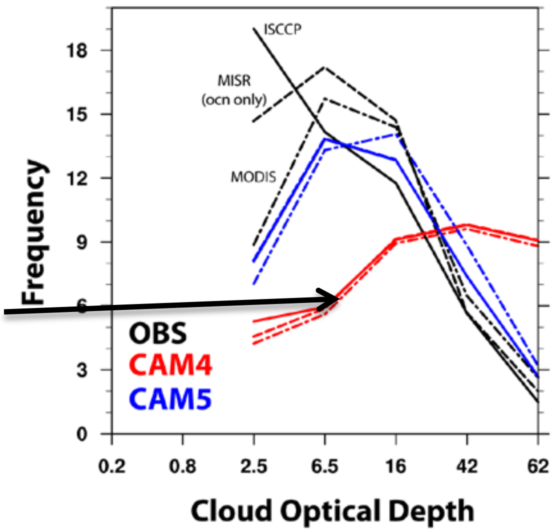

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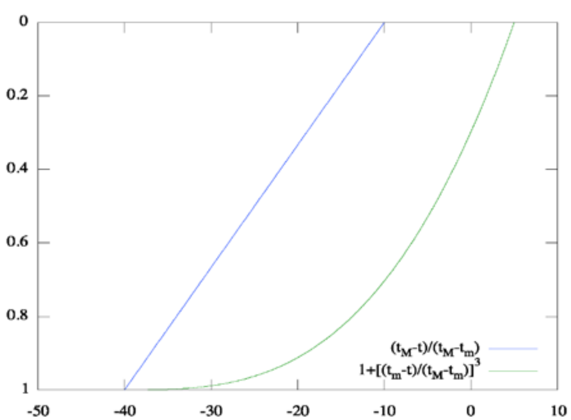
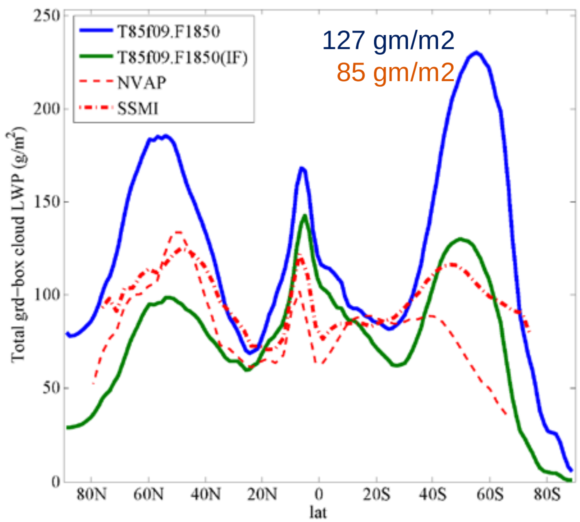
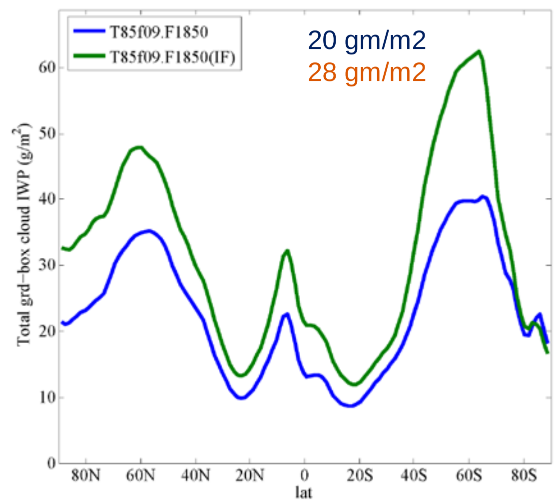


Diagnosed relationship between condensed water and ice inconsistent with newer observations and detailed microphysics simulations

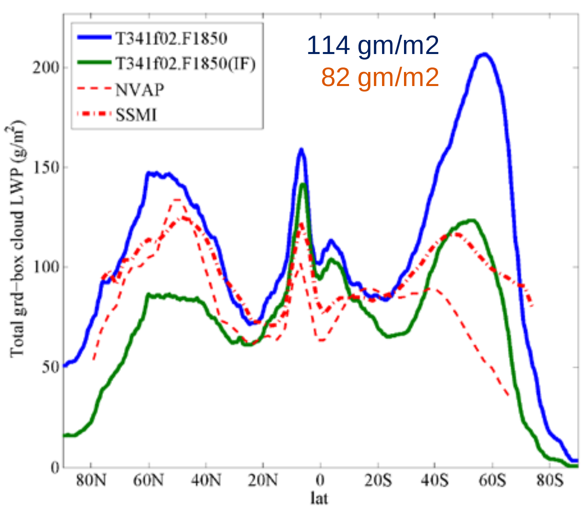
Creation of T341 CAM4 Configuration

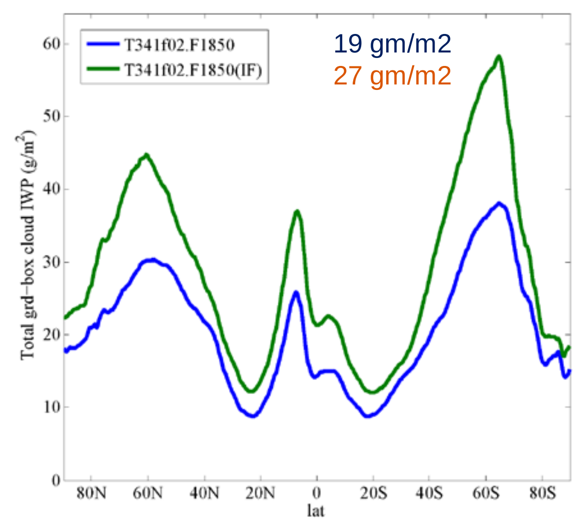
- More realistic diagnostic cloud condensate relationship (Hack and Archibald)





T85





T341

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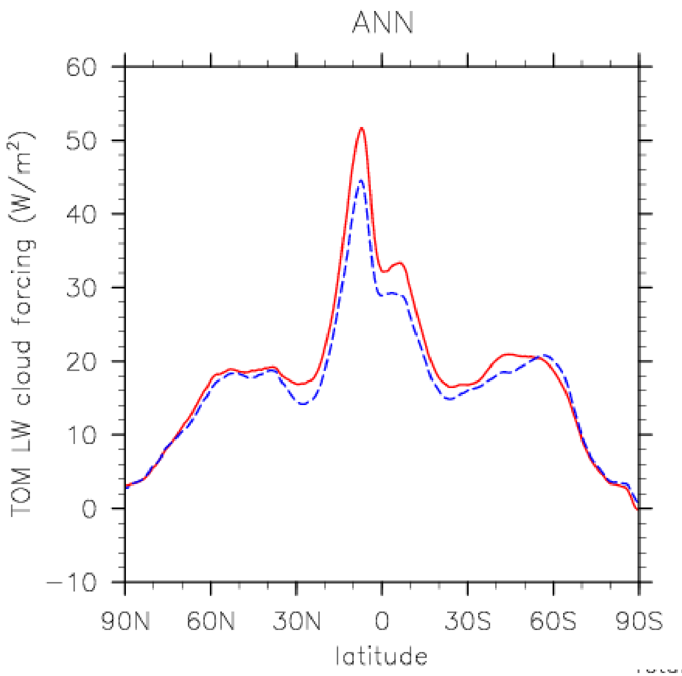
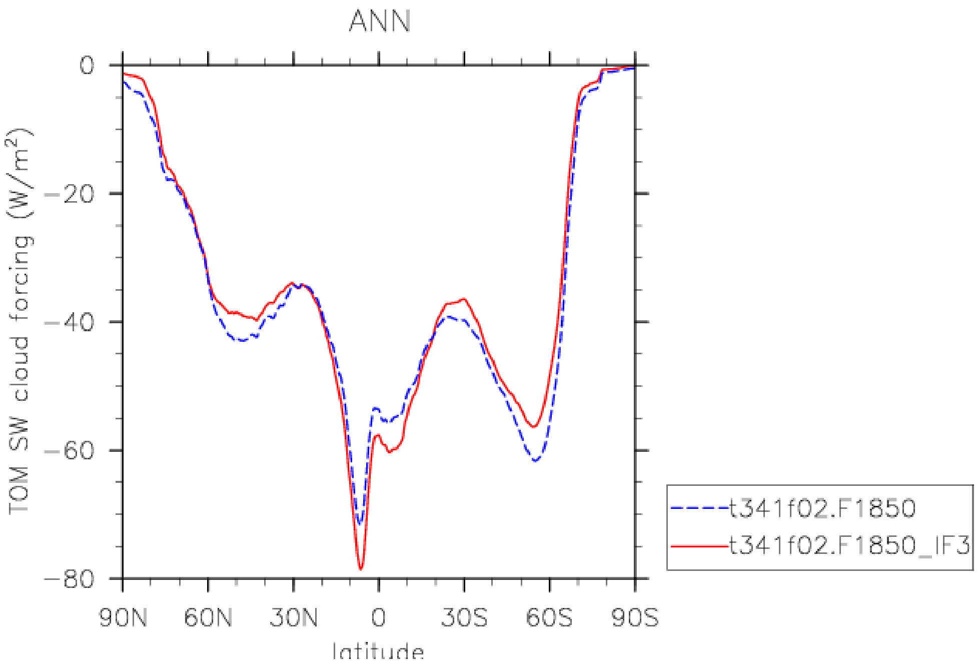
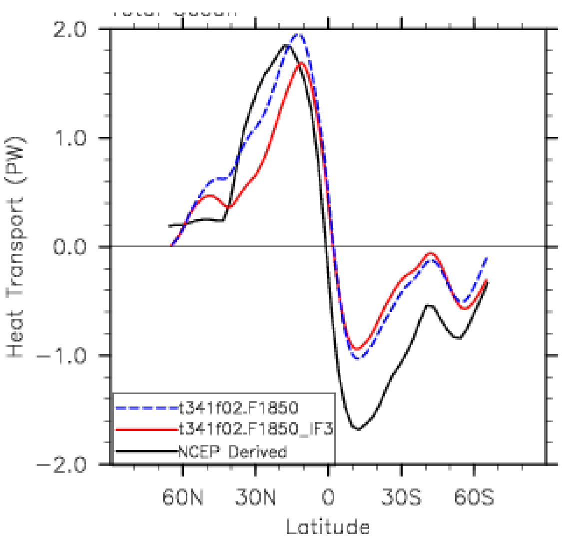
Creation of T341 CAM4 Configuration

- Energetically similar atmospheric component model



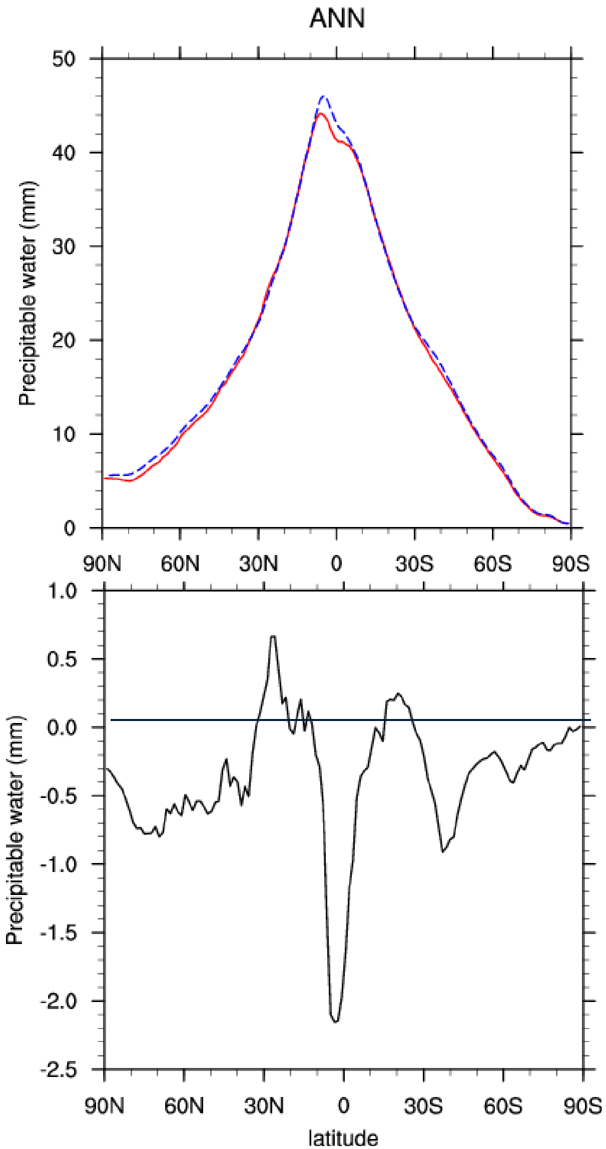


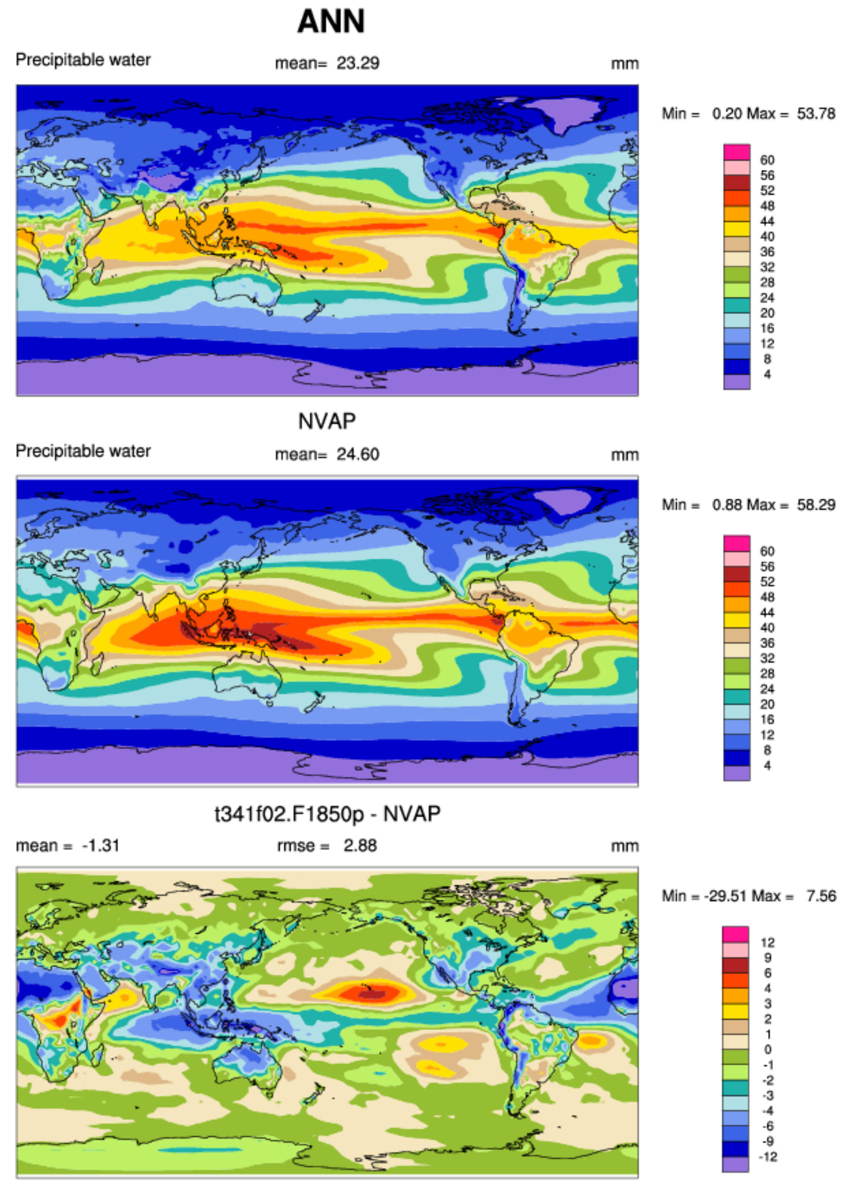


Very similar northward ocean transport requirements

Creation of T341 CAM4 Configuration

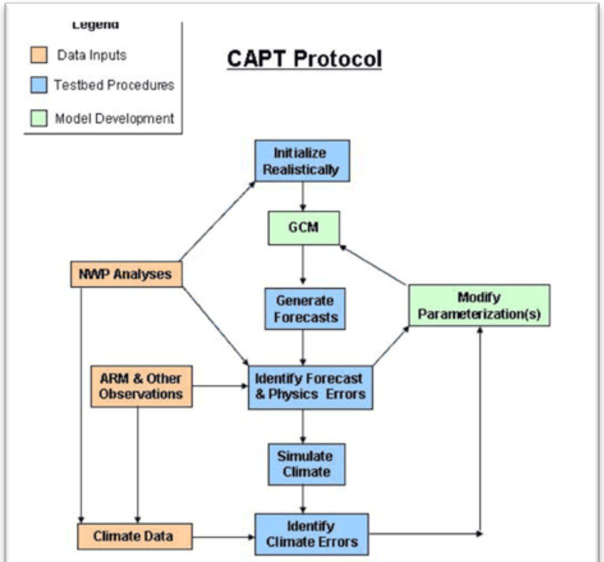
- Points to need for fundamental research into maintenance of water cycle





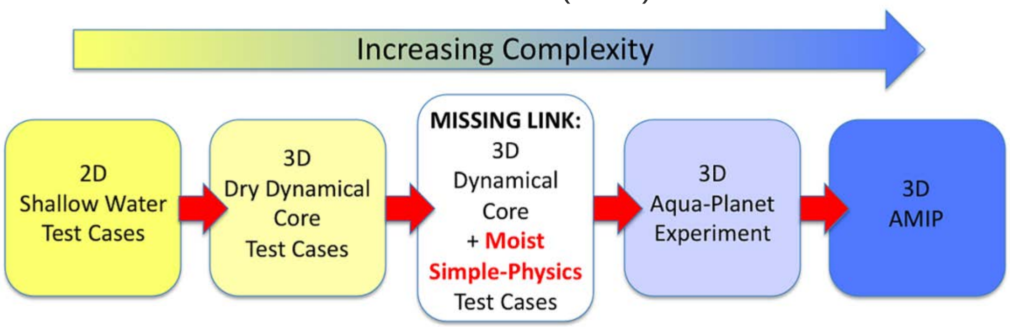
Validation frameworks

- Deterministic time scales

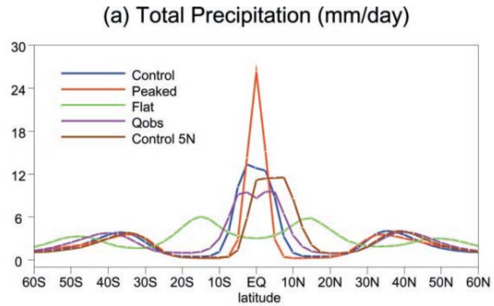


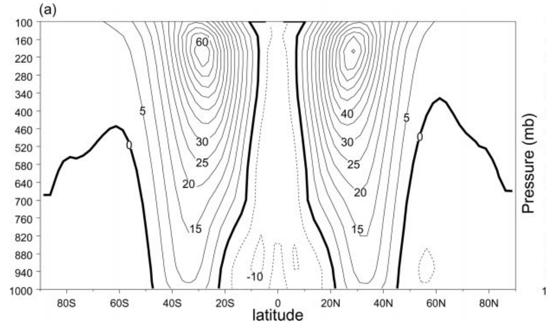
Klein, Williamson, et al.

Reed and Jablonowski (2012)



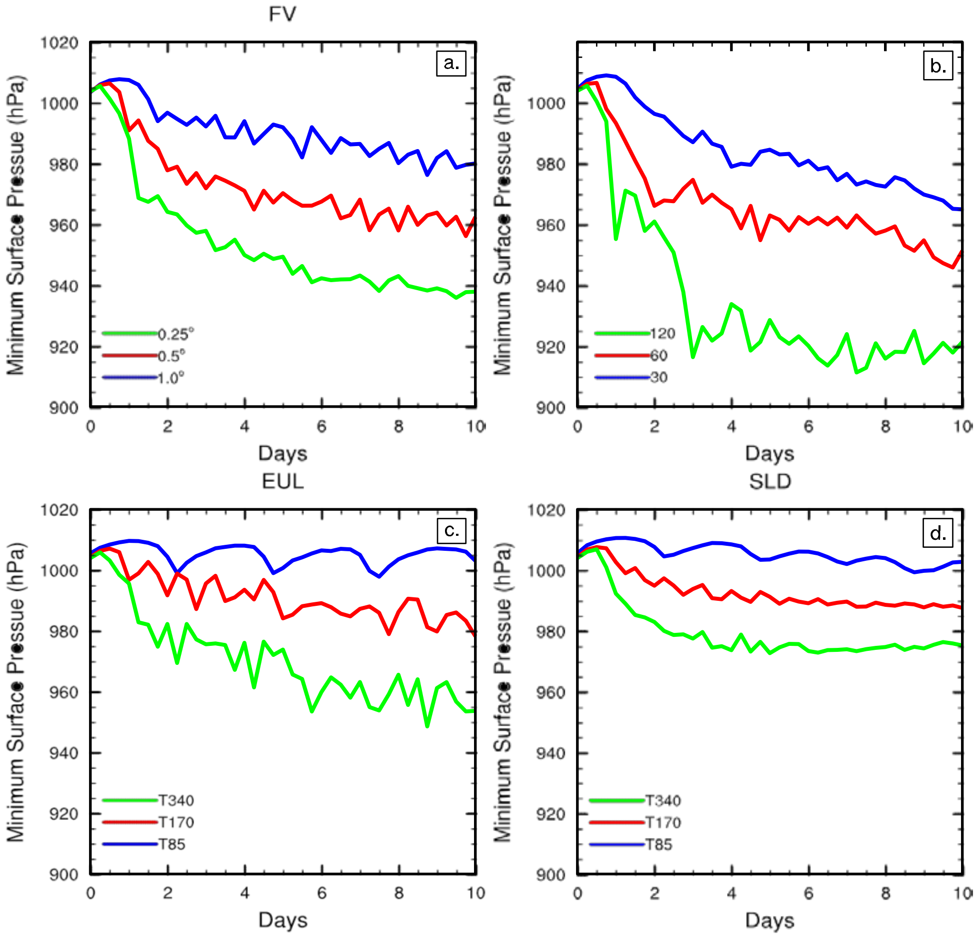
- Climate time scales
  - aqua-planet configurations (Neale and Hoskins, 2000)



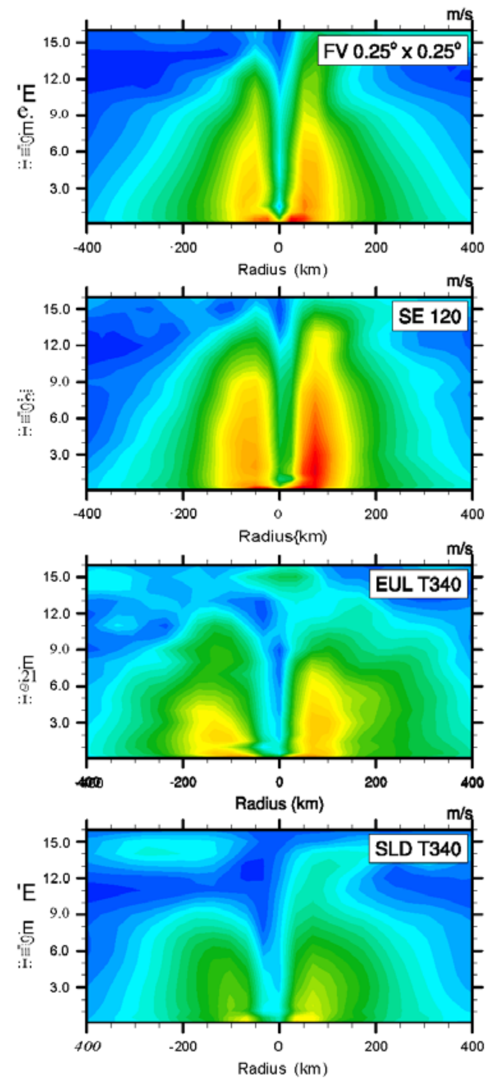


In context of new atmospheric test case

- Identifying simple test cases that allow for phase change is hard



Which solution is the “right” one?



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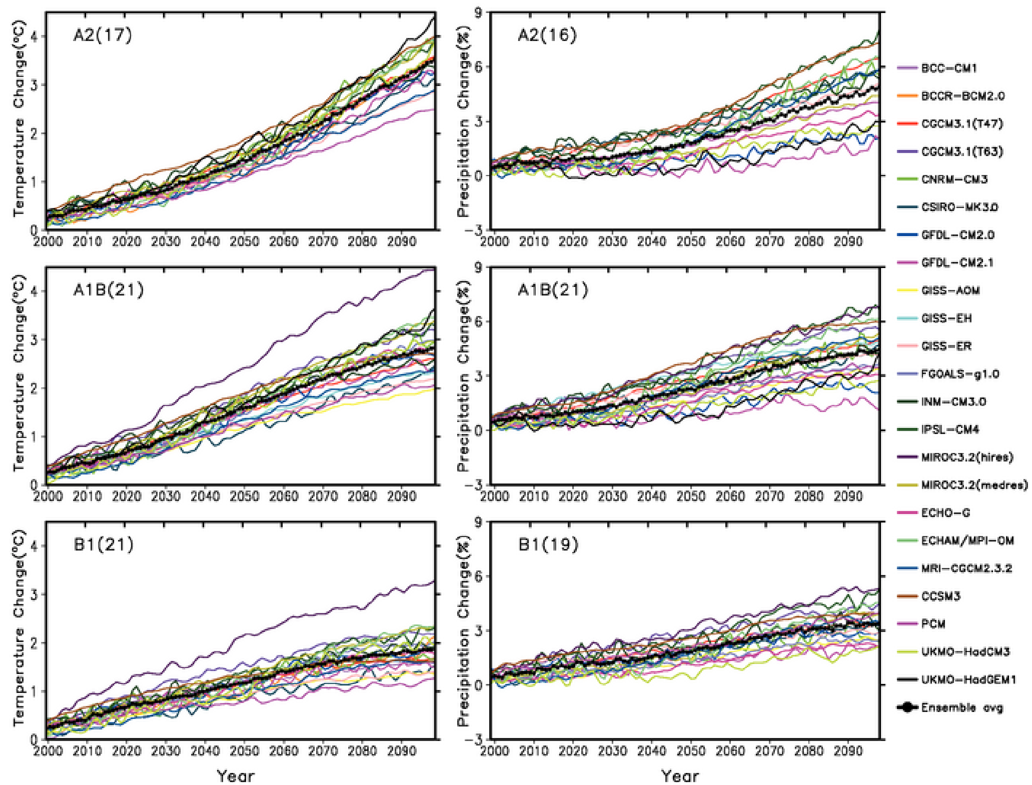
Comprehensive explorations of parameter space moving far beyond expert capabilities

- CAM5
  - far more complex and sophisticated framework than earlier models
  - manual optimization of parametric formulations too laborious and incomplete

- All models more complex
  - disagreement in projections remain large
  - growing emphasis on understanding sources of uncertainty in global simulation tools
  - there is agreement that the answer likely lies in formulation of non-resolvable physics



Uncertainty Quantification

- Uncertainty
  - how accurately does a mathematical model describe the true physics and what is the impact of model uncertainty (structural or parametric) on outputs from the model?
  - Structural uncertainty
    - do the equations accurately describe the physics?
  - Parametric uncertainty
    - how accurate are the model parameters?

Uncertainty quantification in climate models is challenged by the sparsity of the available climate data due to the high computational cost of the model runs. Another feature that prevents classical uncertainty analyses from being easily applicable is the bifurcative behavior in the climate data with respect to certain parameters.

Uncertainty Quantification in the Presence of Limited Climate Model Data with Discontinuities, Sargsyan et al. [2009]

One example of growing community efforts

21 Parameters in Initial UQ Studies

Richard Klein, Curt Covey, Don Lucas, John Tannahill, Yuhing Zhang, Peter Gleckler, Steve Klein, Garder Johanneson, Carol Woodward, Jeff Hittinger, and many others

	Variable Name	Description	Nmlist Prefix	File Name	Source*
1	rhminh	Minimum RH for high stable cloud formation	cldfrc_	cloud_fraction.F90	J
2	rhminl	Minimum RH for low stable cloud formation	cldfrc_	cloud_fraction.F90	J+S
3	rliqice	Liquid drop size over sea ice	cldopt_	pkg_cldoptics.F90	R
4	rliqland	Liquid drop size over land	cldopt_	pkg_cldoptics.F90	R
5	rliqocean	Liquid drop size over ocean	cldopt_	pkg_cldoptics.F90	R
6	ice_stokes_fac	Ice Stokes factor scaling fall speed	cldsed_	pkg_cld_sedimnent.F90	S
7	capnc	Cloud particle # dens. over cold land/ocean	cldwat_	cldwat.F90	R
8	capnsi	Cloud particle # dens. over sea ice	cldwat_	cldwat.F90	R
9	capnw	Cloud particle # dens. over warm land	cldwat_	cldwat.F90	R
10	conke	Stratiform precip. evaporation efficiency	cldwat_	cldwat.F90	J
11	icritc	Threshold for cold ice autoconversion	cldwat_	cldwat.F90	S
12	icritw	Threshold for warm ice autoconversion	cldwat_	cldwat.F90	S
13	r3lcrit	Crit. radius where liq. conversion begins	cldwat_	cldwat.F90	R
14	ricr	Critical Richardson # for boundary layer	hbdiff_	hb_diff.F90	K/B
15	c0/shallow	Shallow convec. precip. efficiency parameter	hkconv_	hk_conv.F90	J
16	cmftau	Time scale for consump. rate of shallow CAPE	hkconv_	hk_conv.F90	K/B
17	alfa	Initial cloud downdraft mass flux	zmconv_	zm_conv.F90	J
18	c0/deep	Deep convec. precip. efficiency parameter	zmconv_	zm_conv.F90	J
19	dmpdz	Parcel fractional mass entrainment rate	zmconv_	zm_conv.F90	S
20	ke	Environmental air entrainment rate	zmconv_	zm_conv.F90	J
21	tau	Time scale for consump. rate of deep CAPE	zmconv_	zm_conv.F90	J

* J = Jackson et al. (2008) J Clim 21: 6698; R = P. Rasch (2009) suggestion; S = Sanderson (2009) talk at CCSM Workshop; SK = S. Klein + D. Bader (2009) suggestion

Reducing uncertainty

Climate Science for a Sustainable Energy Future (CSSEF)

- Accelerate incorporation of new knowledge, including process data and observations, into climate models
- Develop new methods for rapid evaluation of improved models.
- Develop novel approaches to exploit computing at the level of tens of petaflops in climate models

Identify the most important unresolved processes

Identify critical underutilized datasets

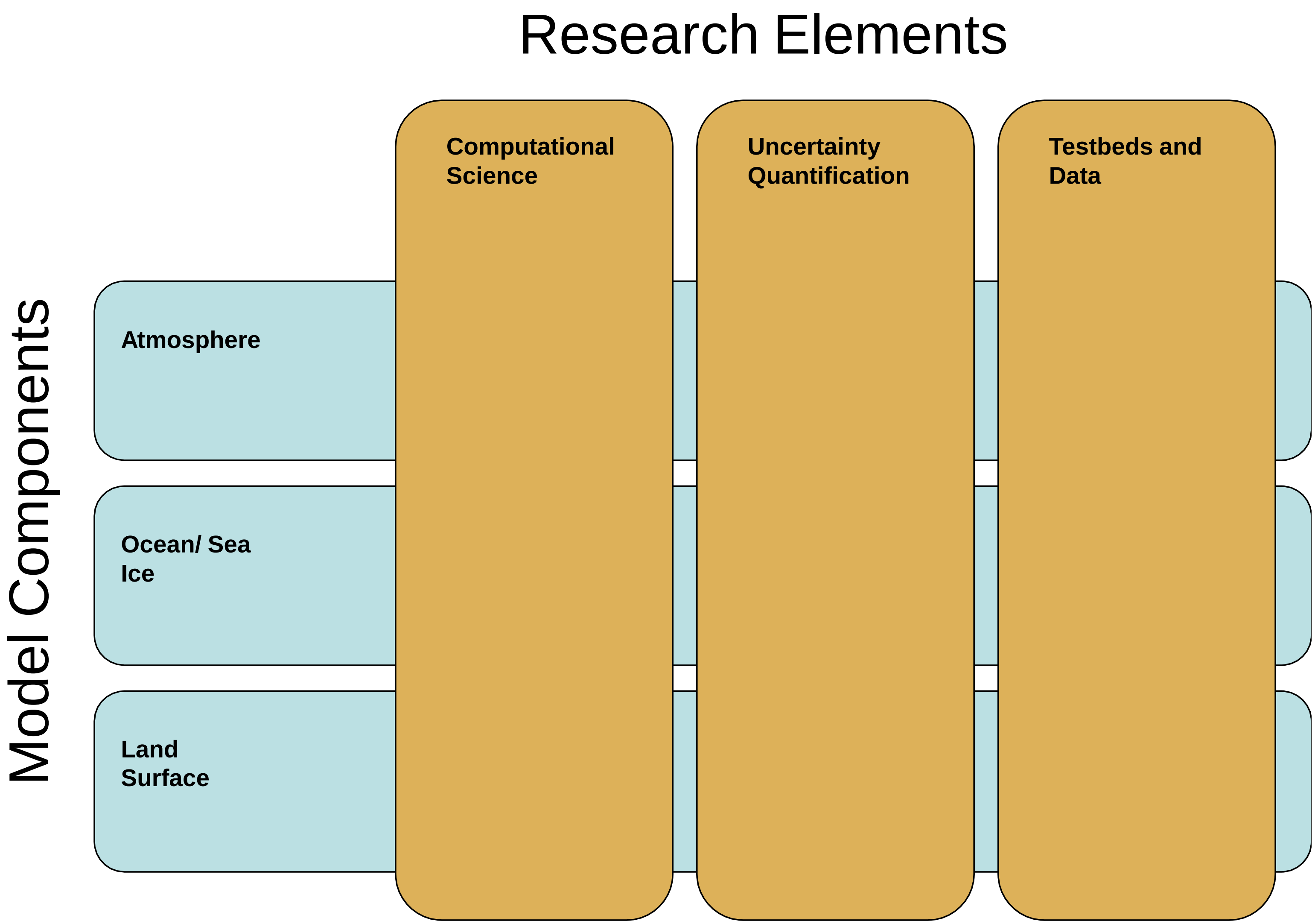
Develop comprehensive testbeds

Formal incorporation of uncertainty quantification

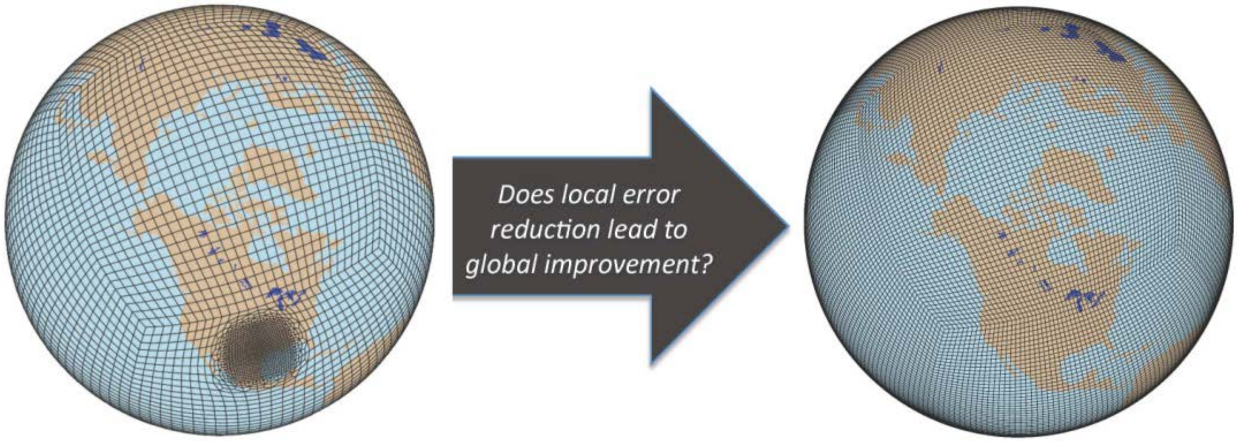
comprehensive multi-variate optimization, with formal parametric uncertainty estimates and characterization of error propagation

Reducing uncertainty

Climate Science for a Sustainable Energy Future (CSSEF)



Atmospheric Testbed



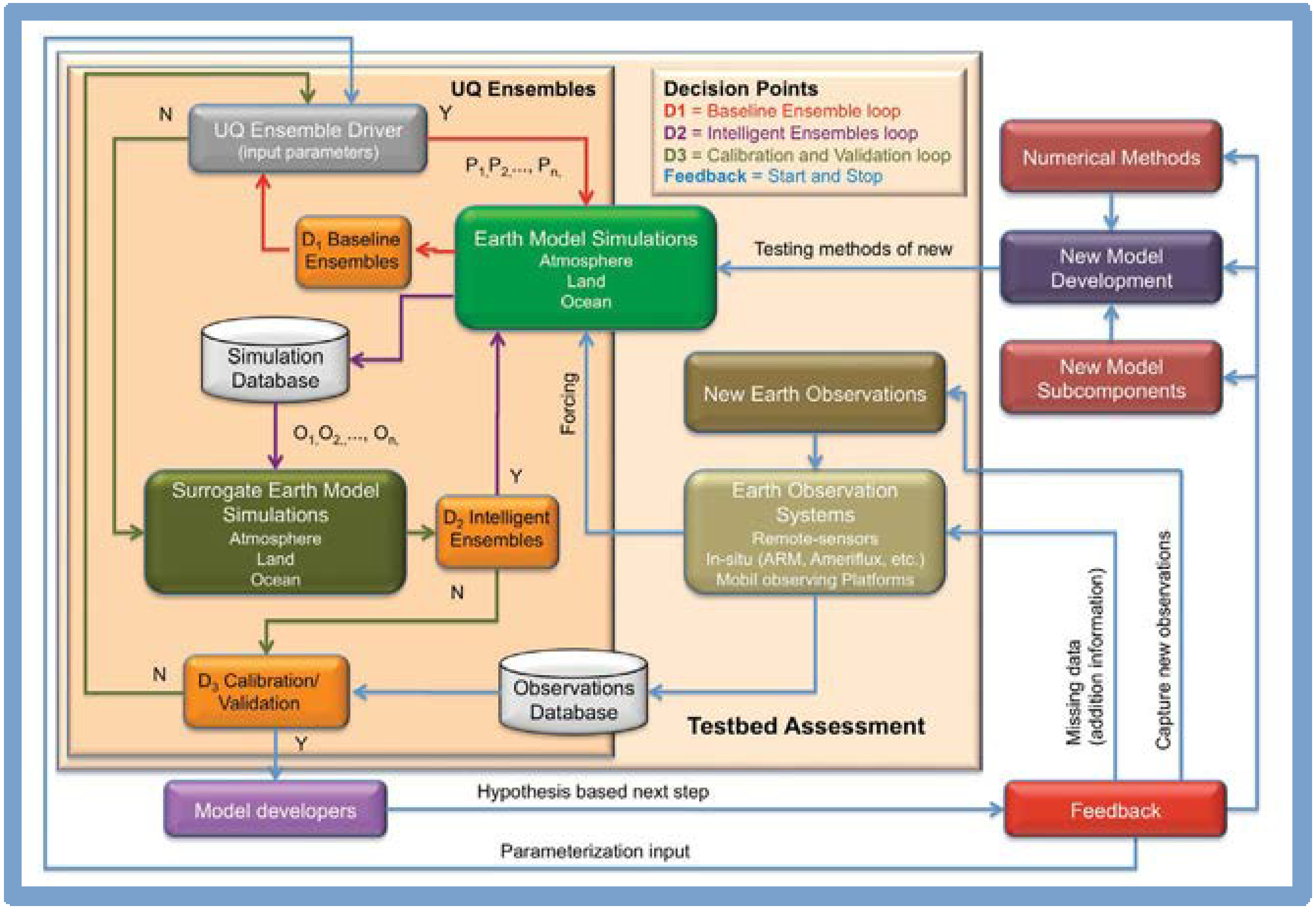
Calibration Platform

Validation Platform

Characteristics of Calibration and Validation Platforms

	Calibration Platform	Validation Platform
Model Construction	Global model with static mesh refinement above sites of interest	Global model with uniform grid
Forcing	Weather-forecast mode with nudging to analysis data on coarse outer grid	Free-running climate mode with initial condition from analysis data
Initial Resolution	1/8° fine mesh transitioning to 1°	1/8° everywhere
Uncertainty Quantification Methods	Parameter tuning: calibration of uncertain parameters with local data sets	Ensemble of simulations with parameter sets generated by parameter tuning
Data sets	Local water cycle data sets such as ACRF site data	Global data sets such as satellite or re-analysis data

CSSEF Testbed



The CSSEF testbed and development system was designed by the crosscutting Data Infrastructure and Testbed team based on requirements set by CSSEF modelers and observational scientists.

Summary

- Why are the models different from one another?
  - tied up in approximations and completeness of formulation
  - "tuning" is a part of the approximation process
- Ideas for systematic approach to improving models?
  - exploit observations on hierarchy of time and space scales
  - exploit hierarchy of modeling tools to promote understanding
  - formally include systematic methods for exploring structural and parametric uncertainty
    - Observations are an essential component of this process
- How can we judge whether the models are improving (metrics)?
  - depends on the question, but models frequently have strengths and weaknesses
  - demonstrating quantitative reductions in uncertainties provides a defensible argument

The End