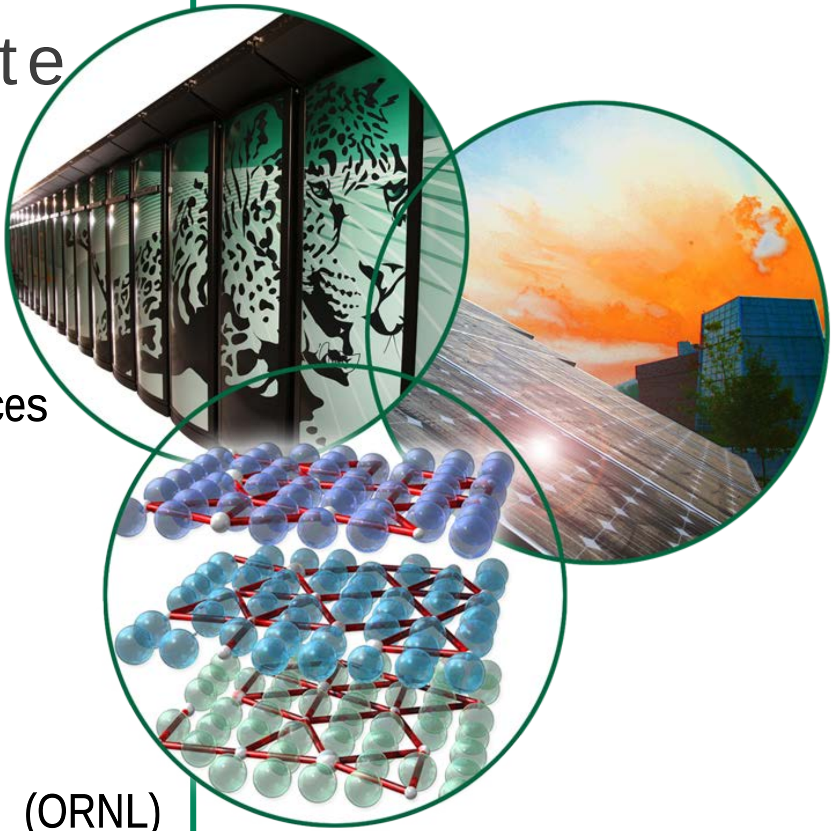
Ultra High Resolution Global Climate Simulation to Explore and Quantify Predictive Skill for Climate Means, Variability and Extremes



James J. Hack
Director, National Center for Computational Sciences
Oak Ridge National Laboratory

DOE BER Modeling Science Team Meeting

Washington, DC

19 September 2011

The Team

Jim Hack	(ORNL)
Phil Jones	(LANL)
Bill Collins	(LBNL)
Ken Sperber	(LLNL)

and many others!!

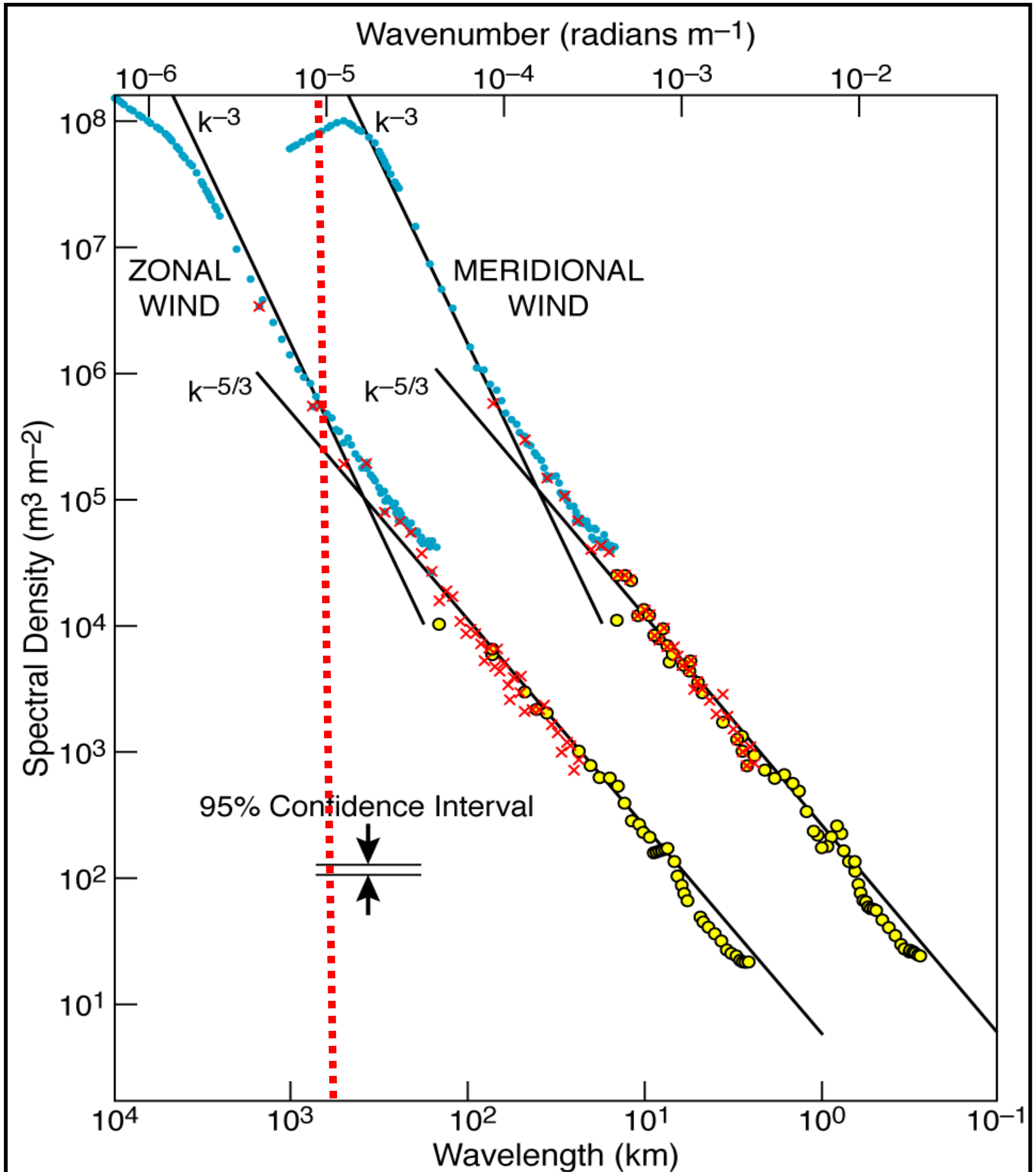
Experimental Protocol

- Simulation biases in earlier investigations point to need to address several important details about the high-resolution configuration
  - Initial ocean state
  - Proper representation of climate system's energy balance
  - Potential role for atmospheric dynamical core to introduce systematic biases
- Experimental protocol provides for
  - Exploration of realistic initial ocean state free of excessive drift
  - Spinup of system to provide best representation of global energy budget
  - An experimental suite designed to address resolution hypotheses
  - Exploration of three atmospheric dynamical cores (FV, spectral, spectral element)
  - Comprehensive and systematic plan for simulation evaluation
    - Systematic bias, low/high frequency modes of variability, regional climate quality, analysis of extremes

First Steps

- ***Multiple-resolution CCSM coupled modeling capability***
- ***Develop robust evaluation frameworks***

Kinetic energy spectra from aircraft



Unresolved processes and upscale energy transports in models

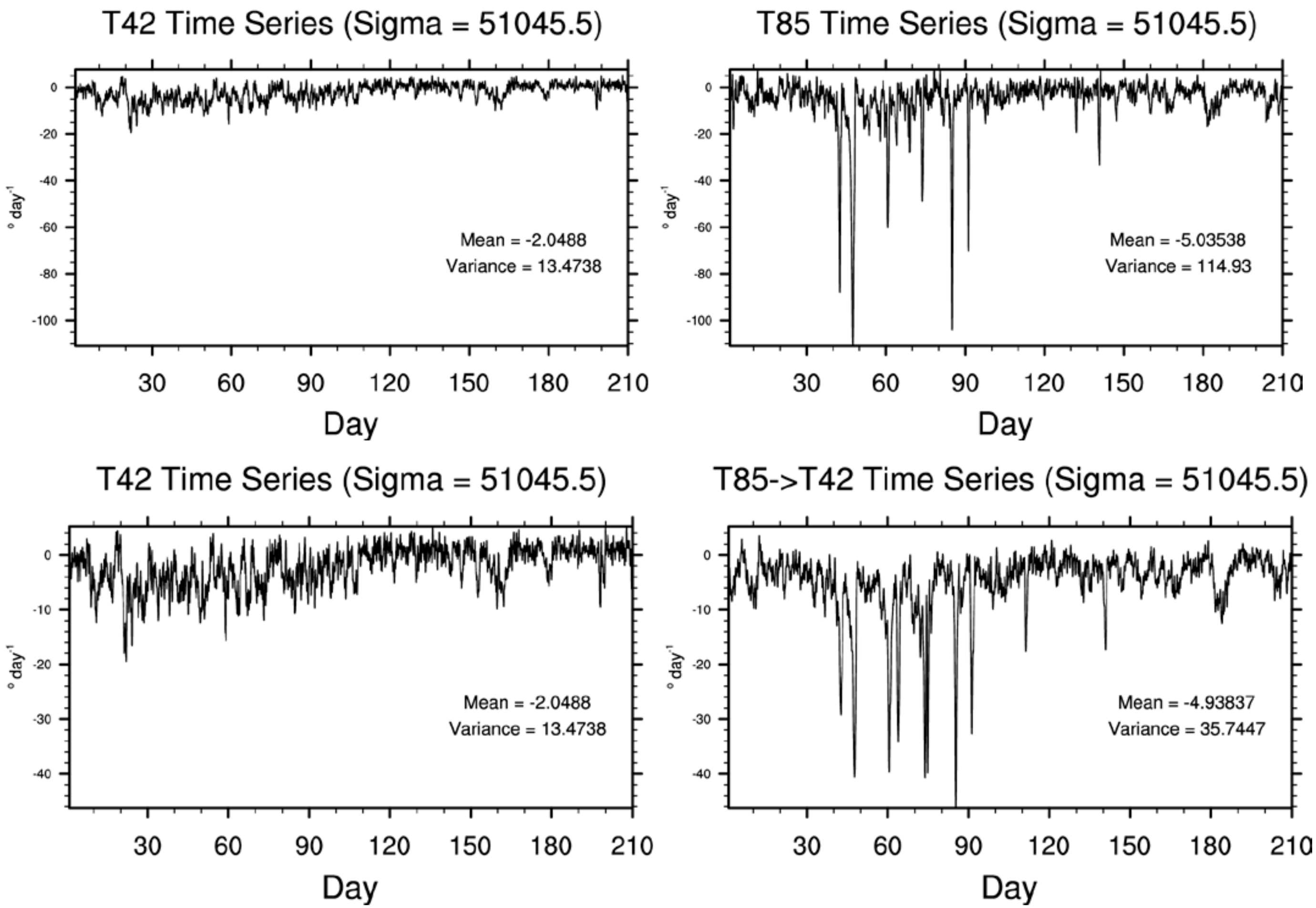
- Traditionally assume that effects of unresolved scales can be represented through parametrizations based on bulk formulae.
- Inherently assumes that there is no coupling between dynamics and physics on these unresolved scales.
- Essentially ignores upscale energy cascades

Nastrom and Gage, 1985

Original image from Julia Slingo

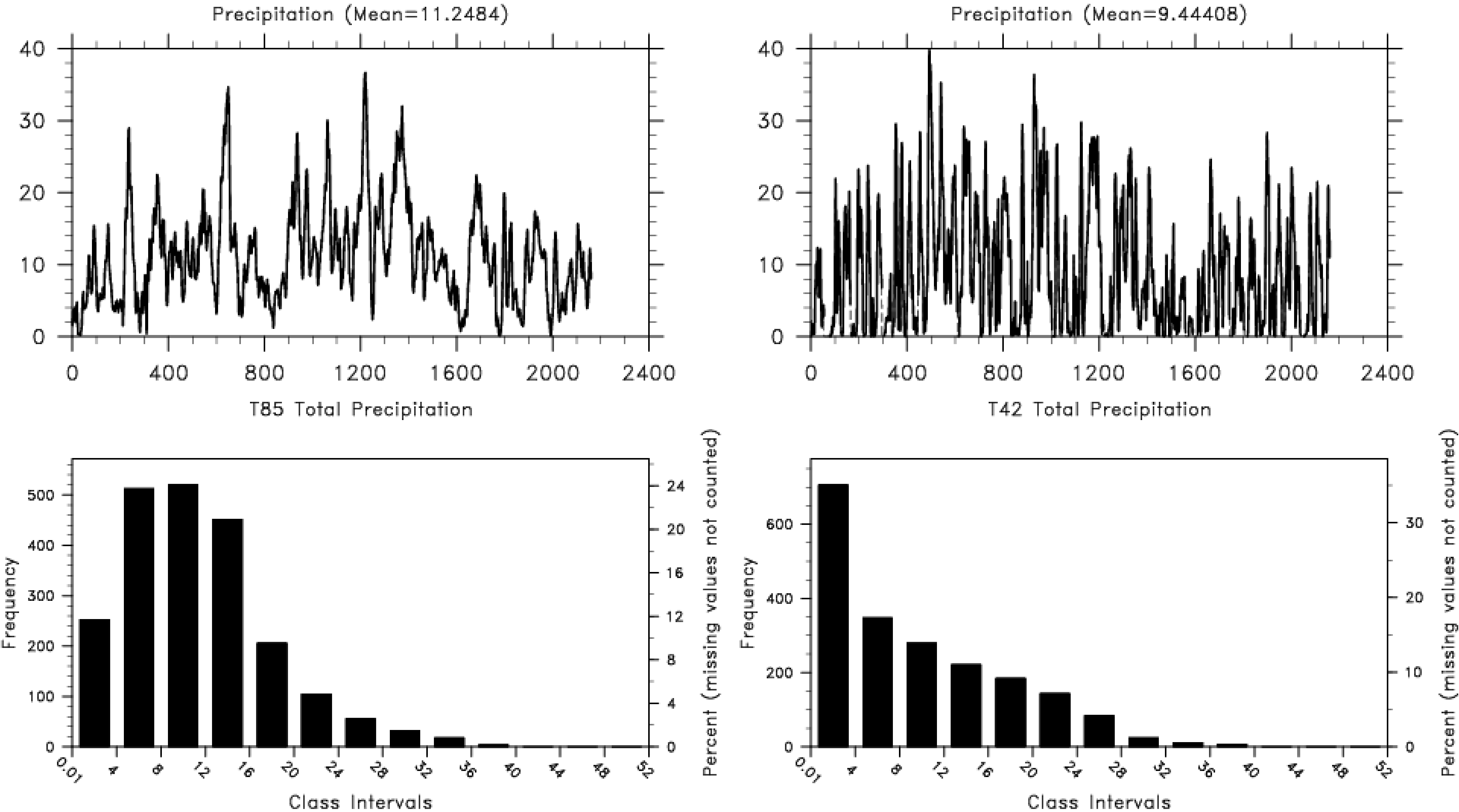
Middle atmospheric thermodynamic time series

$$-\nabla \cdot \overline{\mathbf{V}s} - \frac{\partial \overline{\omega s}}{\partial p}$$



Hack and Caron

Regional Simulation of Warm Pool Precipitation



Hack and Caron

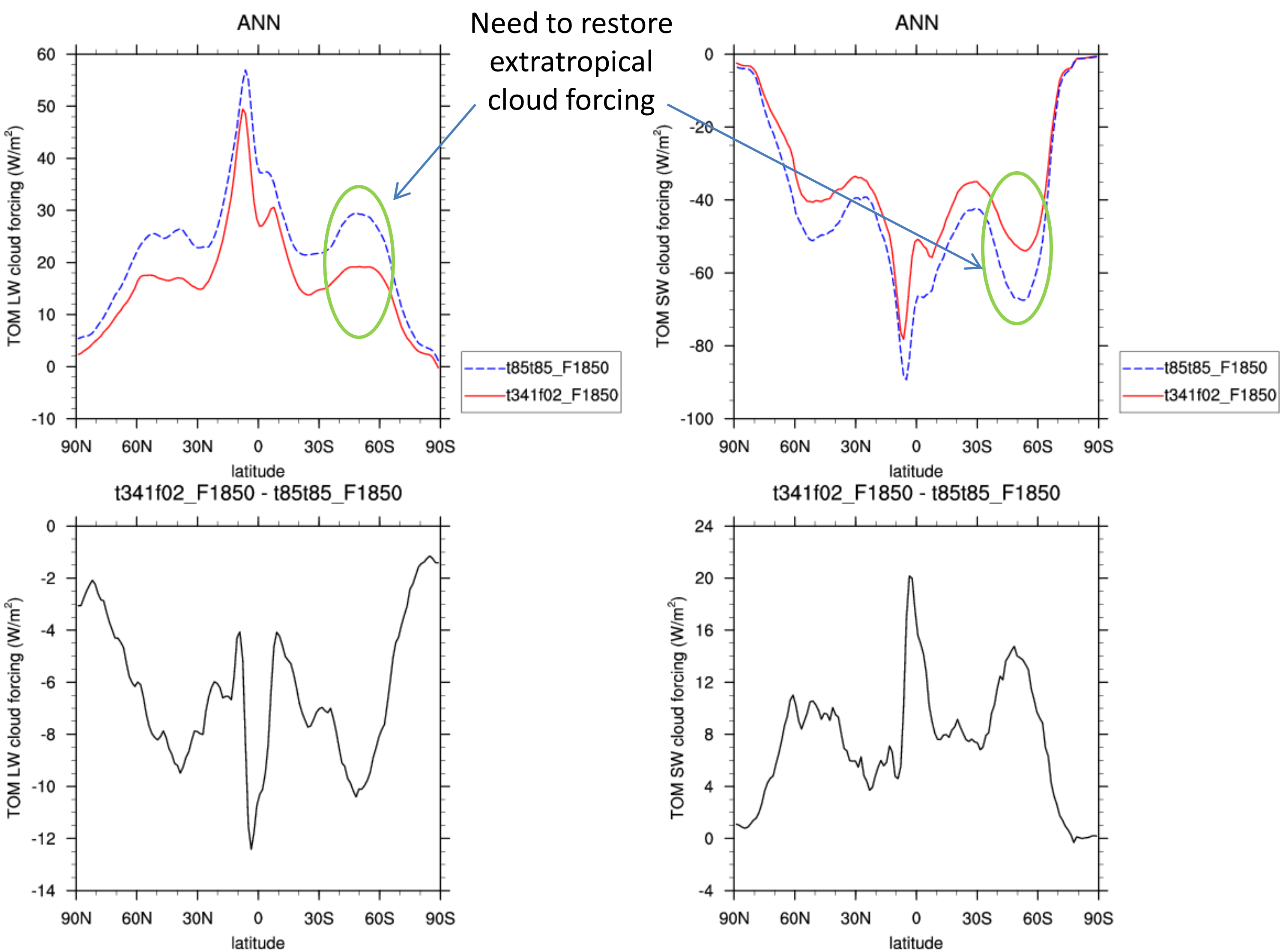
Multi-scale multi-physics systems

- Parameterized physics behavior varies with resolution
  - changes with horizontal resolution (difficult challenge)
    - time and space truncation properties
  - changes with vertical resolution (extremely difficult challenge)

- Parameterized processes must be “tuned”
  - main constraint is mean statistical behavior
  - other constraints relate to behavior of individual processes
    - unfortunately observational constraints are limited

Creation of T341 Configuration

- Simulation properties exhibit systematic deterioration of radiation budget



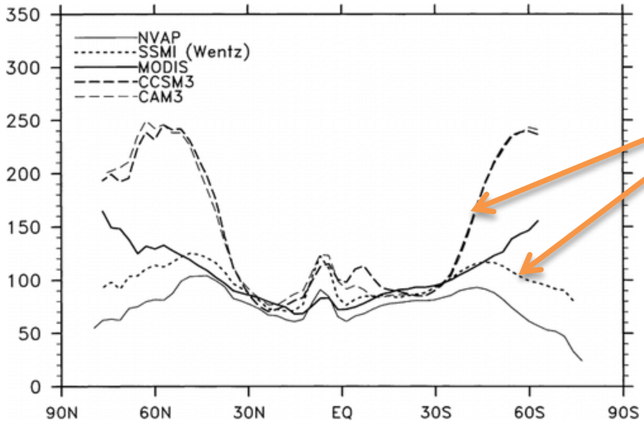
CCSM4 (CAM4) Tuning Parameter Perturbation Study T85T85.F1850

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)

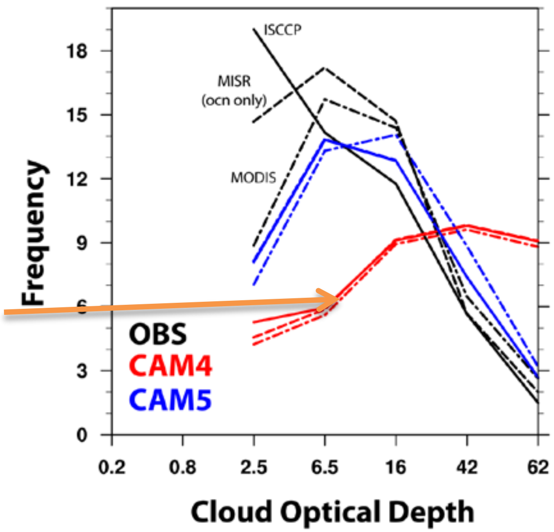
Creation of T341 Configuration

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



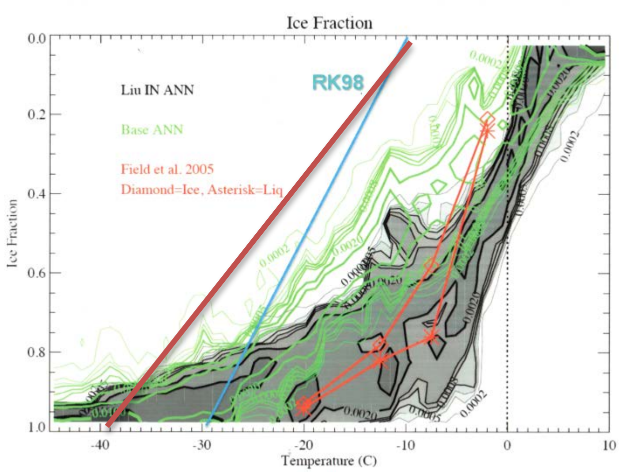
Apparent excessive liquid water path lengths (CAM3)

Hack et al. (2006)



Too many optically thick clouds

Jennifer Kay, NCAR (2011)

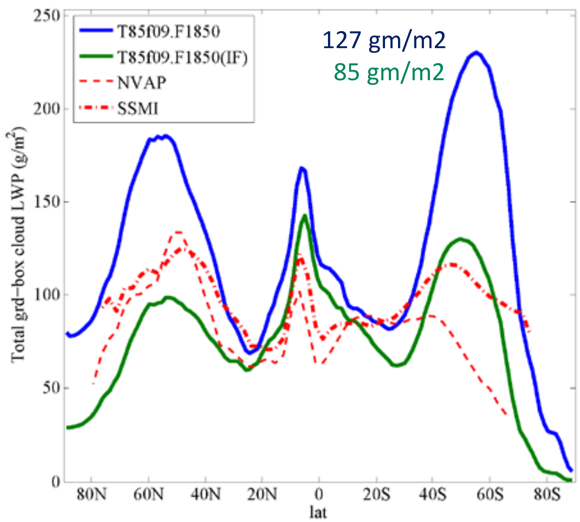


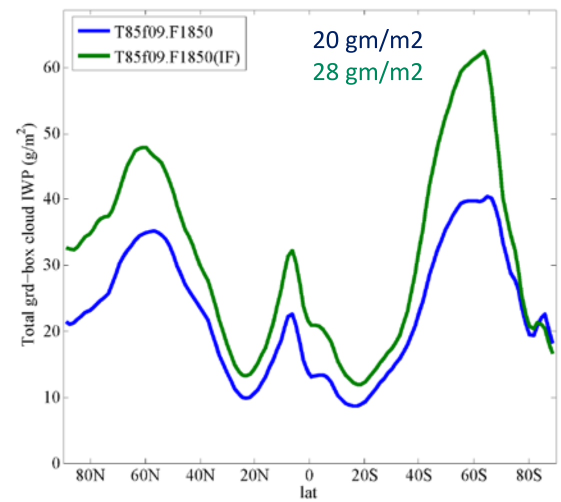
Diagnosed relationship between condensed water and ice inconsistent with newer observations and detailed microphysics simulations

Andrew Gettelman, NCAR (2010)

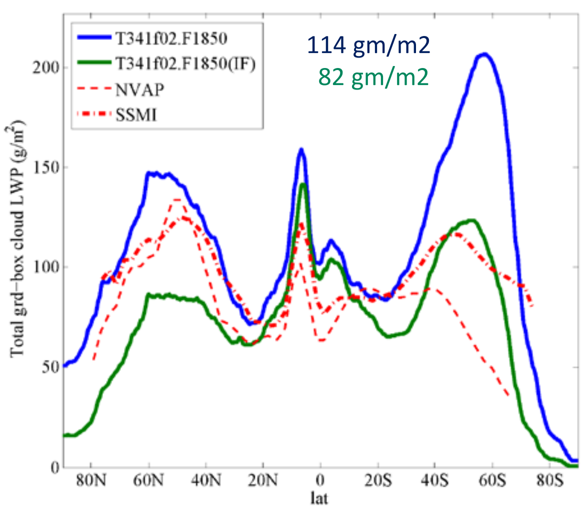
Creation of T341 Configuration

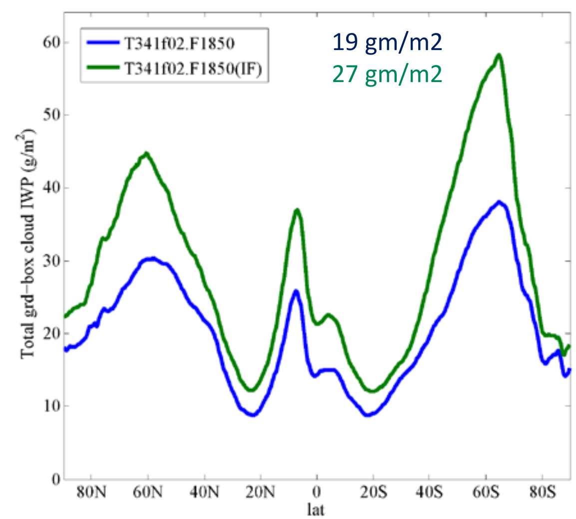
- More realistic diagnostic cloud condensate relationship (Hack and Archibald)





T85

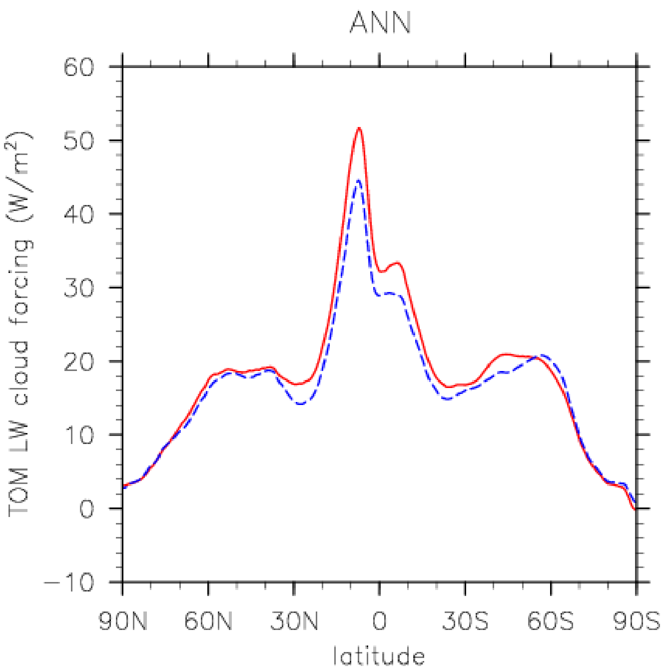


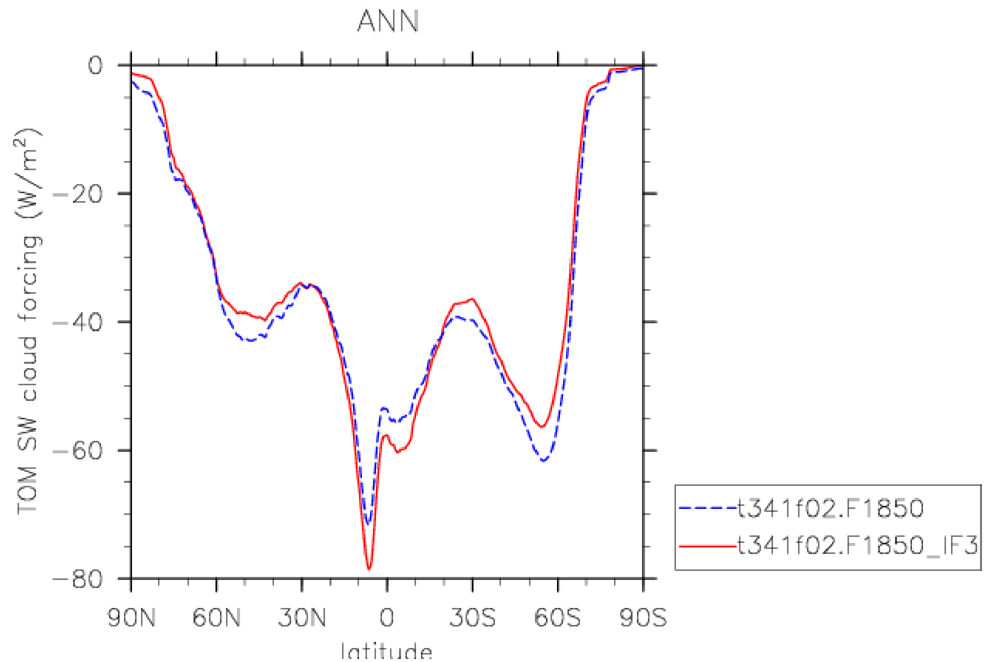


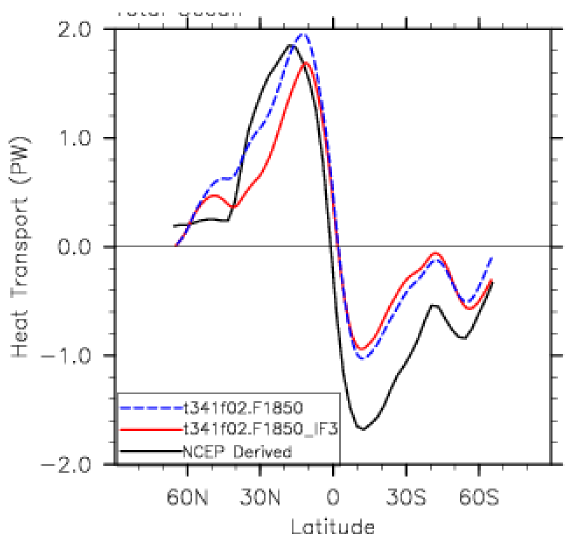
T341

Creation of T341 Configuration

- Energetically similar atmospheric component model



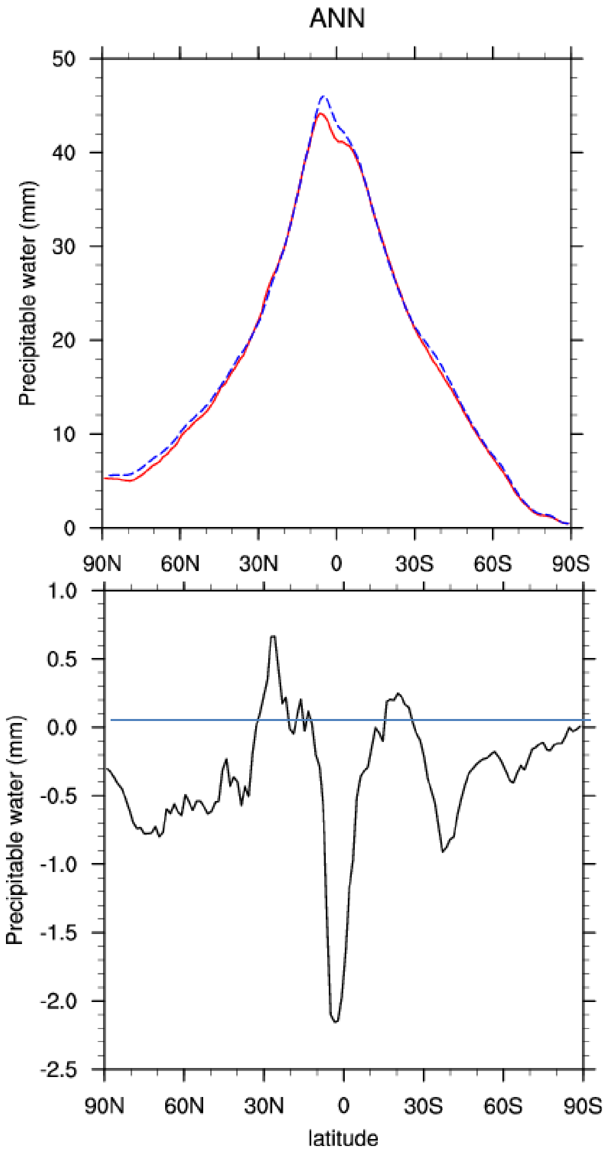


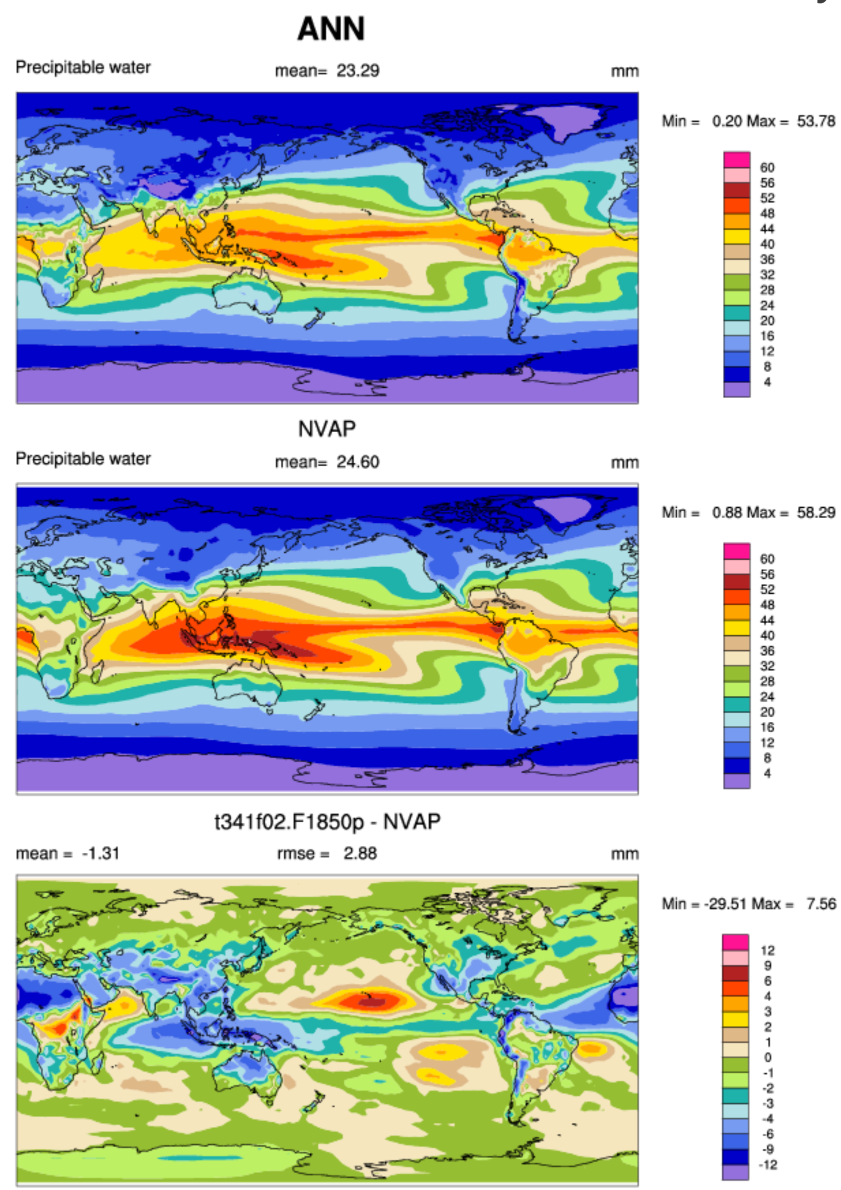


Very similar northward ocean transport requirements

Creation of T341 Configuration

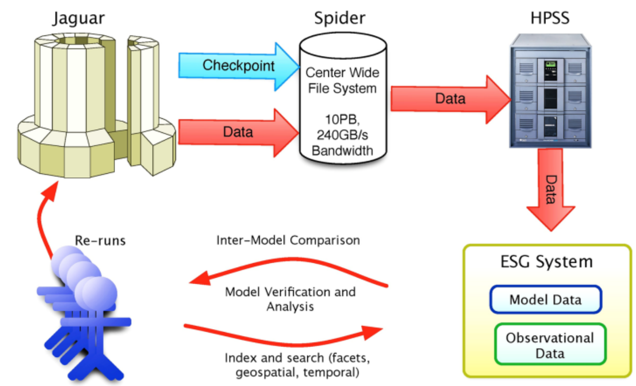
- Points to need for fundamental research into maintenance of water cycle

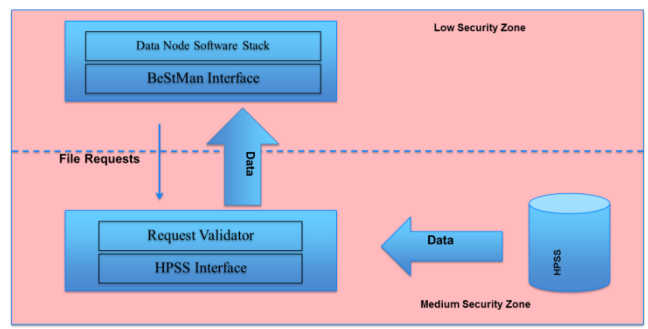


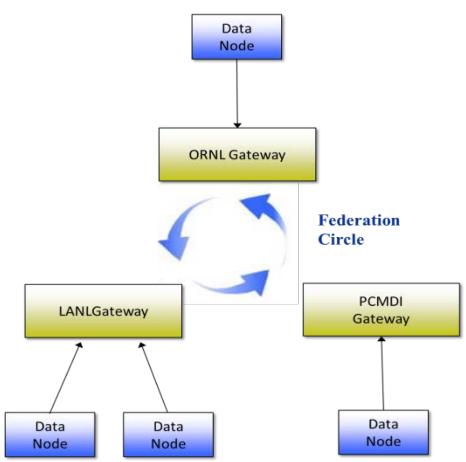


Experimental suite under construction

- Simulation and sampling plan
  - Need to archive and export >300 TB to partners
- Development of automated workflow for high resolution production simulations
  - Manual system not scalable
  - Initial configuration for Jaguar, but can be exported hardened and exported







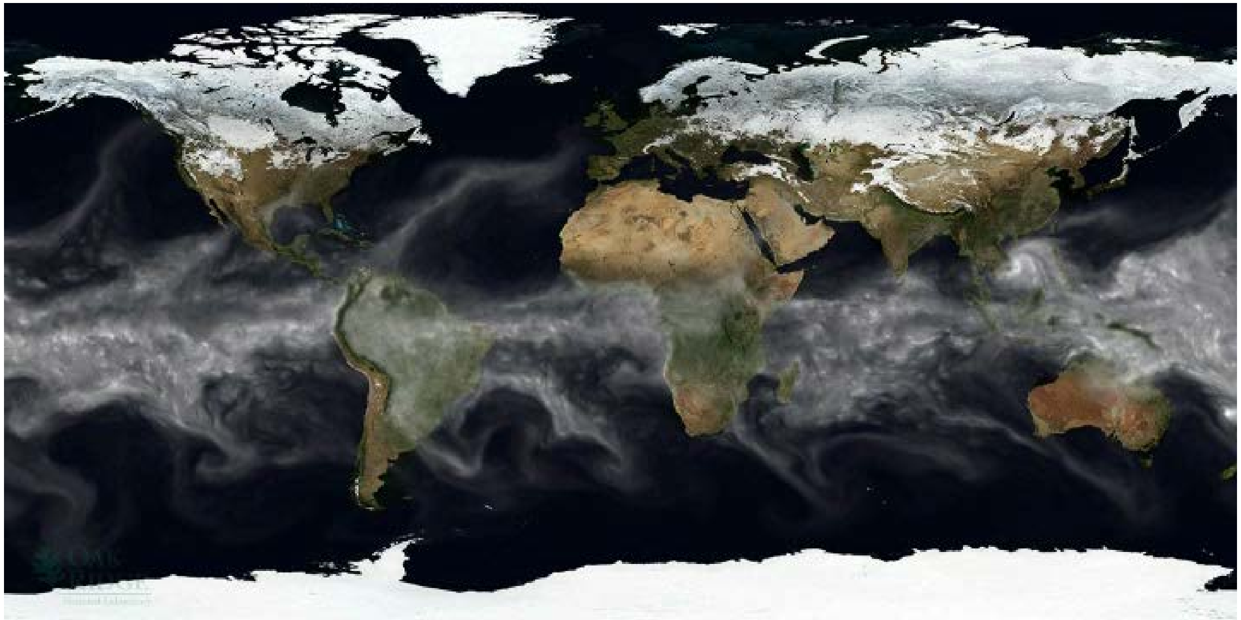
- High Volume Climate Data Server
  - http://cds.ccs.ornl.gov
  - Integrated with Earth System Grid (ESG)

Shipman and collaborators leveraging ESG effort

See Flanery at al. poster

Modeling framework status

- High and low resolution component simulations are underway
  - T85 coupled ensembles in production (see Evans et al. presentation)
  - T341 moving to production (see Evans, McKenna, et al. poster)
    - multiple cloud configurations being explored
    - beginning migration to spectral element dycore, CAM-SE (coordinated with CSSEF)
    - Performance and scaling issues optimized in context of solution sampling (see Worley poster)
    - leveraging ASCR investments in migrating CAM-SE to next generation architectures (see Archibald presentation)

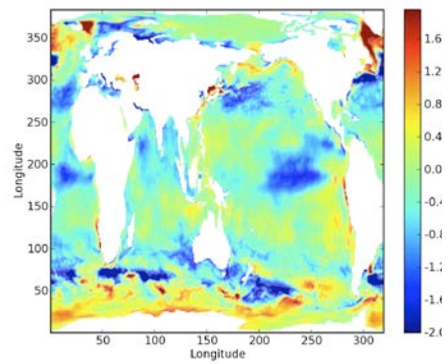


See Mahajan and Ashfaq presentations on simulation analyses

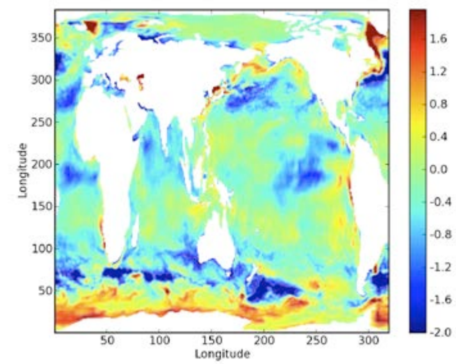
Ocean Data Assimilation

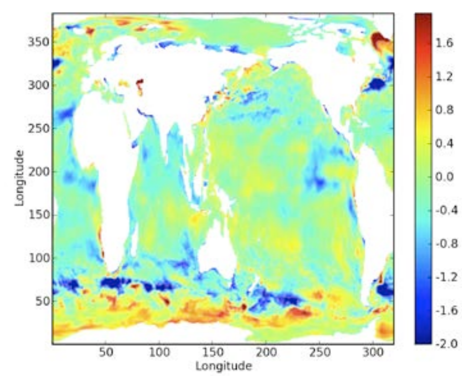
- Goal: Assimilation at very high resolution
- POP working with DART
- Initial issues: inflation
  - Ensemble spread less than model bias
  - Assimilation has no impact
- Improvements
  - Simple bias correction
  - Spread restoration using background variability from control simulation
- Future
  - Hybrid EnKF-3DVar for multi-scale assimilation
  - State estimation for ARGO period
  - AMOC representation with DA

SST bias in control

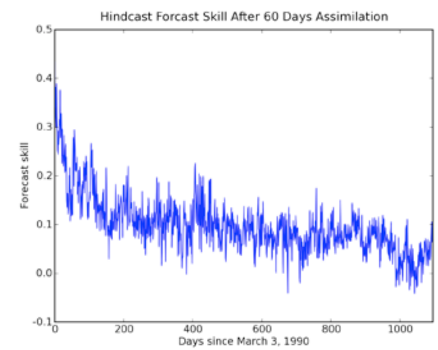


SST bias with initial DA – no improvement





Improved simulation with bias correction and spread restoration (inflation)



Hindcast skill improves with DA, esp. over six months and up to a year

A Prototype Two-Decade Fully-Coupled Fine Resolution CCSM Simulation: McClean et al. (Ocean Modelling, 39,10-30, 2011)

Motivation

How realistic are the climatologies of the simulated upper ocean circulation in a fully-coupled fine resolution prototype CCSM4 simulation (McClean et al., 2011) and a stand-alone forced 0.1° POP (Maltrud et al., 2010) compared to present-day observations?

What impact does full air-sea coupling at fine resolution have on both the large-scale and mesoscale oceanic circulations?

LLNL Grand Challenge Simulation

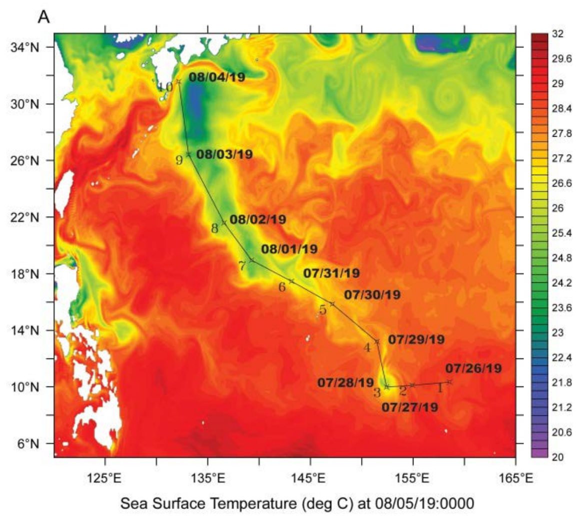
0.25° CAM3.5 (FV),CLM3

0.1° POP2.0,CICE4.0

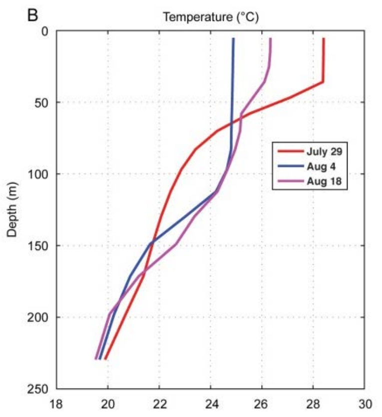
Coupler 7.0

See McClean et al. Poster

SCRIPPS INSTITUTION OF OCEANOGRAPHY
GLOBAL DISCOVERIES FOR TOMORROW'S WORLD



First Global Simulation to Resolve Both Atmosphere and Ocean Tropical Cyclone Behavior



Mixed layer response to passage of category 4 typhoon over Station 9

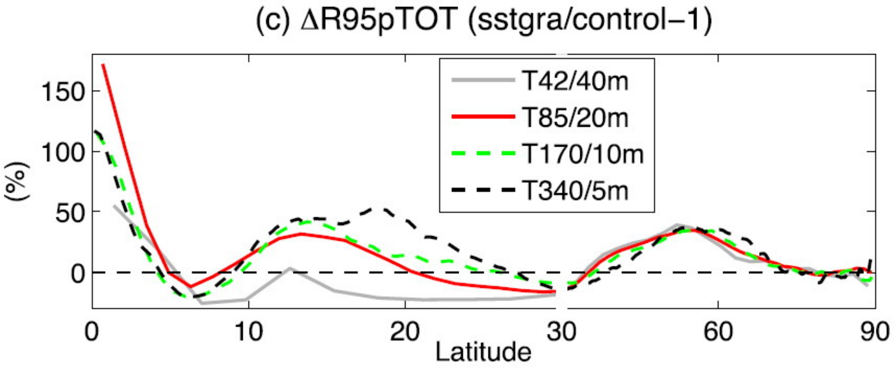
Impact of horizontal resolution on the simulation and projection of extreme precipitation

Objective

Low resolution climate models lack the capacity in simulating the statistics of extreme rainfall events and produce heterogeneous projections for their responses to future climate change. Mechanisms for extreme precipitation need to be better understood for robust simulation and projection of these events from global to regional scales.

Experiment

- Using idealized "aquaplanet" boundary conditions and remapping technique to test the "convergence" of extreme simulations and projections across horizontal resolutions
- Ten experiments at four horizontal resolutions and different time steps
- Elimination of the resolution-dependent signals from the boundary conditions helps isolate the mechanisms driving extremes



See Li Poster

Results:

- Precipitation extremes do not converge with climate-model horizontal resolutions, primarily due to the parameterization of prognostic stable precipitation.
- Updraft appears to contribute to the resolution dependency of extreme precipitation and to be the driving physical factor for the extreme events
- Horizontal model resolution plays important roles in extreme precipitation projections, strongly affecting the global warming signals in low-mid latitude regions. We illustrated that the effects of horizontal resolution have to been taken into account to develop more robust projections of precipitation extremes.

Can high-resolution climate models resolve more tropical storms? An assessment of the impact of horizontal resolution on tropical storm statistics

Fuyu Li, William Collins, Michael Wehner (LBNL)

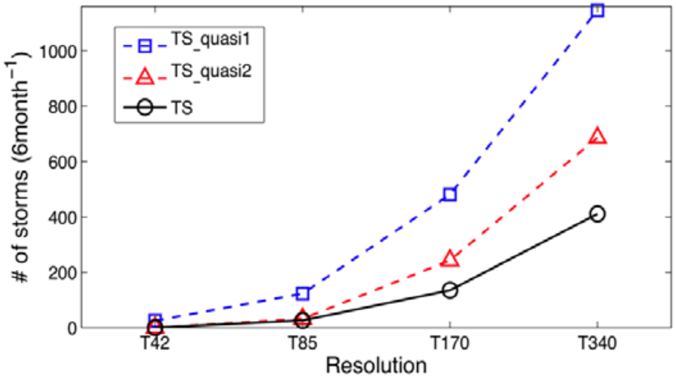
Objective

High-resolution climate models have been shown to improve the statistics of tropical storms, but there have been no deep understanding of how and why. We look at the self-initializing tropical storms with no external forcing, no seasonal variation, and no climate change signals across the runs with different horizontal resolution.

Experiment

CAM3 aquaplanet simulations:

- four resolutions: T42, T85, T170, T340;
- 6 month simulation period with 6 month spin up



Storm counts during 6 month period for: (a) blue: all storm systems (vorticity criteria only); (b) red: tropical storms/depressions (vorticity+warm core); (c) black: 'true' tropical storms (vorticity + warm core + wind):

Results:

✓ Increasing horizontal resolution helps to detect more tropical storms, primarily due to simulated higher vorticity, and T42 detects too few storms even weighted by the total number of grid cells

✓ High resolution runs produce more storm systems at the lower latitudes. They improve the simulations of the intensities (lower depressions and stronger precipitation) and the structure of tropical storms.

✓ More hurricanes are detected in high resolution runs, but still no category 4-5 hurricanes in aqua-planet world

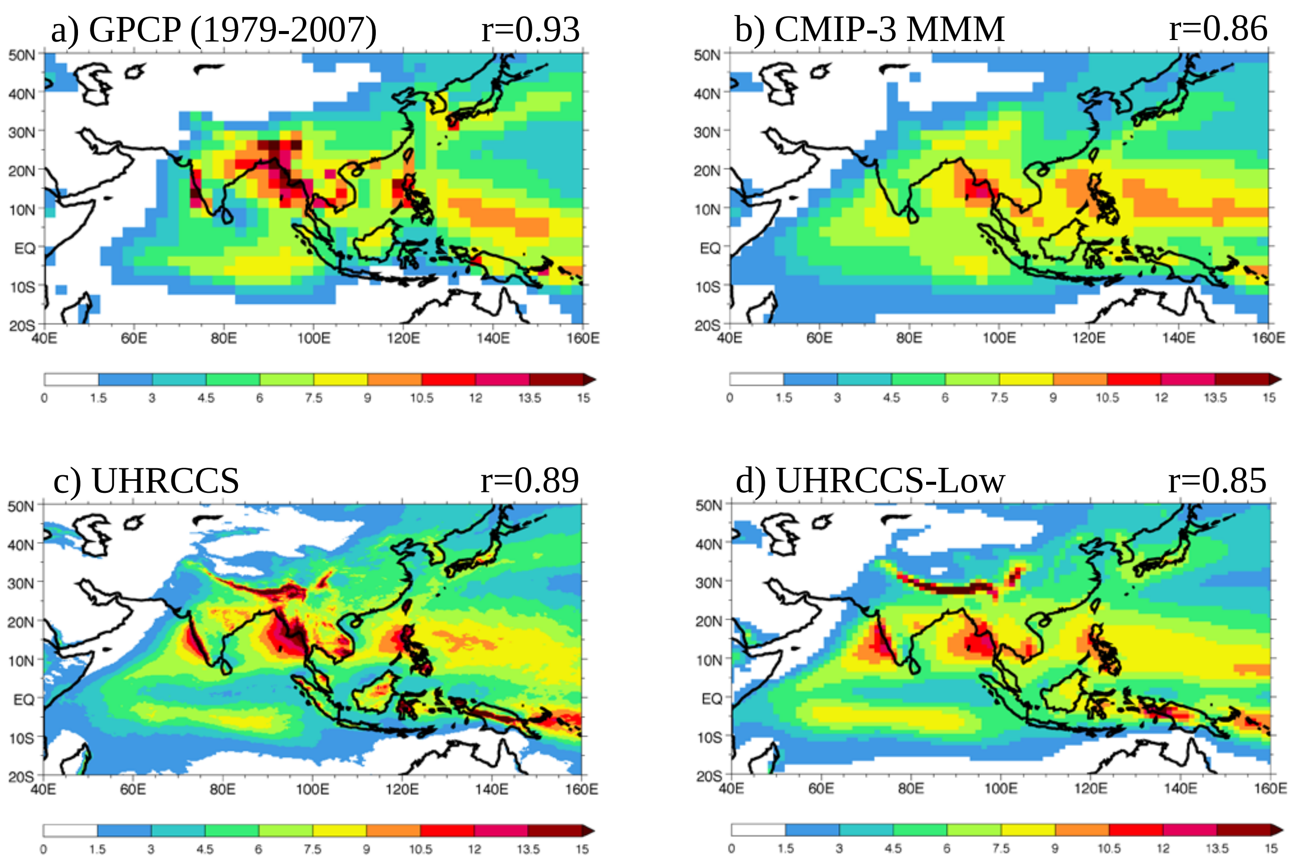
See Li et al. Poster

Observations vs. Development Version of CCSM4: JJAS Rainfall Climatology

Program for Climate Model Diagnosis and Intercomparison

Sperber and colleagues (*see poster and presentations*)

- The development version of CCSM4 has skill nearly the same or better skill than the CMIP3 multi-model mean based on the pattern correlation
- High resolution (0.25° atmos. x 0.1° ocean) outperforms low-resolution (~1.25° atmos. x ~1° Ocean)

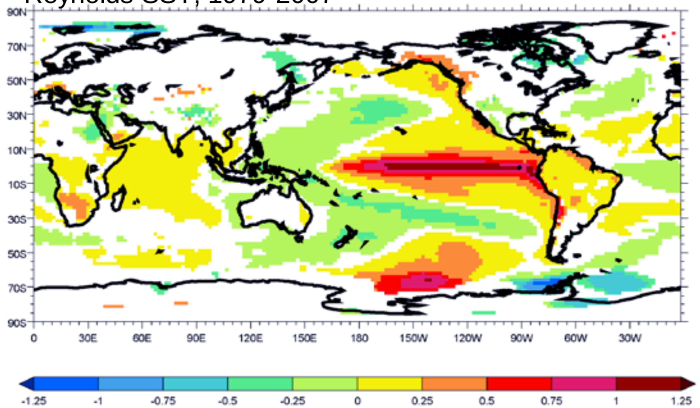


ENSO Teleconnections: SST (°C)

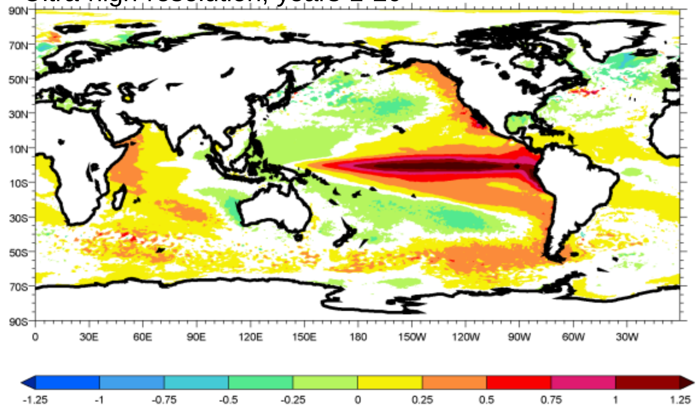
Sperber and colleagues (*see poster and presentations*)

- NINO3.4 SST teleconnection with monthly anomalies of SST. The models well simulate the SST teleconnection, though the warming extends too far west in the equatorial western Pacific Ocean. Also represented are the signals in the Indian Ocean, the high latitudes, and to a lesser extent in the Atlantic Ocean

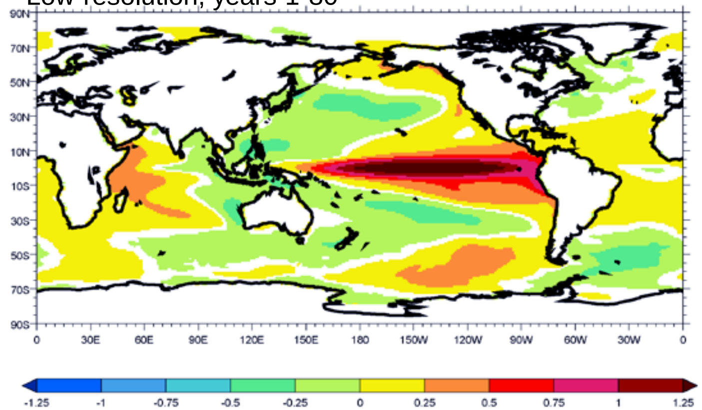
Reynolds SST; 1979-2007



Ultra-high-resolution, years 1-20



Low-resolution, years 1-80



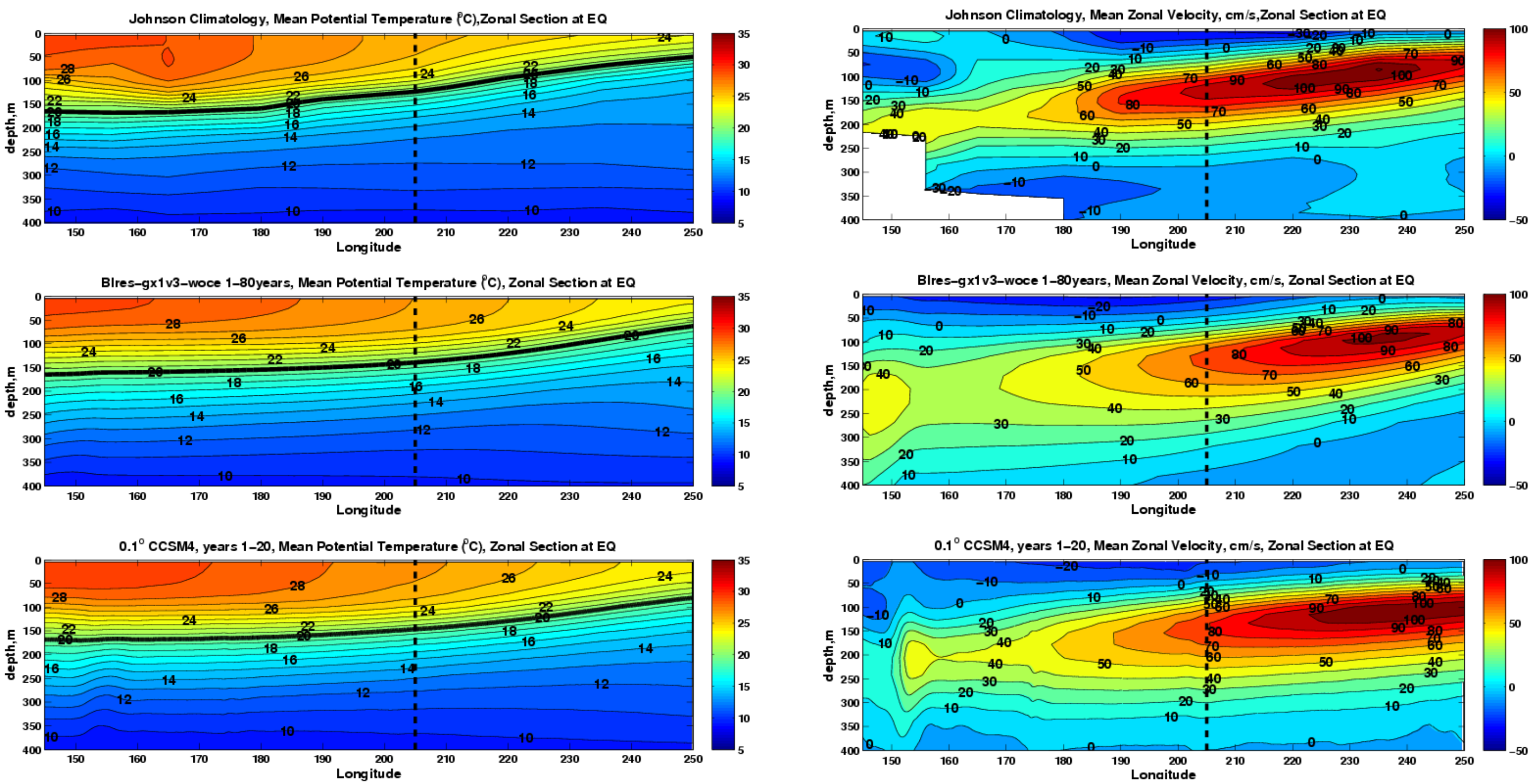
Here, the NINO3.4 SST index (smoothed with a 5-month running mean) is linearly regressed against monthly anomalies of key variables to validate the model simulation of the El Nino/Southern Oscillation. The plots shown are for a 1 standard deviation perturbation of NINO3.4 SST, thus corresponding to conditions during El Nino. Data is only plotted where the regression is statistically significant at the 5% level.

Observations vs. Development Version of CCSM4: Mean upper ocean structure in EQ Pacific

Program for Climate Model Diagnosis and Intercomparison

Detelina Ivanova (*see poster*)

Compared to *Johnson et al*. (2002) climatology, based on TOGA/TAO data set, both models (Blres-gx1v3 and 0.1°CCSM4, with same vertical resolution) realistically simulate the equatorial thermocline and currents. Below are shown zonal sections of temperature and zonal velocity demonstrating a good agreement of the models' depth of 20°C isotherm and core (maximum speed) of the Equatorial Undercurrent with the observed.



Summary

- Systematic progress
  - viable energy-balanced high-resolution simulation framework
    - production simulation work now underway
    - large-scale systematic biases in radiative forcing → fundamental physics deficiencies
  - concurrent investments in new comprehensive diagnostic frameworks
    - driven by work with idealized simulation configurations
    - enabled by early high-resolution coupled simulation experiments
  - building infrastructure required for sharing work on broader scale
    - automated workflow around ORNL high-volume climate data server
    - exploiting ongoing Earth Systems Grid investments
- Multi-institutional research connections of clear value
  - CSSEF
  - Development of Frameworks for Robust Regional Climate Modeling
  - Ultra-scale Visualization Climate Data Analysis Tools (UV-CDAT)
  - Visual Data Exploration and Analysis of Ultra-large Climate Data

The End

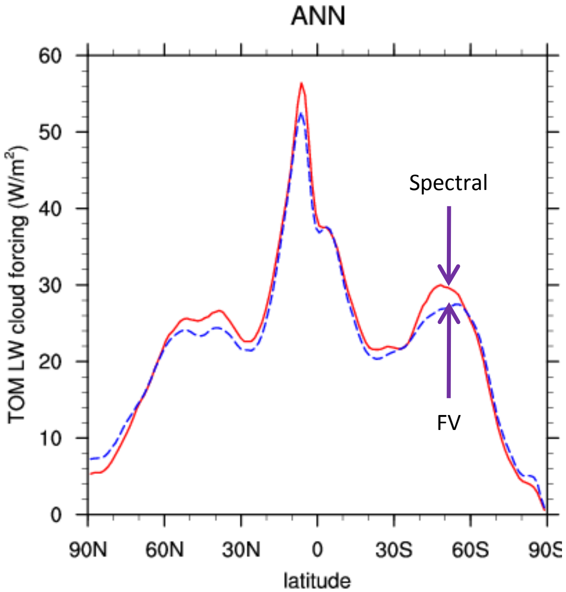
The Multi-Laboratory Team

- *ORNL*
  - Experience in developing atmospheric and carbon cycle modeling frameworks
  - Unique high-performance computational experience
- *LANL*
  - Experience in developing global ocean circulation models, sea ice models, and the next generation of land ice models
  - Experience developing scalable numerical algorithms, including mapping algorithms
- *LBNL*
  - Experience in atmospheric radiative transfer (aerosol and cloud effects)
  - Experience with exploring physical and dynamical errors with increasing resolution
- *LLNL*
  - Bring long and unique experience in model evaluation
  - Development of new and innovative analysis, diagnostics and evaluation metrics

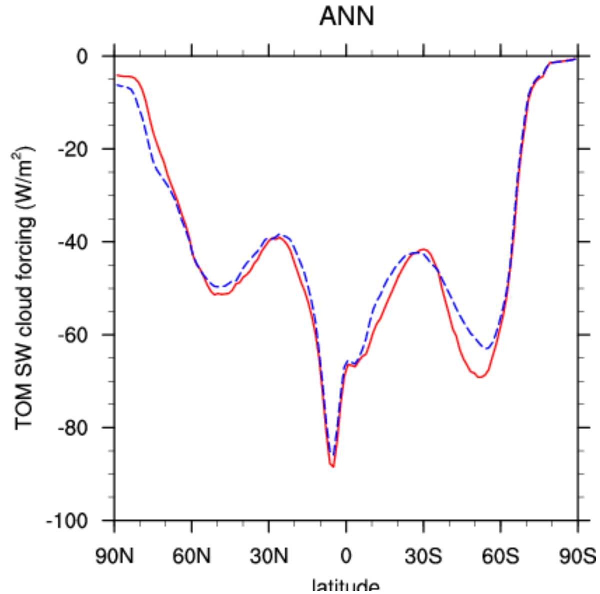
Creation of T85 Configuration

- Simulation properties equal or superior to released Finite Volume configuration

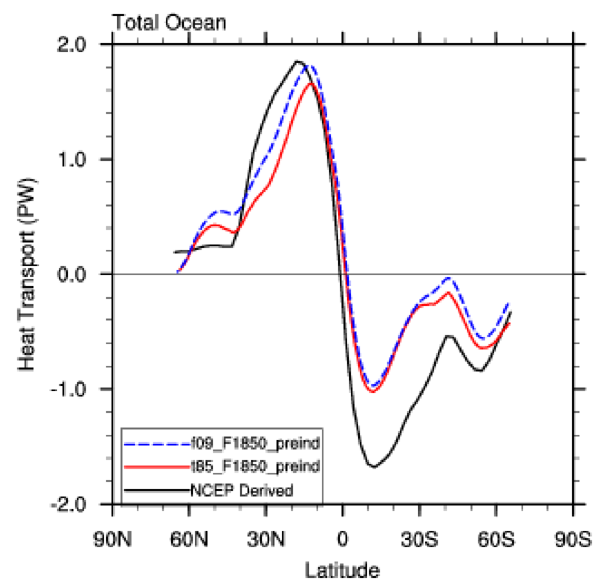
Long Wave Cloud Forcing



Short Wave Cloud Forcing



Implied Ocean Heat Transport



Objective

Test the hypothesis that higher resolution models are needed

- To include explicit simulation of non-linear phenomena and interactions on the small scale that have feedbacks on large scale climate features
- To provide accurate and explicit simulations of local to regional scale phenomena, including low-probability, high-impact hydrological events

Motivation

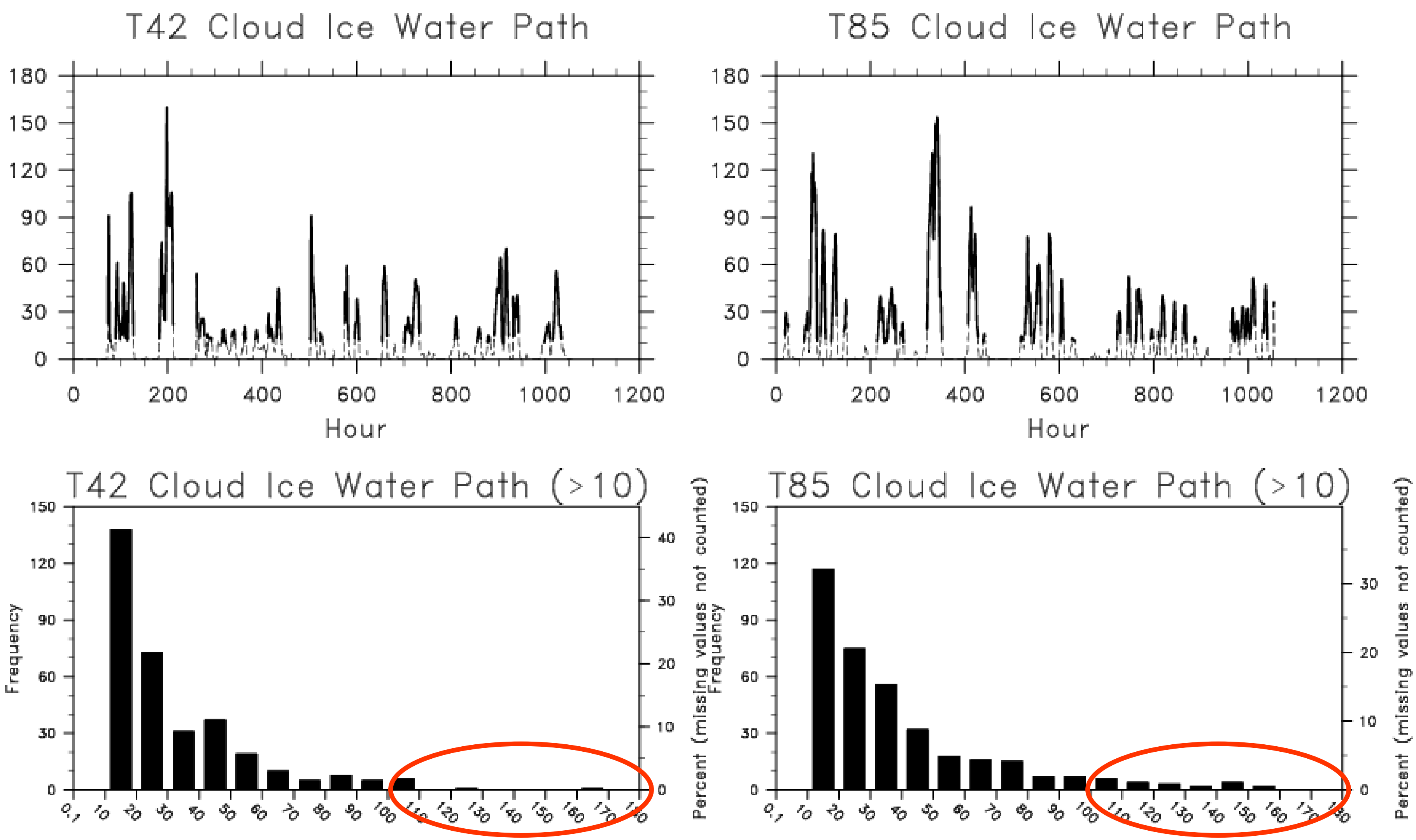
Key Uncertainties of Regional Projections

- Limited study of regional climate change, particularly with regard to extreme events
- AOGCMs show little consistency in projected regional precipitation change
- In regions with topography lack sufficient information about climate change

Climate studies at global NWP/eddy resolving scales

- Better representations of mesoscale storm structure and intensity (TC's and MCC's)
- High resolution needed to correctly simulate complex scale interactions such as monsoon season rainfall events over Asia.
- Mesoscale ocean processes important for ocean component of ocean heat transport

Regional Simulation of Cloud Processes



Southern Great Plains Spring

Hack and Caron

Ongoing Science and Technical challenges

- High accuracy high resolution remapping file creation for accurate interpolation between components
- Creation of mask files for land and ocean at new, higher resolutions
- Configuration of each component at the higher resolution
- Communication fragility and overhead
- I/O fragility and performance
- Scalability across all components
- New algorithm support
- Generation of external boundary datasets
- Exploiting and optimizing new export mechanisms for simulation data