Revolutionizing Climate Modeling: Impacts of High Spatial Resolution

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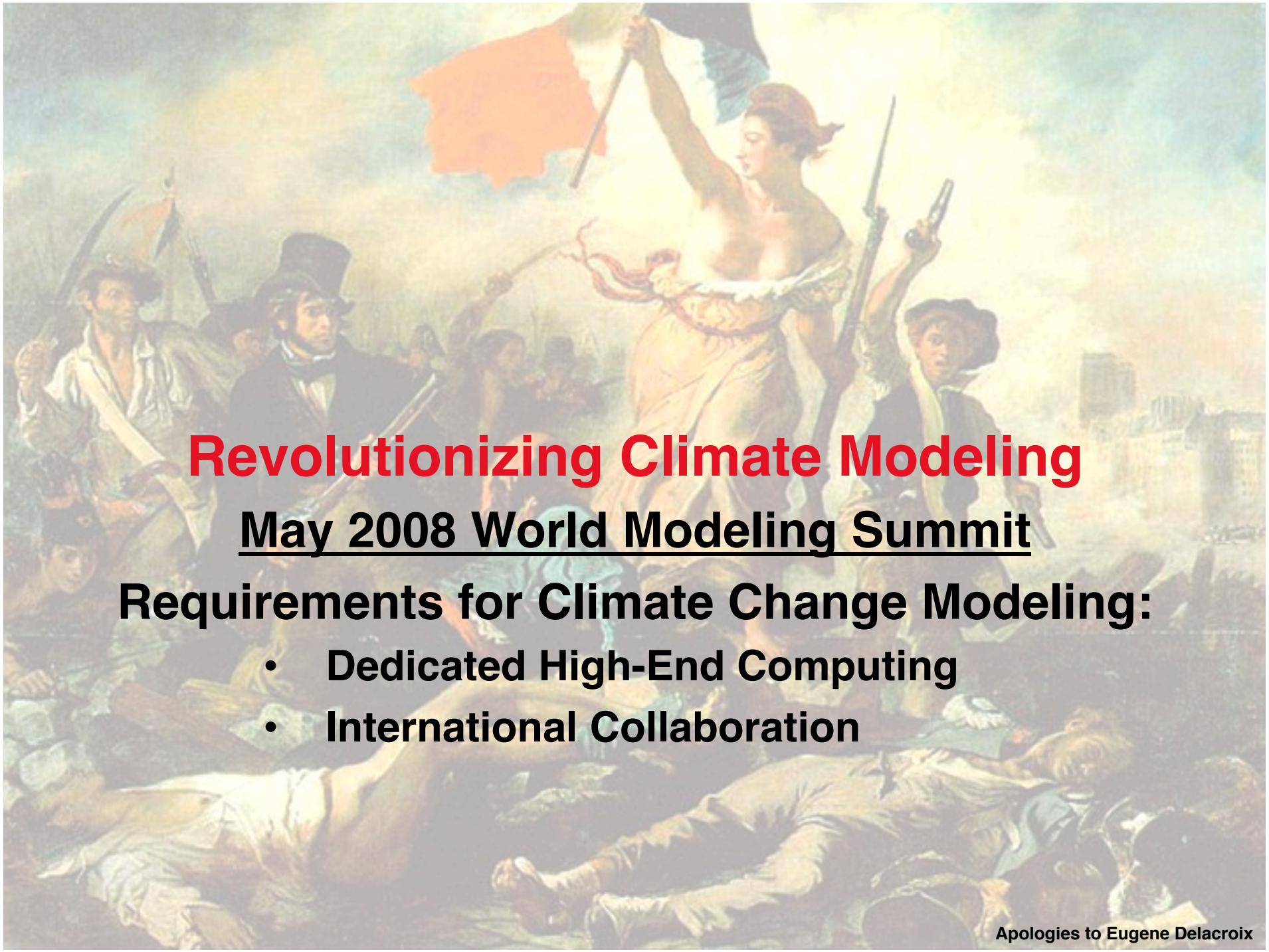
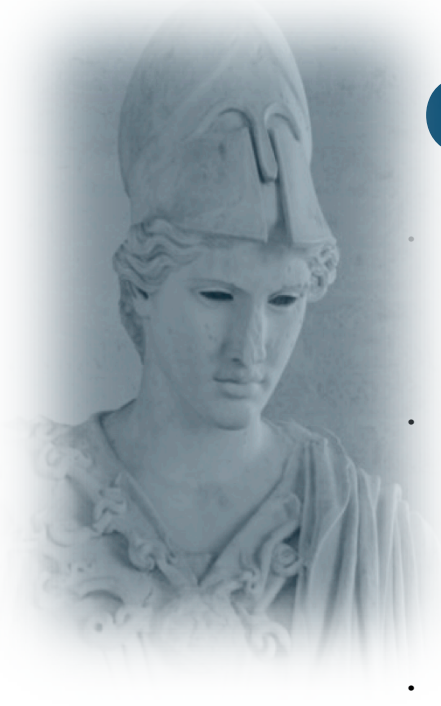
Atmospheric & Oceanic Sci. Dept. Seminar
16 September 2010

Origin of Project Athena

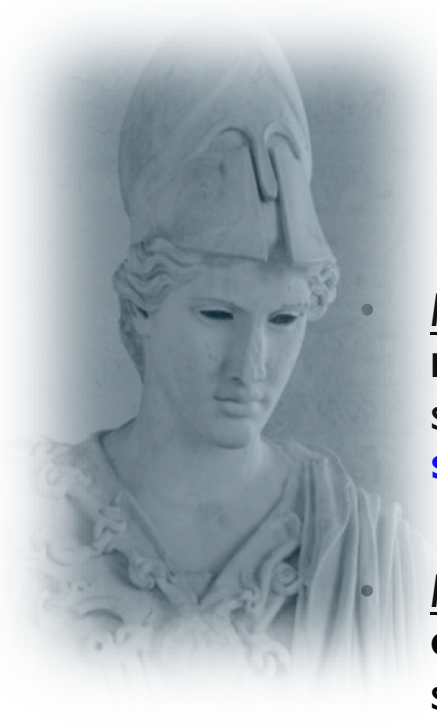
- The World Modeling Summit (WMS) in May 2008 called for a revolution in climate modeling to more rapidly advance improvements in accuracy and reliability


Revolutionizing Climate Modeling
May 2008 World Modeling Summit
Requirements for Climate Change Modeling:
• Dedicated High-End Computing
• International Collaboration
Apologies to Eugene Delacroix



Origin of Project Athena

- The World Modeling Summit (WMS) in May 2008 called for **a revolution in climate modeling** to more rapidly advance improvements in accuracy and reliability
- The WMS recommended **petascale supercomputers dedicated to climate modeling** based in at least 3 international facilities
  - Dedicated petascale machines are needed to provide enough computational capability and a controlled environment to support long runs and the management, analysis and stewardship of very large (petabyte) data sets
- The U.S. **National Science Foundation**, recognizing the importance of the problem, realized that a resource (***Athena***) was available to meet the challenge of the World Modeling Summit and **offered to dedicate the Athena supercomputer for 6 months** in 2009-2010
- An international collaboration was formed among groups in the U.S., Japan and the U.K. to use Athena to take up the challenge

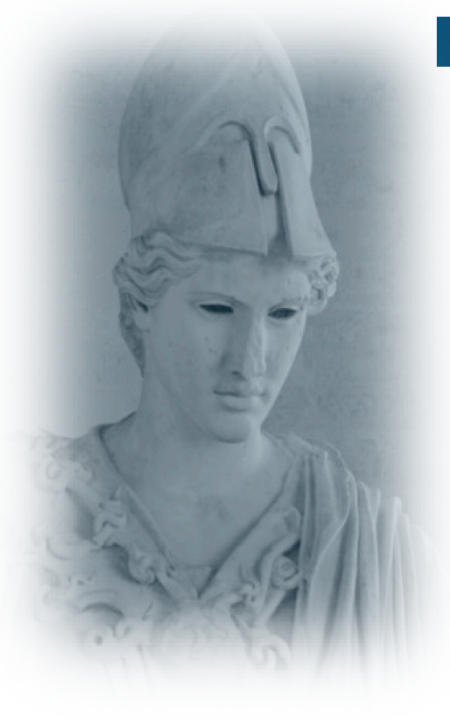


Project Athena: Science Goals

- *Hypothesis*: Increasing climate model resolution to **accurately resolve mesoscale phenomena in the atmosphere** (and ocean and land surface) can **dramatically improve the fidelity of the models in simulating climate** – mean, variances, covariances, and extreme events.

- *Hypothesis*: Simulating the **effect of increasing greenhouse gases on regional aspects of climate, especially extremes**, may, for some regions, **depend critically on the spatial resolution** of the climate model.

- *Hypothesis*: **Explicitly resolving important processes,** such as clouds in the atmosphere (and eddies in the ocean and landscape features on the continental surface), *without parameterization*, can **improve the fidelity of the models**, especially in describing the regional structure of weather and climate.



Project Athena: Collaborating Groups

COLA - Center for Ocean-Land-Atmosphere Studies, USA (NSF-funded)
ECMWF - European Center for Medium-range Weather Forecasts, UK
JAMSTEC - Japan Agency for Marine-Earth Science and Technology, Research Institute for Global Change, Japan
University of Tokyo, Japan
NICS - National Institute for Computational Sciences, USA (NSF-funded)
Cray Inc.

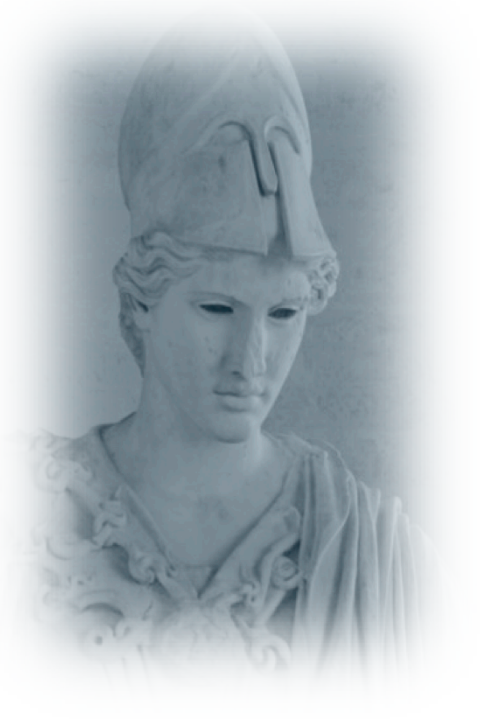
Codes

NICAM: Nonhydrostatic Icosahedral Atmospheric Model
IFS: ECMWF Integrated Forecast System

Supercomputers

Athena: Cray XT4 - 4512 quad-core Opteron nodes (18048)
#30 on Top500 list (November 2009) – dedicated Oct'09 – Mar'10

Kraken: Cray XT5 - 8256 dual hex-core Opteron nodes (99072)
#3 on Top500 list (November 2009) replaced Athena – allocation of 5M SUs



Many Thanks To …

ECMWF

- Mats Hamrud
- Thomas Jung
- Martin Miller
- Tim Palmer (co-PI)
- Peter Towers
- Nils Wedi

NICS

- Phil Andrews (co-PI)
- Troy Baer
- Matt Ezell
- Christian Halloy
- Dwayne John
- Bruce Loftis
- Kwai Wong

Cray

- Pete Johnsen
- Per Nyberg

JAMSTEC/U. Tokyo

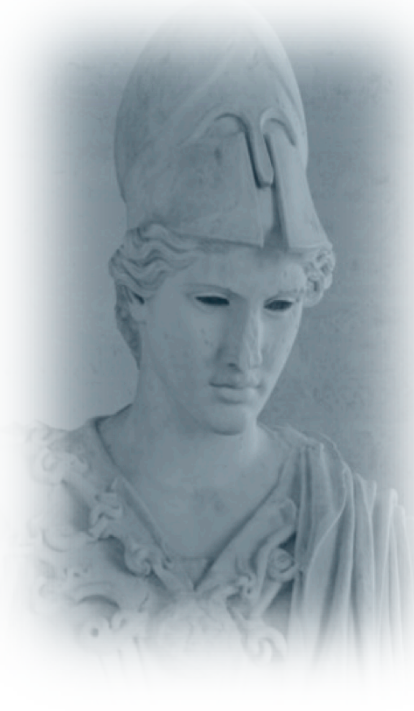
- Chihiro Kodama
- Masaki Satoh (co-PI, U. Tokyo)
- Hirofumi Tomita (co-PI, JAMSTEC)
- Yohei Yamada

NSF

- AGS: Jay Fein
- OCI: Steve Meacham, Rob Pennington

COLA

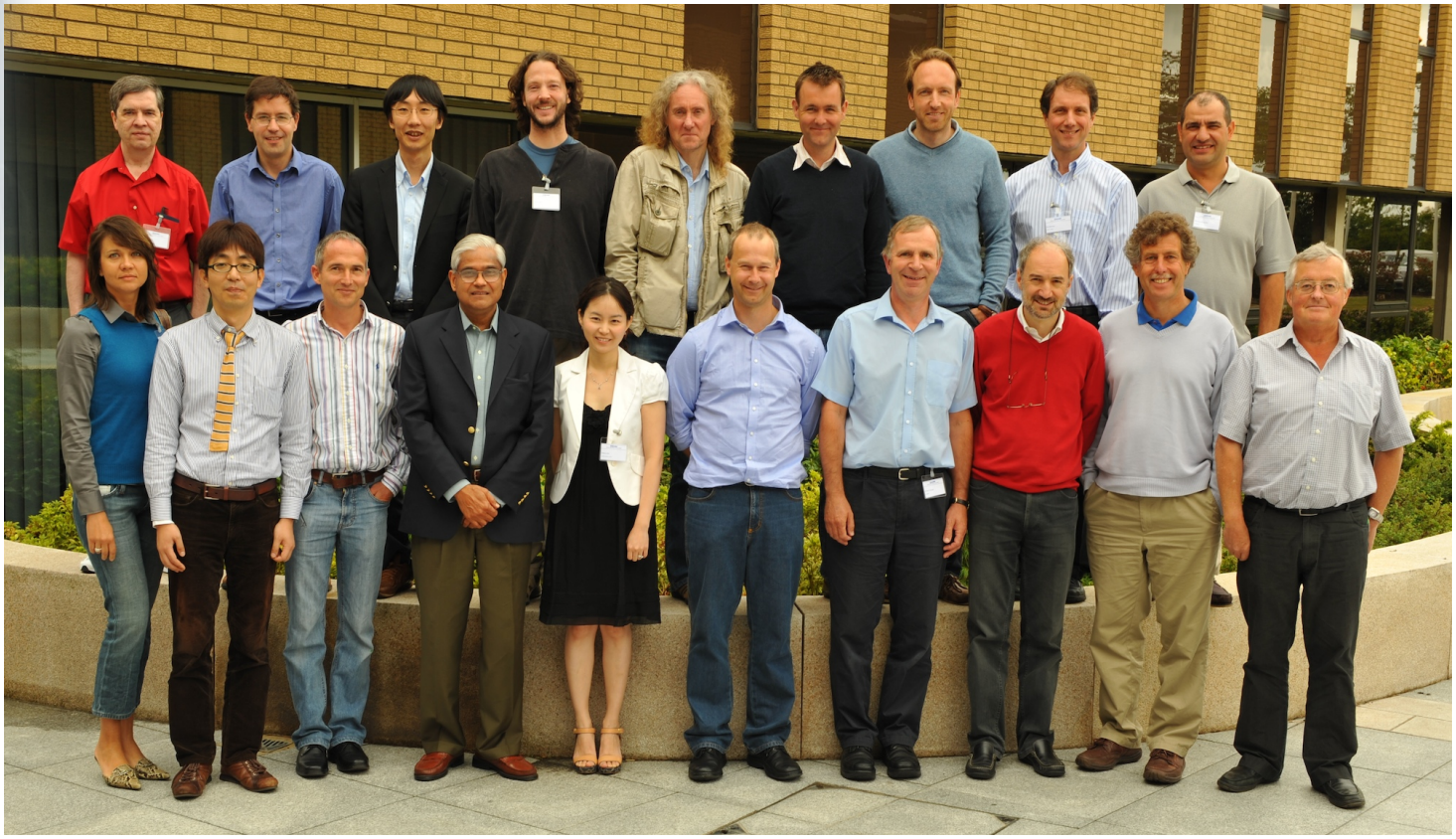
- Deepthi Achutavarier
- Jennifer Adams
- Eric Altshuler
- Ben Cash
- Paul Dirmeyer
- Bohua Huang
- Emilia Jin
- Jim Kinter (PI)
- Larry Marx
- Julia Manganello
- Cristiana Stan
- Tom Wakefield



Athena Workshop

ECMWF, reading, UK

7-8 June 2010



Marx Forbes Kodama Cash Hodges Shaffrey Jung Kinter Fuentes

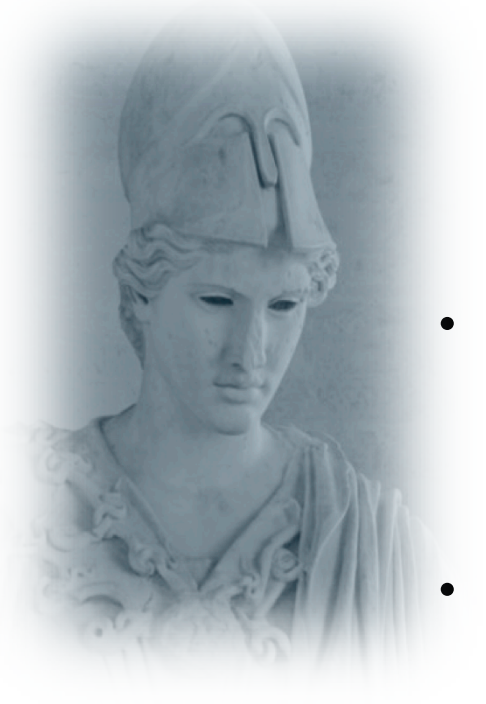
Manganello Tomita Bechtold Shukla Jin Wedi Towers Molteni Palmer Miller

National Institute for Computational Sciences

A UT/ORNL PARTNERSHIP
NATIONAL INSTITUTE FOR COMPUTATIONAL SCIENCES
NICS

University of Tennessee and ORNL partnership

- NICS is funded by the National Science Foundation, is located at Oak Ridge National Lab, and is managed by the University of Tennessee
- NICS operates the first academic petascale supercomputer in the world
- Leverages the capabilities of the ORNL computing complex

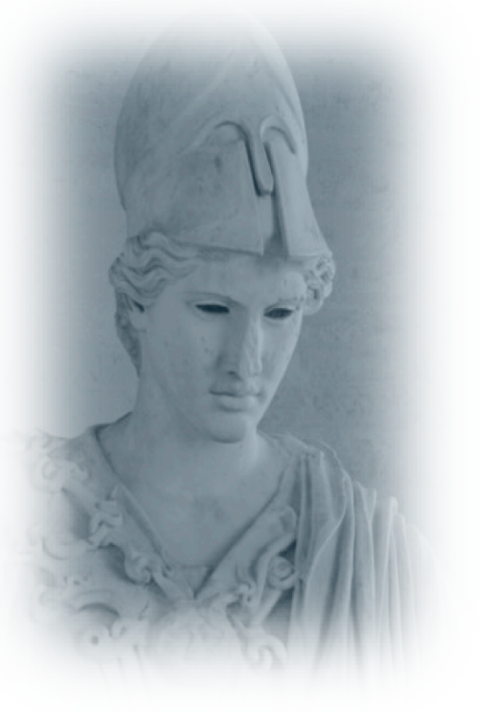


NICS and Athena

- NICS provides and supports computational resources for academic researchers: Cray XT5 and XT4, SGI UltraViolet for visualization and data analysis, CPU-GPU cluster, scratch and archival storage, …
- The Cray XT4 – Athena – the first NICS machine in 2008
  - 4512 nodes @ AMD 2.3 GHz quad-core processor + 4 GB RAM
  - 18,048 cores + 17.6 TB aggregate memory
  - 165 TFLOPS peak performance
  - Other resources: 85 TB Lustre file system, 258 TB auxilliary file system (called *Nakji*) and a 5-node, 16-core 128-GB system (called *Verne*) to help with data analysis and management
  - Replaced by Cray XT5 – Kraken – in March 2009

NICS Support for COLA Team

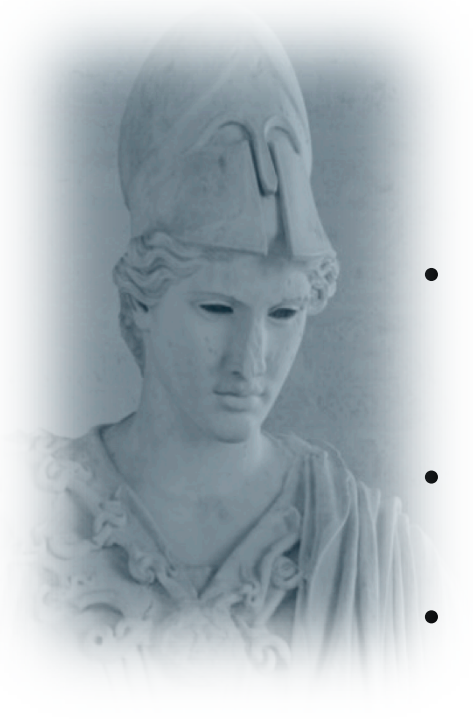
- The Athena project received an extraordinarily high level of direct support.
  - Contract with Cray provided h/w support during business hours.
  - NICS systems staff (Matt and Rick) and computational science staff (Kwai, Christian, Dwayne) attentive seemingly 24/7.
  - NICS management and staff were committed to making this project a success.
  - COLA viewed as a partner not a customer.
- Direct support was very smooth because NICS and COLA teams were able to rise to the challenges.



NICS *Athena* Support Team

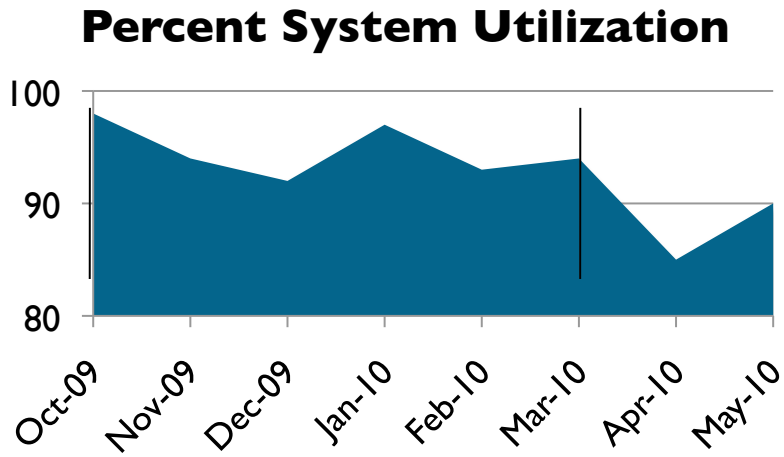
Christian Rick Bruce

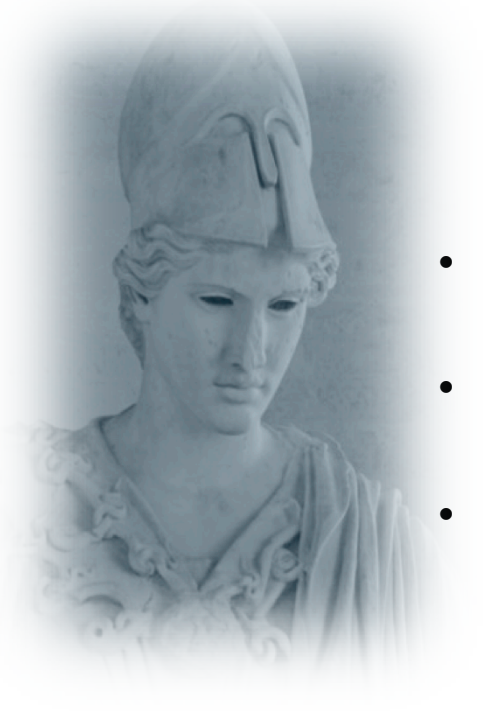
Matt Kwai Dwayne



Production Computing

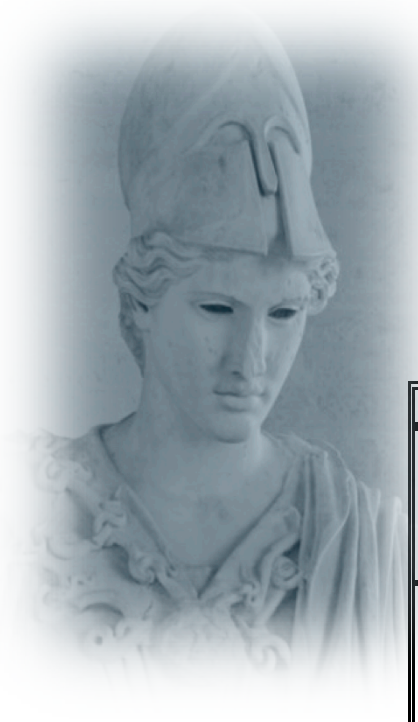
- Supporting a single project on Athena provided some flexibility not otherwise available. NICS could change priorities and queuing parameters to be more effective.
- *Supercomputer Tetris Problem:* keeping the scheduler busy running 2 codes and using extra nodes for post-processing.
- COLA and ECMWF staff over 70M hours over 6 months on Athena – out of a potential ~79M hours.
- Athena has been very reliable.





NICS Lessons Learned

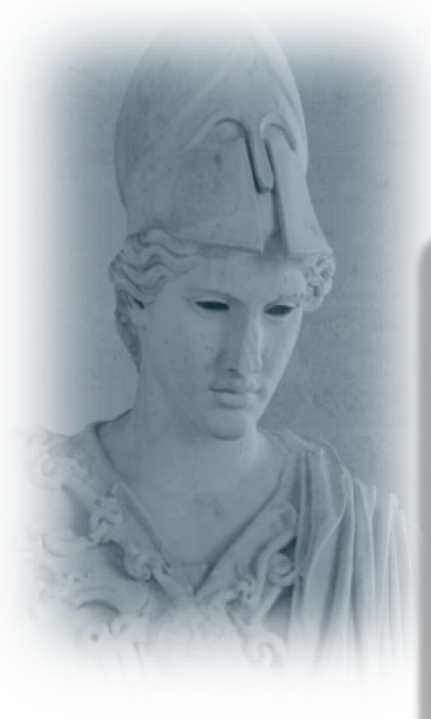
- **Dedicated usage** of a relatively big supercomputer **greatly enhances productivity**
- Dealing with **only a few users** and their requirements allows for **more efficient utilization**
- *Challenge*: Dedicated simulation projects like Project Athena can **generate enormous amounts of data** to be archived, analyzed and managed. NICS (and TeraGrid) do not currently have enough storage capacity. **Data management is a big challenge**.
- Preparation time: 2 to 3 weeks at least were needed before the beginning of dedicated runs to test and optimize the codes and to plan strategies for optimal use of the system. **Communication throughout the project was essential**: (weekly telecons, email lists, personal calls, …)
- Project Athena was a **valuable experience for NICS**, demonstrating the value of developing good teamwork practices through **real partnership between science groups and computational support group**.



Athena Experiments

	Resolution	Grid Size	# Cases	Time Period	Data Volume	Comments
NICAM		7 km	8*	103 days	639 TB	21 May - 31 Aug 2001-2009 * unable to complete 2003
IFS 13-month Hindcasts	T159	125 km	48	395 days	0.7 TB	1 Nov - 30 Nov (next year) 1960 - 2007
	T511	39 km			7 TB	
	T1279	15 km			41 TB	
	T2047	10 km	20		51 TB	
IFS 103-day Hindcasts	T159	125 km	9	102 days	0.03 TB	21 May - 30 Aug 2001 - 2009 (a la NICAM)
	T511	39 km			0.3 TB	
	T1279	15 km			2 TB	
	T2047	10 km			6 TB	
IFS 10-Member Ensembles (Summers)	T511	39 km	6	132 days	2.7 TB	Selected years
	T1279	15 km			17 TB	
IFS 10-Member Ensembles (Winters)	T511	39 km	6	151 days	3.2 TB	1 Nov - 31 Mar Selected years
	T1279	15 km			20 TB	
IFS AMIP	T159	125 km	1	47 years	0.6 TB	1961 - 2007
	T1279	15 km			38 TB	
IFS Time Slice	T159	125 km	1	47 years	0.6 TB	2071 - 2117
	T1279	15 km			38 TB	
Total					874 TB	

http://wxmaps.org/athena/home/



Web Page

http://wxmaps.org/Athena/home

Home
Experiments
Data Catalog
Workshop Agenda
Publications
Acknowledgments

Movies:
NICAM Precip (354Mb)

Model Output:
IFS Hindcast
IFS AMIP
IFS Time Slice
NICAM Hindcast

Project Athena: High Resolution Global Climate Simulations

COLA | ECMWF | JAMSTEC | NICS

About Project Athena

Responding to the call for a revolution in seamless weather and climate modeling made at the World Modeling Summit, held in May 2008 in Reading, UK (Shukla et al., 2009), Project Athena brought together an international team of over 30 people from six institutions on three continents (see the Acknowlegements for a complete list), including climate and weather scientists and modelers, and experts in high-end computing (HEC) to determine the feasibility of using dedicated HEC resources to rapidly accelerate progress in addressing one of the most critical problems facing the global community, namely, simulating climate variability and global climate change.

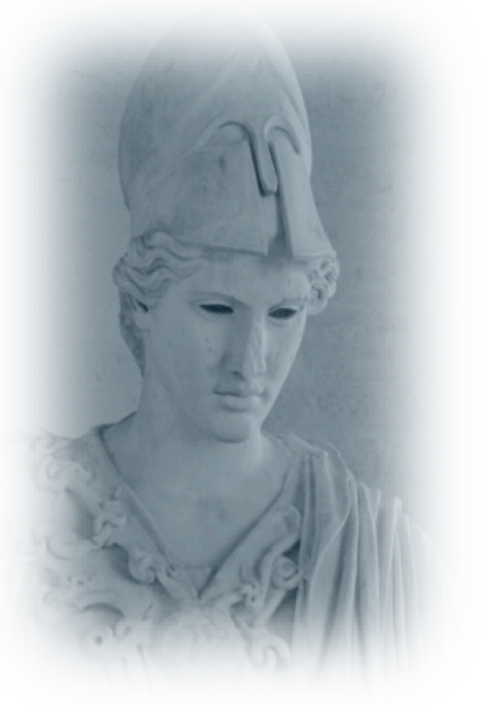
Computationally-intensive experiments with two different models of the global atmosphere made use of the entire 18,048-core Athena Cray XT-4 supercomputer at the University of Tennessee's National Institute for Computational Sciences, based at the Oak Ridge National Laboratory, with support from the U.S. National Science Foundation. The numerical experiments were designed to determine whether increasing weather and climate model resolution to accurately resolve cloud systems and mesoscale phenomena in the atmosphere can improve the fidelity of the models' climate simulations.

The Athena supercomputer was placed in dedicated mode for the period from 1 October 2009 to 1 April 2010, for experiments with the European Centre for Medium-range Weather Forecasts (ECMWF) Integrated Forecast System (IFS), and the Non-hydrostatic ICosahedral Atmospheric Model (NICAM) global atmospheric model from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the University of Tokyo. It was the first time that either model was run in such long simulations at the highest possible resolution. It was also the first time that either model was run in the U.S.

Multiple IFS simulations at multiple resolutions (T159 or 128-km grid; T511 or 40-km grid; T1279 or 16-km grid; and T2047 or 10-km grid) for multiple simulated decades were carried out, including experiments with boundary conditions representing end of the 21st century conditions under climate change conditions (so-called "time-slice" experiments). The effect of increasing greenhouse gas concentrations, associated with global warming, on the regional aspects of extreme temperature and precipitation, storminess, floods and droughts in key regions of the world was evaluated in the

Public Sharing of Athena Data

- NSF requires that data must be made publicly available
- The Project Athena data will be invaluable for a large community of climate scientists (unprecedented resolution and simulation duration) who are already clamoring for access to the data
- The *Earth System Grid (ESG)*
  - Network of data nodes and gateways at national labs and research centers in the US that collectively allow secure access to massive distributed data sets
  - ESG can publish data that reside on tape under HPSS
  - ESG supports metadata search, subsets, server-side analysis, etc.
  - ESG services are currently limited to data on spinning disk in CF-compliant NetCDF format
- Discussions have begun to serve a small subset of data on a trial basis



Sample Results

- Basics of model climate
- Resolution dependence of snow
- Diurnal cycle of precipitation
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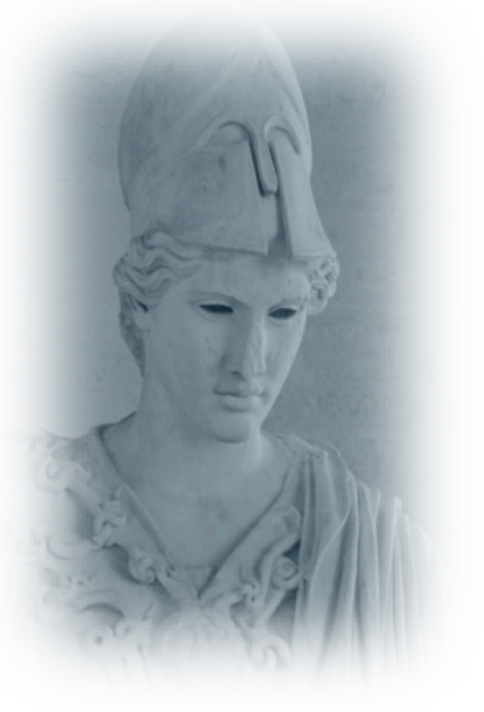

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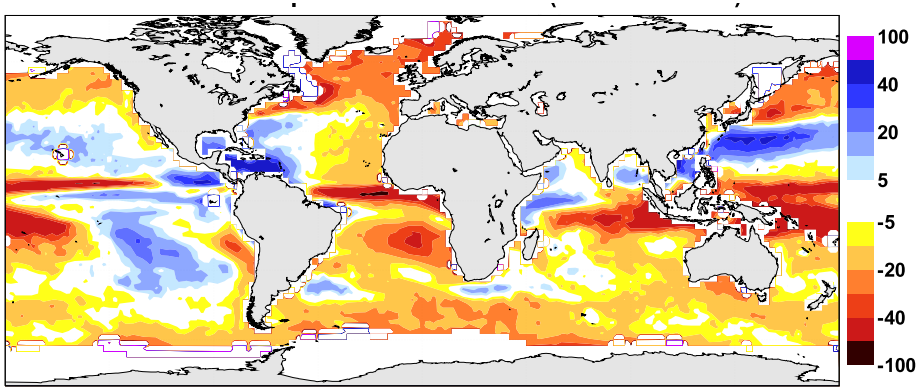
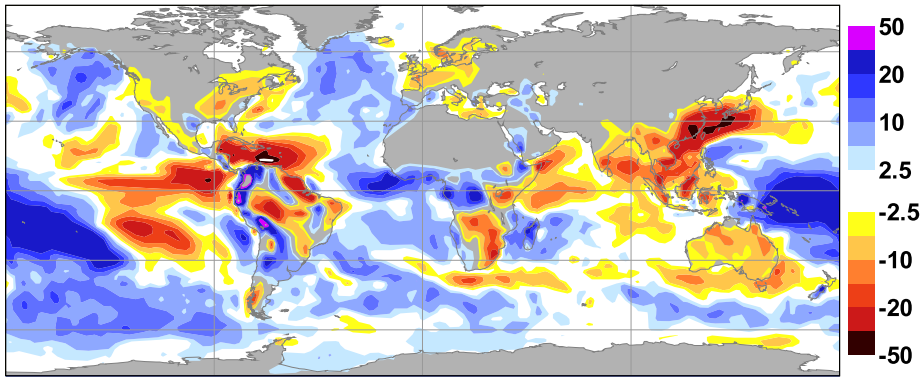
Total Column Liquid Water (DJF 1989-2007)

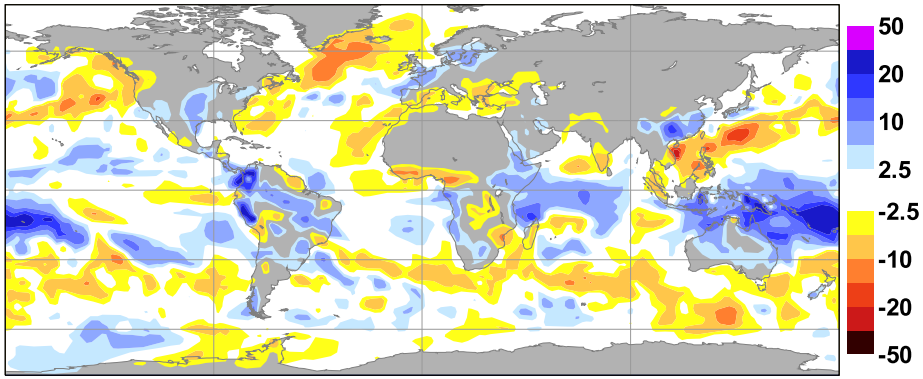
T159-SSM/I



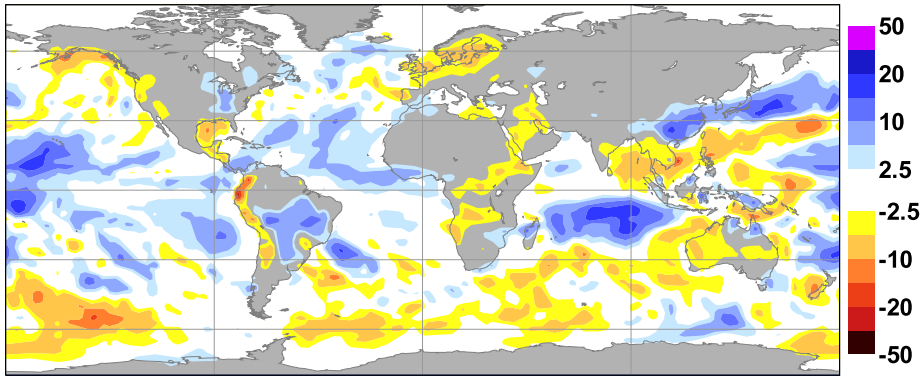
T511-T159



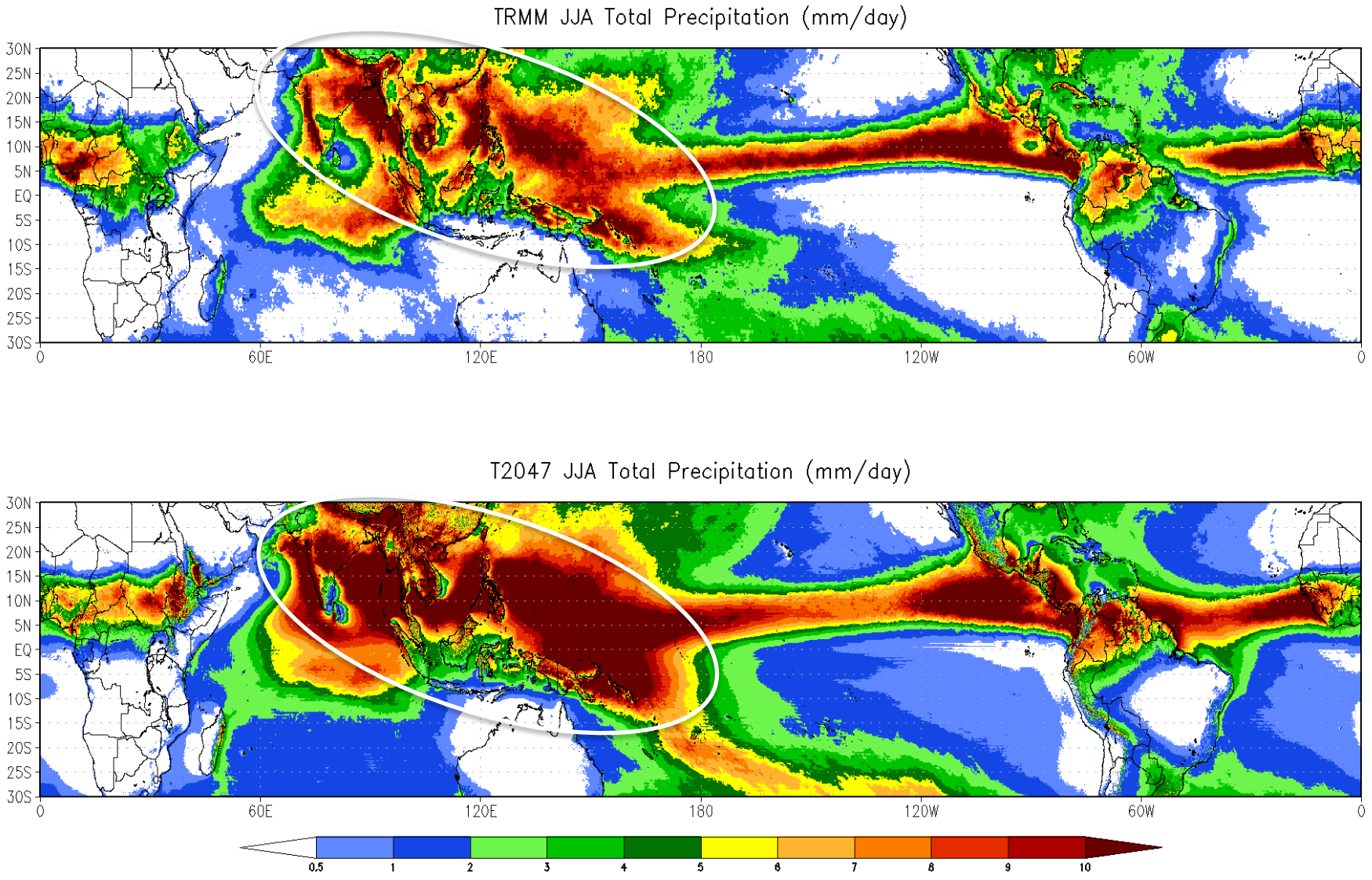
T1279-T511



T2047-T1279



Total JJA Precipitation (2000-2008)



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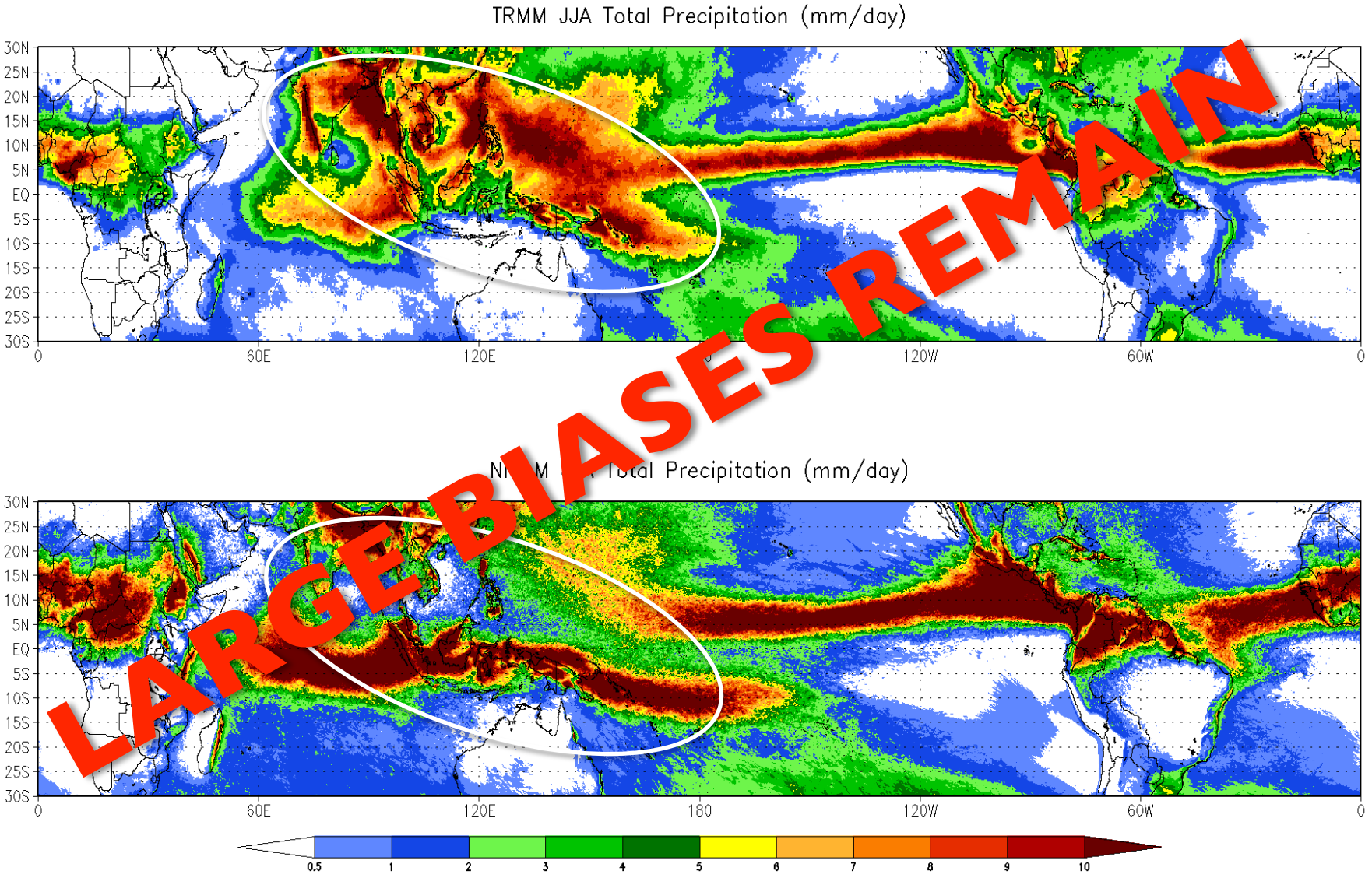
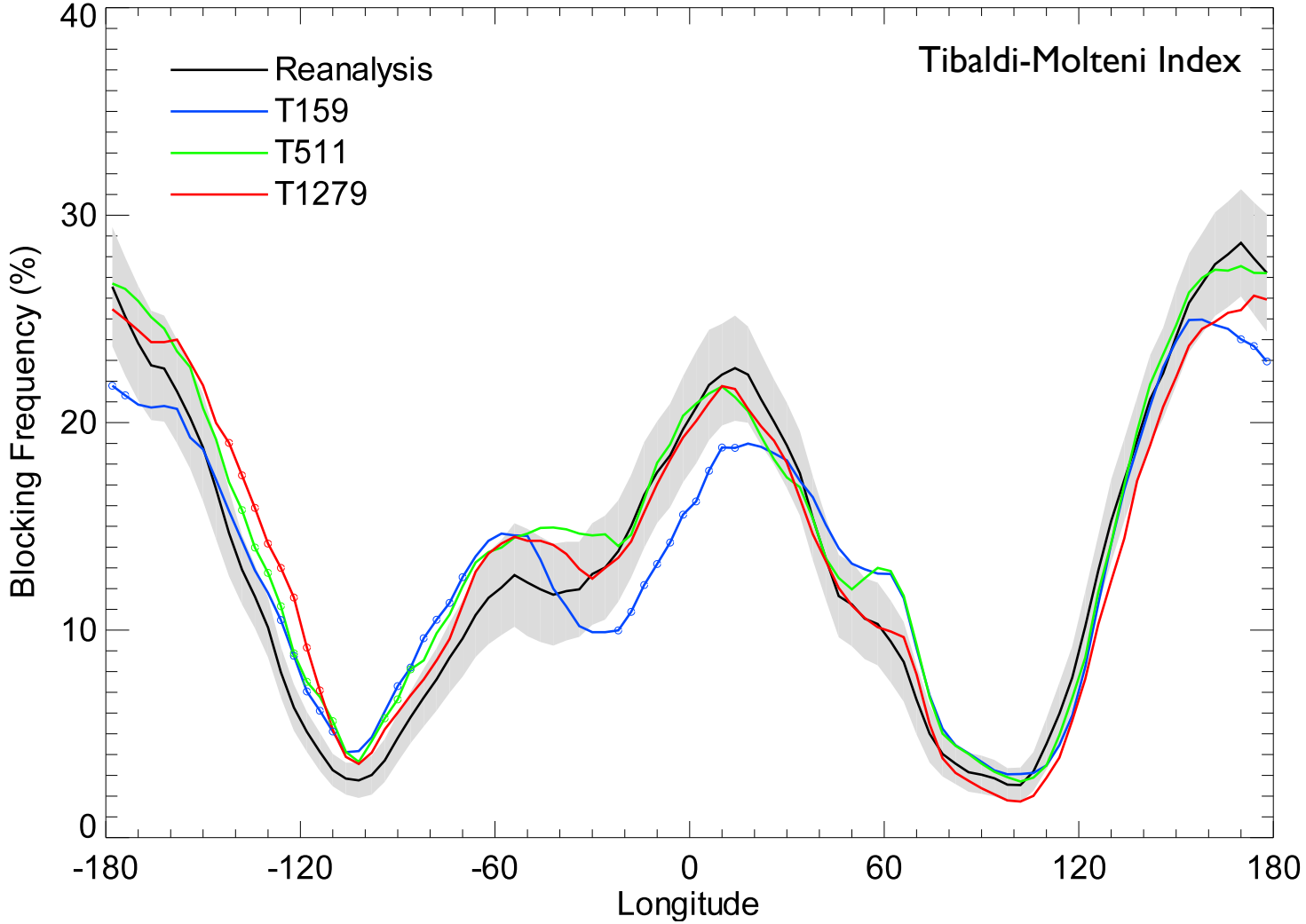
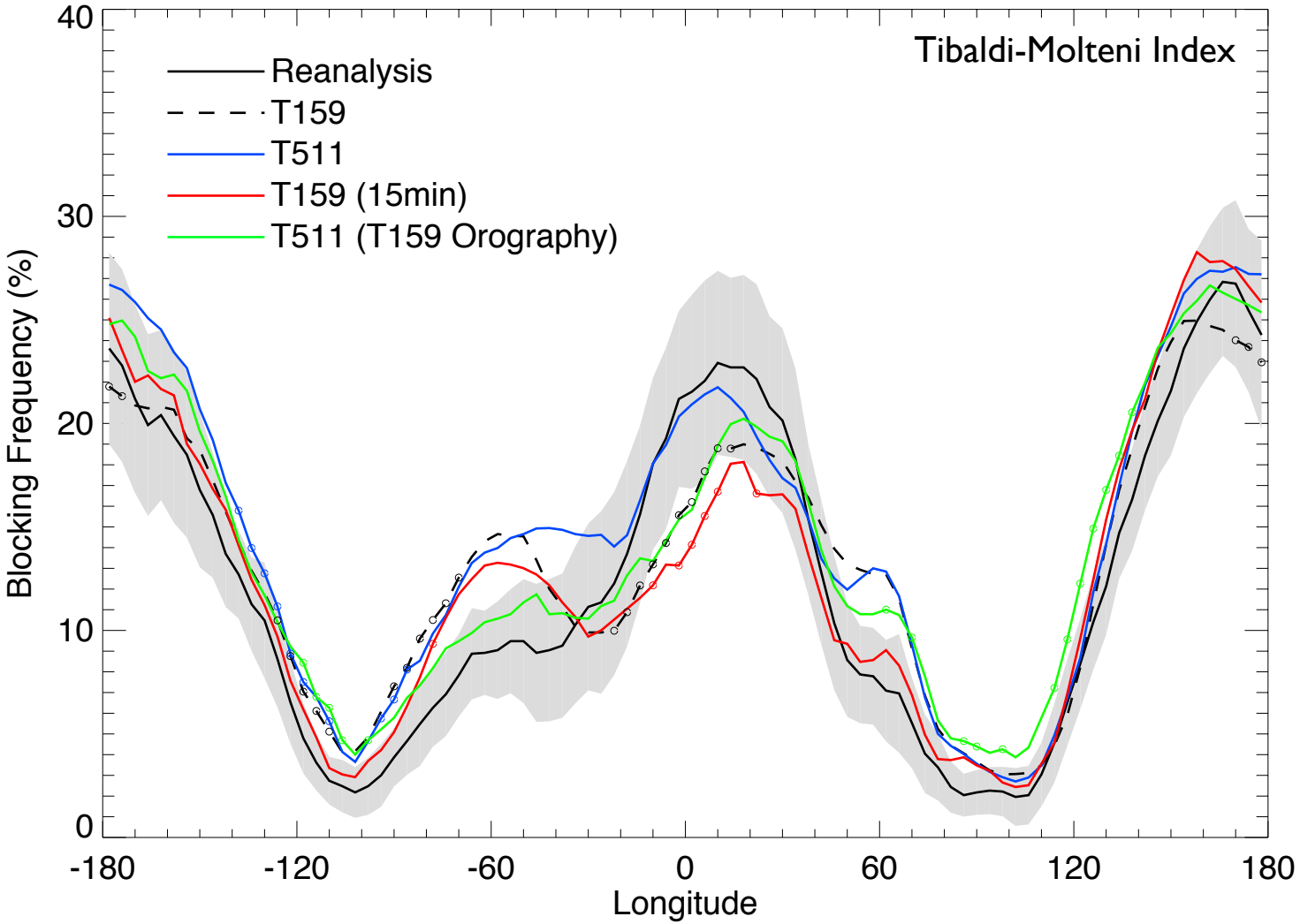
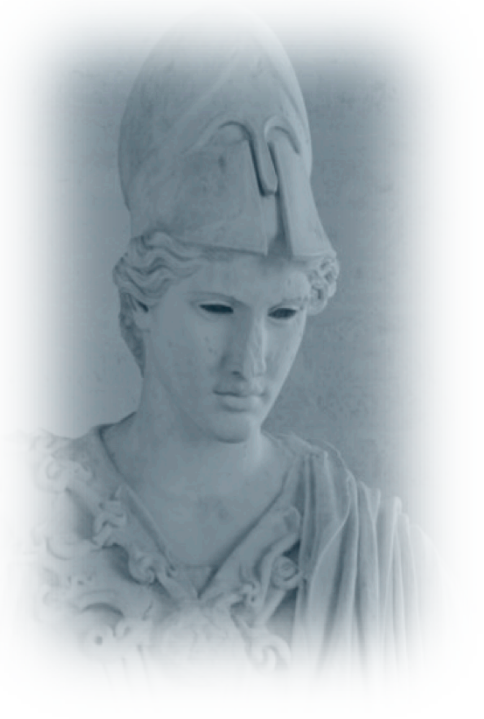


Blocking Frequencies: DJFM 1960-2007



Blocking Frequencies: DJFM 1989-2007





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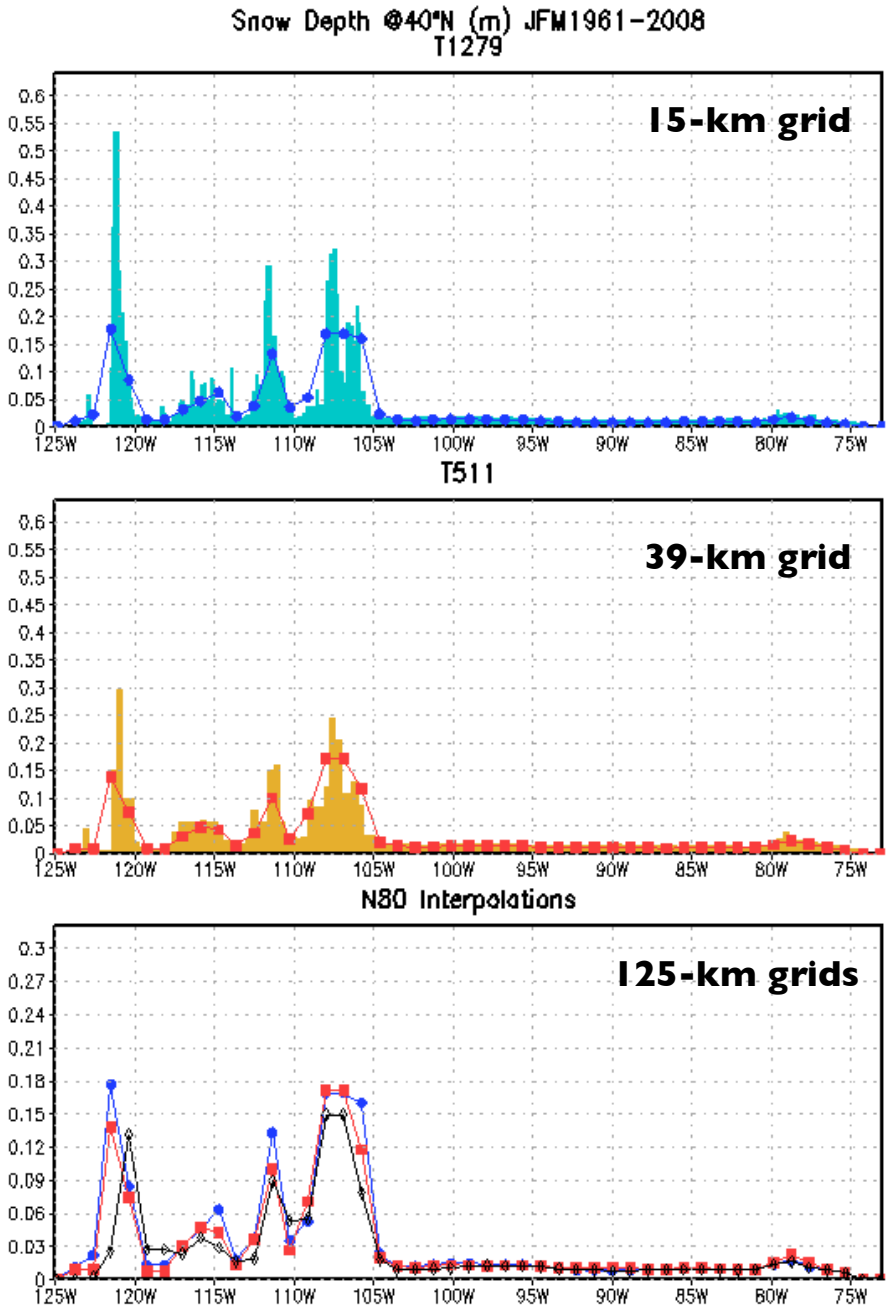
IFS JFM Mean Snow Depth

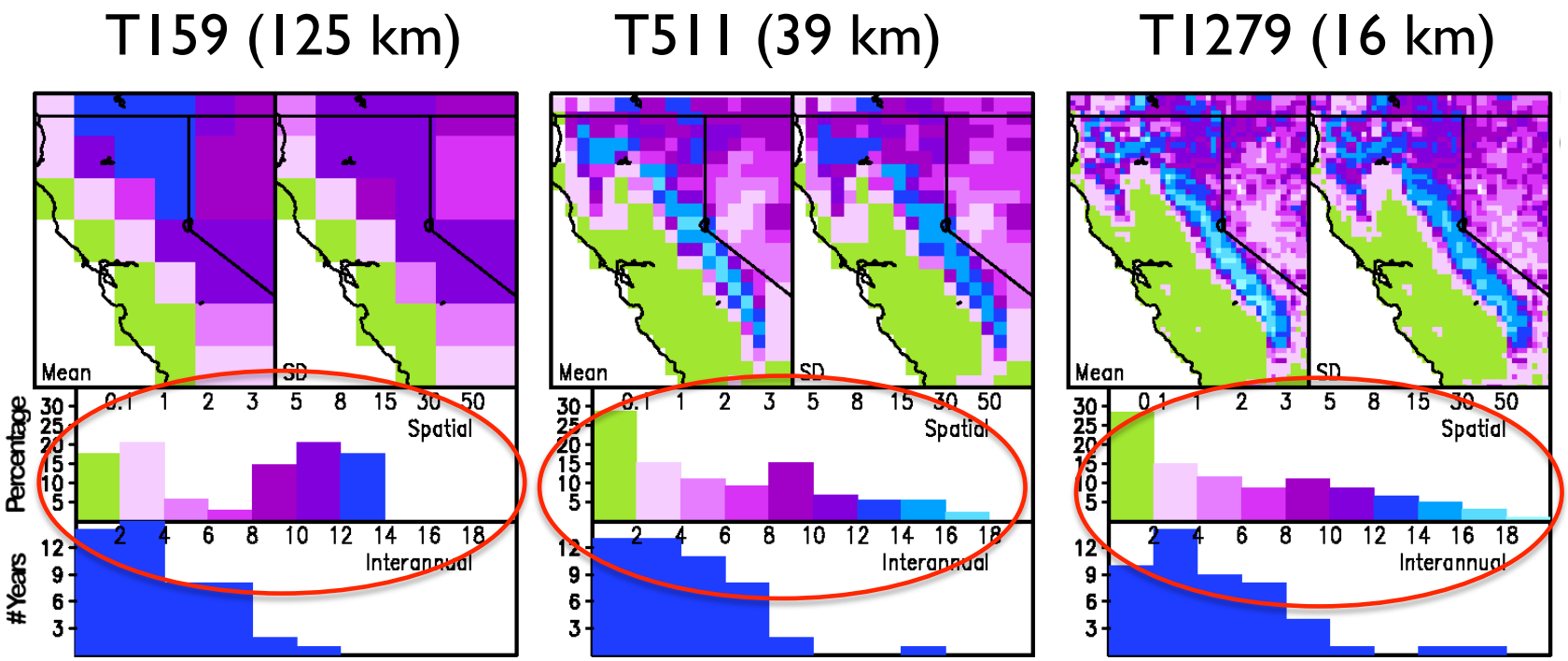
CONUS Transect at 40 N

Interpolated 15-km and 39-km grid data ~agree with native 125-km grid values

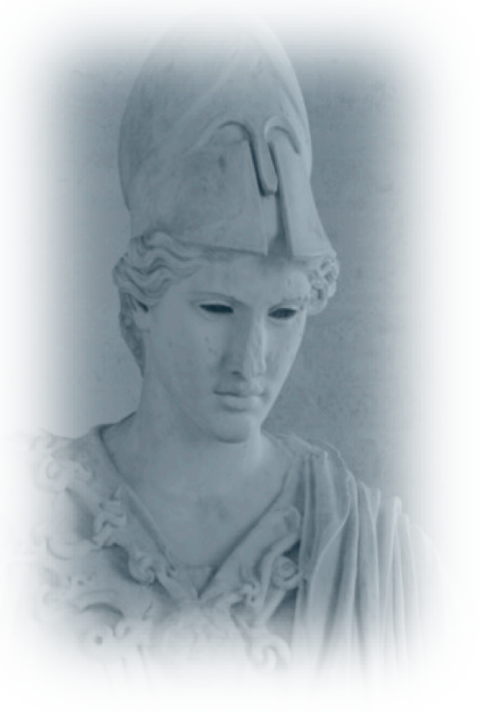
Orographic features are not properly represented at low resolution



Snow Depth (mm) in Western N. America



Decreasing Resolution Biases Distribution



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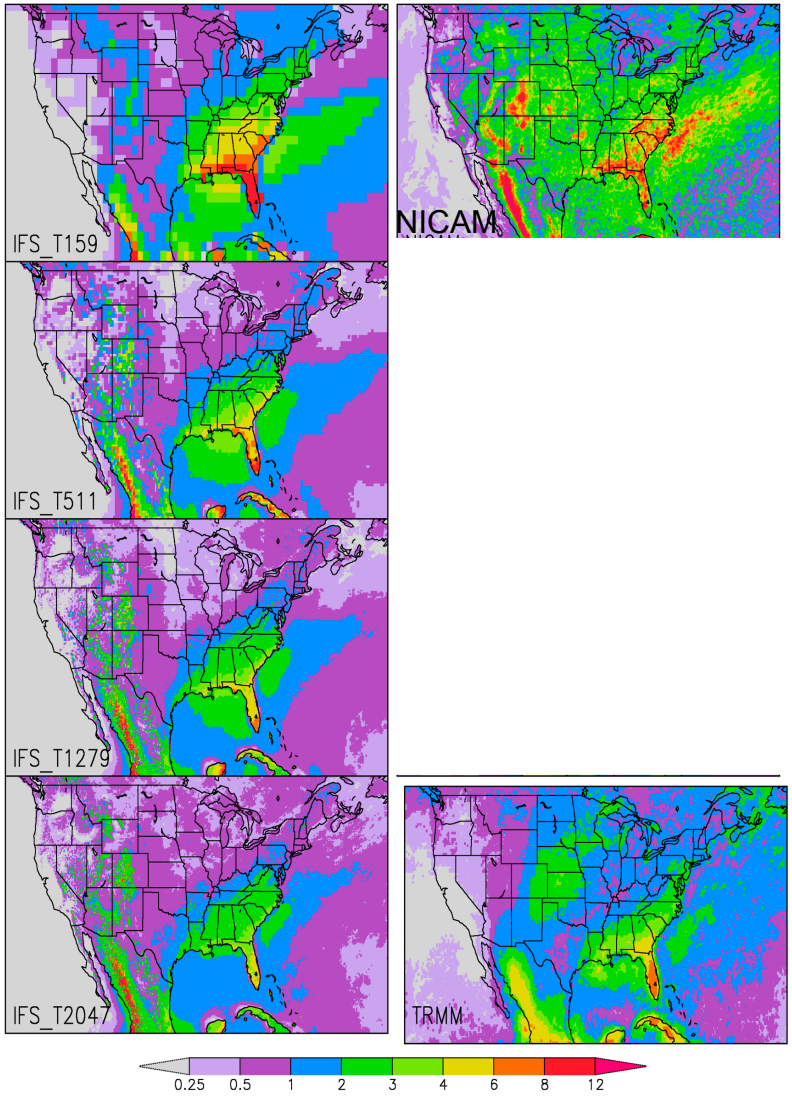
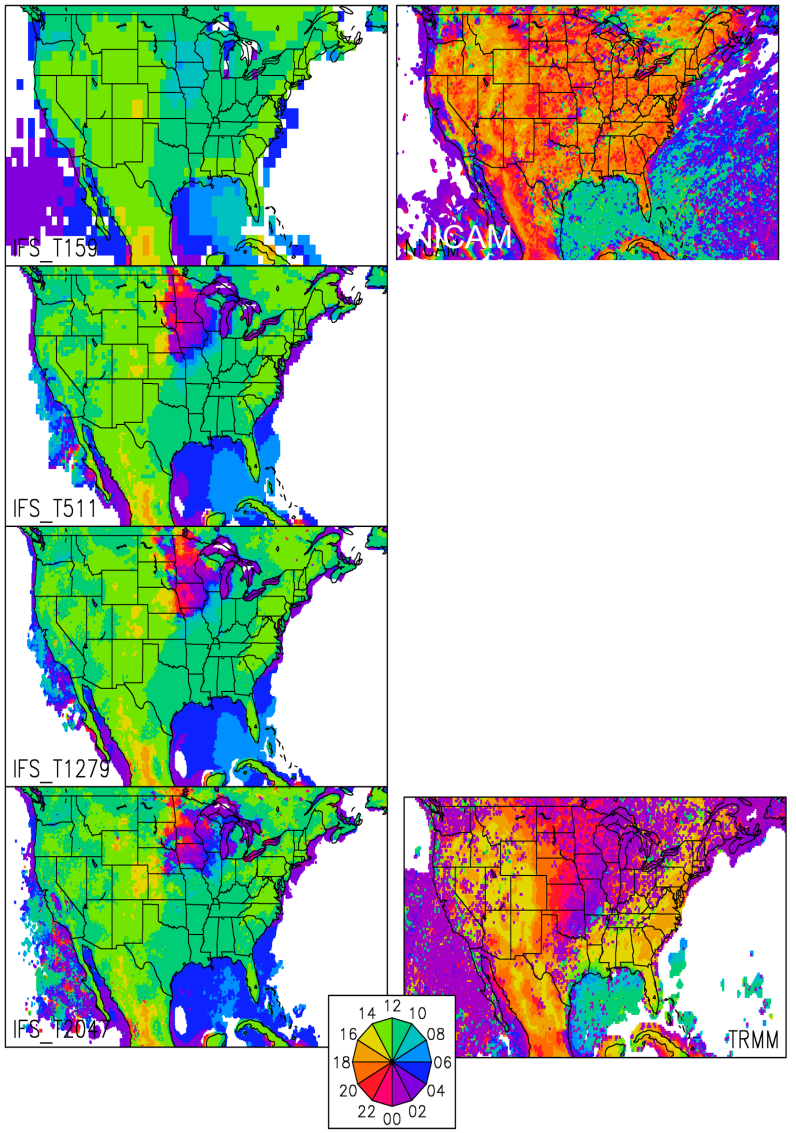
Resolution Dependence of Diurnal Cycle of Precipitation

amplitude



phase



Resolution Dependence of Diurnal Cycle of Precipitation

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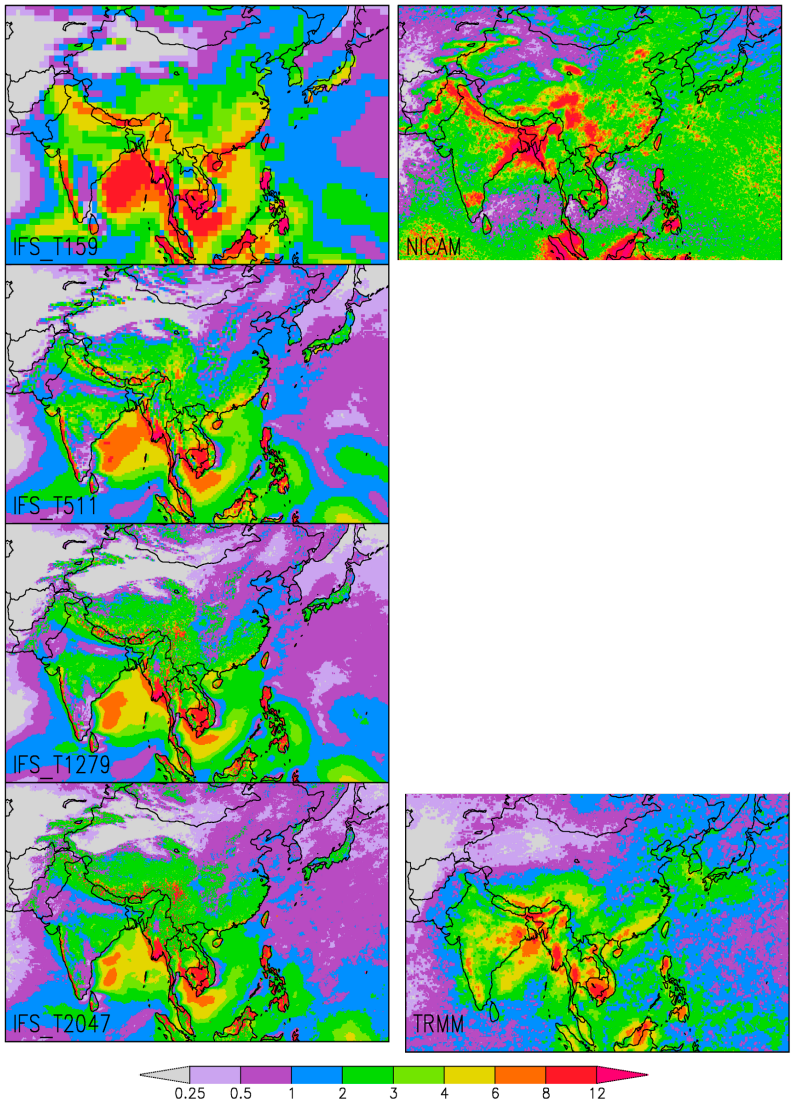

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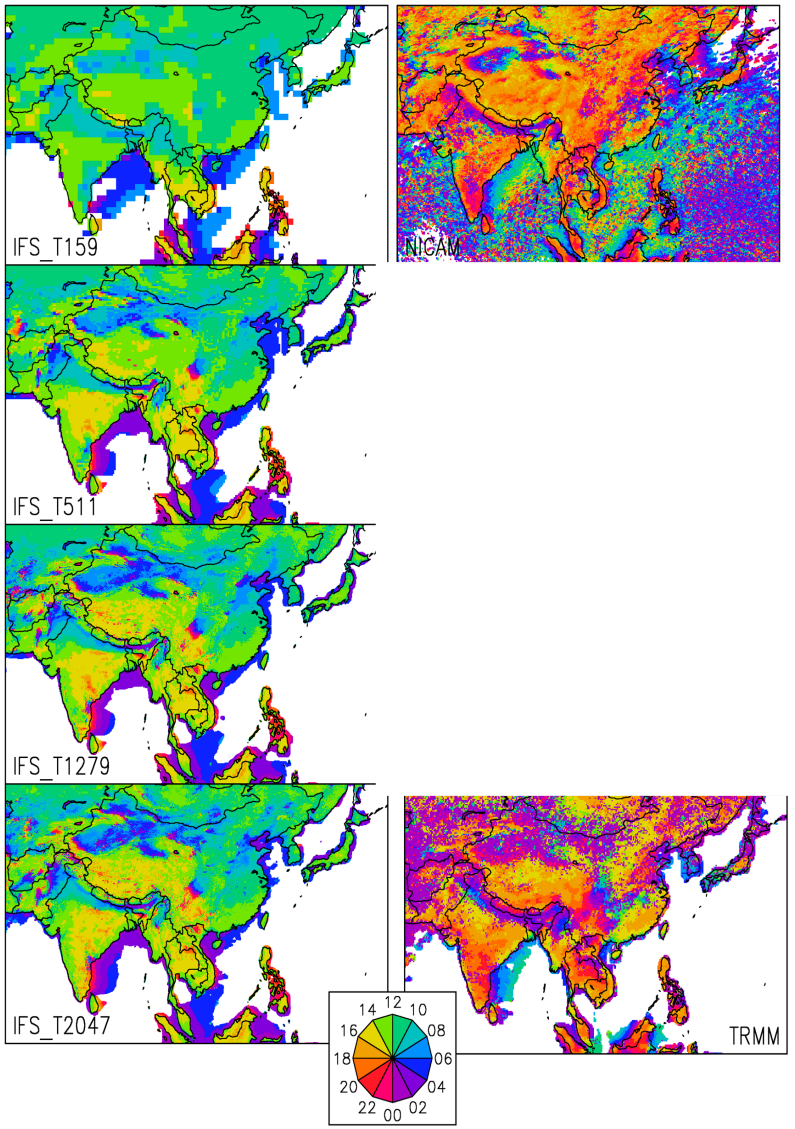

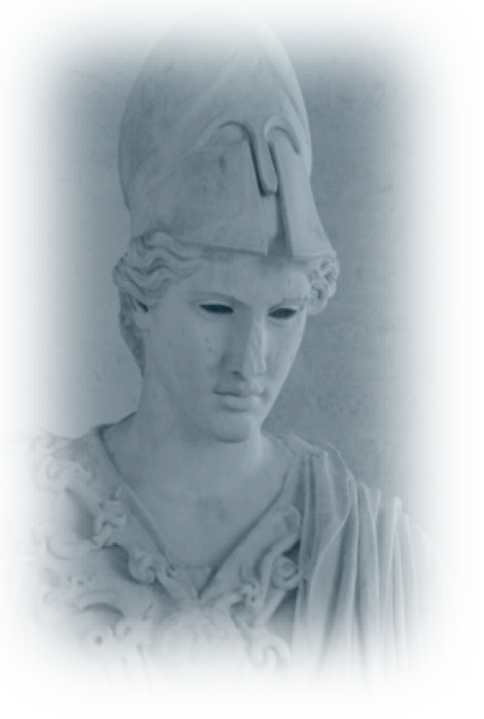

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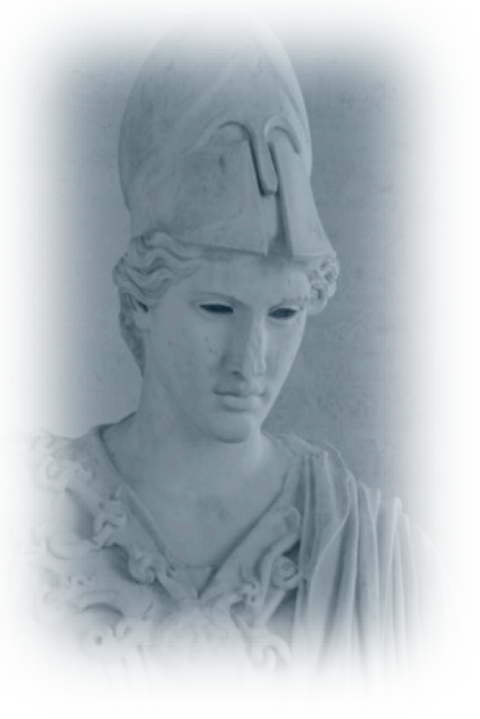

Athena Experiments

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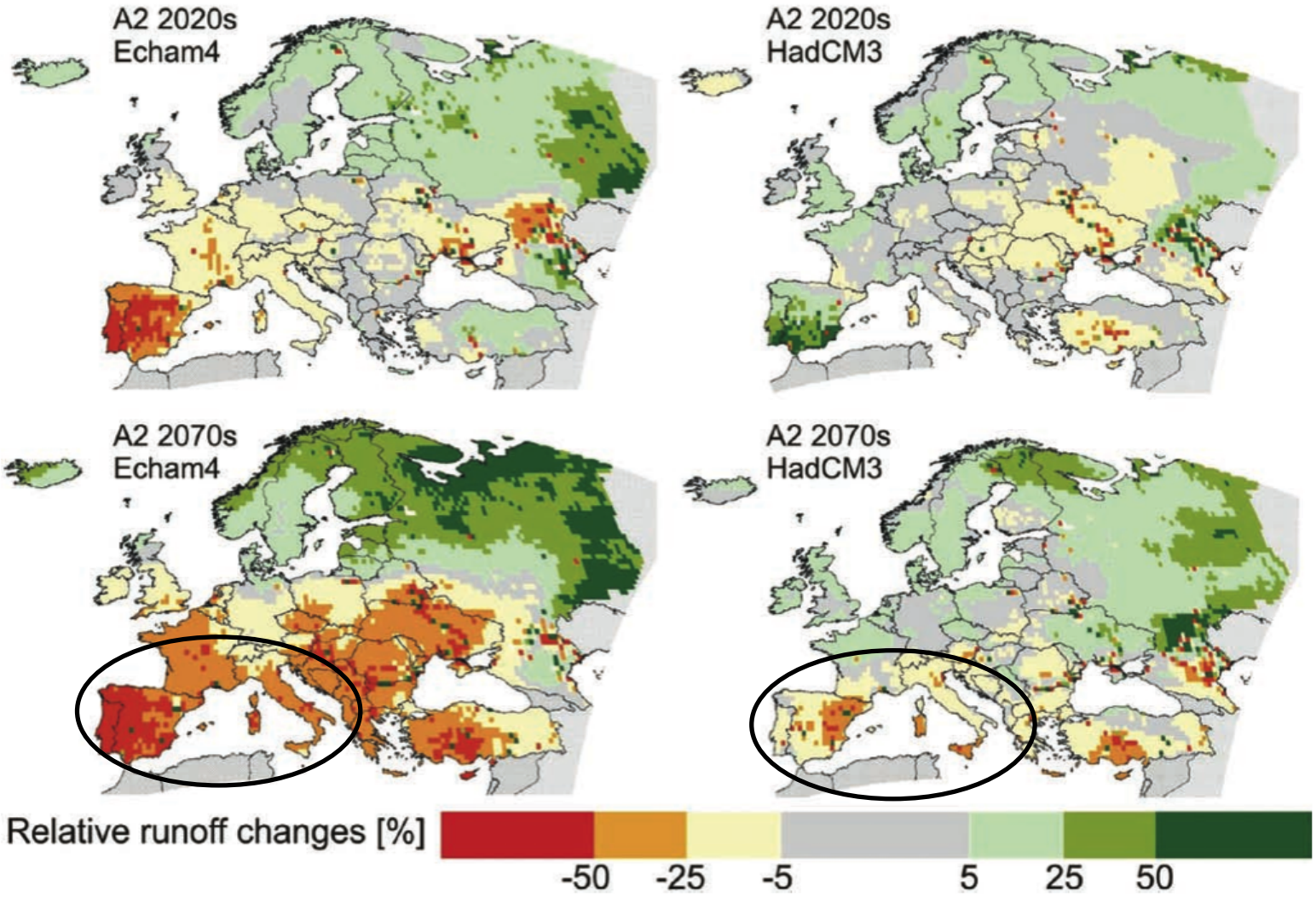
	T1279	15 km			38 TB	

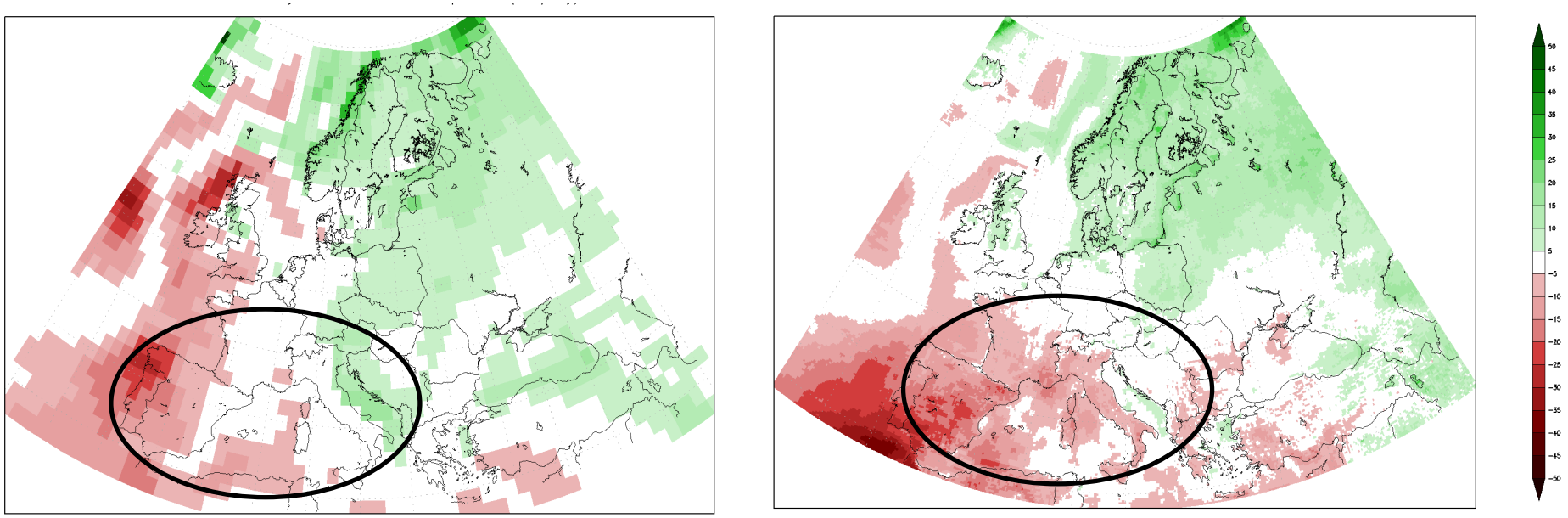
Regional Climate Change – Beyond Today's Models' Ability?



Annual Mean Precipitation Change Europe: 21st C minus 20th C

T159 (125-km)

T1279 (16-km)



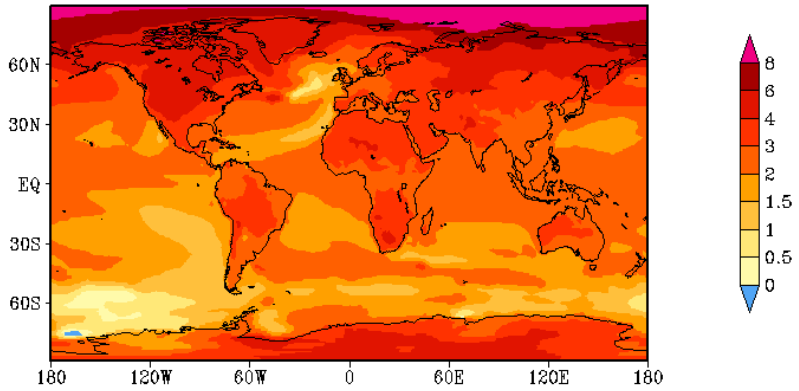
"Time-slice" runs of the ECMWF IFS global atmospheric model with observed SST for the 20th century and CMIP3 projections of SST for the 21st century at two different model resolutions

The continental-scale pattern of precipitation change associated with global warming is the same, but the regional details are quite different, particularly in southern Europe.

Temperature Change (21st C – 20th C)

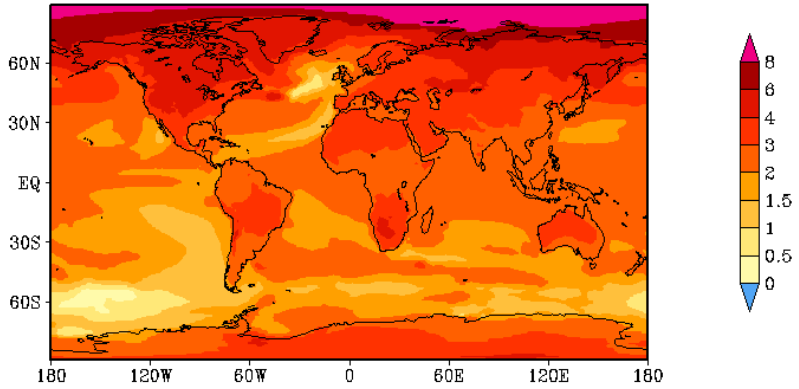
Annual

128-km



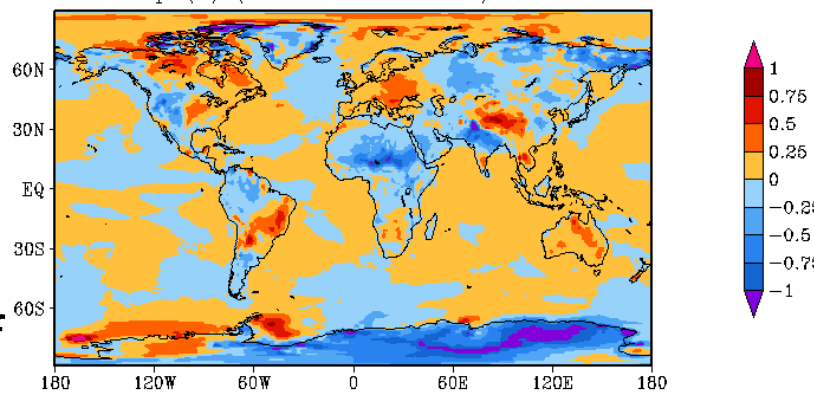
IFS ANN 2−m Temp (K) T1279 TIMESLICE minus AMIP

16-km



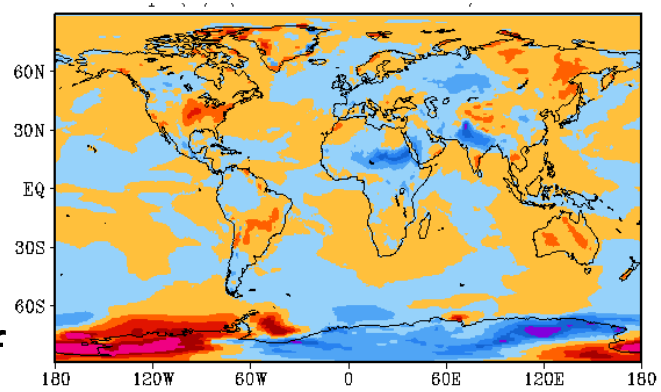
J 2−m Temp (K) (T1279 minus T159) TIMESLICE minus AMIP

diff



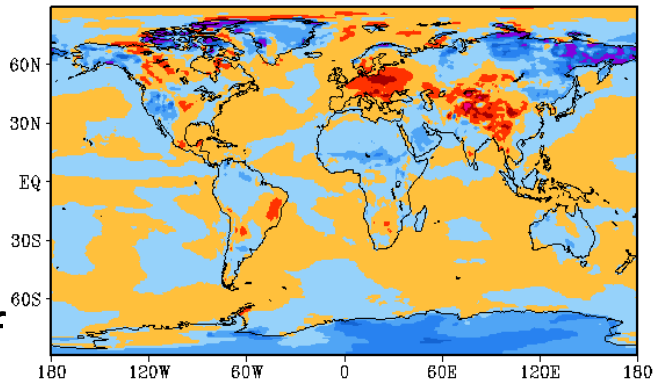
JJA

diff



DJF

diff

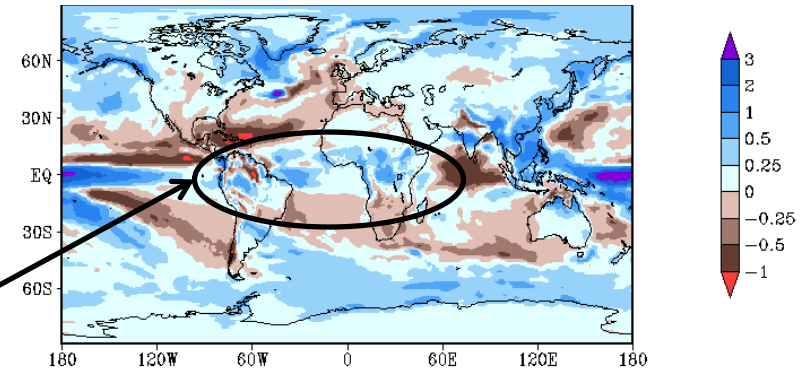


Precipitation Change (21st C – 20th C)

Annual

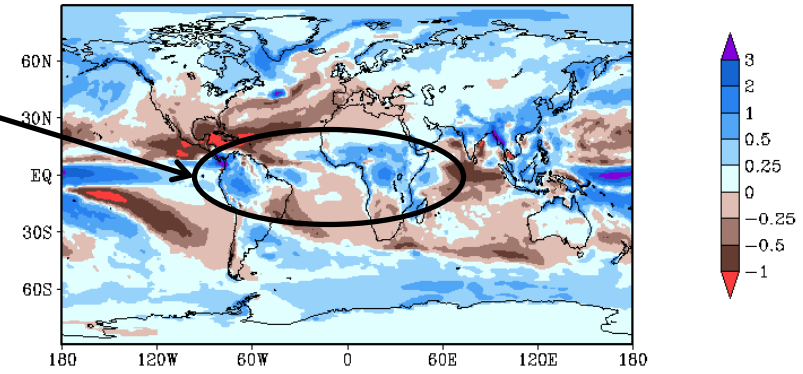
128-km

Wetter Sahel & Amazon in 21st C



IFS ANN Precip (mm/d) T1279 TIMESLICE minus AMIP

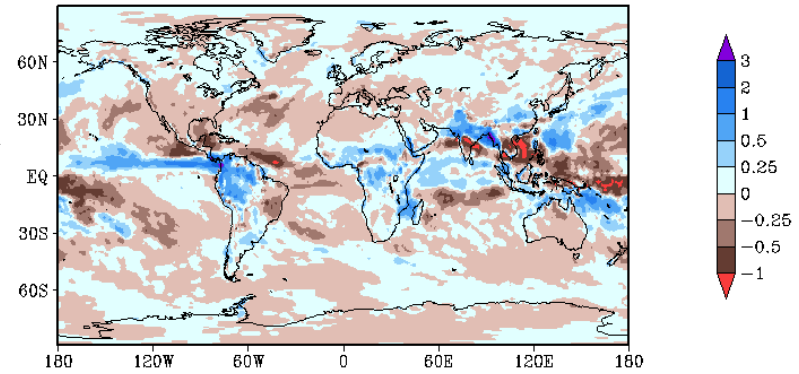
16-km



N Precip (mm/d) (T1279 minus T159) TIMESLICE minus AMIP

Drier overall in 16-km run

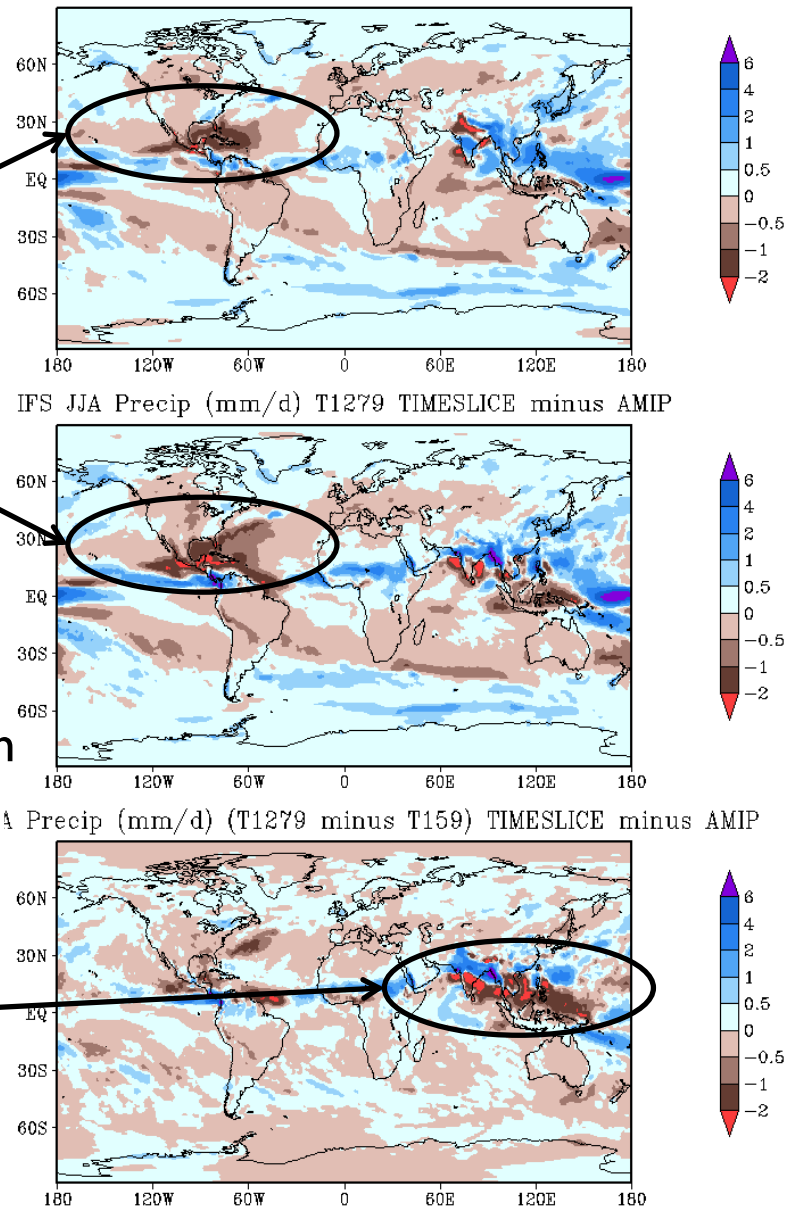
diff



Precipitation Change (21st C – 20th C)

JJA

Less rainfall in tropical cyclone regions of Atlantic and eastern Pacific in 21st C

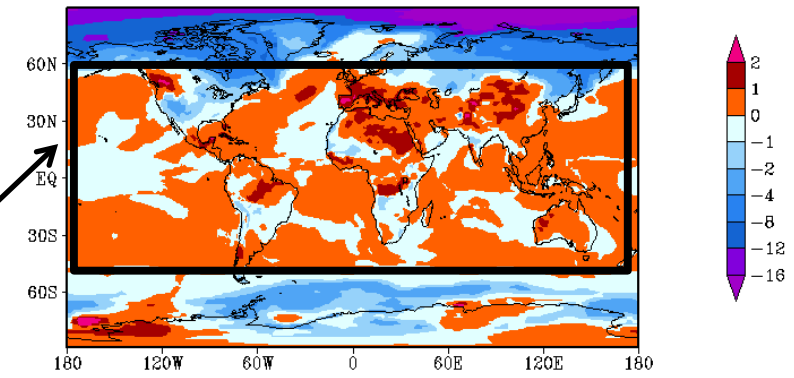


Monsoon changes make northern region of south Asia wetter

Annual T Range Change (21st C – 20th C)

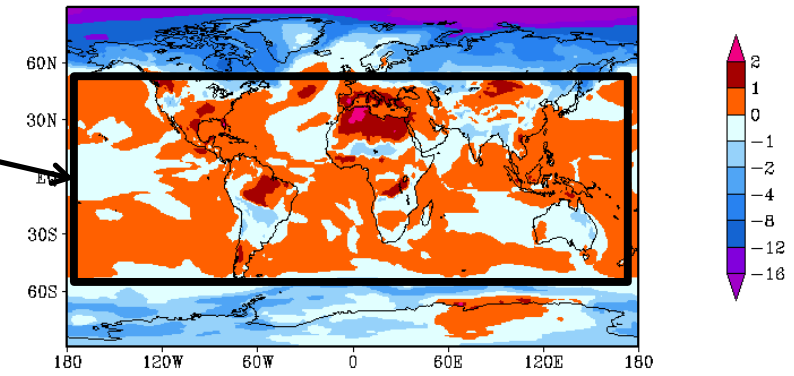
July minus January

128-km



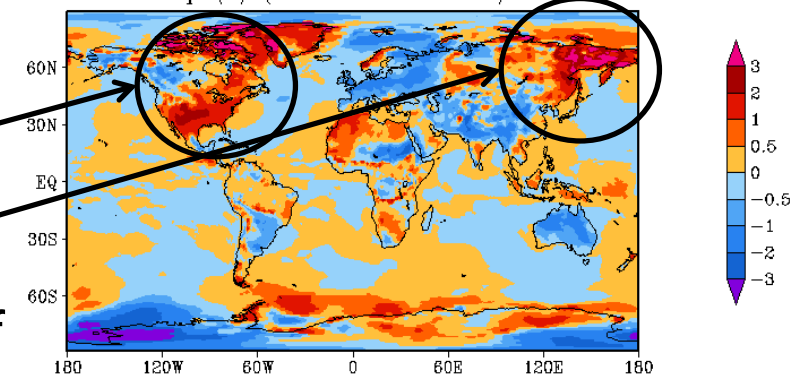
FS Jul−Jan 2−m Temp (K) T1279 TIMESLICE minus AMIP

16-km



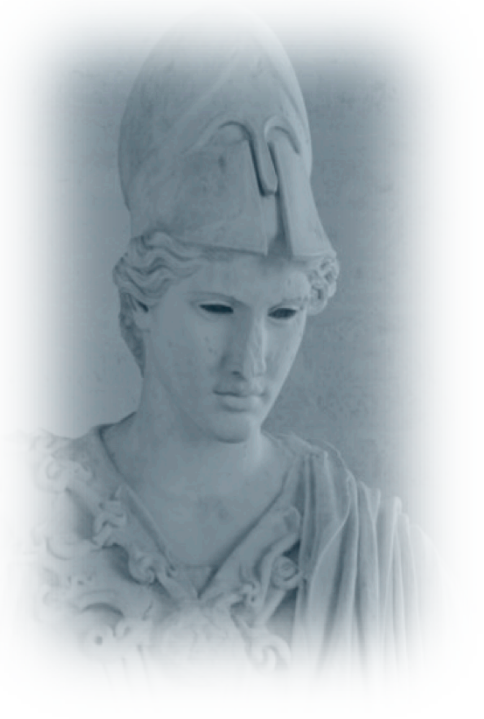
Jan 2−m Temp (K) (T1279 minus T159) TIMESLICE minus AMIP

diff



July warms up more than January between 50S and 50N (opposite poleward of 50°) except over US in low-res run

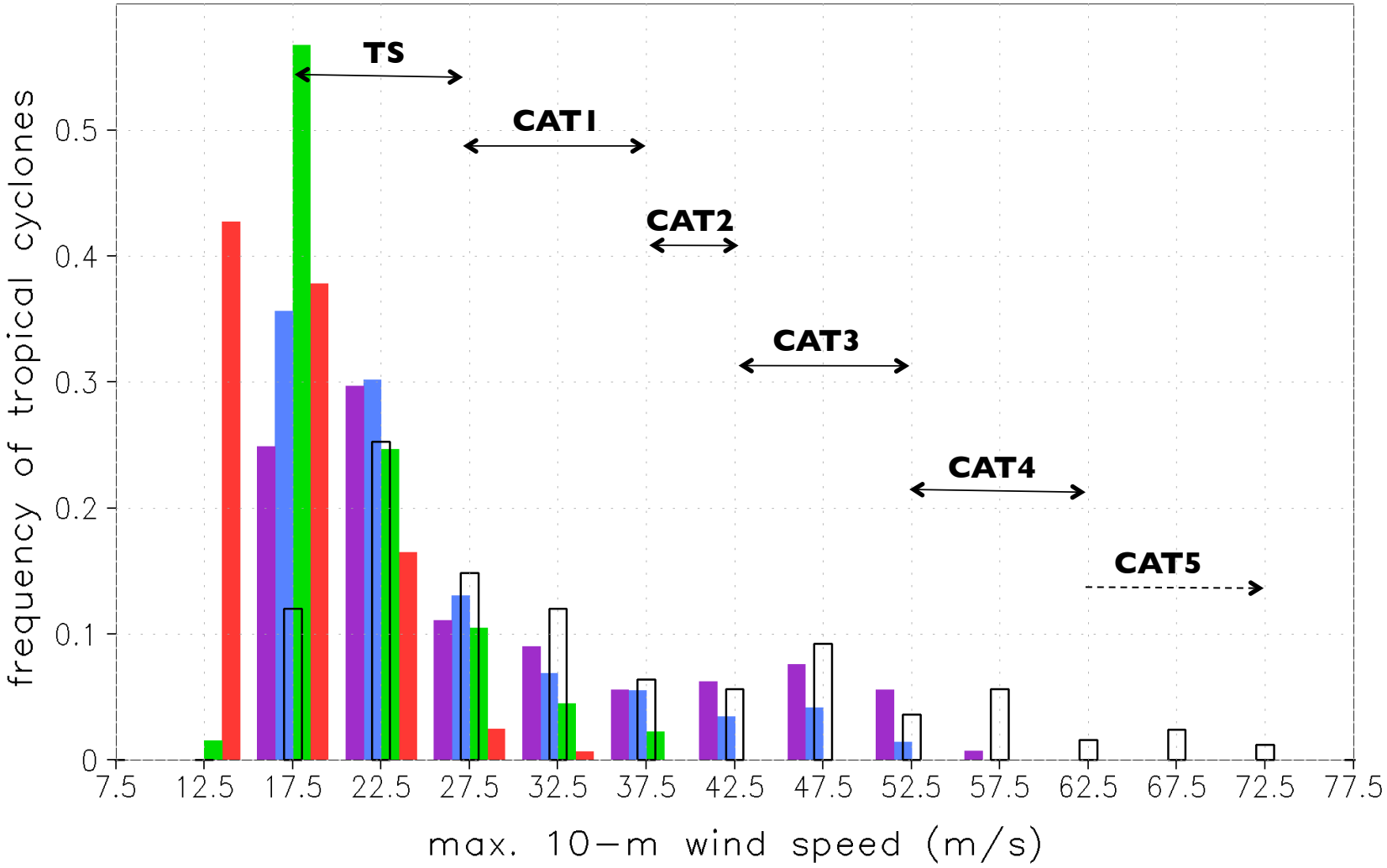
Largest difference due to resolution occurs in North America, eastern Siberia



Sample Results

- Basics of model climate
- Resolution dependence of snow
- Diurnal cycle of precipitation
- Projection of climate change
- Tropical cyclones
  - NICAM simulation (21 May – 31 August 2009)

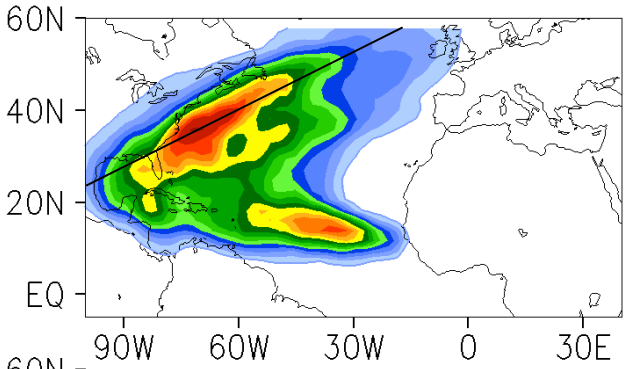
North Atlantic Tropical Cyclones Intensity Distribution
IFS, March-November, 1990-2008



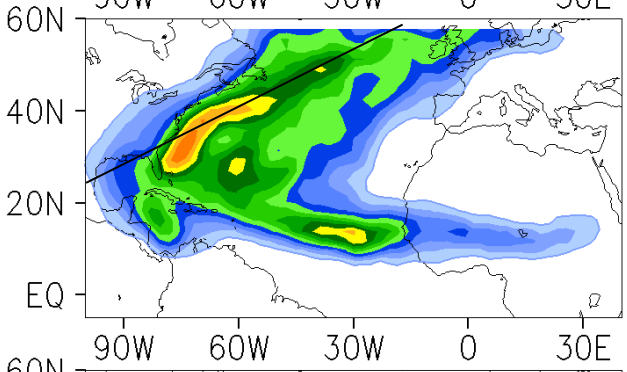
OBS **T2047** **T1279** **T511** **T159**

North Atlantic Tropical Cyclones Track Density
IFS, March-November, 1990-2008

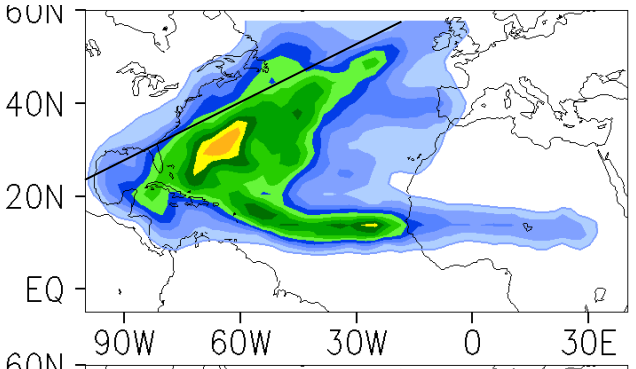
OBS



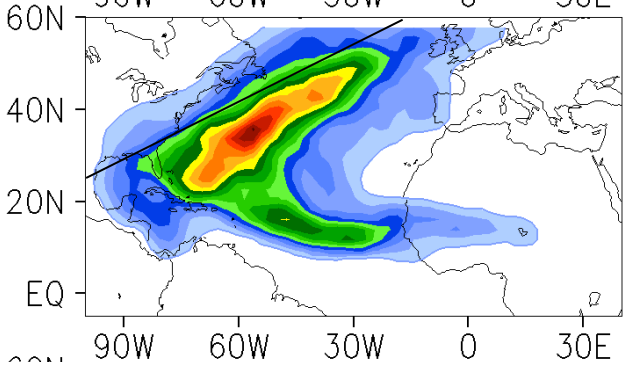
T2047



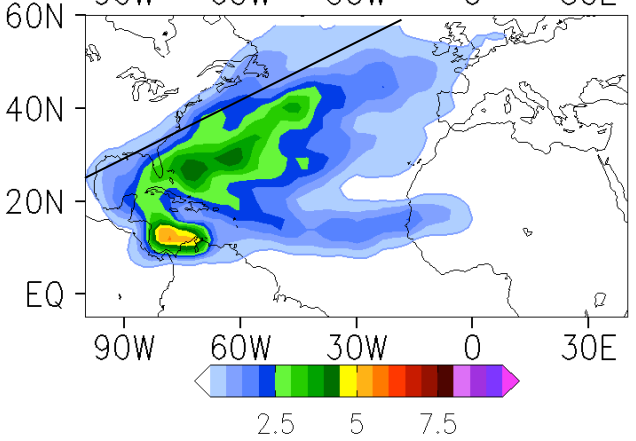
T511



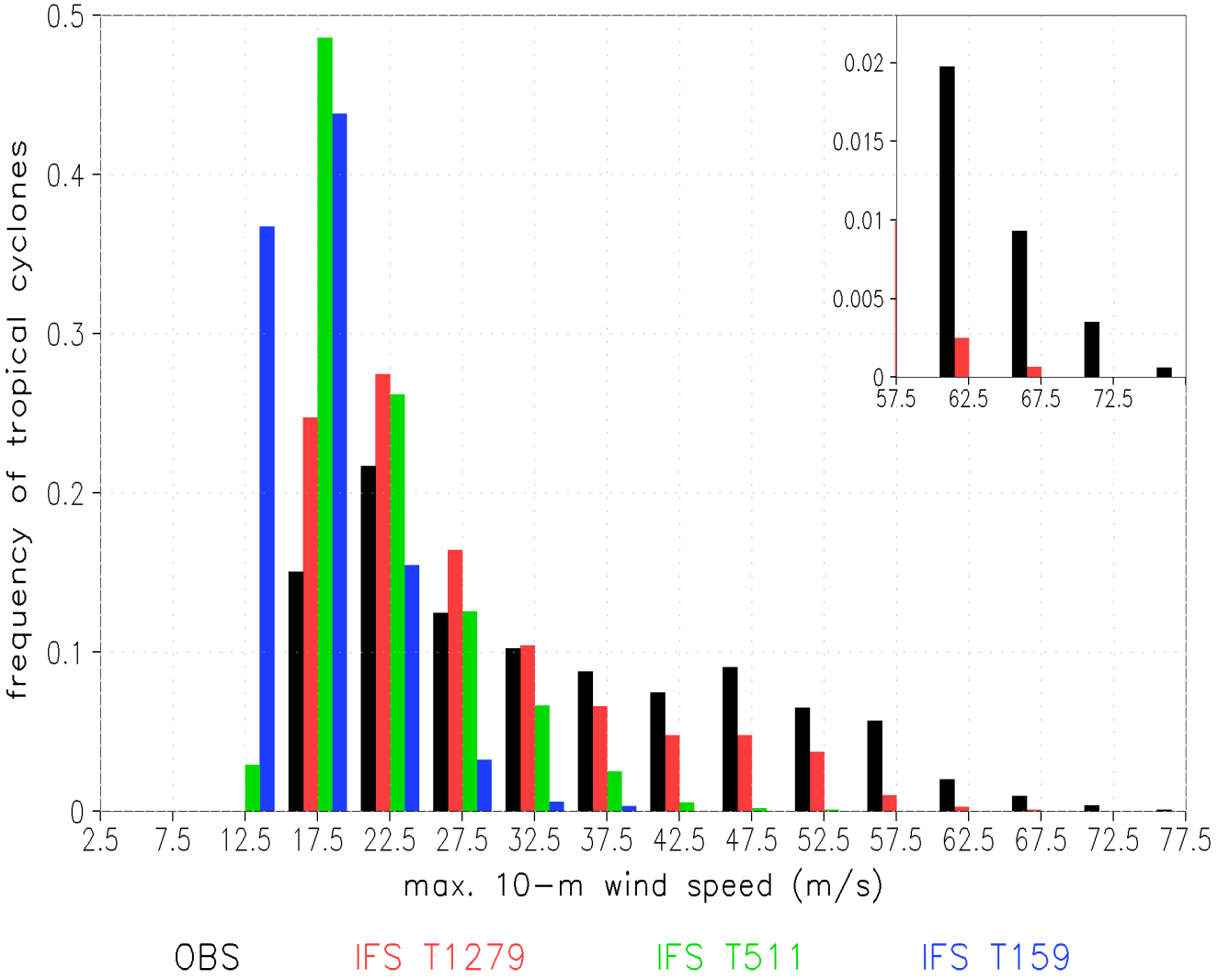
T1279



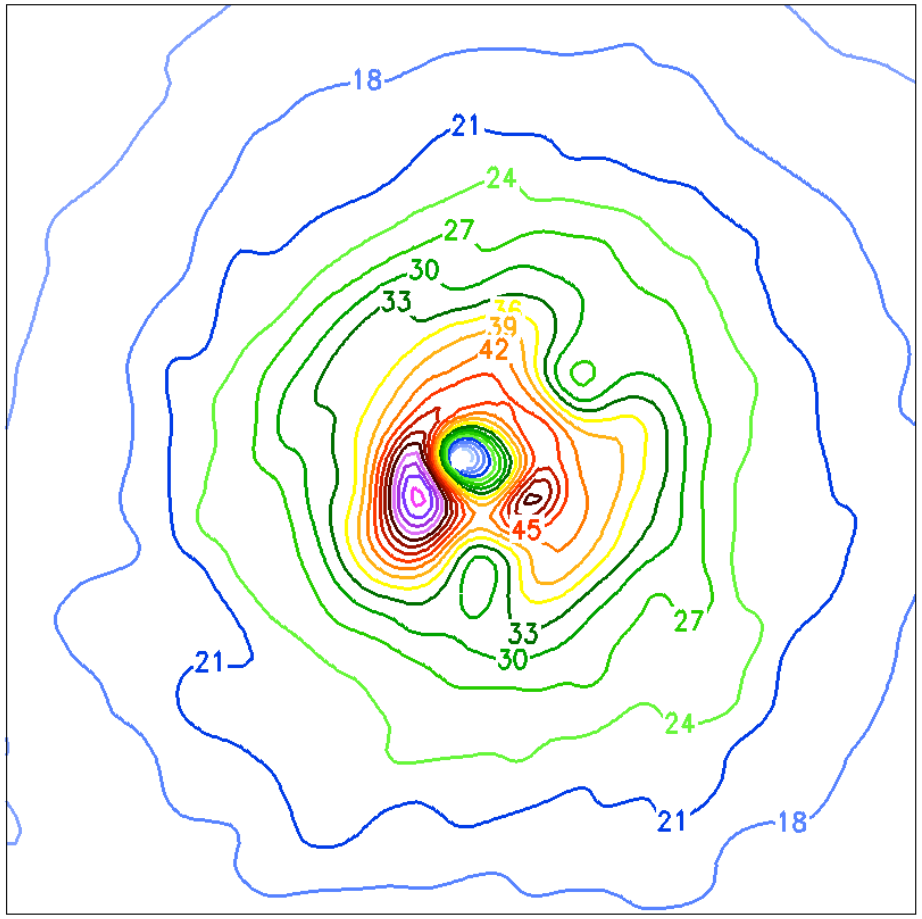
T159



Resolution Dependence of Tropical Cyclones in Global Simulations

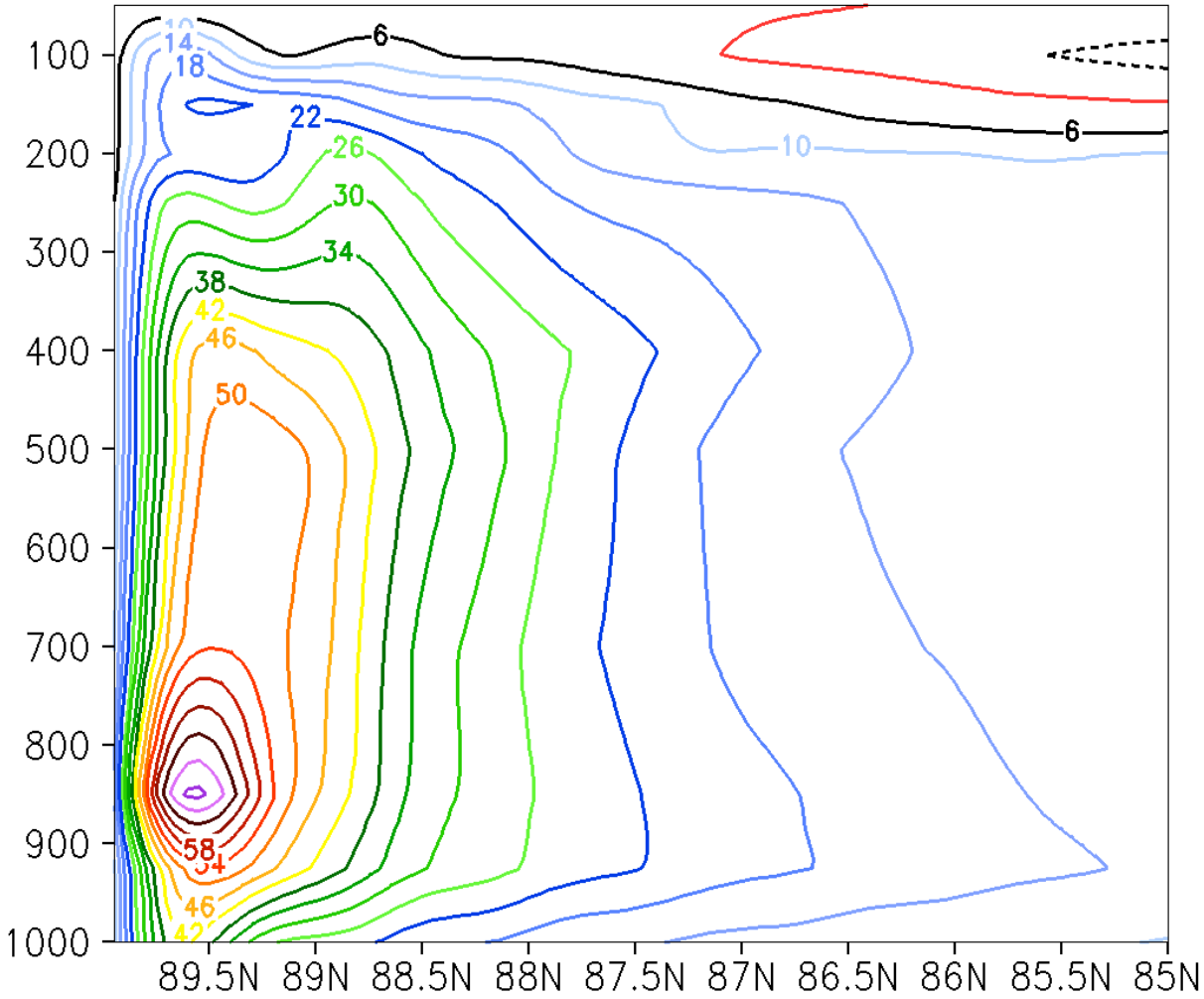


10–m Wind Speed at Max Intensity of the strongest WPac TC, m/s
IFS T1279, 13–mo. hindcast run, MJJASON season, 1989

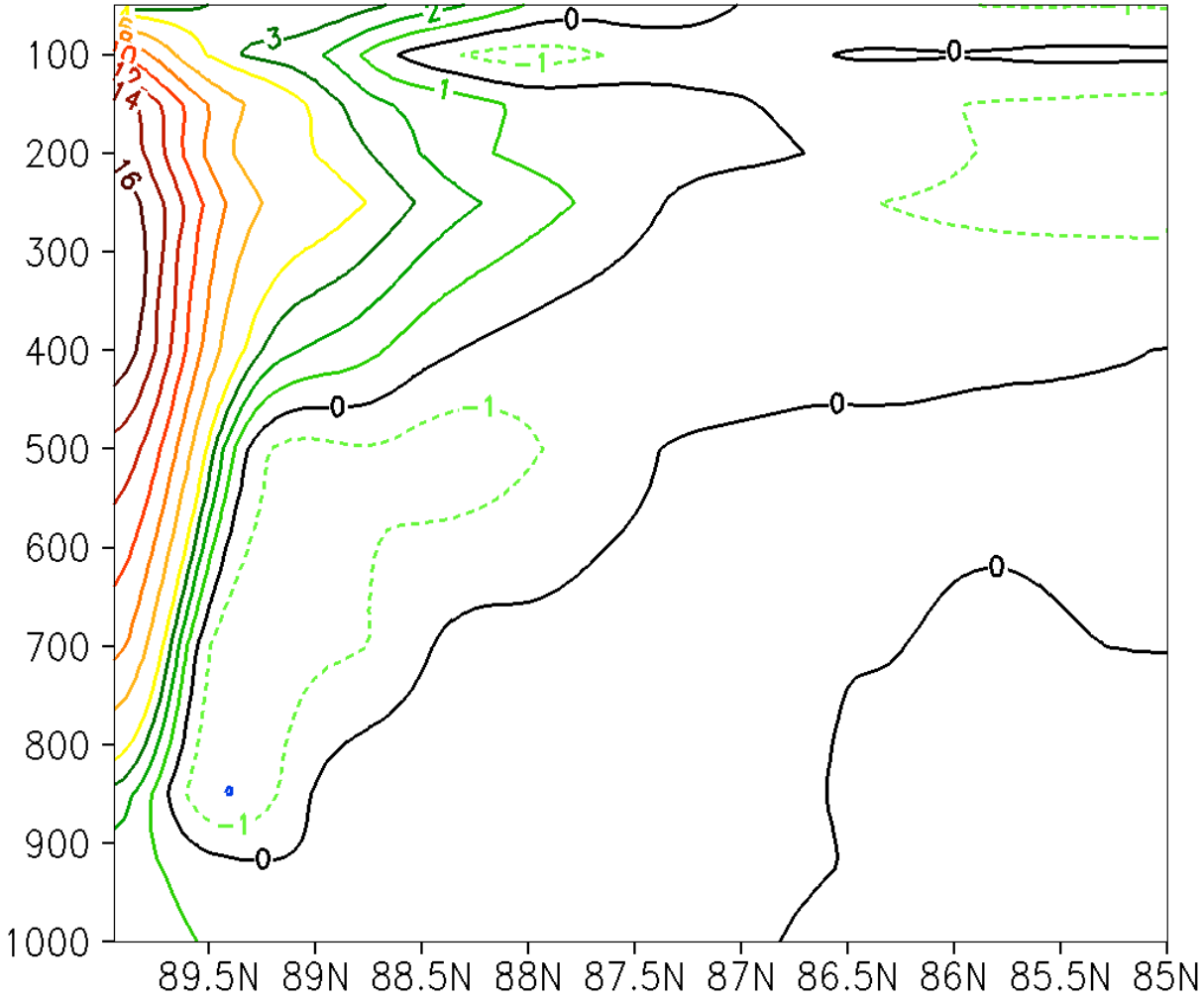


rad = 2 deg.

Mean Azimuthal Tangential Wind at Max Intensity of the strongest WPac TC, m/s
IFS T1279, 13–mo. hindcast run, MJJASON season, 1989

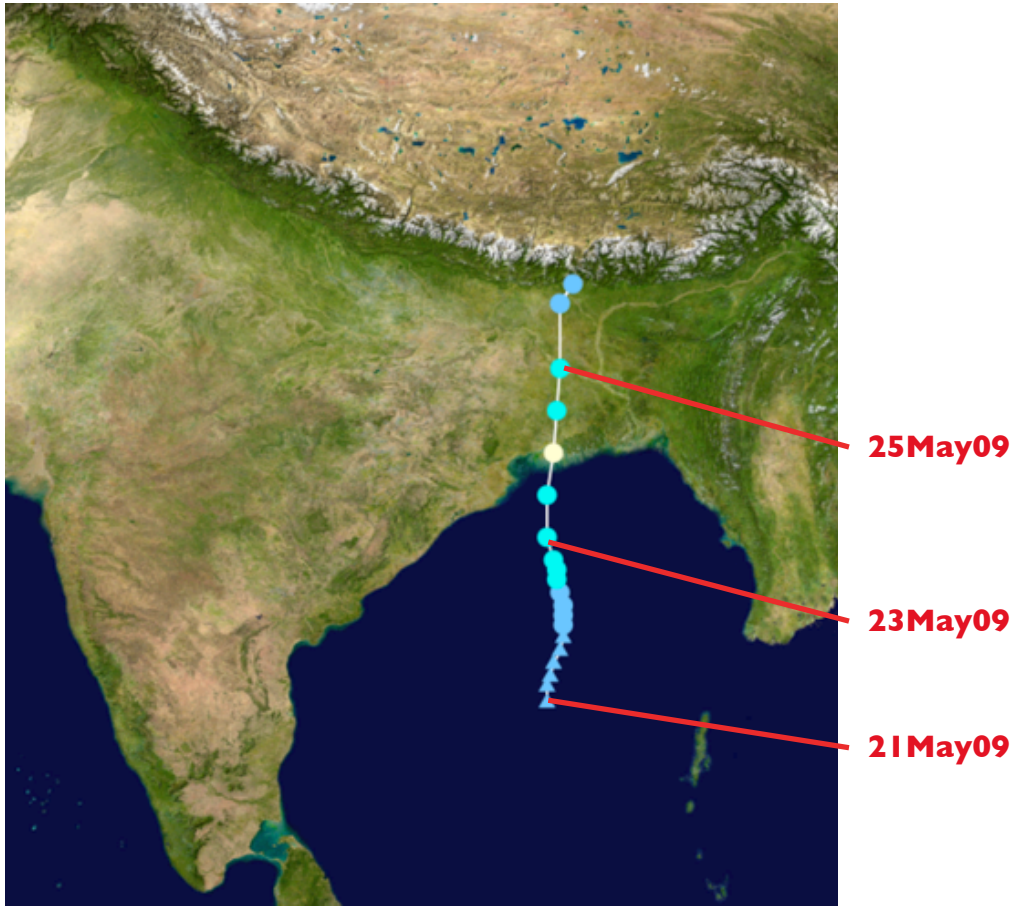


Mean Azimuthal Temperature Anomaly at Max Intensity of the strongest WPac TC,
IFS T1279, 13-mo. hindcast run, MJJASON season, 1989, deg. K



May 2009 - Tropical Cyclone Aila

<u>Single case example</u>: NICAM simulation accurately predicted development, evolution and track of TC Aila over 5-day period

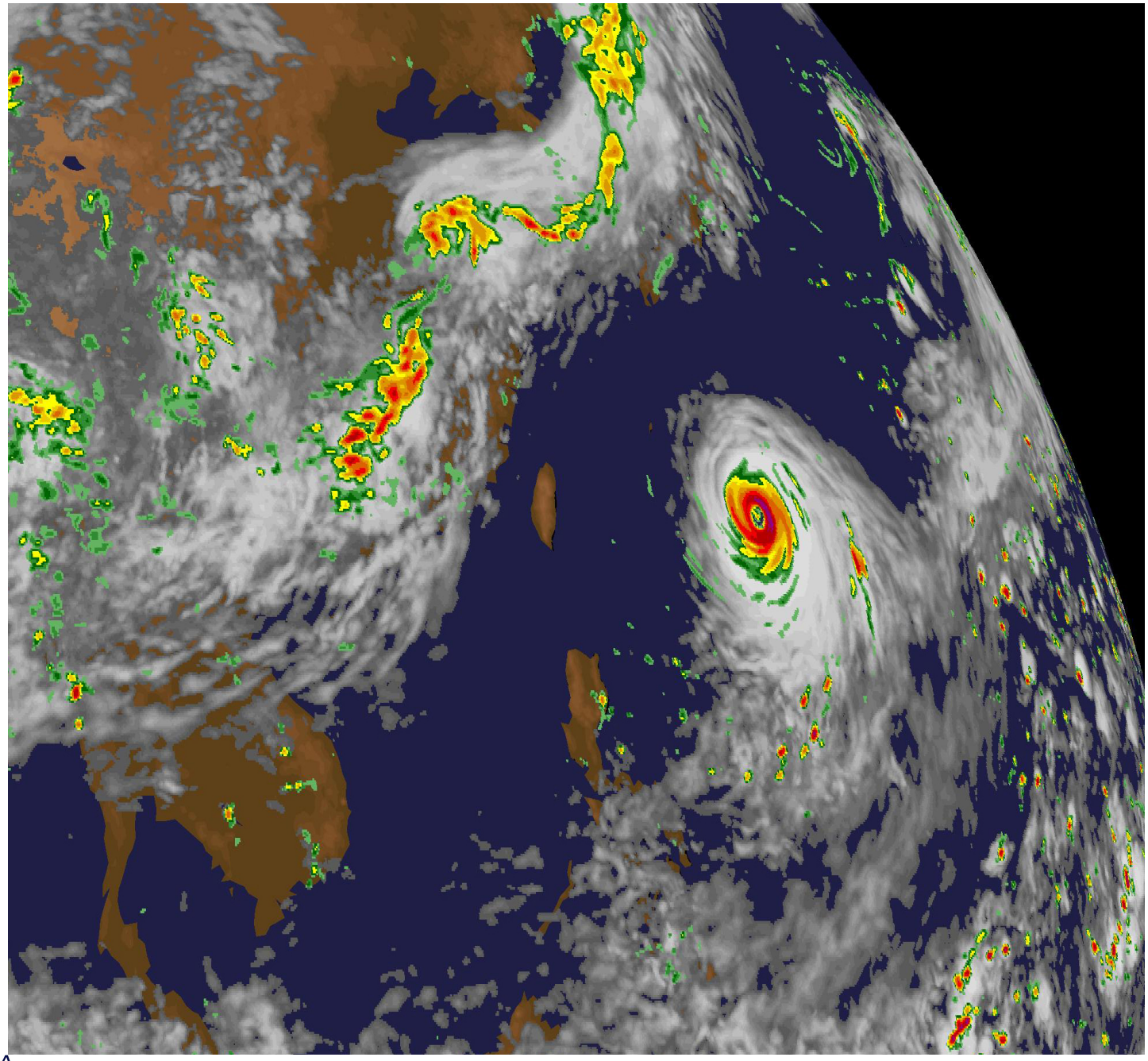


Tropical Cyclone Aila made landfall in India on the Bangladesh border region on May 25 as a borderline category 1 hurricane. TC Aila had sustained winds of 65 - 75 mph at landfall. Approximately 150,000 people were left homeless in India, and at least 45 people have died. In Bangladesh,10,000 people are homeless, and 89 have died with hundreds missing. The death toll is expected to rise.

Credit: NOAA

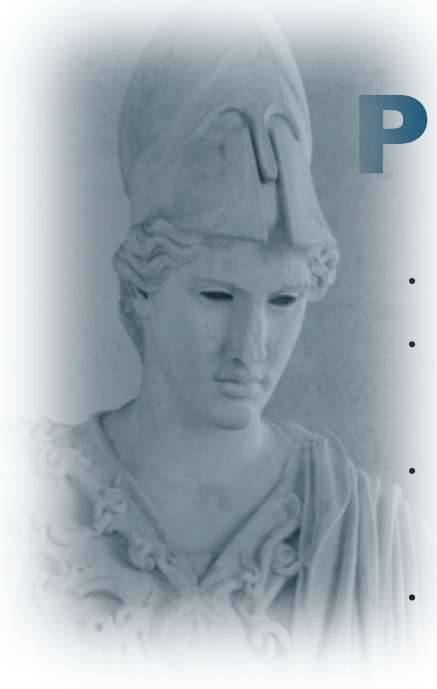
NICAM Animation

21 May – 31 August 2009



Project Athena: Summary

- **Good news:** Extreme spatial resolution (highest possible with hydrostatic dynamics and parameterized clouds) **does not change qualitative features of climate simulation** → our large-scale intuition still works for the most part
- **As expected:** High spatial resolution provides **higher fidelity representation of features sensitive to orography**
- **Unexpected: Nonlinear dynamical effects** can alter simulation changes due to spatial resolution improvements much more and possibly in different ways than we might have expected
- **Bad news** (expected?): There really is a **"no-man's land"** between resolutions for which parameterized clouds are appropriate (> 15 km grid) and for which resolved clouds are appropriate (<< 7 km grid)



Project Athena: Summary

- **NSF impetus**: Act on results of 2008 World Modeling Summit
- **Hypothesis**: High spatial resolution and process-resolving models can dramatically improve simulation of climate
- **COLA role**: formed and led an international collaboration involving **over 30 people in 6 groups on 3 continents**
- Two state-of-the-art global AGCMs at the **highest possible spatial resolution**
- **Dedicated supercomputer** at NICS for Oct'09 – Mar'10
- **Data ~900 TB total**
- **Overall results** look very **promising**
- Long term **- model output data will be invaluable** for large community of climate scientists (unprecedented resolution and simulation duration) and computational scientists (lessons learned from running dedicated production at nearly petascale)