New Modeling Capabilities

Advancing NOAA Climate Science

Presented by

Shian-Jiann Lin, Alistair Adcroft & Isaac Held

Exploring the next frontier of climate modeling
with
ultra-high resolution non-hydrostatic model

using the GFDL FV3:
The non-hydrostatic Finite-Volume dynamical core on the Cubed-sphere

Ultra-high-res Models under development

Goals:

- To unify "regional-global" and "weather-climate" models - A true seamless modeling system, a model that has no built-in scale limitation!
- To improve realism of climate simulations and to provide regional details for stakeholders
- To enable seasonal to decadal predictability of high impact weather events previously thought too difficult or impossible

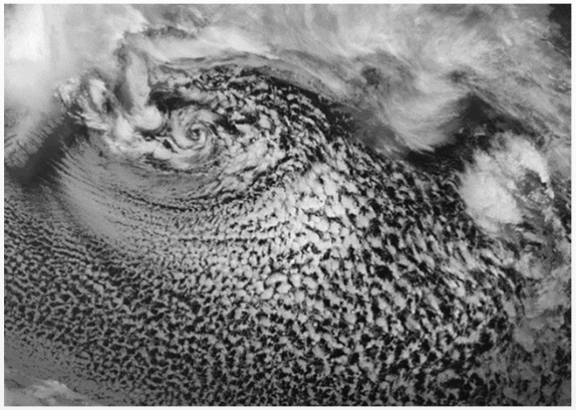
Examples:

1. Coupled ***cloud-permitting*** model (~3.5 km, global quasi-uniform resolution): computationally expensive; use mainly as a learning tool (software, dynamics & physics) –> lessons learned trickling down to main stream production models
2. A *km-scale* ***thunderstorm-resolving*** *"*Global *regional climate* model" with 3-5 km over CONUS (Continental US), and ~1 km with a 2-way nest (Harris & Lin 2013)
   - Seasonal prediction of ***hurricanes with region specific information***
   - Seasonal prediction of ***tornado outbreak***
3. Same as 2, but for W. Pacific to study Asian monsoon & typhoons

Some fine-scale phenomena that used to be impossible to simulate in a global model are now within reach

Cloud streets off US east coast

Polar low near Iceland



Tornado-producing thunderstorm

Pineapple express

Extending the predictability of high-impact weather events from seasonal to decadal

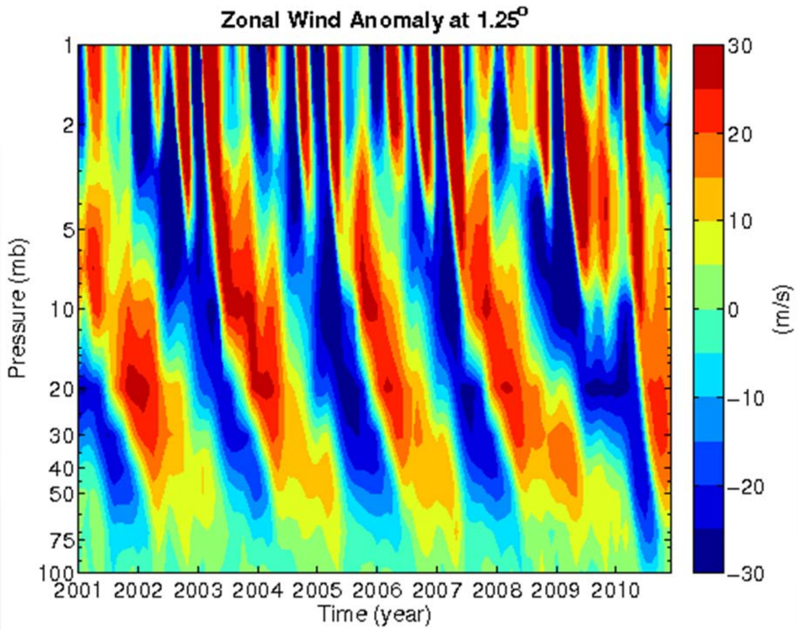
Main sources of the seasonal predictability:

- Initialized state (atmosphere, land, and ocean) – counting on long memory in the land model and ocean
- Low-frequency tropospheric oscillations: **MJOs** (Madden Julian Oscillations)

Decadal predictability?

- Large-scale stratospheric phenomena: **QBOs** (Quasi-Biennial Oscillations)

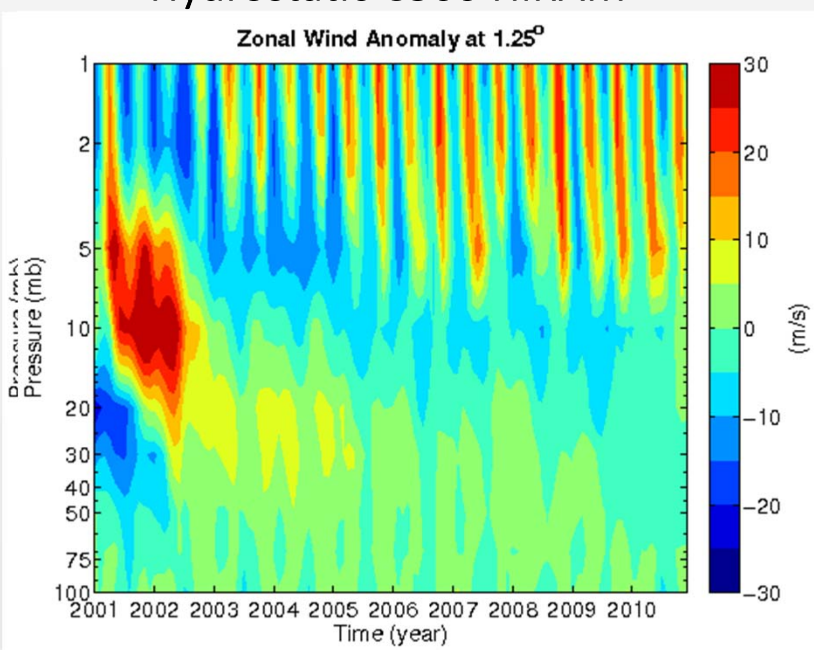
NASA Merra Data (analysis)



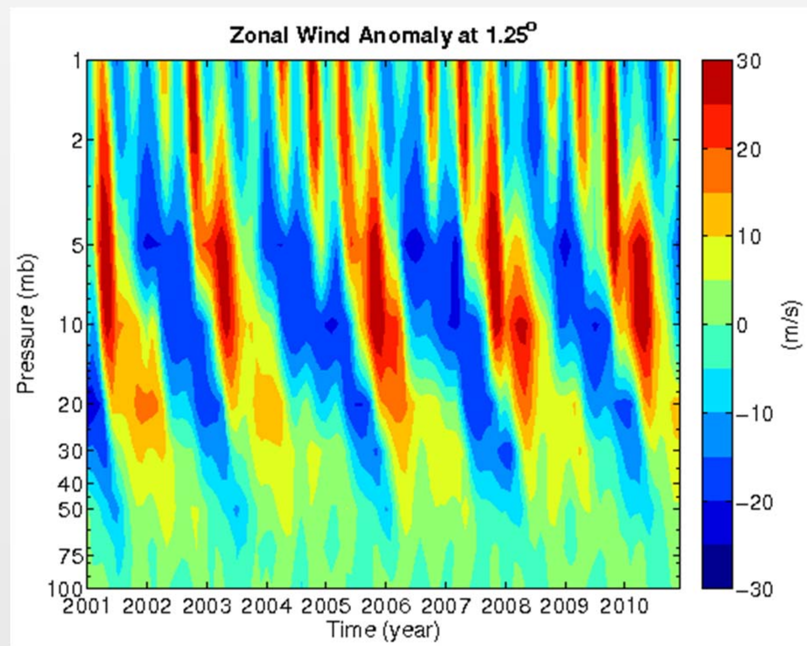
QBOs:

- QBOs are extremely difficult to simulate in free-running GCMs
- QBOs are believed to have significant impacts to sudden warming, stratospheric ozone, monsoon, and (some also believe) hurricanes & winter storms
- Some decadal predictability is achievable with an initialized state and if the model can simulate QBOs

Hydrostatic C360 HiRAM

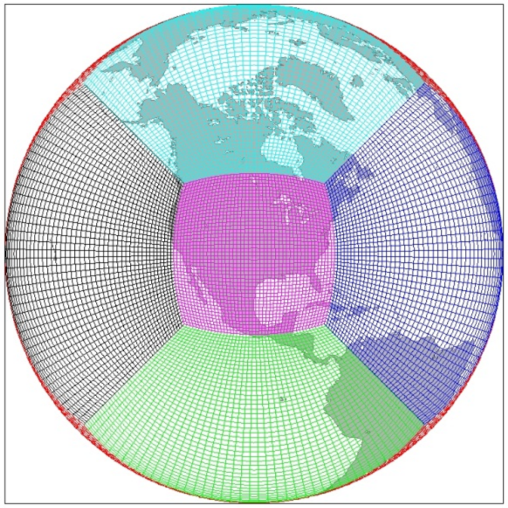


Non-hydrostatic C360 HiRAM

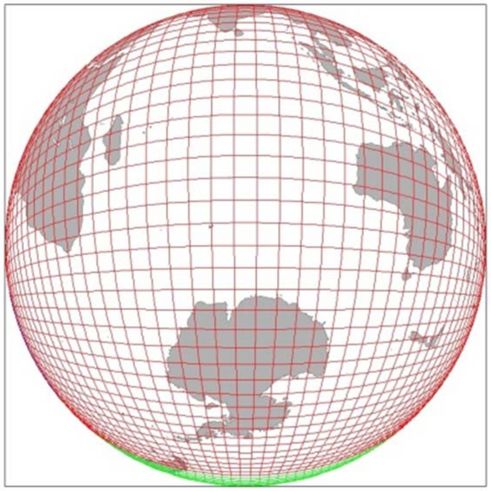


GFDL's thunderstorm-resolving model for CONUS (center: Oklahoma City)

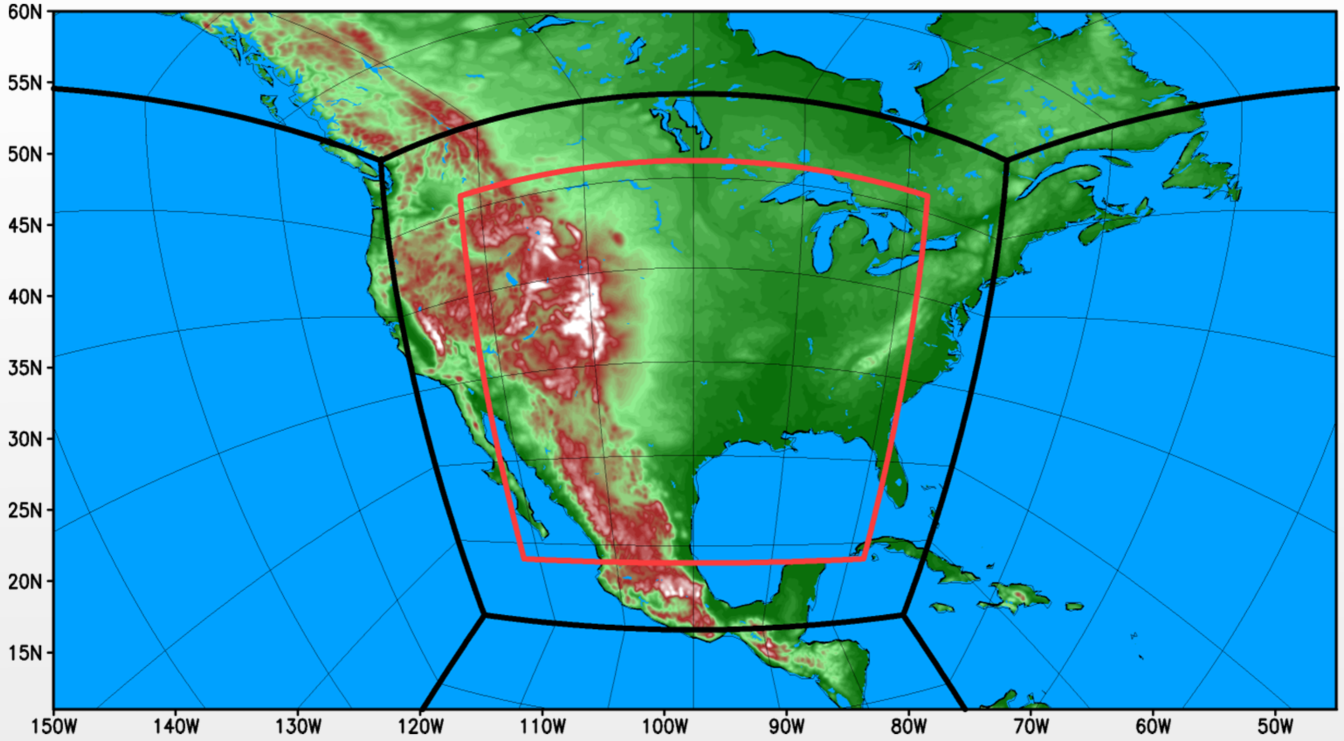
Oklahoma City



Back side of OKC



Stretched + nested weather-climate model

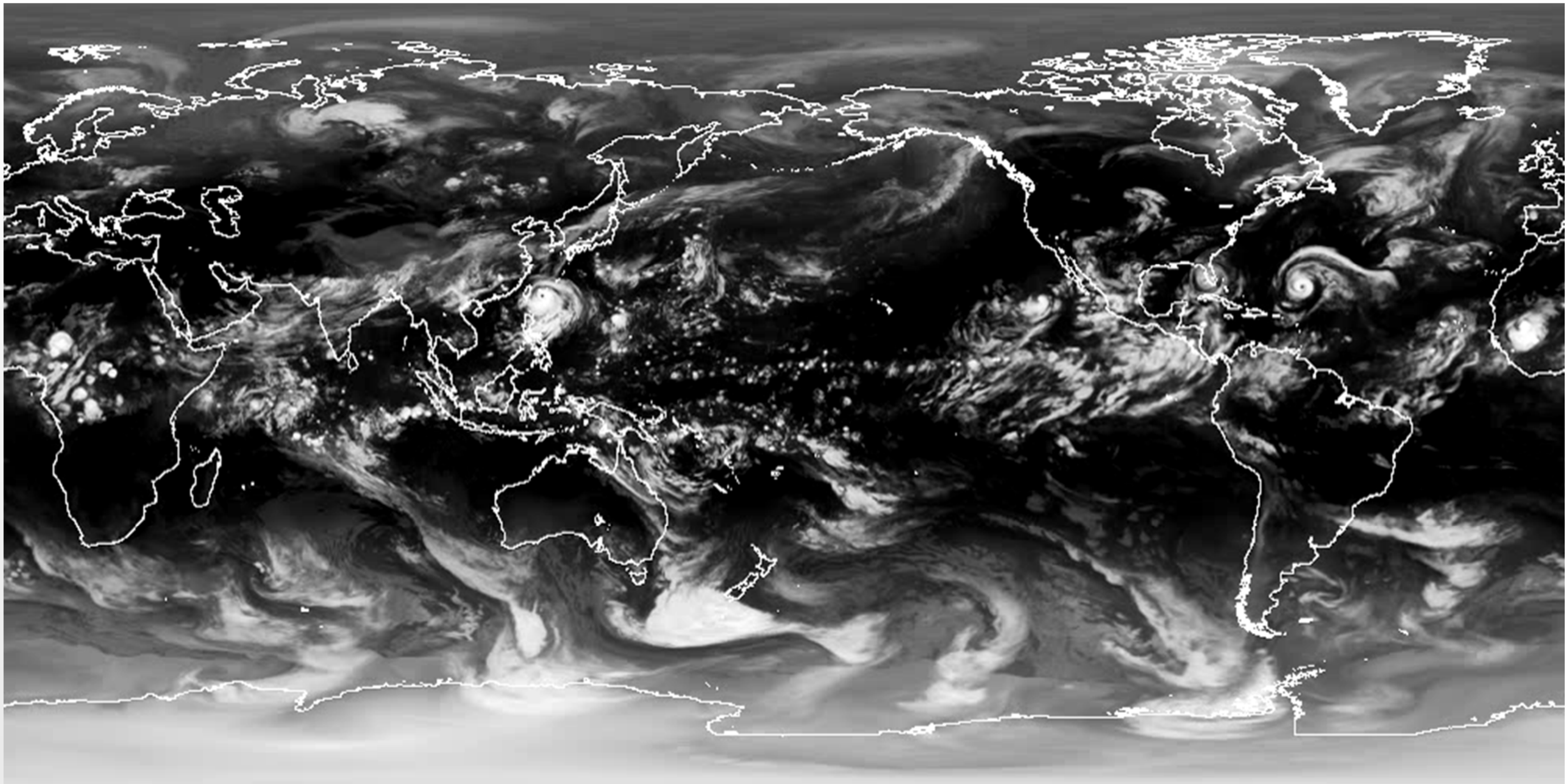


Resolution: 3-5 km without the nest (black)
~1 km with a 2-way nest (red)

Cloud-permitting simulation of the 2008 hurricane season

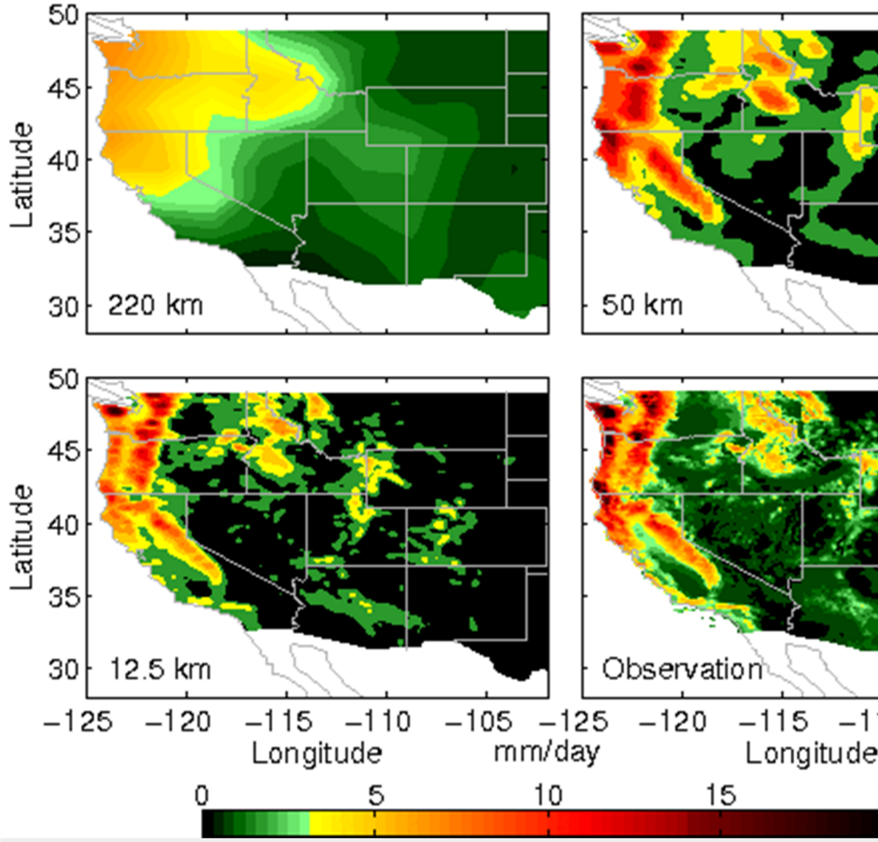
(3-5 km over E. Asia)

OLR: Aug 24 – Sep 04, 2008



Resolving cat-5 typhoons
intensity may be too strong without ocean-coupling

DJF precipitation: GFDL HiRAM vs. Observation



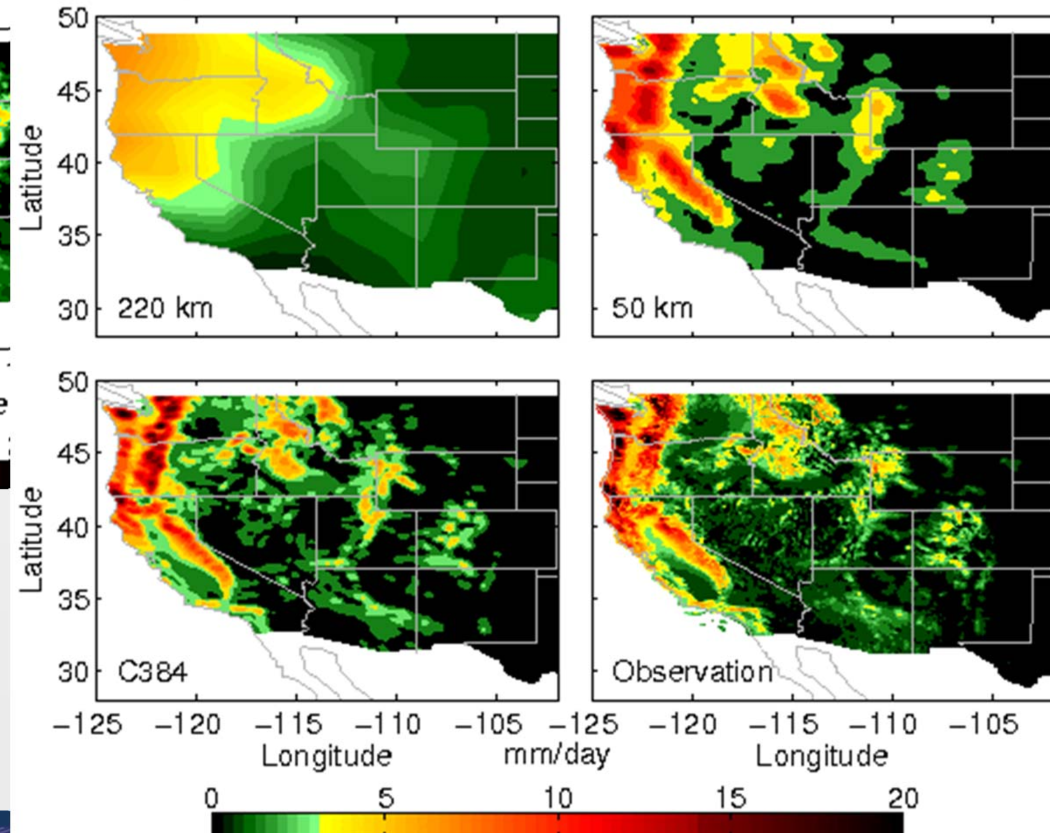
Need hi-res to provide regional details. But global uniform resolution is still too expensive

→

Make hi-res affordable with variable-res approach

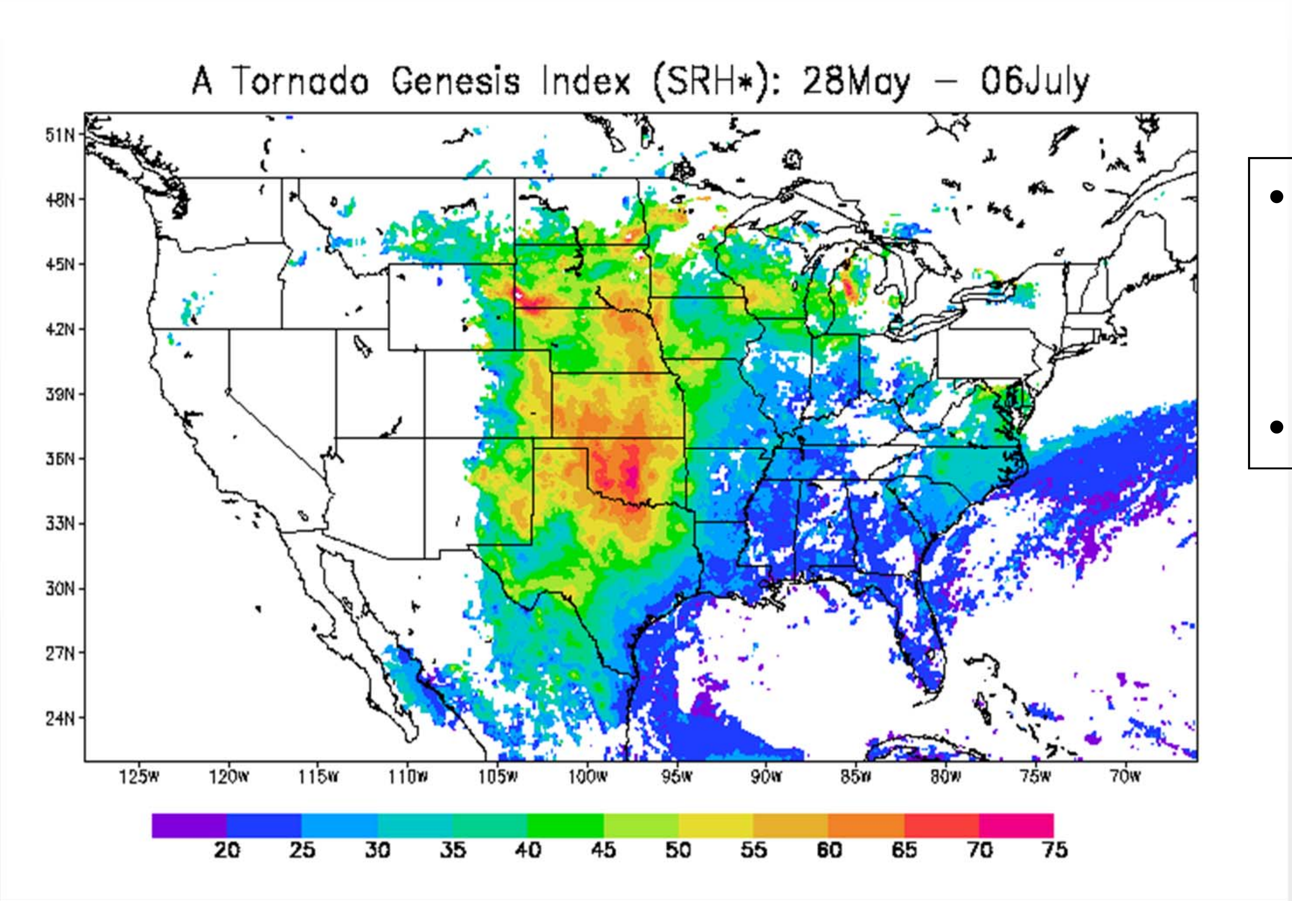
C384 stretched

(~10 km over CONUS)



Simulation of the "Tornado alley"

Preliminary results from GFDL thunderstorm-resolving model
(40-day average of the Storm Relative Helicity*)



- Stretched C1024 HiRAM centered at OKC with 3-5 km resolution over the whole CONUS
- Climate SST

Quality of simulated mean climate with "global regional climate model"

It is important that integrity of large-scale general circulation be maintained (or improved) in the variable-resolution GCM

RMS errors (simulated present-day climate *vs* NCEP re-analyses)

	Variable resolution HiRAM (~10 km over CONUS)	AM2.1	Uncertainties (EC MWF– NCEP)
NH SLP (mb)	0.96	1.8	N/A
Zonal mean T	1.50	1.97	0.88
Zonal mean U-wind (m/s)	1.06	1.71	1.09

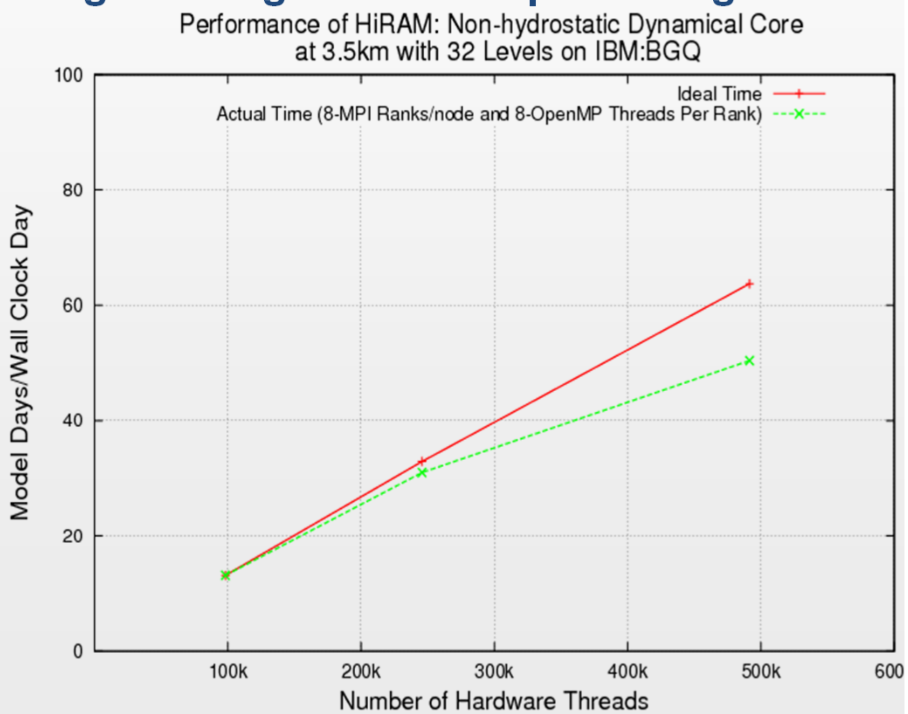
Summary

- **GFDL is leading the community in the development of the ultra-hi-res non-hydrostatic models to improve realism of climate simulations and to provide regional details for stakeholders**. These models are being evaluated for seasonal predictions of high-impact weather events (landfall hurricanes and tornado outbreaks).

- The applications of ***the km-scale climate models*** at GFDL are severely limited by computational resources.

The throughput of the global cloud permitting model (3.5 km) is only ~60 days per day on IBM B/G using 800,000 hardware threads. The throughput of the variable-resolution "global regional climate model" (3-5 km over CONUS) is ~20 days per day on GAEA using 6,144 cores.

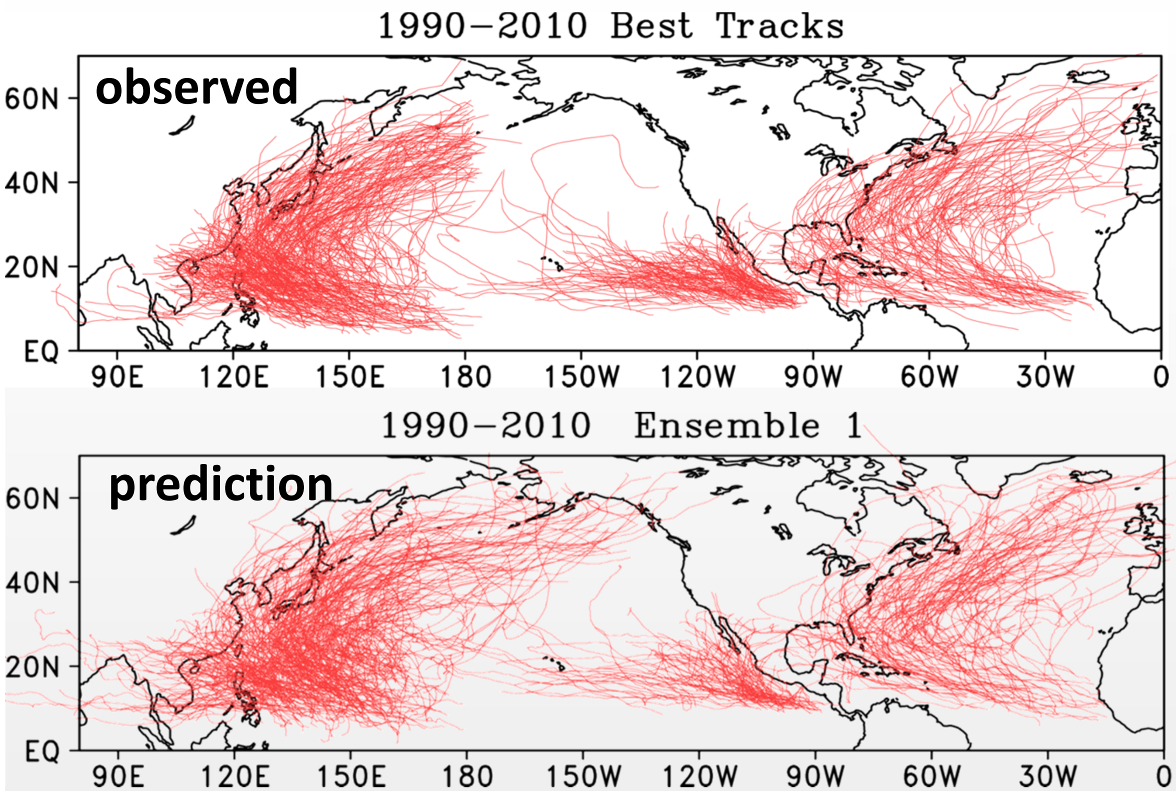
Scaling of the global cloud-permitting model



Backup slides

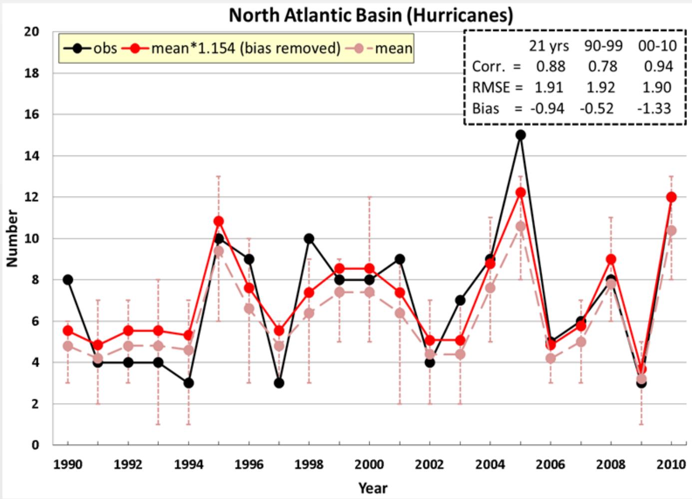
Seasonal hurricane predictions with the 25-km HiRAM

(Chen & Lin 2013)



1990-2010 (J-A-S-O-N)

r = 0.88



Caveat:

Prediction is for total hurricane counts.

Seasonal Prediction of “Katrina” type or “Snady” type hurricanes would be much more useful than just the total numebr.

The Future of Modeling Oceans and Ice

Presented by
Alistair Adcroft
(Stephen Griffies, Robert Hallberg, Matthew Harrison, Sonya Legg, Angelique Melet & Olga Sergienko)

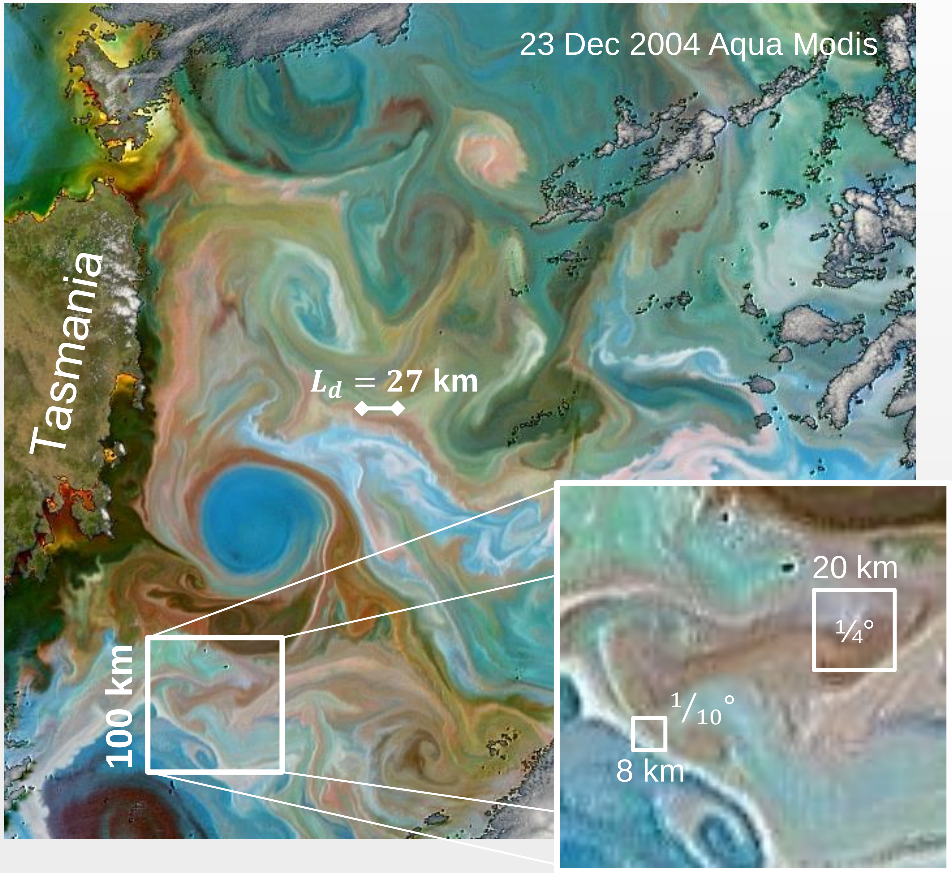
Frontiers in Climate and Earth System Modeling: Advancing the Science

Geophysical Fluid Dynamics Laboratory

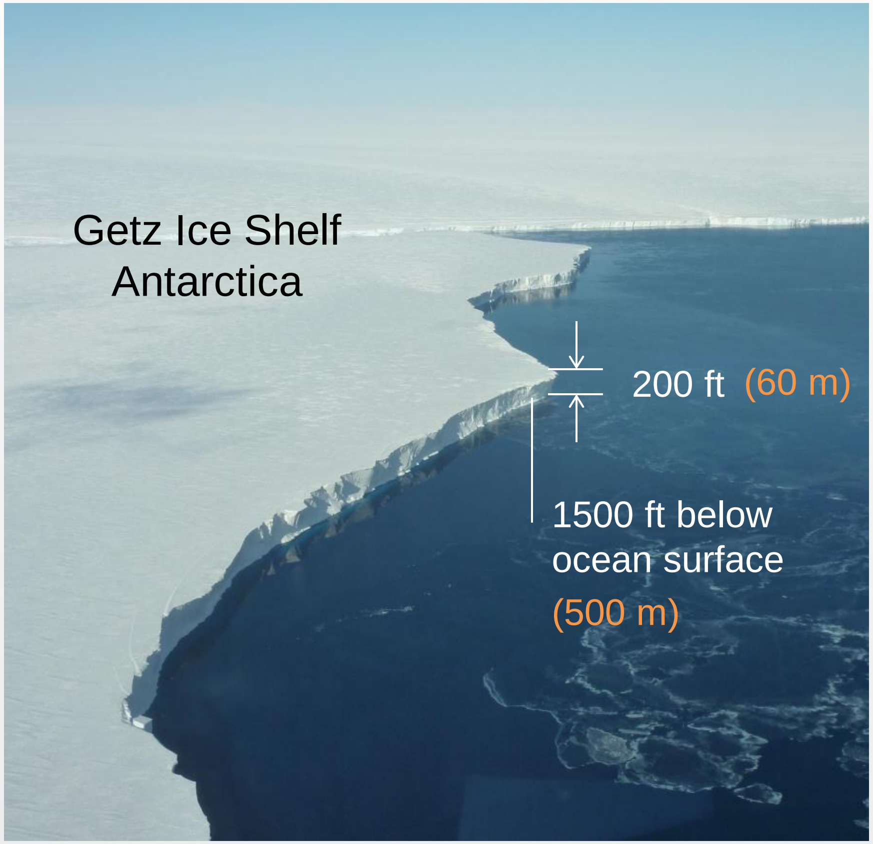
May 20, 2013

Frontiers in ocean/ice-sheet model development

- Role of ocean eddies in climate/earth system



- Sea-level rise and ice-sheet/ocean interaction



Credit: NASA/Dick Ewers

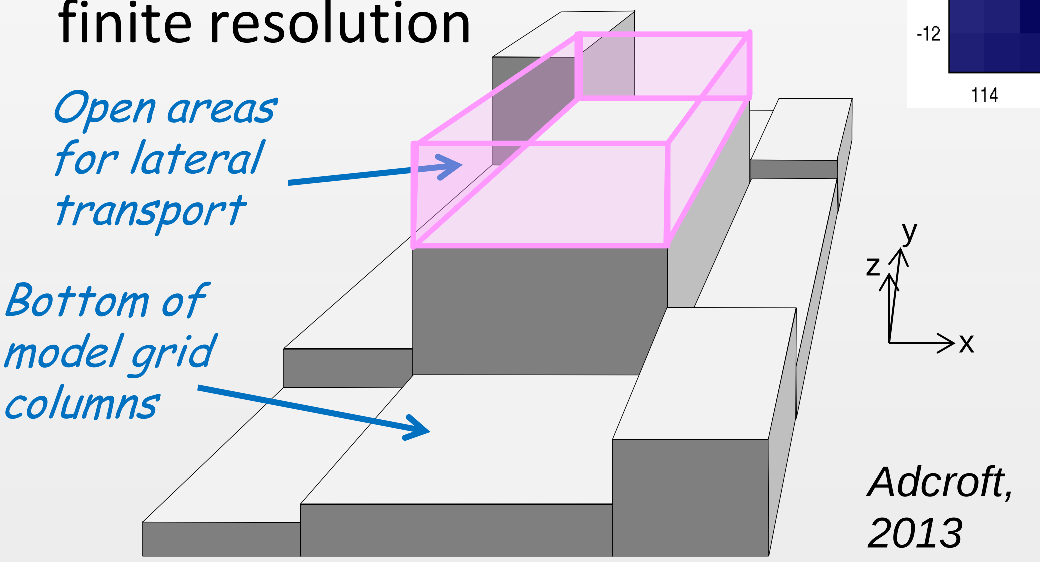
MOM6

- MOM6 unifies the efforts of MOM4/5 and GOLD
  - Initial focus is on construction of p*-coordinate (z-like) ¼° component for CM4
- Arbitrary Lagrangian Eulerian method in the vertical
  - Used for general- & hybrid coordinates
  - Unconditionally stable/accurate
  - **Representation of topography**
  - Wetting/drying
- Global **ice-sheet/ocean coupling**
  - Requires ALE for wetting/drying

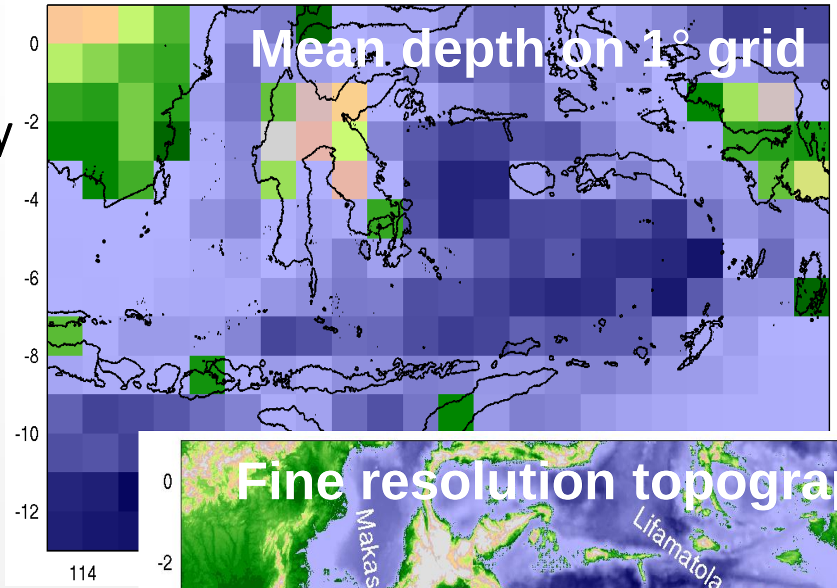
- Energetically consistent closures
  - Patchy convection *Ilicak et al, 2013*
  - **Internal wave driven mixing** (CPT)
  - Community software (CVmix)
  - **Eddies in eddy-permitting models**
  - Second order mesoscale closure
- Boundary layer physics
  - Mixed layers
  - Overflows
- Numerics and formulation
  - Transport schemes
  - Solvers
  - Dynamically integrated sea-ice
  - Reduced cost of bio-tracers

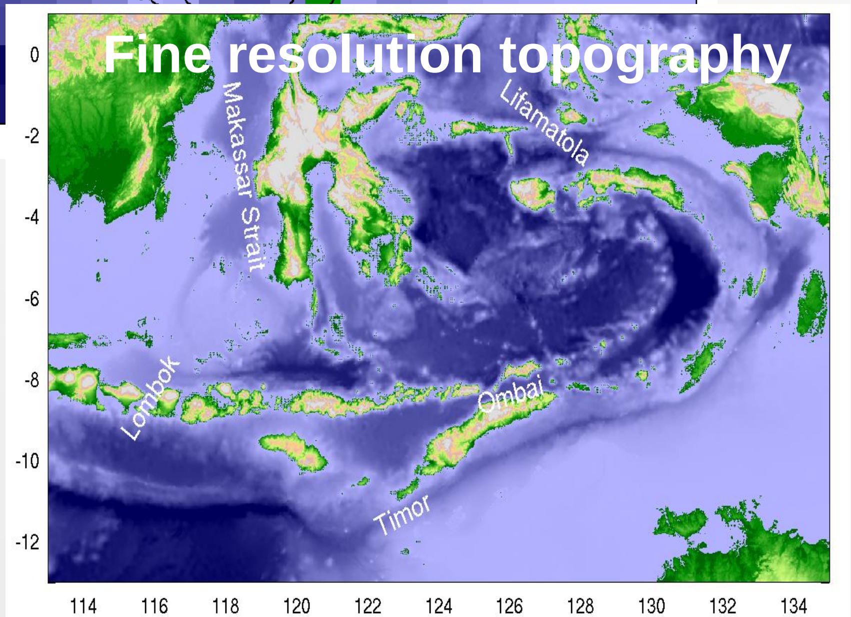
Representation of bathymetry

- Ocean bathymetry plays leading role in shaping ocean circulation
  - Modelers always adjust topography because not all features are resolved by a single column value
- Using finite volume methods permits “correct” geometry at finite resolution



e.g. Indonesian Throughflow





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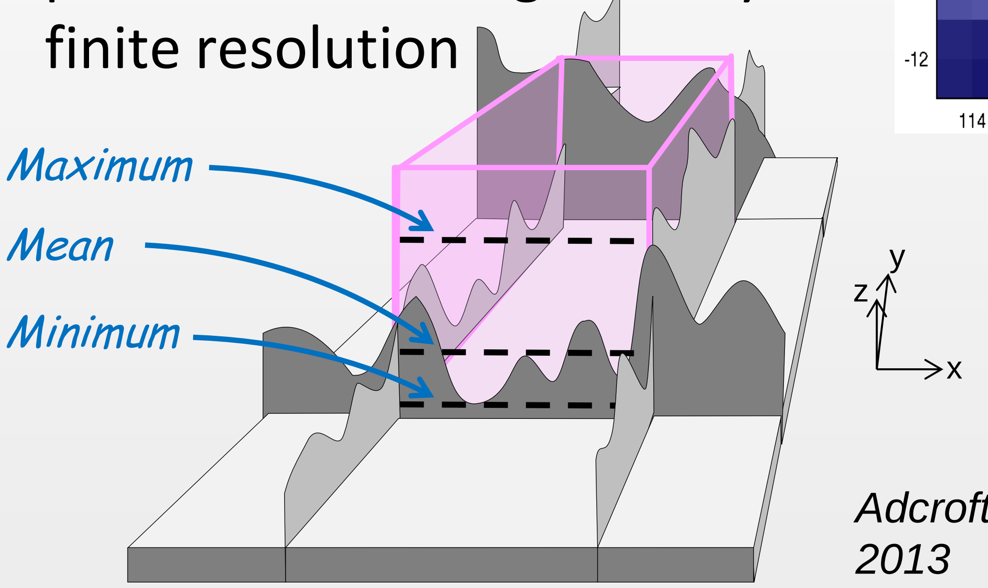
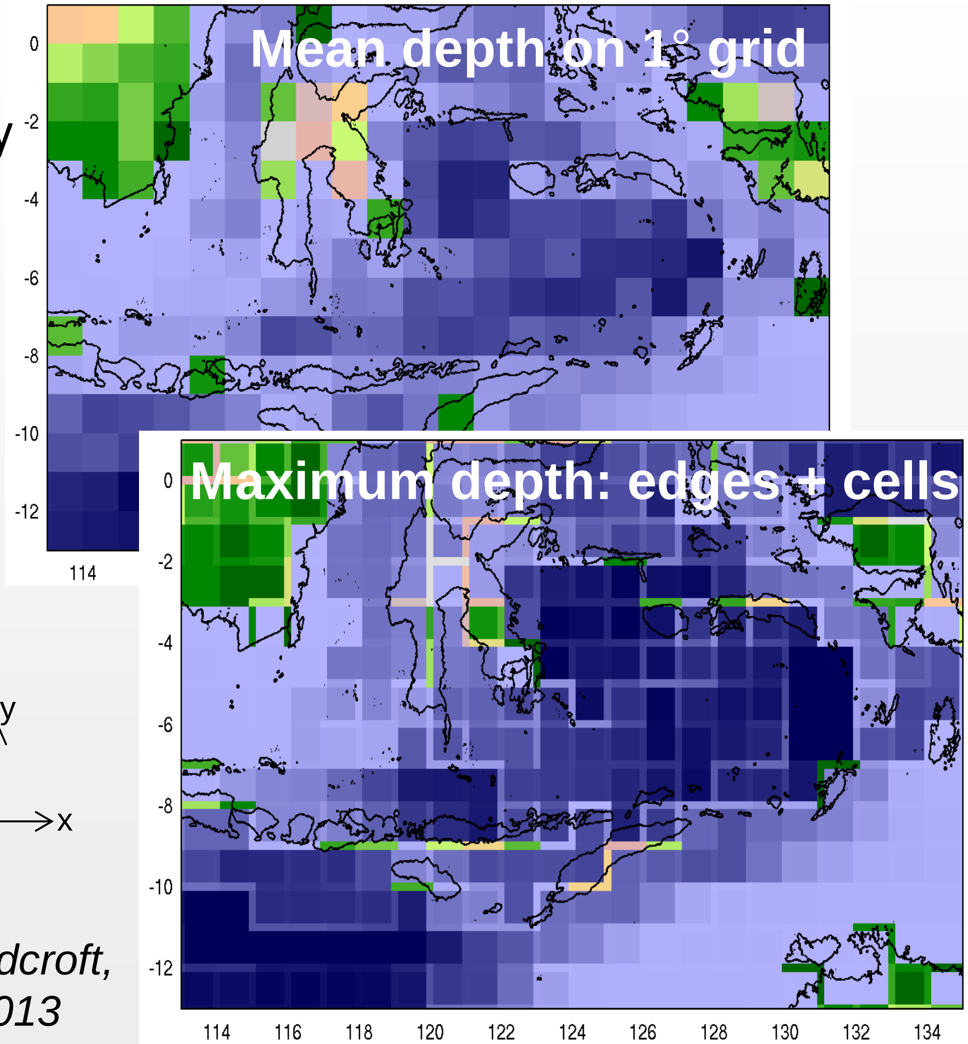


Adcroft, 2013

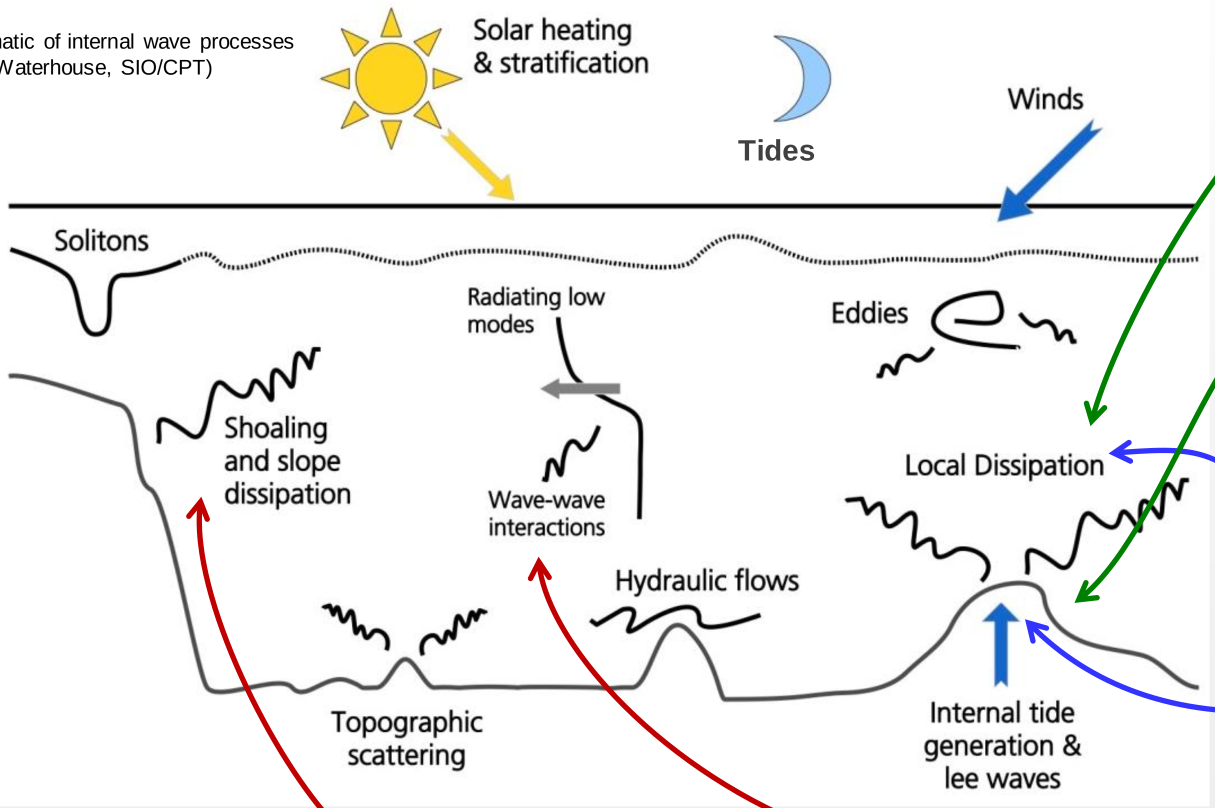
e.g. Indonesian Throughflow



Physically-based, energetically-consistent parameterizations of diapycnal mixing

As part of NOAA/NSF Internal Wave-Driven Mixing **C**limate **P**rocess **T**eam, we are developing and implementing parameterizations of sub-grid-scale mixing which allow mixing to vary spatially and **evolve in a changing climate**.

Schematic of internal wave processes (Amy Waterhouse, SIO/CPT)



Implemented in MOM6:

- Vertical profile of local dissipation. *Polzin, 2009; Melet et al, 2013a*
- Parameterization of lee-waves. *Nikurashin and Ferrari, 2011; Melet et al, 2013b*

Developed:

- Local dissipation at tall steep topography. *Klymak, Legg and Pinkel, 2010; Klymak et al, 2012*
- Contribution to generation from abyssal hills. *Melet et al, 2013c*

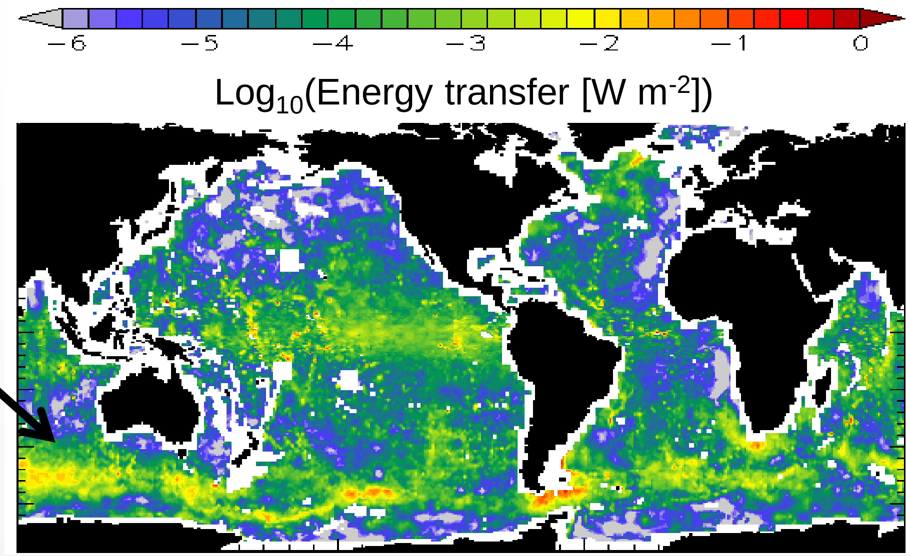
Under development:

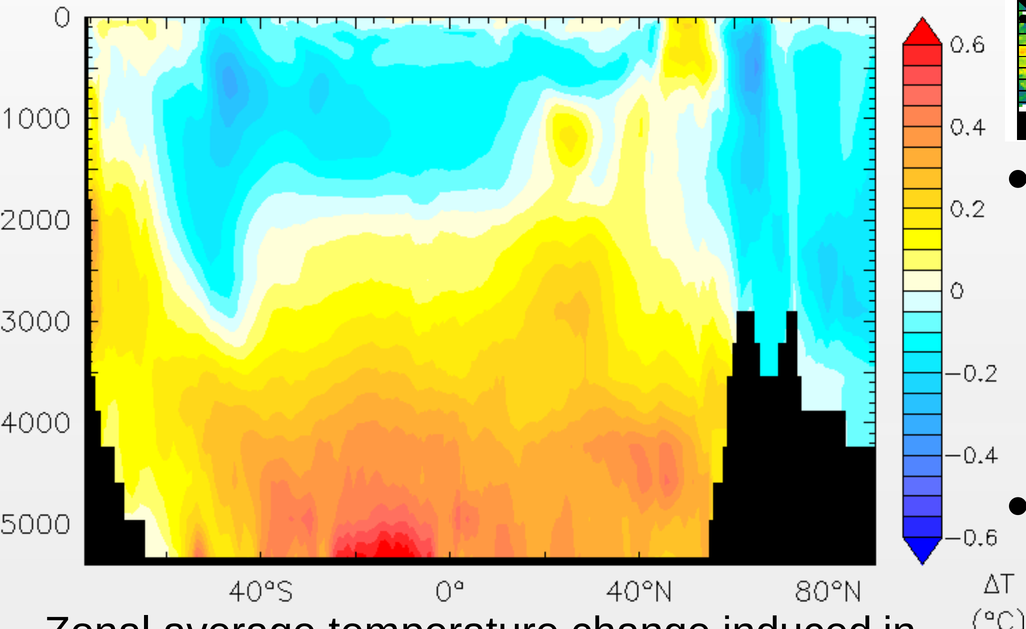
- Low-mode shoaling and reflection. *Legg, 2013*
- Latitudinal dependence of wave-wave interactions. *Nikurashin and Legg, 2011*

CPT: Impact of Lee-wave driven mixing

- Lee-wave energy is most significant in Southern Ocean

Nikurashin and Ferrari, 2011





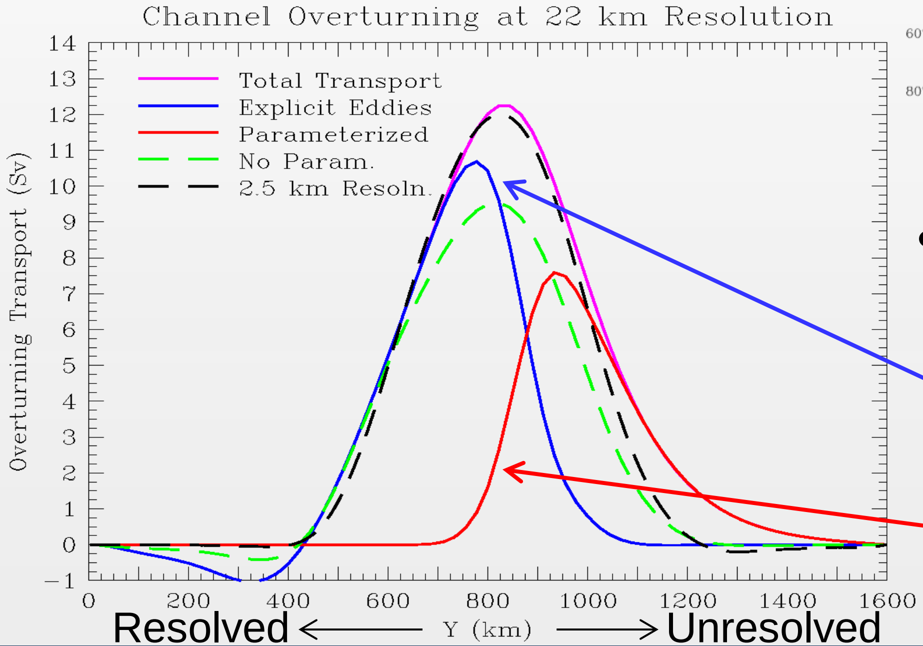
Zonal average temperature change induced in CM2G by extra source of energy for mixing

- Addition of lee-wave driven mixing parameterization systematically warms deep ocean & cools upper ocean
- Adding missing physics improves model credibility

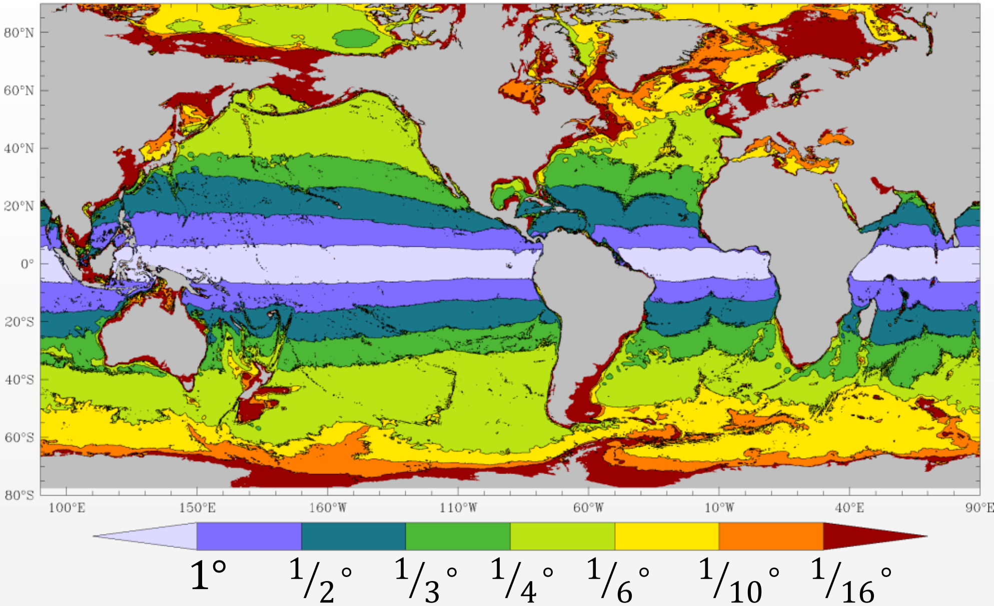
Melet, Hallberg, Nikurashin and Legg, 2013

Parameterizing eddies in an eddy-permitting regime

- Even “fine-resolution” ocean models cannot resolve first-mode eddies everywhere
- Adding a global eddy parameterization dampens the eddies that could be resolved



Mercator resolution that resolves deformation radius



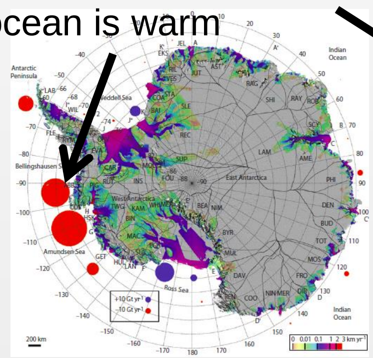
- Resolution-aware eddy parameterization
  - Allows baroclinic instability to proceed when resolution is sufficient
  - Parameterizes eddy fluxes otherwise

Hallberg, 2013

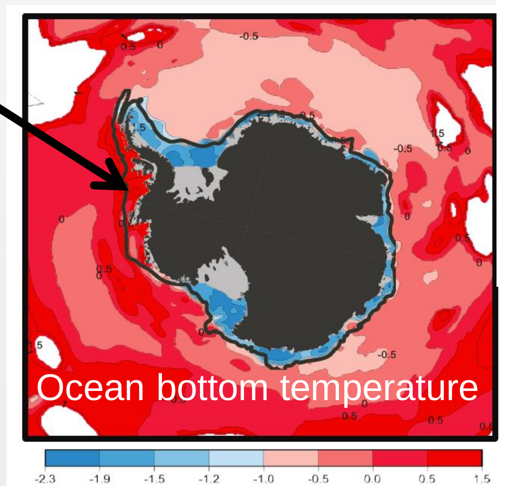
Ice-sheet/ocean coupling

- Ice-sheet dynamics are biggest uncertainty in sea-level rise
- Dynamics of grounding line is affected by interactions with oceans
- Largest mass loss is observed where warm ocean reaches ice
- Confined ice shelves <u>dynamically</u> interacting with warm water spontaneously form melt channels
- MOM6 permits moving grounding lines

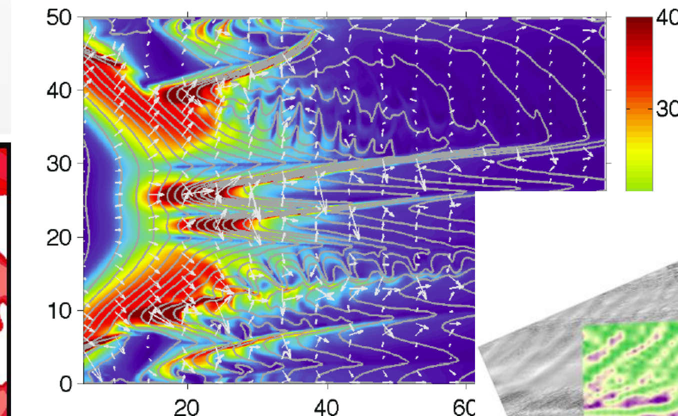
Mass loss occurs where ocean is warm



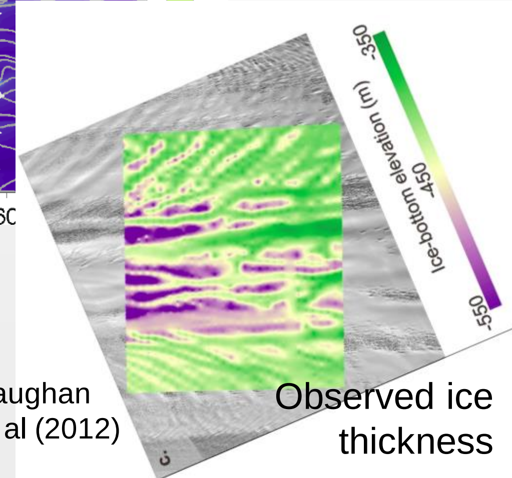
Observed mass balance



Modeled melt rate & ice thickness



Pine Island Glacier



Vaughan et al (2012)

Observed ice thickness

Goldberg et al. 2012a,b; Sergienko et al, 2013

Directions

- Building towards more flexible ocean model
  - Single unified GFDL ocean model (MOM6)
  - Focus on improving physical content (in contrast to other groups working on alternative horizontal grids)
- Increasingly realistic capabilities
  - Narrow channels, overflows, grounding of icebergs & sea-ice, …
  - Coupled comprehensive ice-sheet model
- Physically consistent formulations
  - Energetically consistent parameterizations
  - More diverse range of phenomena (e.g. tides, eddies, overflows, estuaries)
- MOM6 will follow the long tradition of community ocean modeling

Development of GFDL's next generation IPCC-class model

Presented by Isaac Held
for the Model Development Team

Frontiers in Climate and Earth System Modeling: Advancing the Science

Geophysical Fluid Dynamics Laboratory

May 20, 2013

Model development diversified after AR4

CM2 (our AR4 model) evolved in numerous directions in past 7 years:

ESM2M, ESM2G:	carbon cycle
CM2.1 + data assimilation:	seasonal-decadal initialized forecasts
CM3:	aerosols, indirect effect, chemistry
HiRAM:	hi res atmosphere, tropical storms
CM2.5	hi res coupled model

5-10 year Strategic Science Plan, 2011:

endorsed goal of high resolution Earth System Model combining strengths of GFDL's multiple AR5 modeling streams

GFDL has formed a new Model Development Team (MDT)

Goal of the MDT

In the 2013-2016 time frame, we will design and develop GFDL's best attempt at a climate model suitable for

a) projection of climate change up to several hundred years into the future,
b) attribution of climate change over the past century,
c) prediction on seasonal to decadal time scales

keeping in mind the needs for improved regional climate information and assessments of diverse climate impacts.

The model will be capable of running from emissions in regard to both the carbon cycle and aerosols.

MDT taps into large fraction of Lab's expertise

New MDT established in Dec 2012:

Steering Committee:
Isaac Held
Shian-Jiann Lin
Ron Stouffer
Rong Zhang
Steve Griffies
Yi Ming
V. Balaji
V. Ramaswamy (ex officio)

Working Group Leads
Chris Golaz (Atmos)
Ming Zhao (Atmos)
Alistair Adcroft (Oceans)
Elena Shevliakova (Land)
Chris Milly (Land)

Diagnostic and Evaluation Team Heads:
Larry Horowitz, John Krasting

+ many other very active working group members

New model configurations are being tested

Target horizontal resolution for CM4/ESM4:
50 km atmosphere + ¼ degree ocean (MOM6)

Determined by

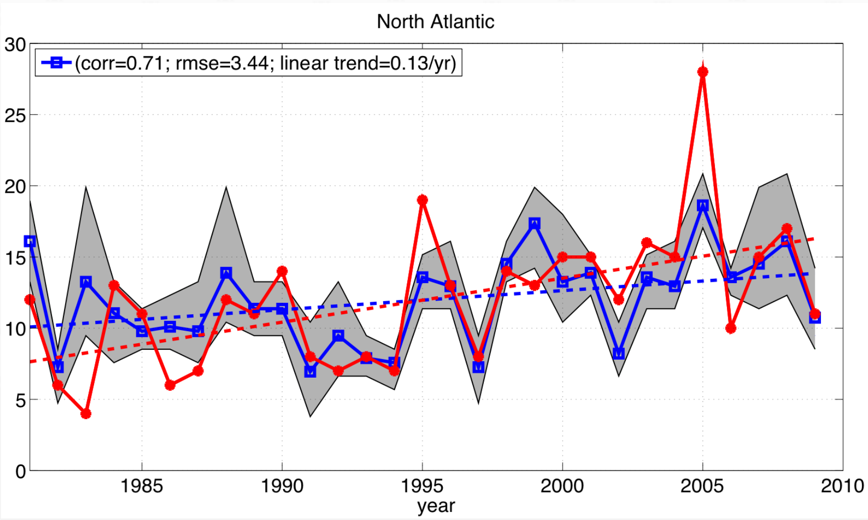
1) Lab's experience regarding resources needed to develop and utilize a model for centennial-scale climate projections:
at least 3-5 years/day throughput on no more than 1/8 of computational resource

2) the GAEA computational resource

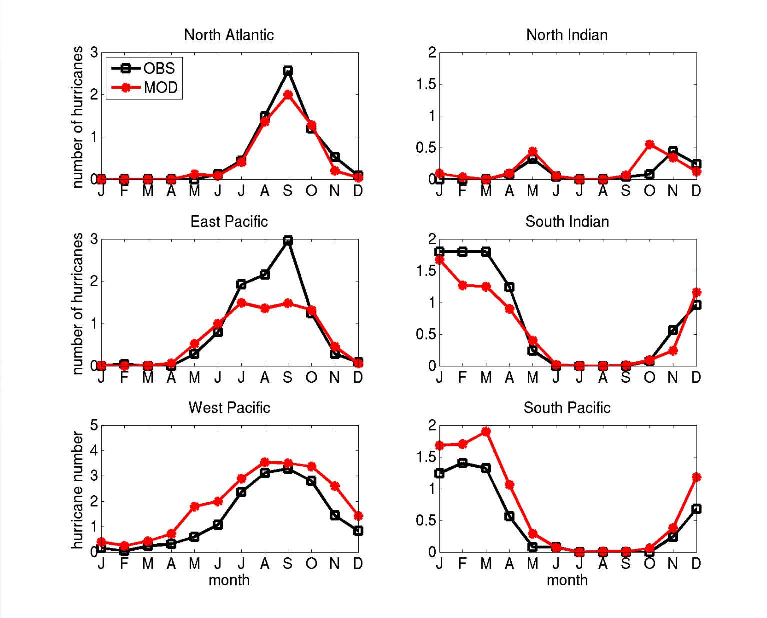
Increases in hardware resources and significant software development would allow us to redefine this trunk model towards higher resolution and/or
greater comprehensiveness, e.g. full eddy-resolving ocean resolution;
more complete stratosphere/troposphere chemistry module

Our AR5 models have redefined our metrics

HiRAM Atmosphere/land 50 km model
S-J- Lin, Ming Zhao



tropical cyclones in North Atlantic over last 30 years

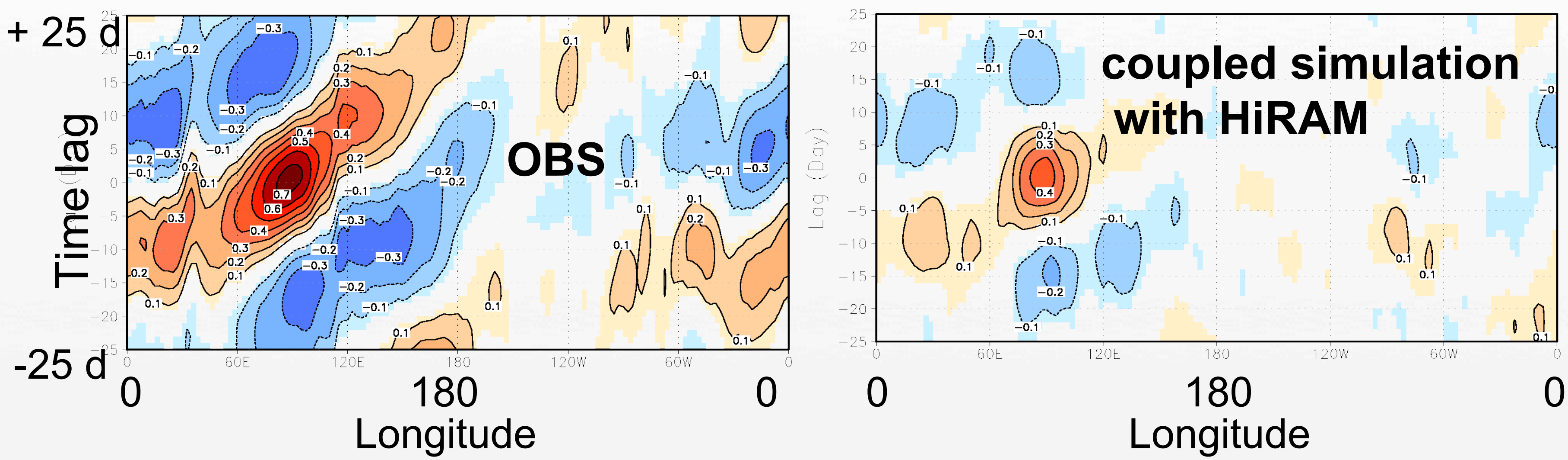


Seasonal cycle of hurricanes in different ocean basins

Example: Hurricane frequency

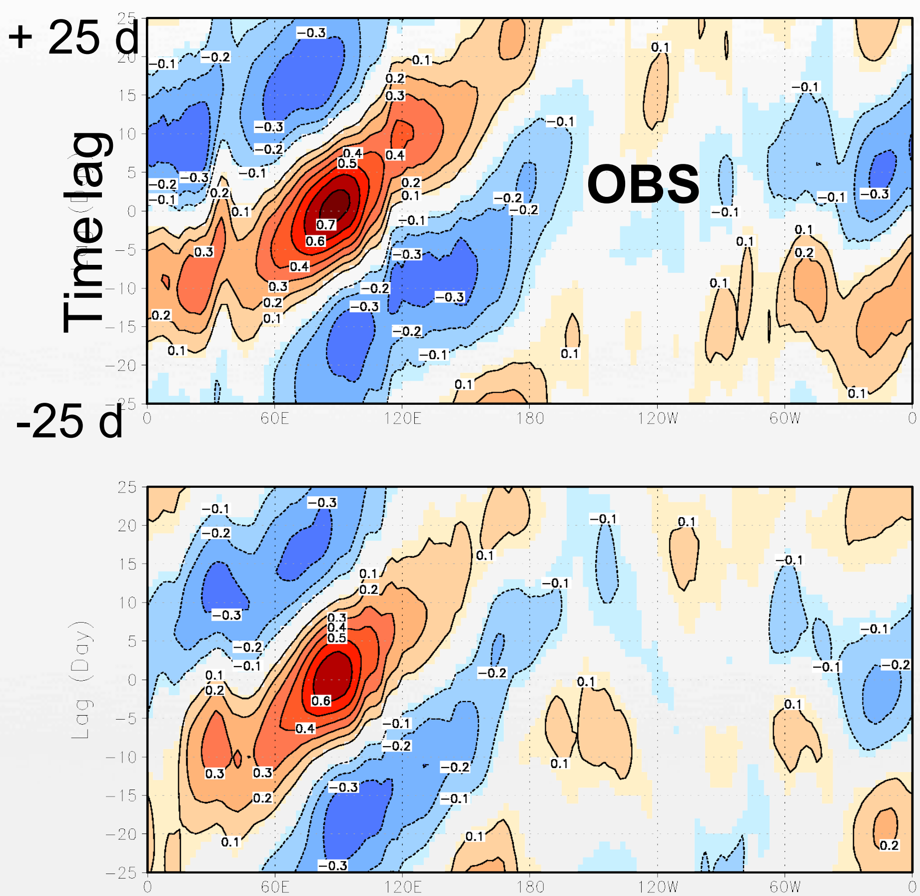
Example of important metric: Madden-Julian Oscillation(MJO)

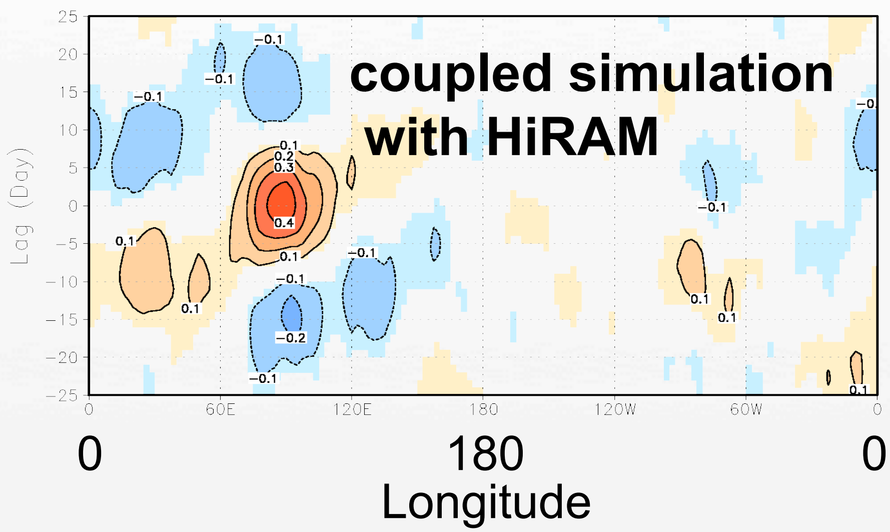
Equatorial outgoing longwave radiation; correlation(time lag, longitude)
(US CLIVAR MJO standard diagnostic)



Recent progress: MJO in new atmospheric configuration

Equatorial outgoing longwave radiation; correlation(time lag, longitude)
(US CLIVAR MJO standard diagnostic)





coupled simulation
with alternative convection
scheme (Ming Zhao)

A few examples of challenges facing the MDT

Oceanic mesoscale eddies

Can we make a ¼ degree model look like an eddy-resolving model (CM2.6)?

Aerosol/cloud interactions

How do we best combine bottom-up (process-oriented) perspective and top-down constraints provided by 20th century observations?

Atmospheric boundary layer/low cloud feedbacks

Are we in a position to incorporate a dramatically new type of boundary layer/shallow convection module similar to CLUBB?

Software

Can we find more concurrency to improve wall clock performance so that we can increase complexity/resolution relevant to MDT goals

Challenges for the MDT and GFDL

How do we entrain as much of the Lab's expertise as possible into the MDT process without impacting individual and small group initiatives?

How do we best entrain expertise outside of the lab into model development? (Climate Process Teams have been helpful, especially on oceanic side)

How do we balance the need for interim models of more immediately utility with developments that have much longer gestation times

How do we optimize new software development/new hardware both for expanding our "trunk" model and for research with very different resolutions/complexity/ensemble sizes