Characteristics of Global Weather Models on Icosahedral Grids

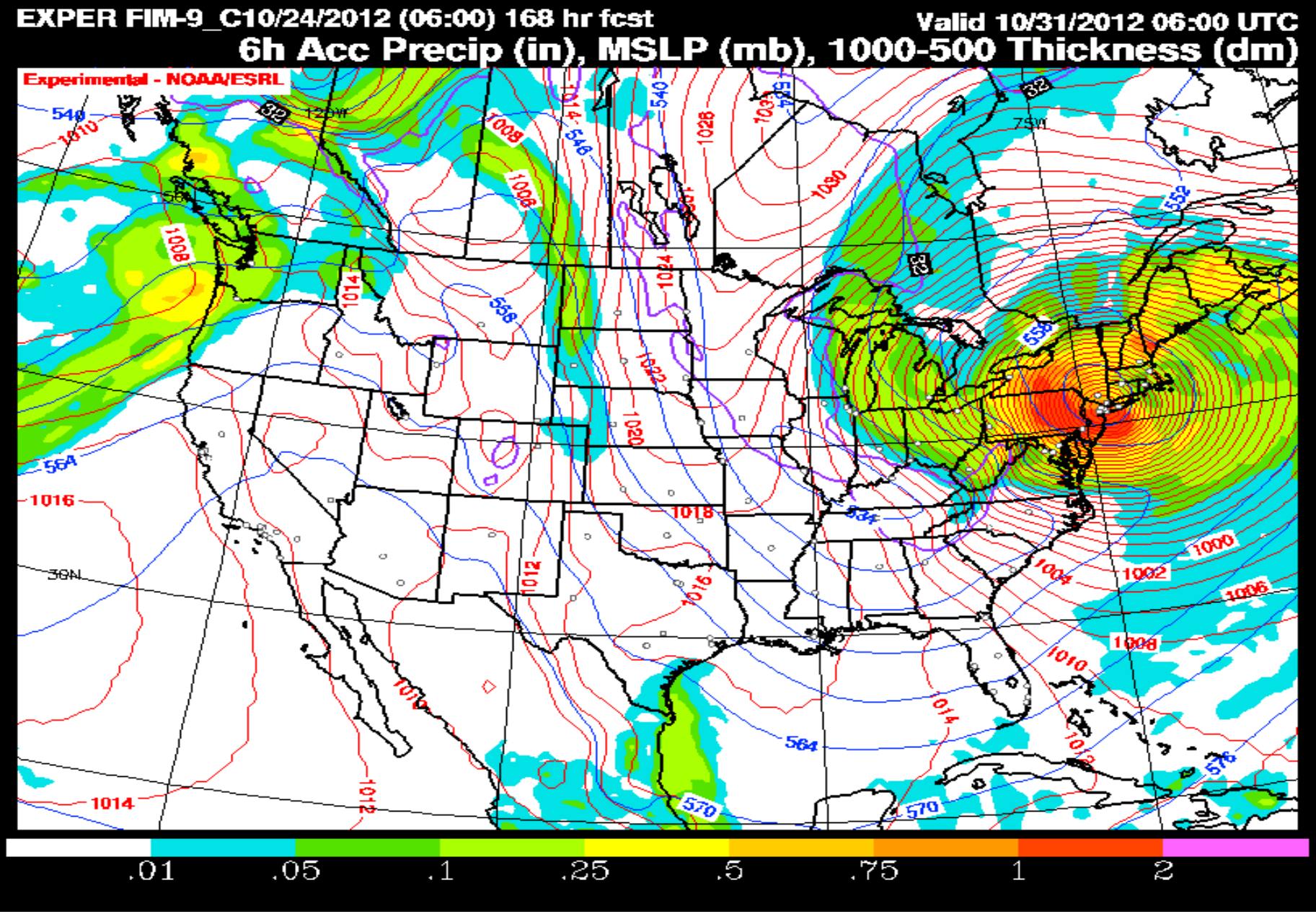
Typhoon Workshop
Taipei, Taiwan
May 20, 2014

Alexander E. MacDonald

NOAA
Earth System Research Laboratory

PROLOGUE:
Models Matter!

Breezy Point New York, morning after Hurricane Sandy. No fatalities.

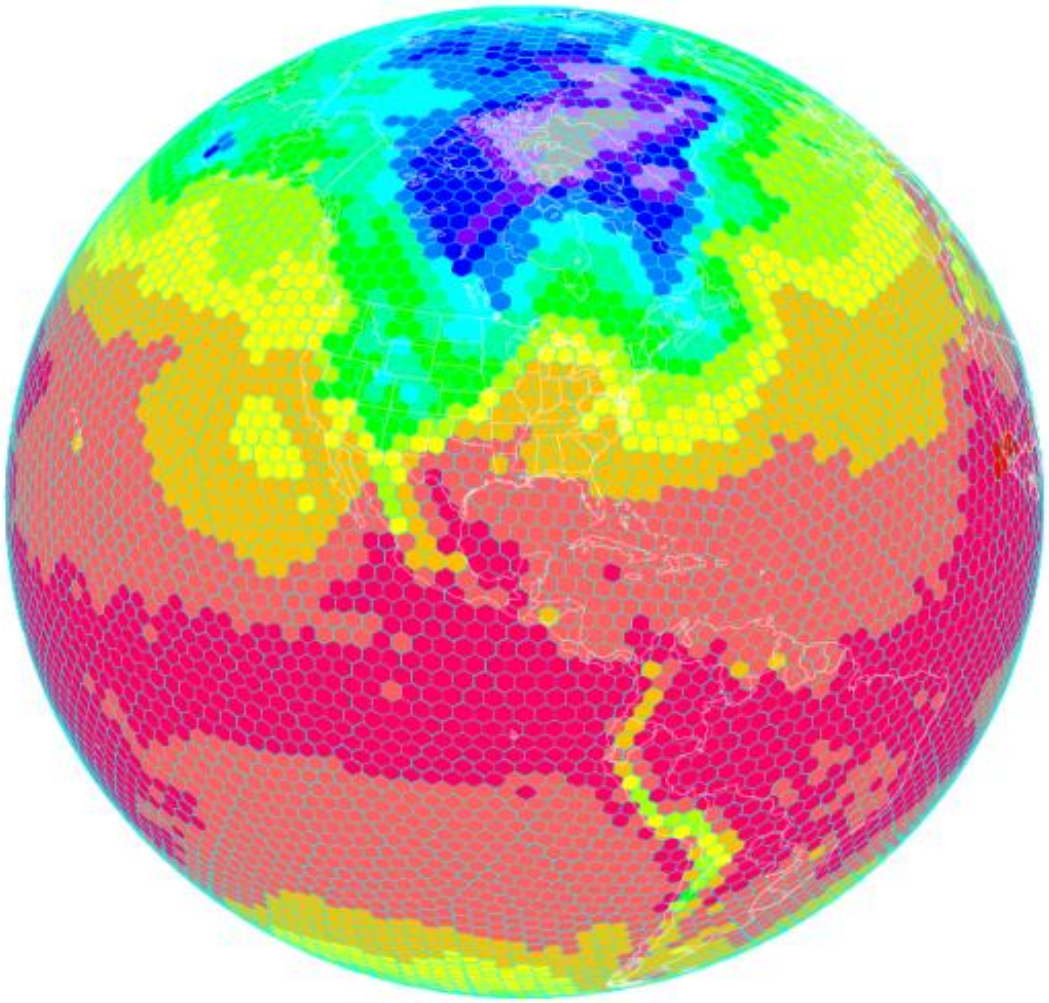


Wednesday, October 24: ESRL's FIM predicts 948 mb low into northern New Jersey.

Some Examples of Global Icosahedral Models

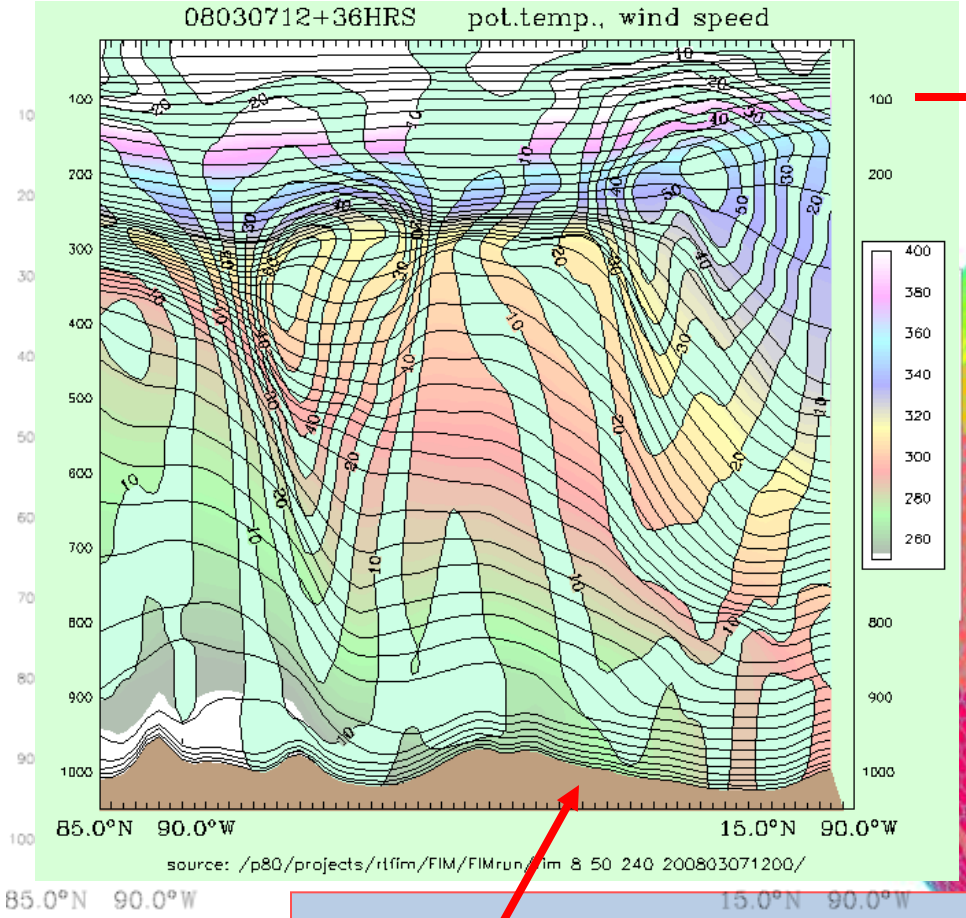
Model	Origin	Nonhydro	Arak Grid	GPU?	Vertical	FV or FF
FIM	ESRL	No	A	Yes	Isentropic	FV
ICON	DWD	Yes	C	Unknown	Sigma Z	FF
MPAS	NCAR	Yes	C	Yes	Sigma Z	FF
NICAM	JAMSTEC	Yes	A	Unknown	Sigma P,Z	FV
NIM	ESRL	Yes	A	Yes	Sigma Z	FV

2001: ESRL began design of a new generation of global models.

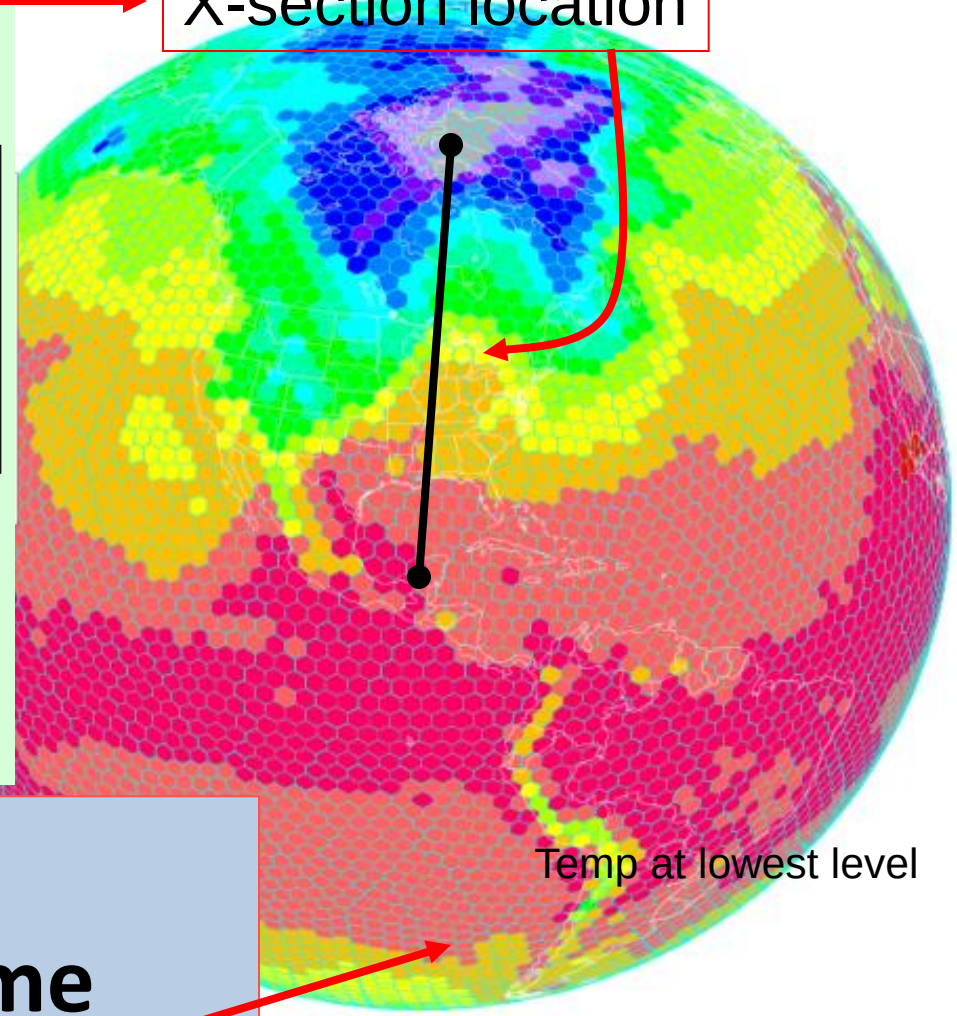


Initial Design: Alexander MacDonald and Jin Luen Lee.
Key decision: Icosahedral grid point model, finite volume (D Randall, SJ Lin)
Key Innovation: Method for coding on irregular grids – MacDonald et al

http://fim.noaa.gov



X-section location



Temp at lowest level

Flow-following-
finite-volume
Icosahedral
Model **FIM**

ESRL's Nonhydrostatic Icosahedral Model (NIM)

Flux form GEs on 3-D control volume on height coord.

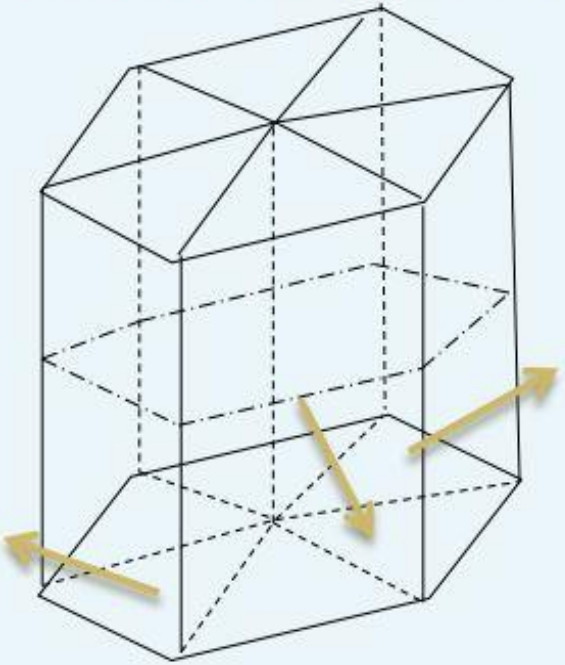
$$
\begin{cases}
\dfrac{\partial U}{\partial t}+\dfrac{\partial (Uu)}{\partial x}+\dfrac{\partial (Vu)}{\partial y}+\dfrac{\partial (Wu)}{\partial z}+\gamma R\pi\dfrac{\partial \Theta'}{\partial x}=F_u \\
\dfrac{\partial V}{\partial t}+\dfrac{\partial (Uv)}{\partial x}+\dfrac{\partial (Vv)}{\partial y}+\dfrac{\partial (Wv)}{\partial z}+\gamma R\pi\dfrac{\partial \Theta'}{\partial y}=F_v \\
\dfrac{\partial W}{\partial t}+\dfrac{\partial (Uw)}{\partial x}+\dfrac{\partial (Vw)}{\partial y}+\dfrac{\partial (Ww)}{\partial z}+\left(\gamma R\pi\dfrac{\partial \Theta'}{\partial z}-\bar{\rho}g\dfrac{\pi'}{\bar{\pi}}+\rho' g\right)=0 \\
\dfrac{\partial \rho}{\partial t}+\dfrac{\partial (U)}{\partial x}+\dfrac{\partial (V)}{\partial y}+\dfrac{\partial (W)}{\partial z}=0. \\
\dfrac{\partial \Theta}{\partial t}+\dfrac{\partial (U\theta)}{\partial x}+\dfrac{\partial (V\theta)}{\partial y}+\dfrac{\partial (W\theta)}{\partial z}=\dfrac{\Theta \dot{H}}{C_p T} \\
\dfrac{\partial (\rho q)}{\partial t}+\dfrac{\partial (Uq)}{\partial x}+\dfrac{\partial (Vq)}{\partial y}+\dfrac{\partial (Wq)}{\partial z}=S_q
\end{cases}
$$

$$(U,V,W,\Theta,\rho)=(\rho u,\rho v,\rho w,\rho\theta,\rho);\quad \Theta(x,y,z,t)=\bar{\Theta}(z)+\Theta'(x,y,z,t)$$

$$\rho(x,y,z,t)=\bar{\rho}(z)+\rho'(x,y,z,t);\qquad \nabla p=\gamma R\pi\nabla\Theta$$

$$p=p_0\left(\frac{R\Theta}{p_0}\right)^{\gamma};\quad \pi=\left(\frac{p}{p_0}\right)^{\kappa}$$

3-D control volume box



Lead Developer: Jin Luen Lee

Important Design Considerations for Global Models

- Numerical accuracy over space and time.
- Uniformity and isotropy of grid formulation.
- Conservation of tracers, dynamic variables, and entropy.
- Cloud permitting (nonhydrostatic, < 4 km resolution).
- Energy and enstrophy cascades and effective resolution.
- Amenability to advanced high performance computers.

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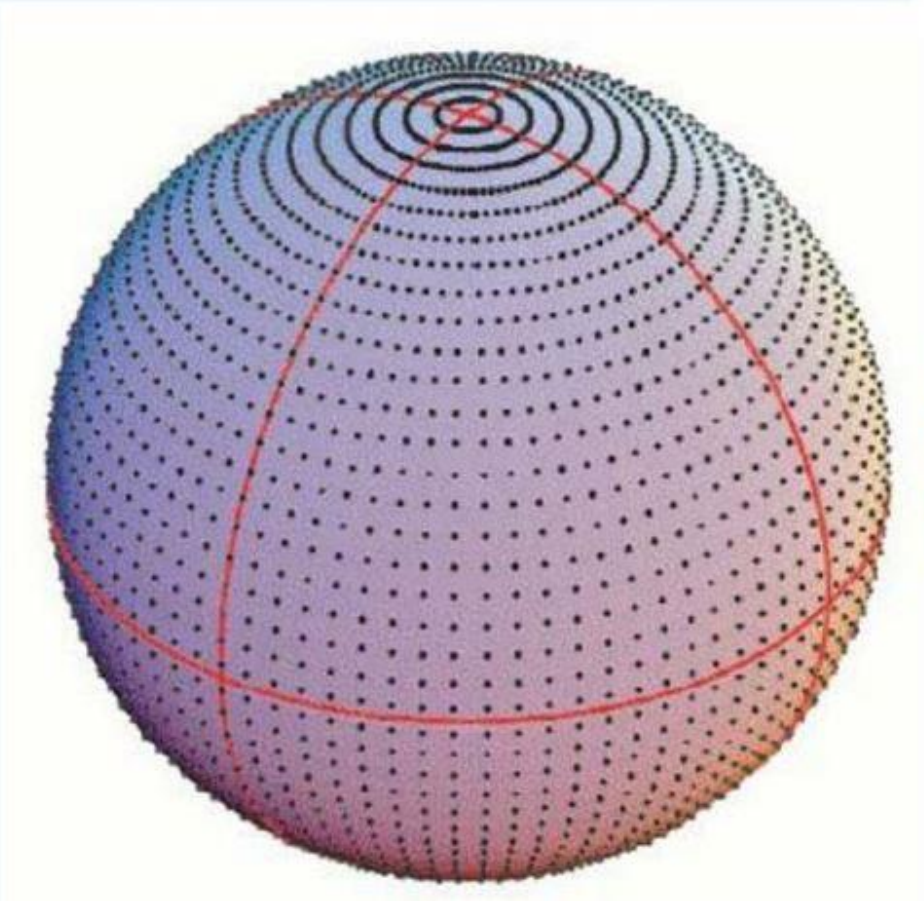
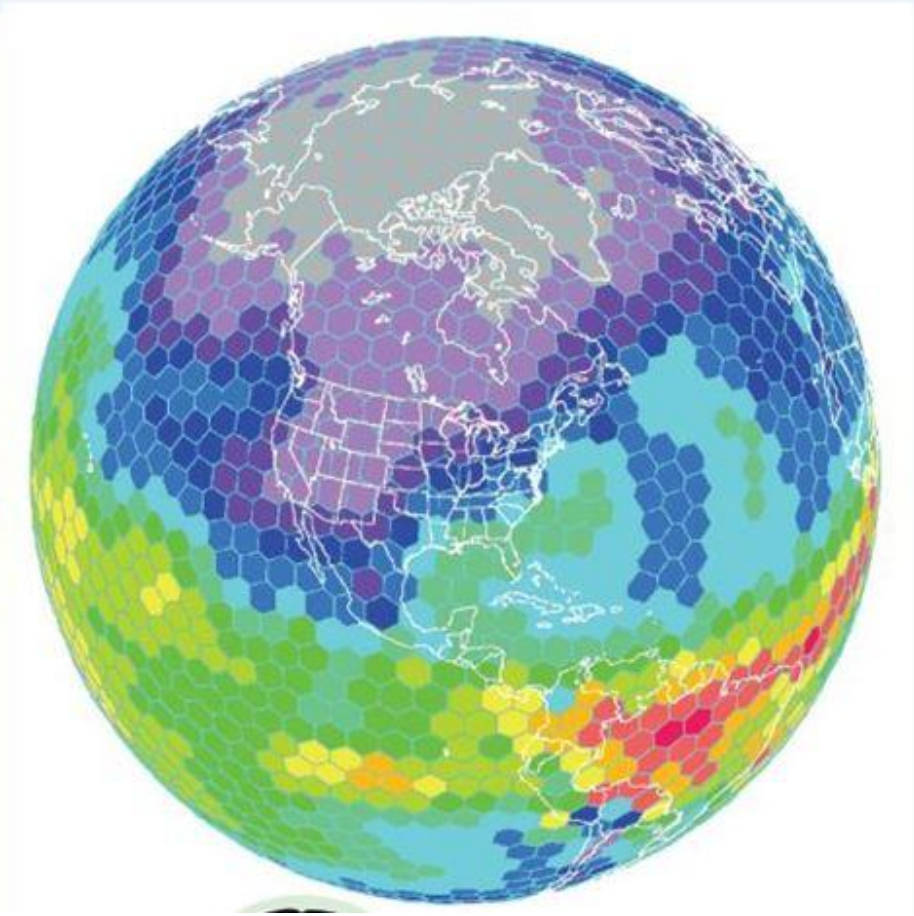
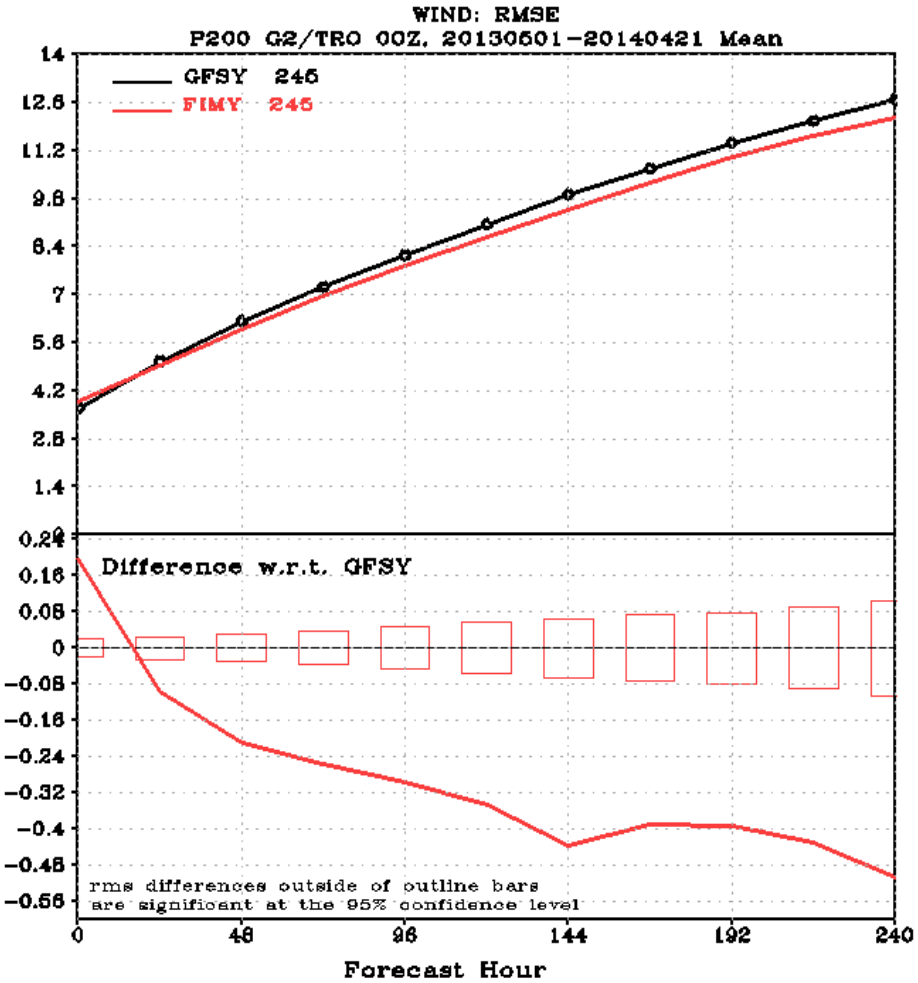
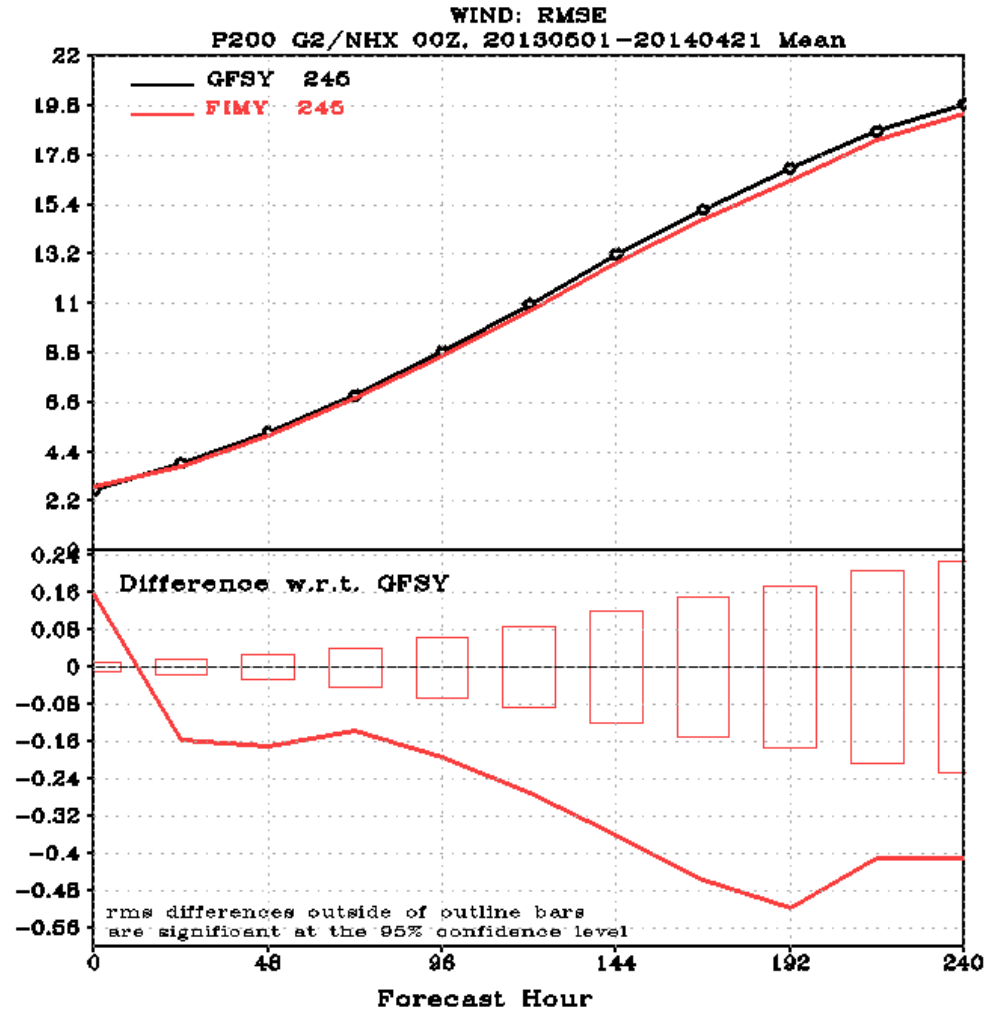
Lat/Lon Model **Icosahedral Model**





Matsuno's groundbreaking analysis of tropical waves showed . . . .
That tropical storms and extended predictions depend on getting the tropics right.
Icosahedral models have excellent properties for the tropics.





200 hPa wind RMS vector error forecasts for 0-10-day forecasts - FIM / GFS

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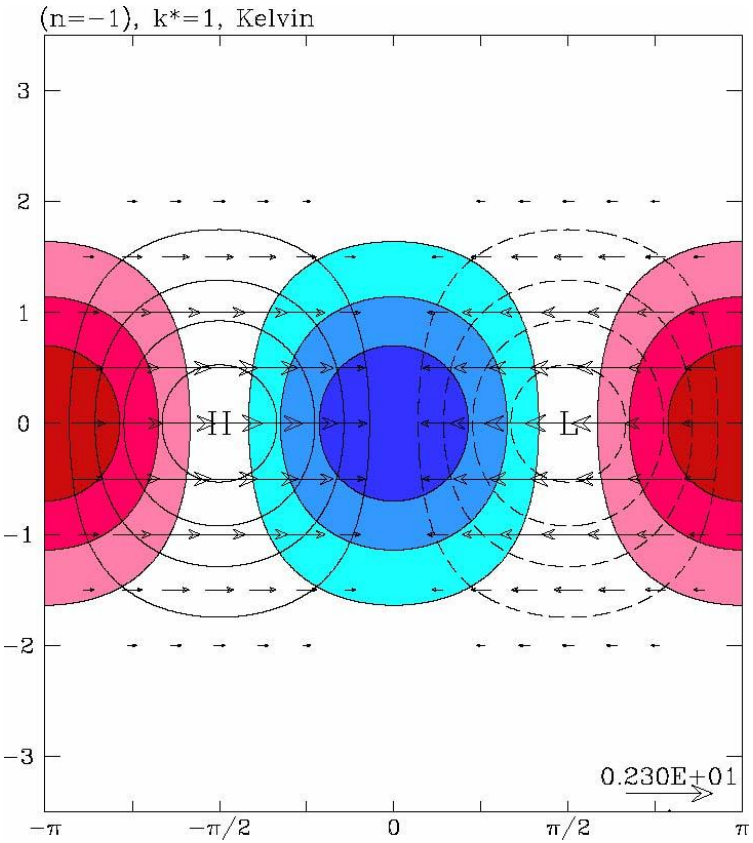
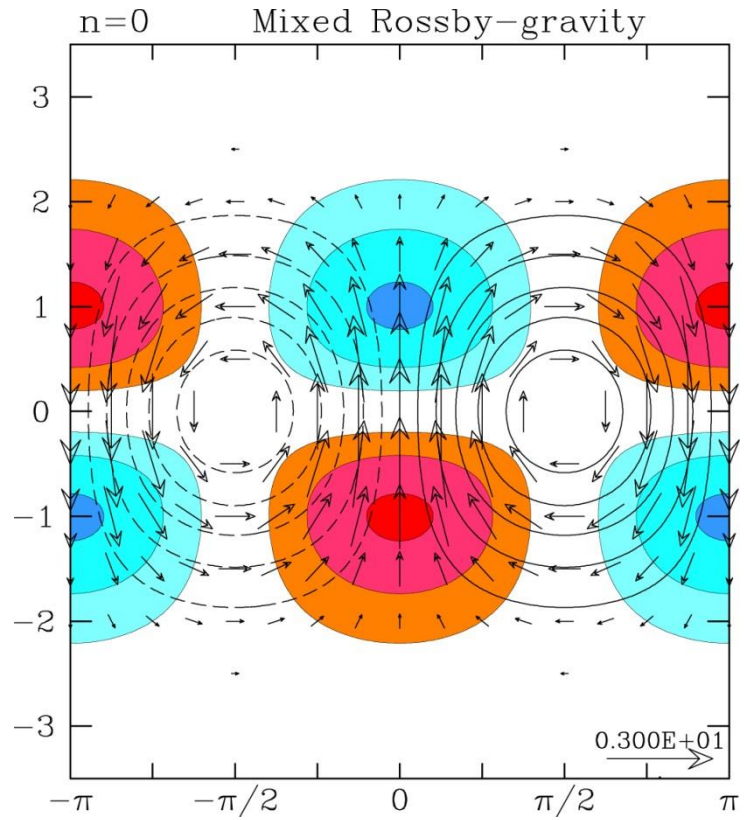
Equatorial Waves
Wavenumber-Frequency Spectral Analysis

- Decompose into Symmetric and Antisymmetric Fields about the Equator

Symmetric

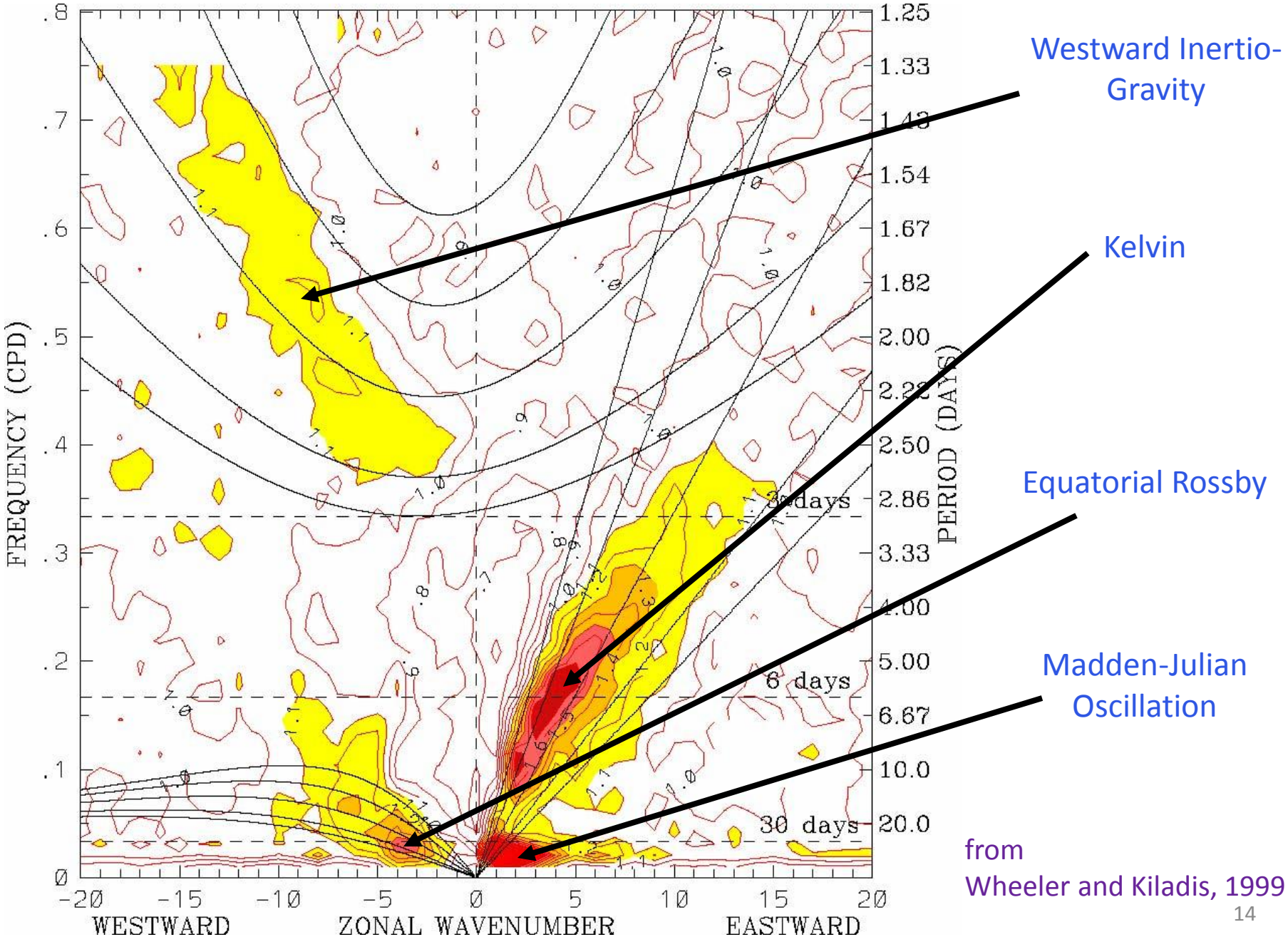


Antisymmetric



Matsuno, 1967. Grid properties and convection crucial.

OLR total/background power spectrum, 15ºS-15ºN, 1983–2005 (Symmetric)

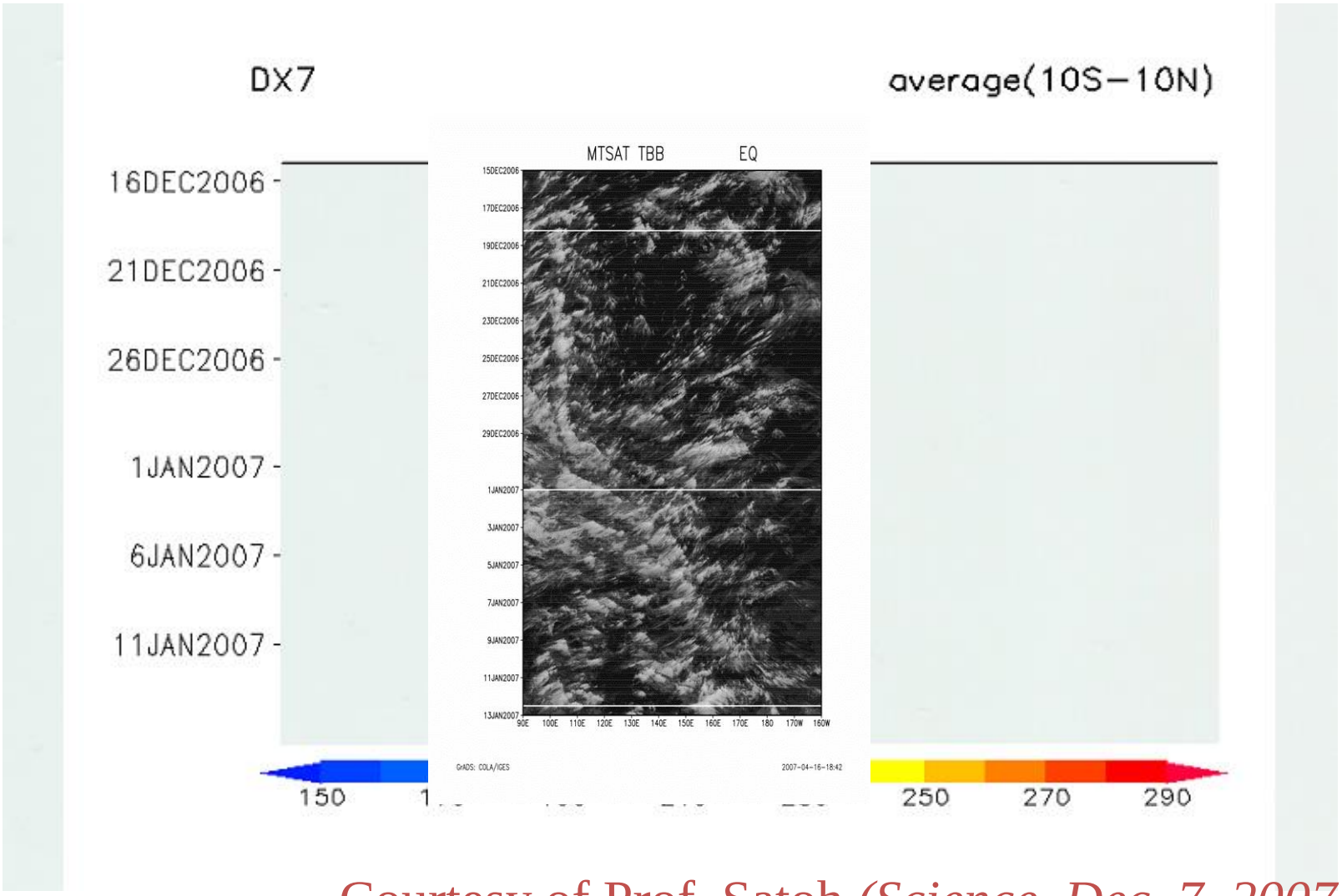


from
Wheeler and Kiladis, 1999

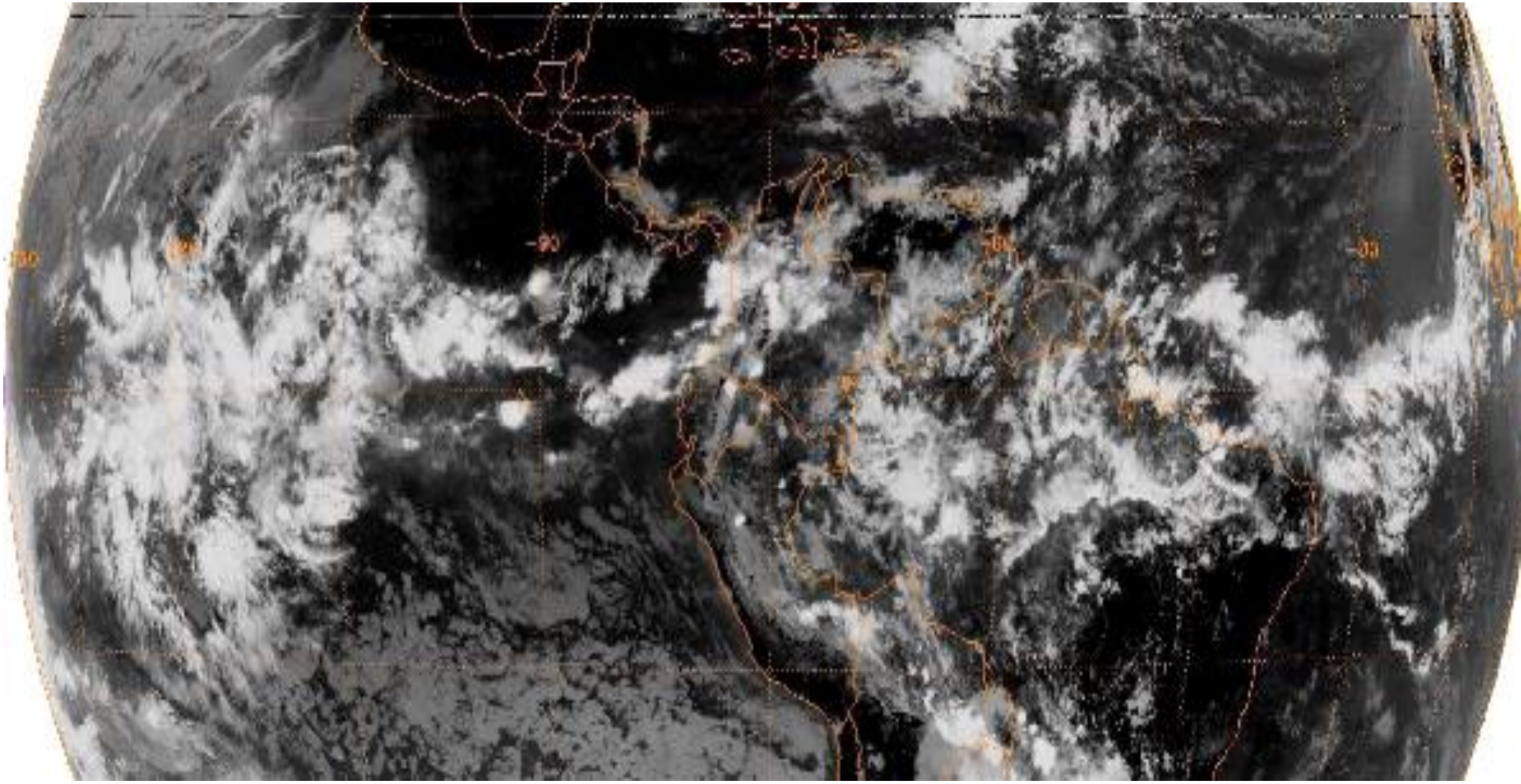
OLR Hovmoller showing MJO simulation

NICAM dx=3.5 km

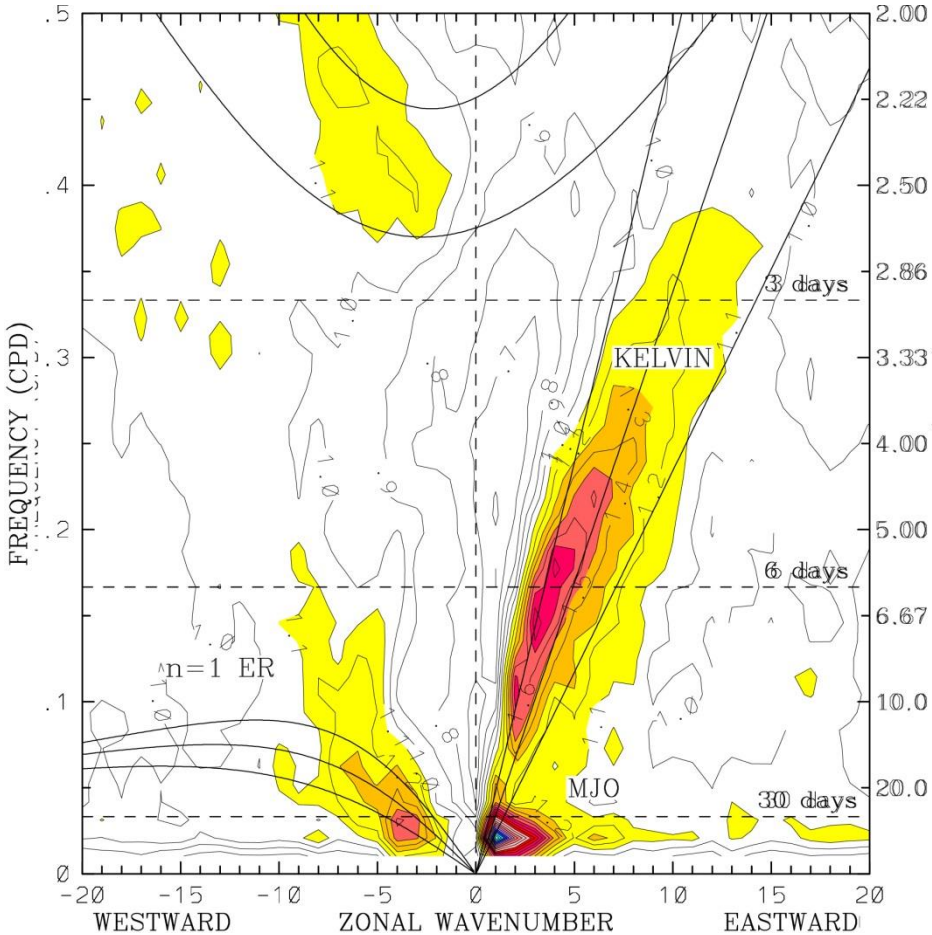
(Non-hydrostatic ICosahedral Atmospheric Model)

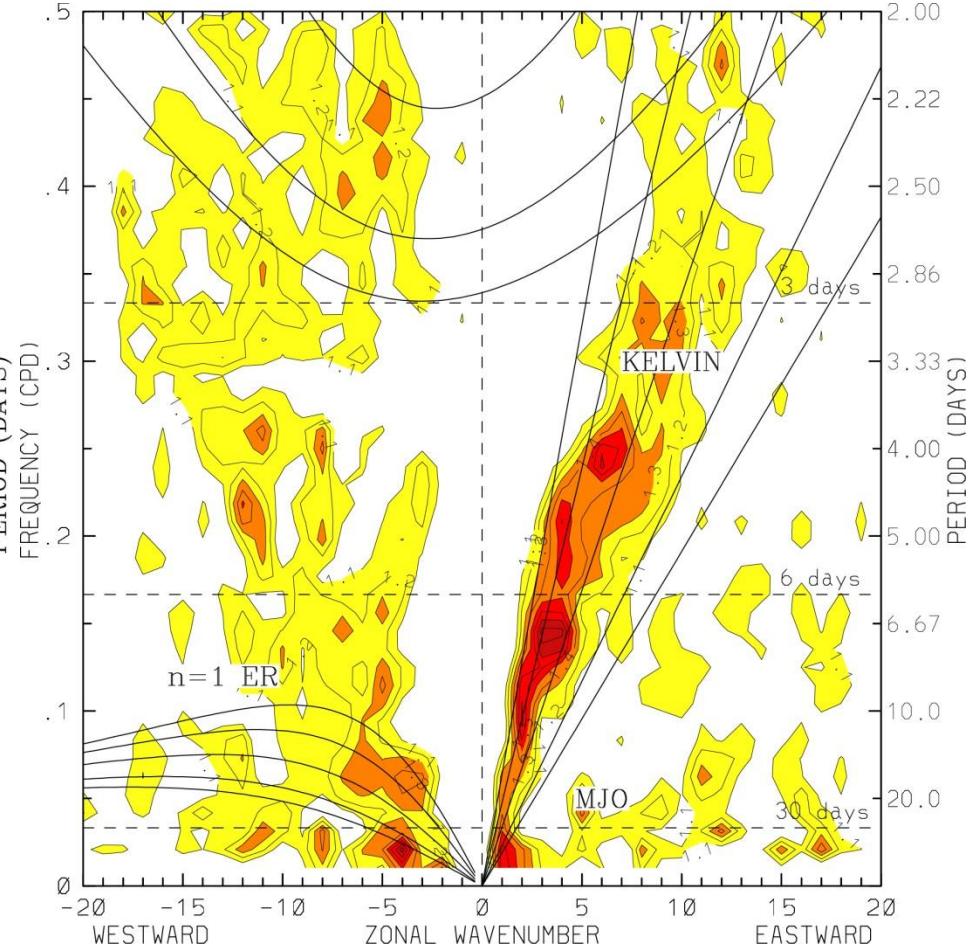


Courtesy of Prof. Satoh *(Science, Dec. 7, 2007)*



Atmospheric Kelvin Wave/MJO propagates across the American Tropics (blue line).





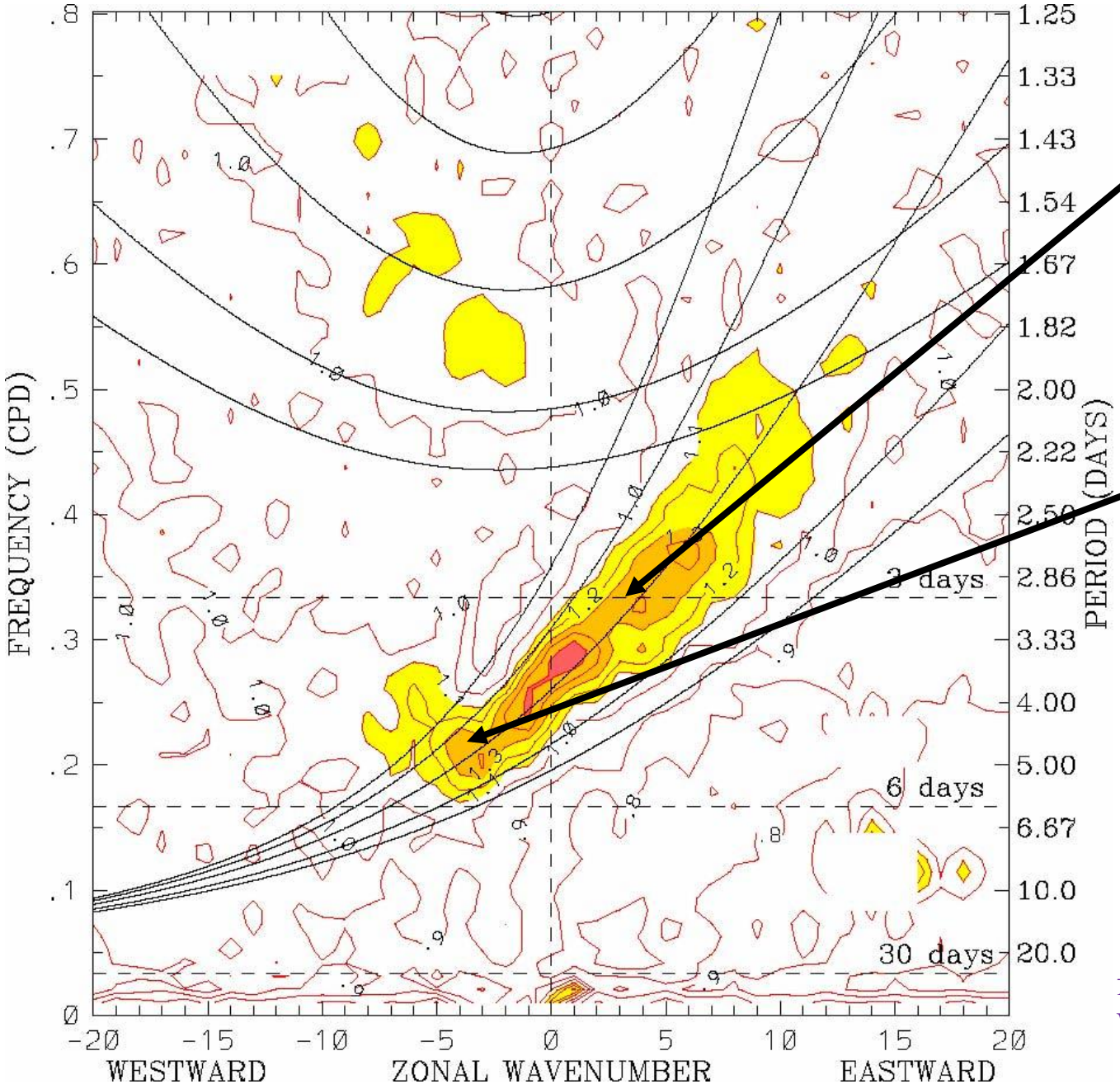
Observed

Outgoing Longwave Radiation

FIM – Grell Physics

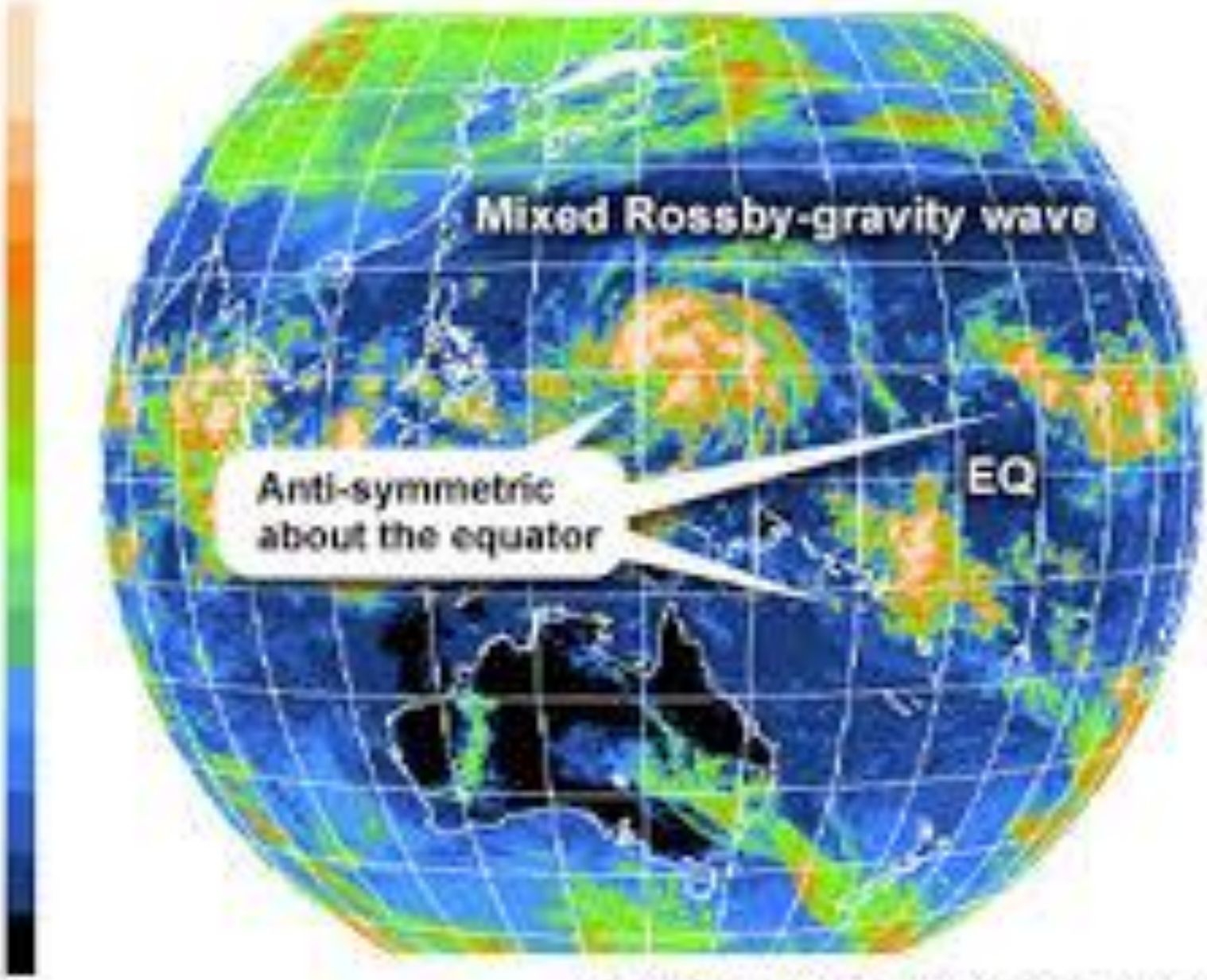
Outgoing Longwave Radiation

OLR power spectrum, 1979–2001 (Antisymmetric)



from
Wheeler and Kiladis, 1999

Enhanced IR Satellite Image at 0000 UTC 21 Nov 2002

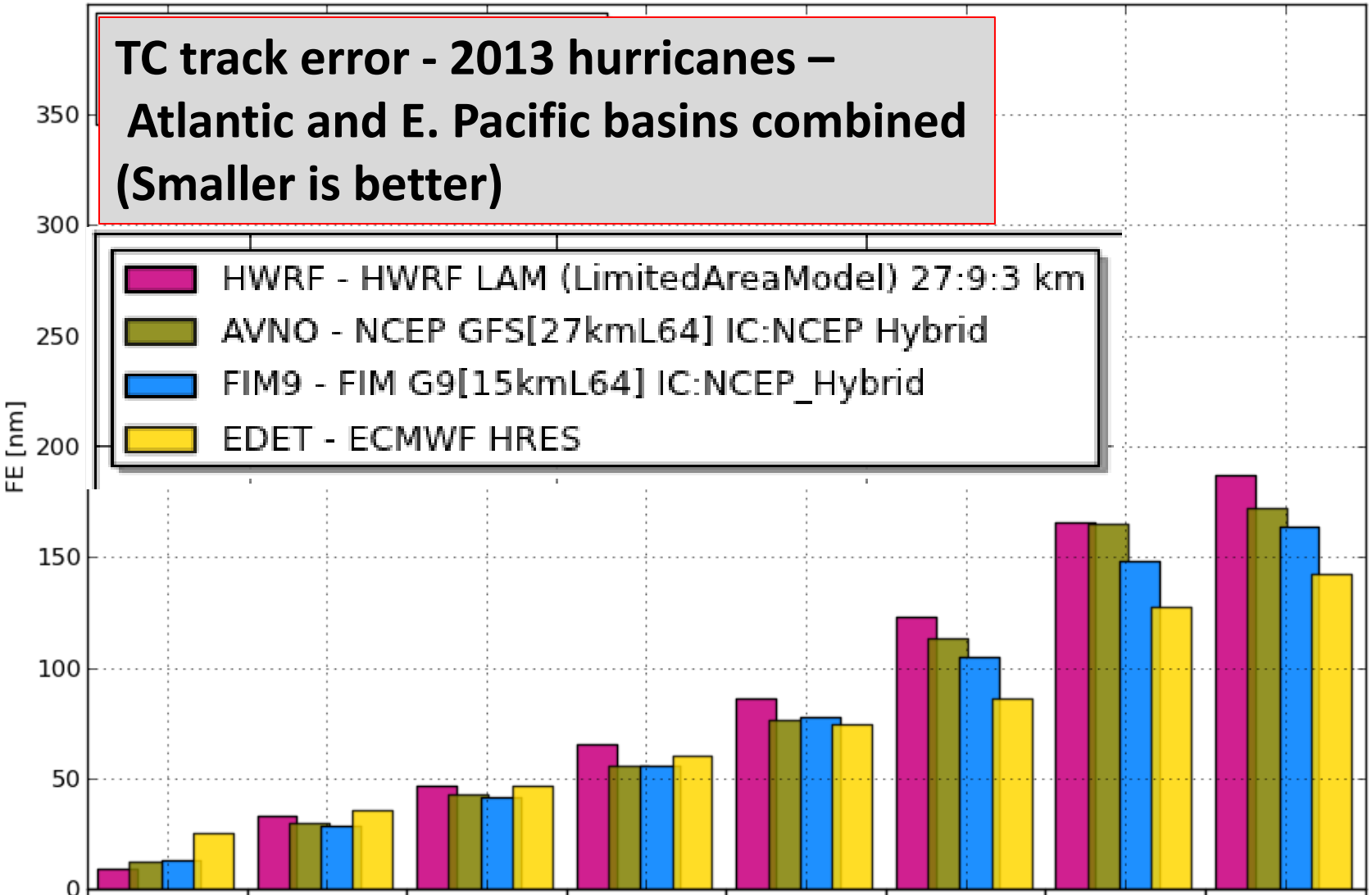


Australian Bureau of Meteorology / JMA

EPAC/LANT 2013 HWRF v GFS v FIM9 v ECMWF

Storms[N] [26]: 01L.13 02E.13 02L.13 03E.13 03L.13 04E.13 04L.13 05E.13 05L.13 06E.13 ... 10L.13 11E.13 11L.13 12L.13 13E.13 13L.13 14E.13 15E.13 16E.13 17E.13

TC track error - 2013 hurricanes – Atlantic and E. Pacific basins combined (Smaller is better)



	0h	12h	24h	36h	48h	72h	96h	120h
hwrf	9[196]	33[159]	47[137]	65[117]	86[96]	123[59]	166[42]	187[28]
avno	12[196]	30[159]	43[137]	56[117]	76[96]	113[59]	165[42]	172[28]
fim9	13[196]	28[159]	42[137]	56[117]	78[96]	105[59]	148[42]	164[28]
edet	25[196]	36[159]	47[137]	60[117]	74[96]	86[59]	127[42]	143[28]

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Conservation of entropy was a guiding principle in our model design effort.

Numerical Uncertainties in the Simulation of Reversible Isentropic Processes and Entropy Conservation

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(Manuscript received 4 December 1998, in final form 31 August 1999)

ABSTRACT

A challenge common to weather, climate, and seasonal numerical prediction is the need to simulate accurately reversible isentropic processes in combination with appropriate determination of sources/sinks of energy and entropy. Ultimately, this task includes the distribution and transport of internal, gravitational, and kinetic energies, the energies of water substances in all forms, and the related thermodynamic processes of phase changes involved with clouds, including condensation, evaporation, and precipitation processes.

All of the processes noted above involve the entropies of matter, radiation, and chemical substances, conservation during transport, and/or changes in entropies by physical processes internal to the atmosphere. With respect to the entropy of matter, a means to study a model's accuracy in simulating internal hydrologic processes is to determine its capability to simulate the appropriate conservation of potential and equivalent potential temperature as surrogates of dry and moist entropy under reversible adiabatic processes in which clouds form, evaporate, and precipitate. In this study, a statistical strategy utilizing the concept of "pure error" is set forth to assess the numerical accuracies of models to simulate reversible processes during 10-day integrations of the global circulation corresponding to the global residence time of water vapor. During the integrations, the sums of squared differences between equivalent potential temperature θ_e numerically simulated by the governing equations of mass, energy, water vapor, and cloud water and a proxy equivalent potential temperature $t\theta_e$ numerically simulated as a conservative property are monitored. Inspection of the differences of θ_e and $t\theta_e$ in time and space and the relative frequency distribution of the differences details bias and random errors that develop from nonlinear numerical inaccuracies in the advection and transport of potential temperature and water substances within the global atmosphere.

A series of nine global simulations employing various versions of Community Climate Models CCM2 and CCM3—all Eulerian spectral numerics, all semi-Lagrangian numerics, mixed Eulerian spectral, and semi-Lagrangian numerics—and the University of Wisconsin—Madison (UW) isentropic-sigma gridpoint model provides an interesting comparison of numerical accuracies in the simulation of reversibility. By day 10, large bias and random differences were identified in the simulation of reversible processes in all of the models except for the UW isentropic-sigma model. The CCM2 and CCM3 simulations yielded systematic differences that varied zonally, vertically, and temporally. Within the comparison, the UW isentropic-sigma model was superior in transporting water vapor and cloud water/ice and in simulating reversibility involving the conservation of dry and moist entropy. The only relative frequency distribution of differences that appeared optimal, in that the distribution remained unbiased and equilibrated with minimal variance as it remained statistically stationary, was the distribution from the UW isentropic-sigma model. All other distributions revealed nonstationary characteristics with spreading and/or shifting of the maxima as the biases and variances of the numerical differences of θ_e and $t\theta_e$ amplified.

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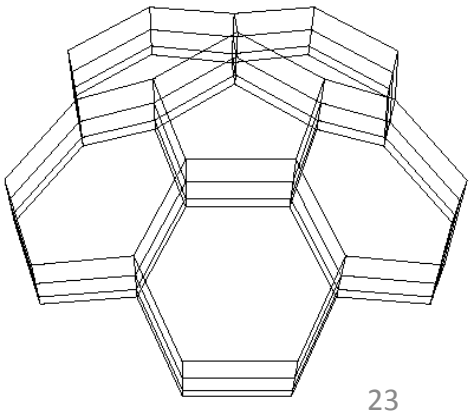
NIM Strategy for Entropy Conservation

- Use of exact same (divergent) equation form for all variables participating in Reversible Isentropic Processes (Pressure, potential temperature, and water vapor).
- No diffusion for thermodynamic variables.
- Finite volume formulation with fixed control volumes.
- Full three dimensional advection (Gauss divergence theorem on the control volume).
- High resolution in the vertical (192 levels).



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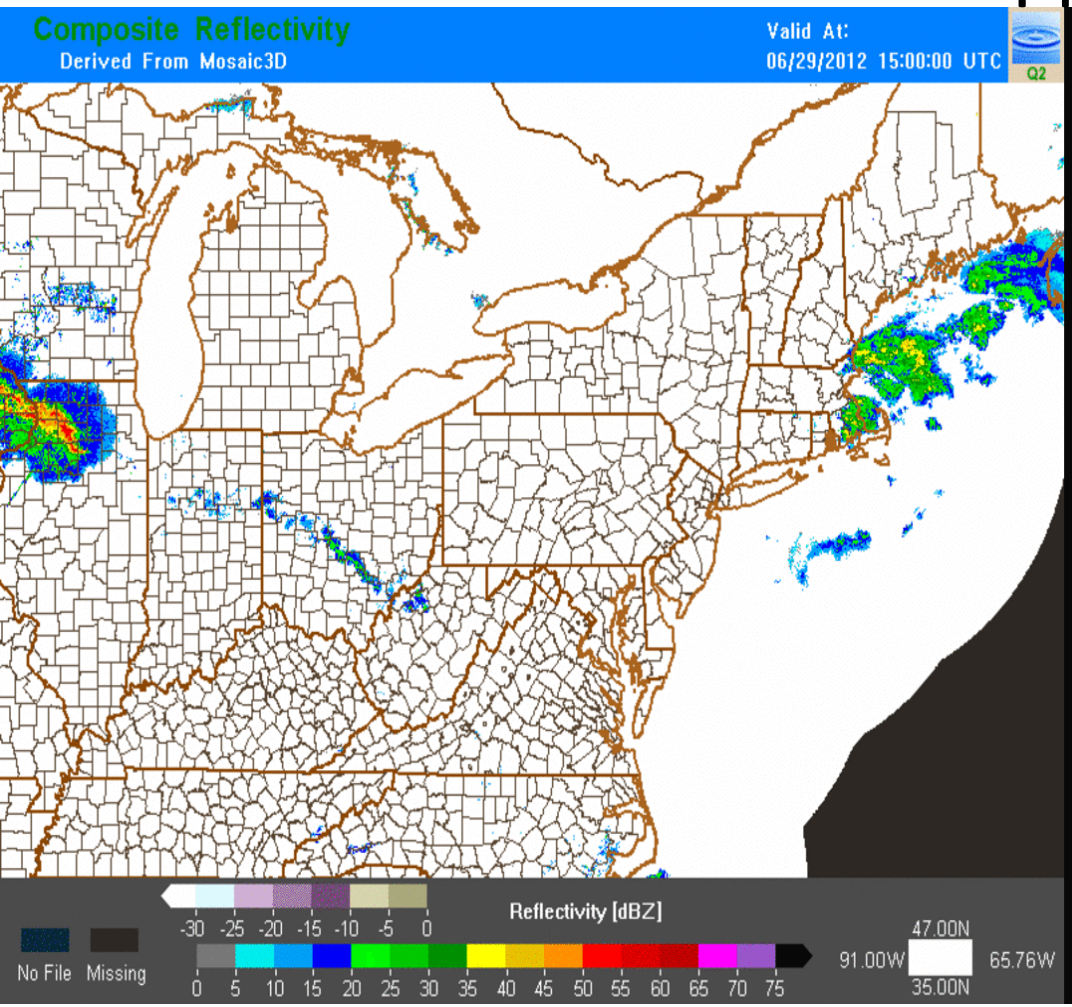
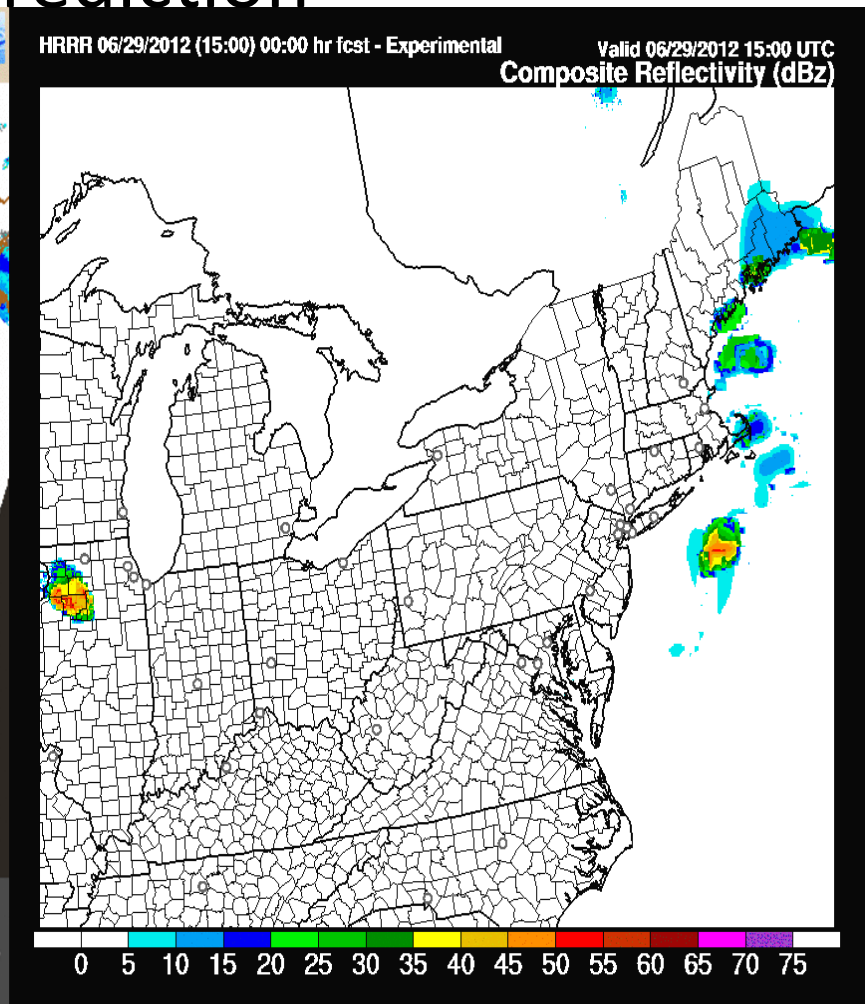
Interlude: Importance of cloud-resolving nonhydrostatic models.

Observed Radar

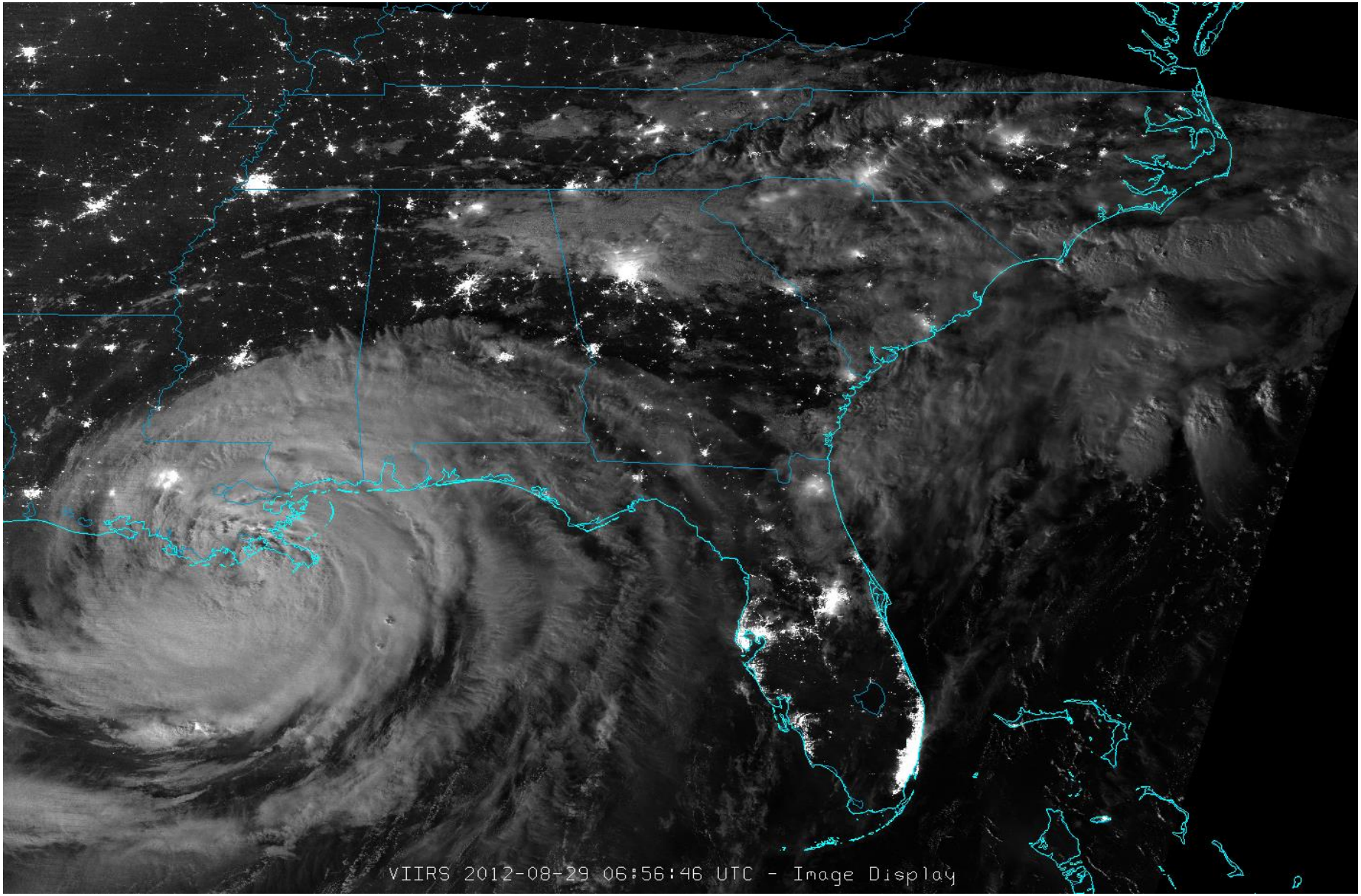


Model Prediction



High Resolution Rapid Refresh Model run on ESRL Supercomputer

Global satellite analysis key tocloud and precip initialization.



Soumi NPP visible image at midnight!

NCAR's MPAS model demonstrates realistic supercell simulation.

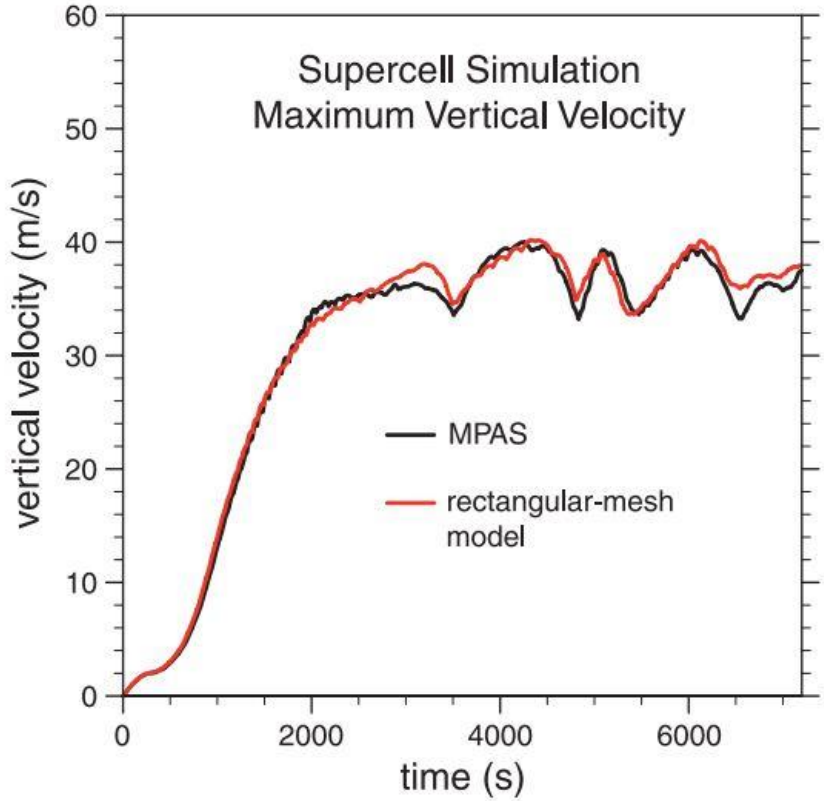


FIG. 5. Maximum vertical velocity for the supercell simulations using MPAS (perfect hexagonal mesh) and a rectangular-mesh model.

A Multiscale Nonhydrostatic Atmospheric Model Using Centroidal Voronoi Tesselations and C-Grid Staggering

WILLIAM C. SKAMAROCK, JOSEPH B. KLEMP, MICHAEL G. DUDA, LAURA D. FOWLER,
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TODD D. RINGLER
Los Alamos National Laboratory, Los Alamos, New Mexico

(Manuscript received 17 August 2011, in final form 6 March 2012)

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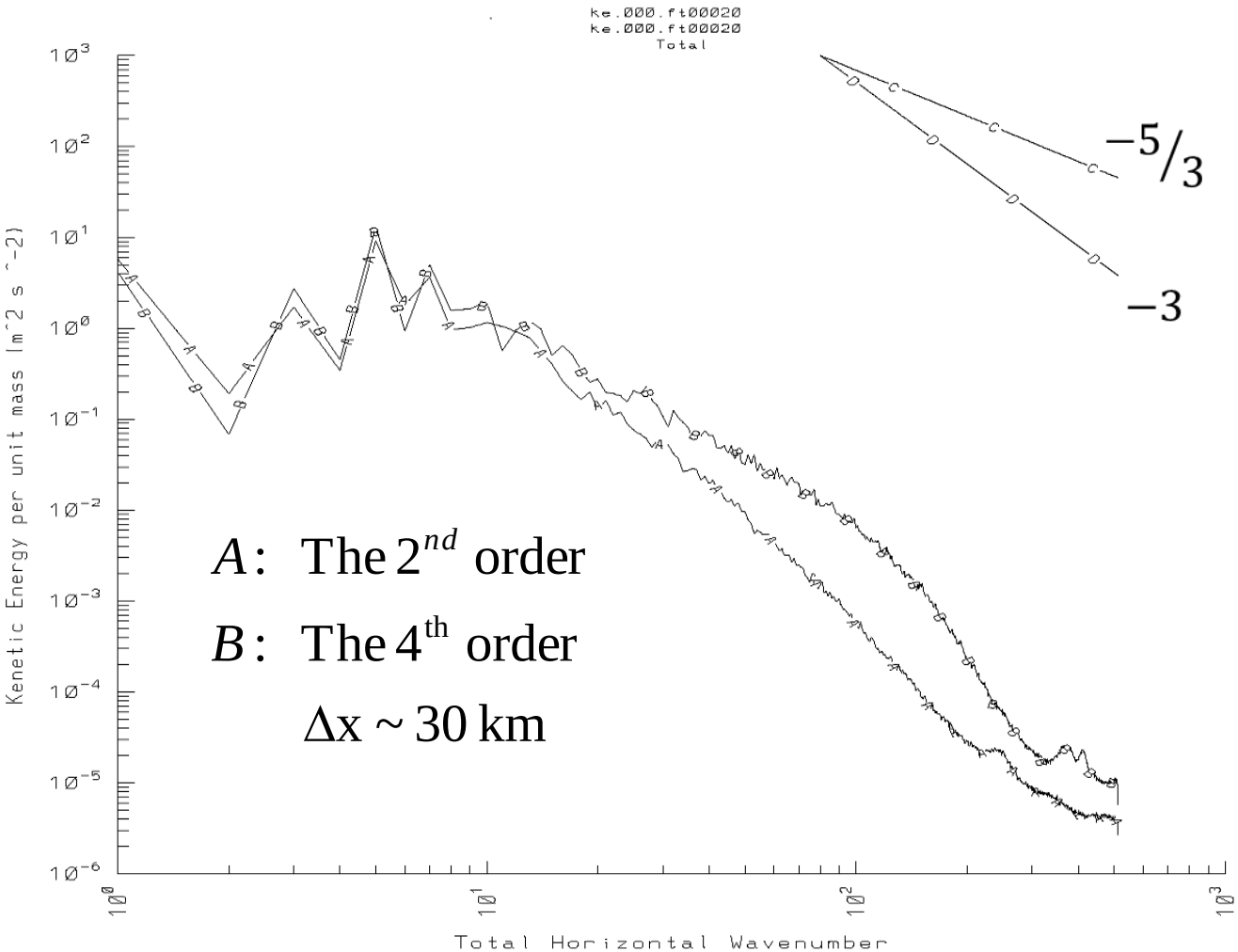
NIM Test, per Skamarock: No divergence damping, high effective resolution.

$$2^{nd}:\ \Delta_{\psi}^{2} = \nabla \bullet k_h \nabla \psi, \quad 4^{th}:\ \Delta_{\psi}^{4} = \nabla \bullet k_h \nabla \left(\Delta_{\psi}^{2}\right)$$

$$k_h = C_s^2 l^2 \left[\left(u_x - v_y\right)^2 + \left(u_y + v_x\right)^2\right]^{1/2} \quad \left(\text{Smagorinsky},1963\right)$$



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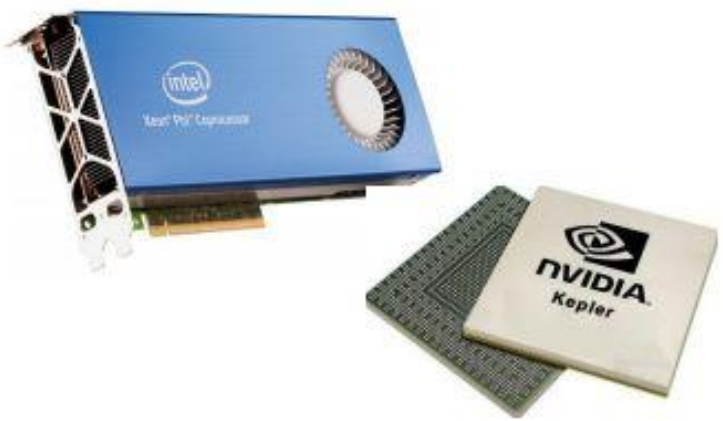
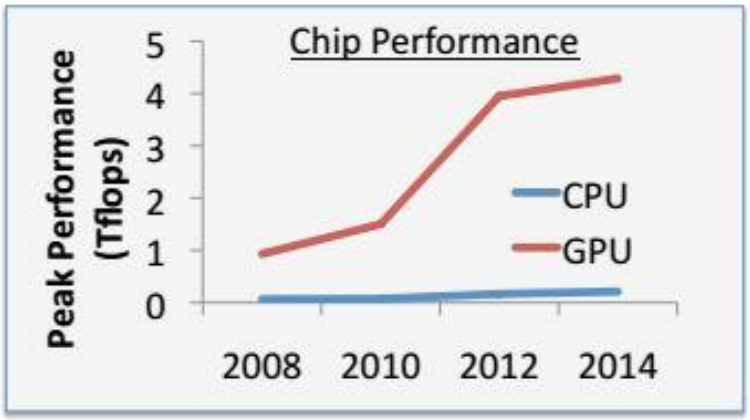
Computer Chip Technologies

	Compute cores	Power	Performance (Tflops)
• GPU			
– NVIDIA Kepler	2880	250w	4.2
– AMD FireStream	~3000	225w	3.2
• Many Integrated Core (MIC)			
– Intel Xeon Phi	61	300w	2.1
• CPU			
– Intel SandyBridge	16	125w	0.15
– Intel IvyBridge	24		0.21

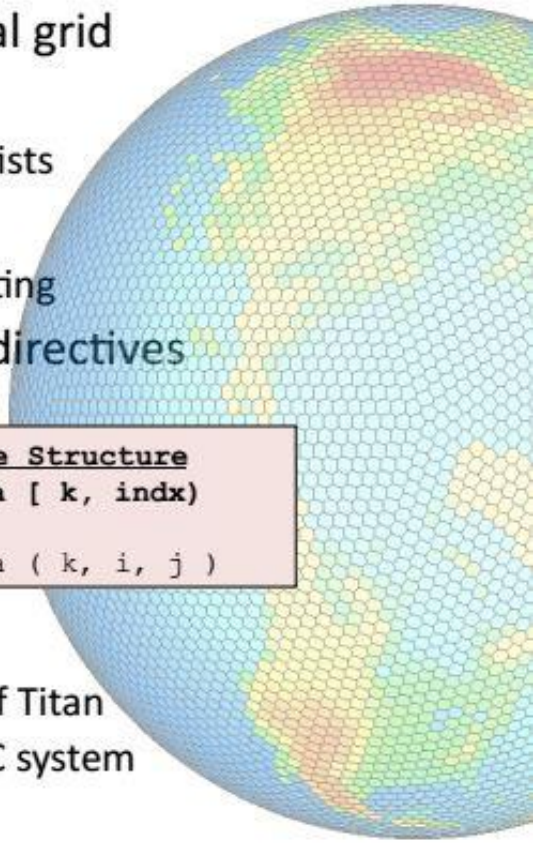




NIM has been developed to run on MPFG – benchmarking 4X performance gain.

Non-Hydrostatic Icosahedral (NIM)

- Uniform, global, hexagonal-based icosahedral grid
- Designed for GPU and MIC
  - Scientists, parallel programmers, computer scientists
- Targeting 3.5KM or finer resolution
  - Estimate 2500 GPU or MIC processors for forecasting
- Single source code for CPU, GPU, MIC using directives
  - CPU OpenMP
  - GPU F2C-ACC, PGI, Cray
  - MIC OpenMP + extensions
  - MPI Scalable Modeling System



```
      Code Structure
NIM:     a [ k, indx)

lat-lon a ( k, i, j )
```

Dynamics: parallelization complete

- Parallel runs to 7.5KM resolution on 5120 GPUs of Titan
  - Similar tests have been done on the TACC MIC system
- Demonstrated good performance and scaling

Physics: parallelization in progress

NIM goal is 3.5 km global weather model running in 2% of realtime in 2016.

Real Weather:
ESRL's FIM for the case of October 21, 2010.

Downstream energy generated the deepest low ever recorded in the US northern plains.

Displayed on ESRL's NOAA Earth Information System.