Design of Global Models To Adhere to Thermodynamic Relationships

Johnson Symposium
AMS 2014

Alexander E. MacDonald

NOAA
Earth System Research Laboratory

PROLOGUE:
Models Matter!

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

Characteristics of Models

Universality: Making models more comprehensive to more closely adhere to the physical processes.

Nonhydrostatic GEs in flux form on Z - coord with 3 - D f - v solvers :

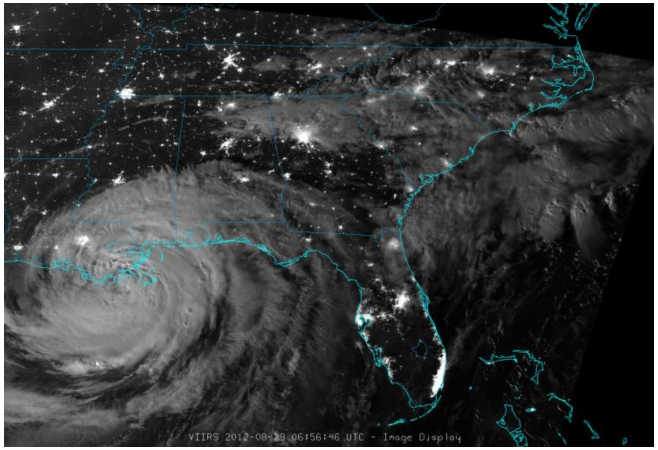
$$\begin{cases} \dfrac{\partial U}{\partial t} + \dfrac{\partial (uU)}{\partial x} + \dfrac{\partial (vU)}{\partial y} + \dfrac{\partial (wU)}{\partial z} + \gamma R \pi \dfrac{\partial \Theta'}{\partial x} = 0 \\ \dfrac{\partial V}{\partial t} + \dfrac{\partial (uV)}{\partial x} + \dfrac{\partial (vV)}{\partial y} + \dfrac{\partial (wV)}{\partial z} + \gamma R \pi \dfrac{\partial \Theta'}{\partial y} = 0 \\ \dfrac{\partial W}{\partial t} + \dfrac{\partial (uW)}{\partial x} + \dfrac{\partial (vW)}{\partial y} + \dfrac{\partial (wW)}{\partial z} + \left(\gamma R \pi \dfrac{\partial \Theta'}{\partial z} - \overline{\rho} g \dfrac{\pi'}{\overline{\pi}} + \rho' g \right) = 0 \\ \dfrac{\partial \Theta'}{\partial t} + \dfrac{\partial (u\Theta)}{\partial x} + \dfrac{\partial (v\Theta)}{\partial y} + \dfrac{\partial (w\Theta)}{\partial z} = \dfrac{\Theta \dot{H}}{C_p T} \\ \dfrac{\partial \rho}{\partial t} + \dfrac{\partial (u\rho)}{\partial x} + \dfrac{\partial (v\rho)}{\partial y} + \dfrac{\partial (w\rho)}{\partial z} = 0. \end{cases}$$

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

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

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

Realism: The degree to which models correspond to observations extended over time and space.



MacDonald, BAMS, Dec. 2005, p. 1759.

Universality

Nonhydrostatic GEs in flux form on Z-coord with 3-D f-v solvers:

$$
\begin{cases}
\dfrac{\partial U}{\partial t}+\dfrac{\partial (uU)}{\partial x}+\dfrac{\partial (vU)}{\partial y}+\dfrac{\partial (wU)}{\partial z}+\gamma R\pi\dfrac{\partial \Theta'}{\partial x}=0\\
\dfrac{\partial V}{\partial t}+\dfrac{\partial (uV)}{\partial x}+\dfrac{\partial (vV)}{\partial y}+\dfrac{\partial (wV)}{\partial z}+\gamma R\pi\dfrac{\partial \Theta'}{\partial y}=0\\
\dfrac{\partial W}{\partial t}+\dfrac{\partial (uW)}{\partial x}+\dfrac{\partial (vW)}{\partial y}+\dfrac{\partial (wW)}{\partial z}+\left(\gamma R\pi\dfrac{\partial \Theta'}{\partial z}-\overline{\rho}g\dfrac{\pi'}{\overline{\pi}}+\rho' g\right)=0\\
\dfrac{\partial \Theta'}{\partial t}+\dfrac{\partial (u\Theta)}{\partial x}+\dfrac{\partial (v\Theta)}{\partial y}+\dfrac{\partial (w\Theta)}{\partial z}=\dfrac{\Theta\dot{H}}{C_pT}\\
\dfrac{\partial \rho}{\partial t}+\dfrac{\partial (u\rho)}{\partial x}+\dfrac{\partial (v\rho)}{\partial y}+\dfrac{\partial (w\rho)}{\partial z}=0.
\end{cases}
$$

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

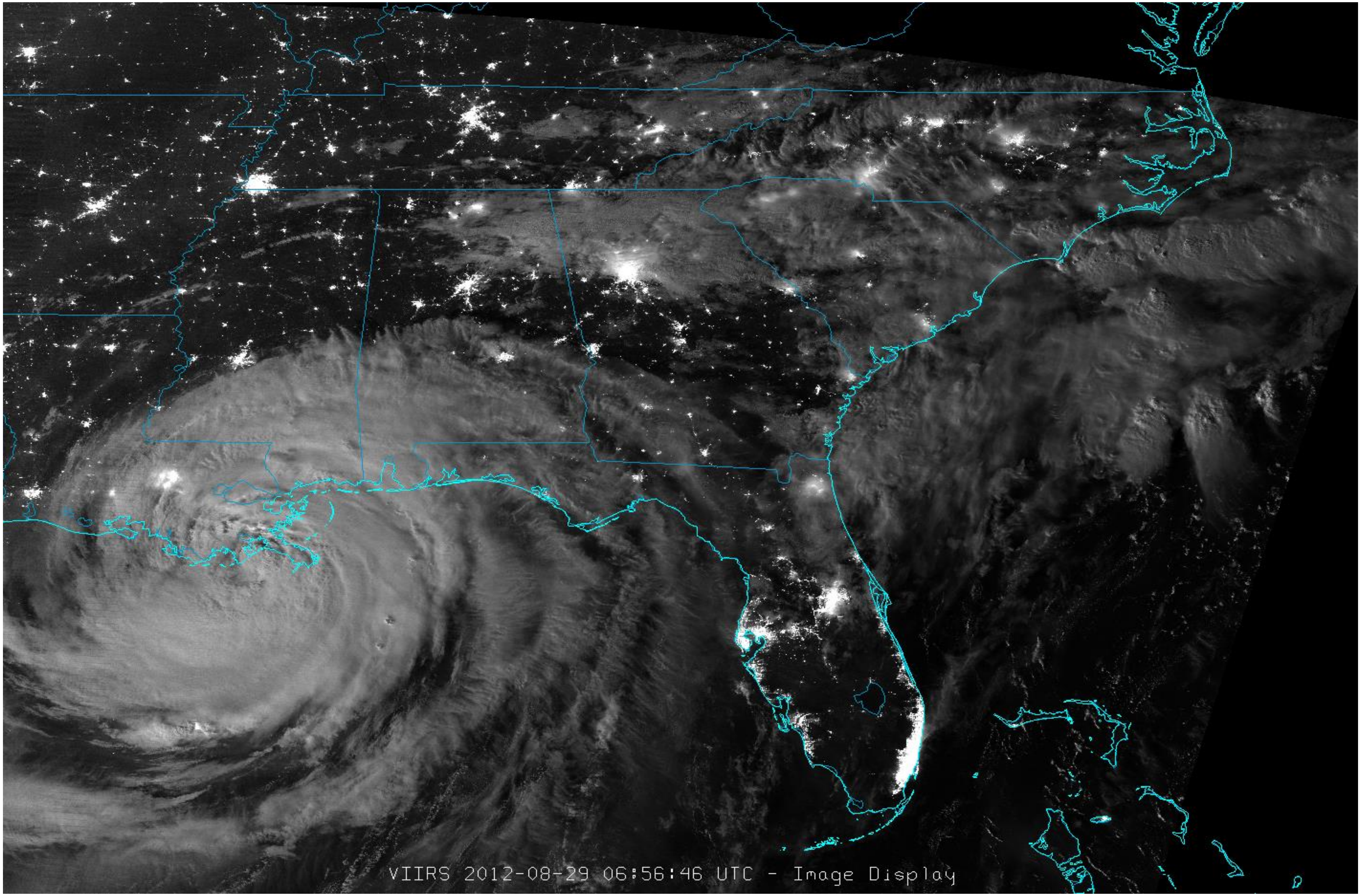
$$\rho(x,z,t)=\overline{\rho}(z)+\rho'(x,z,t);\qquad \nabla p=\gamma R\pi\nabla\Theta$$

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

NIM Model Equations

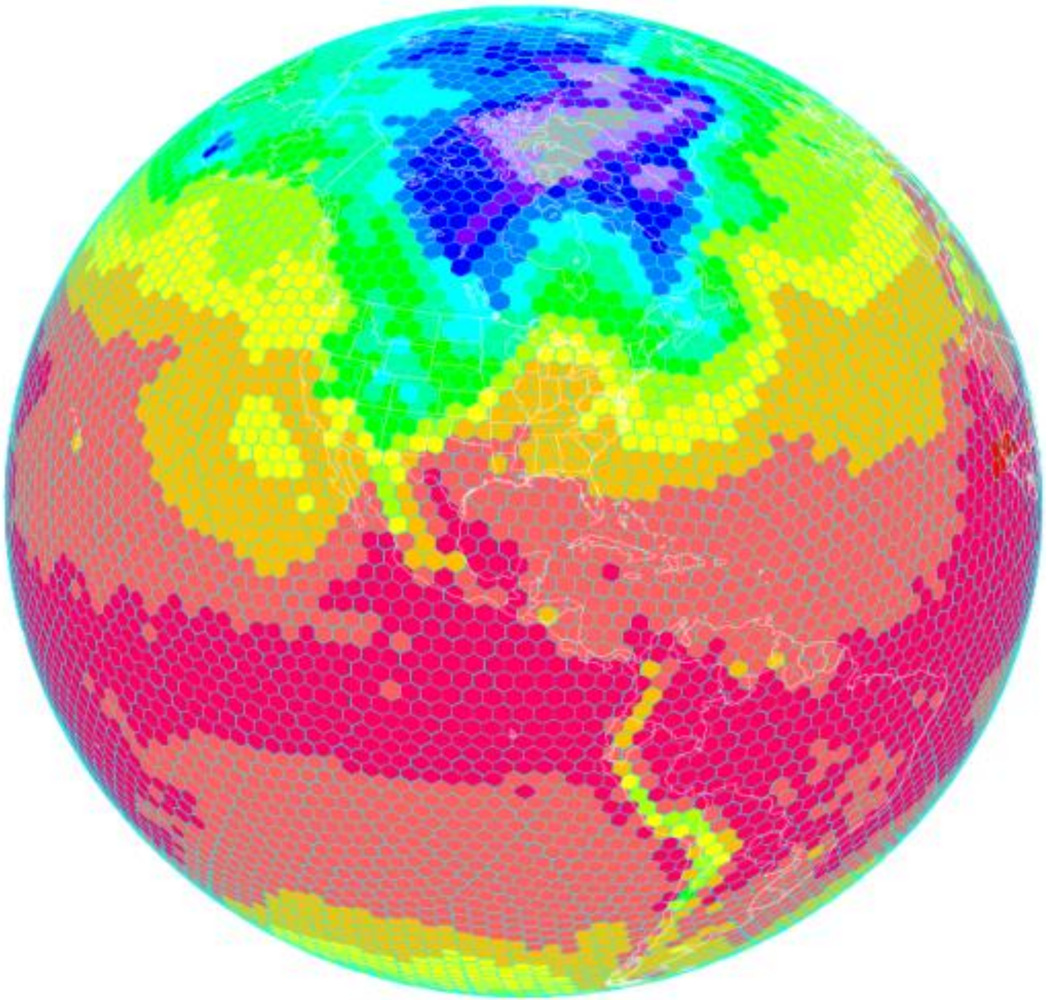
The new generation of global models are fully compressible, and fully non-hydrostatic.

Realism



The models correspond to observations. (Image: Soumi NPP visible image at midnight!)

2001: We 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

Professor Johnson's work on 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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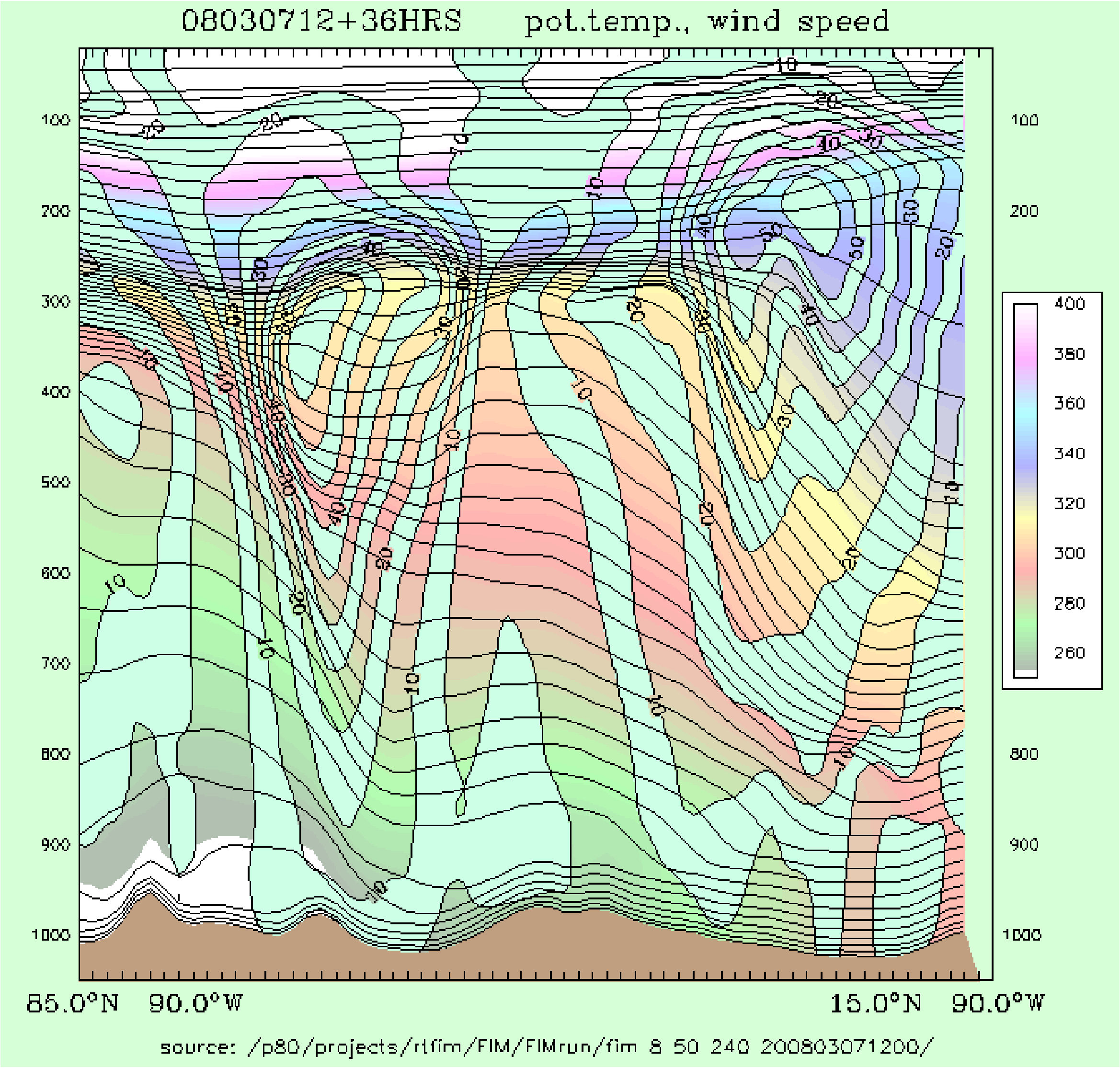
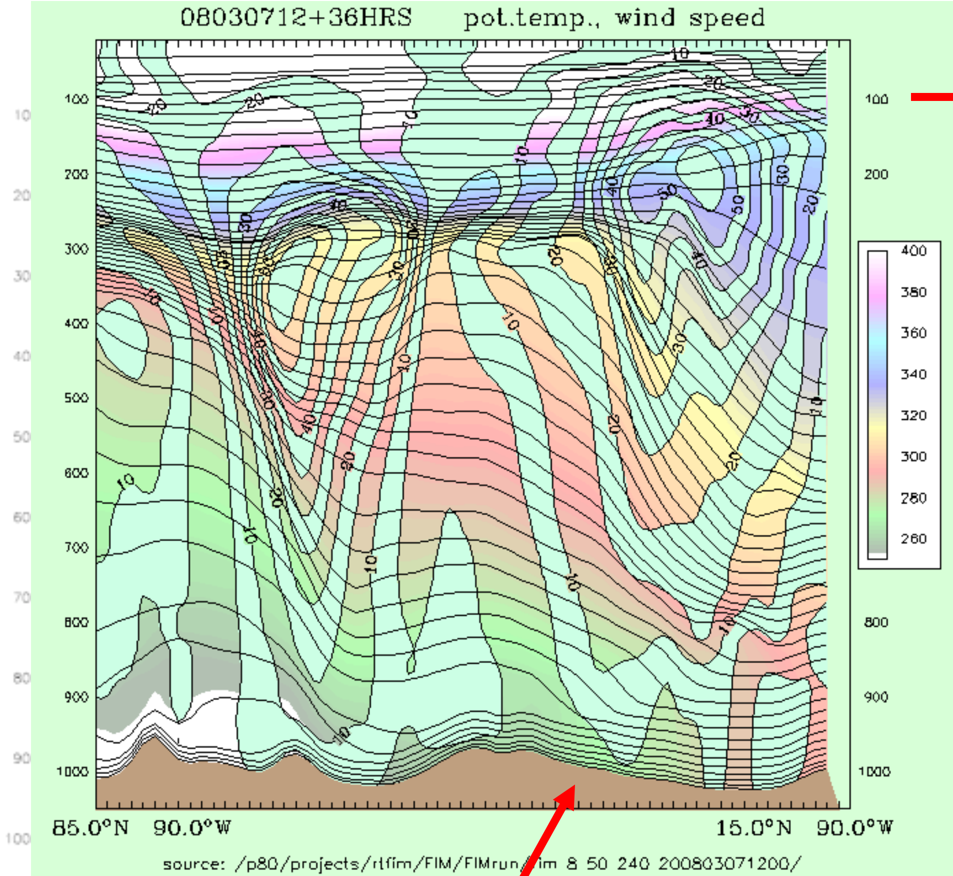
One way to be Don Johnson Compliant: Use isentropic coordinates!

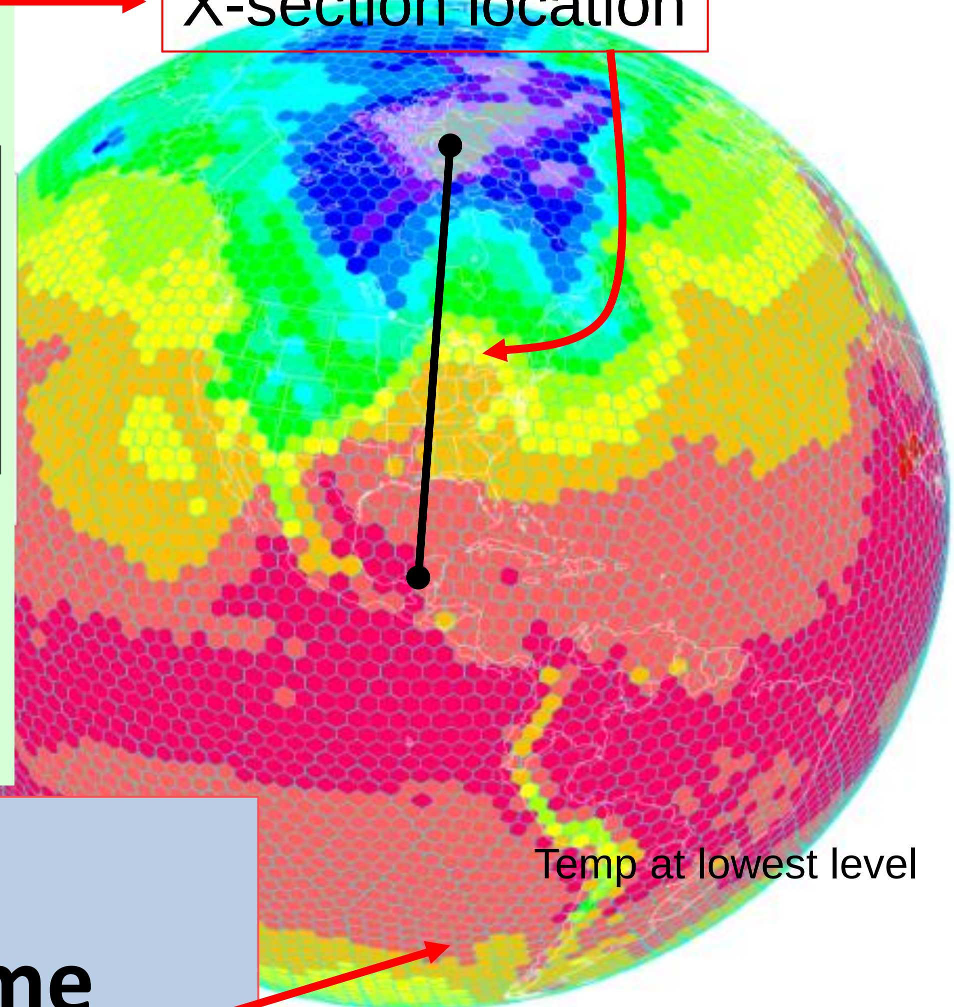


Rainer Bleck, a third designer, was brought in for ALE aspect of model.

http://fim.noaa.gov



X-section location



Temp at lowest level

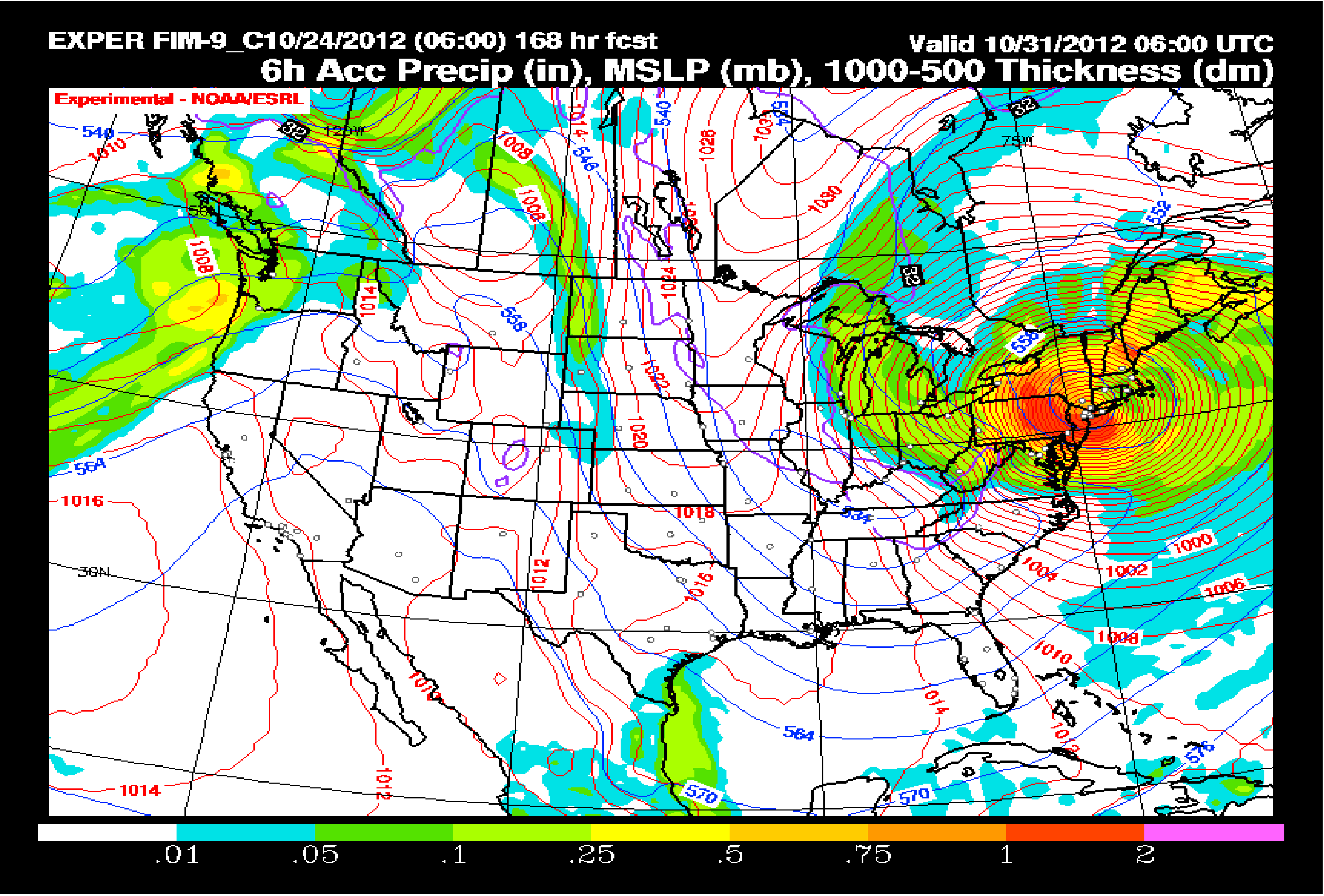
Flow-following-

finite-volume

Icosahedral

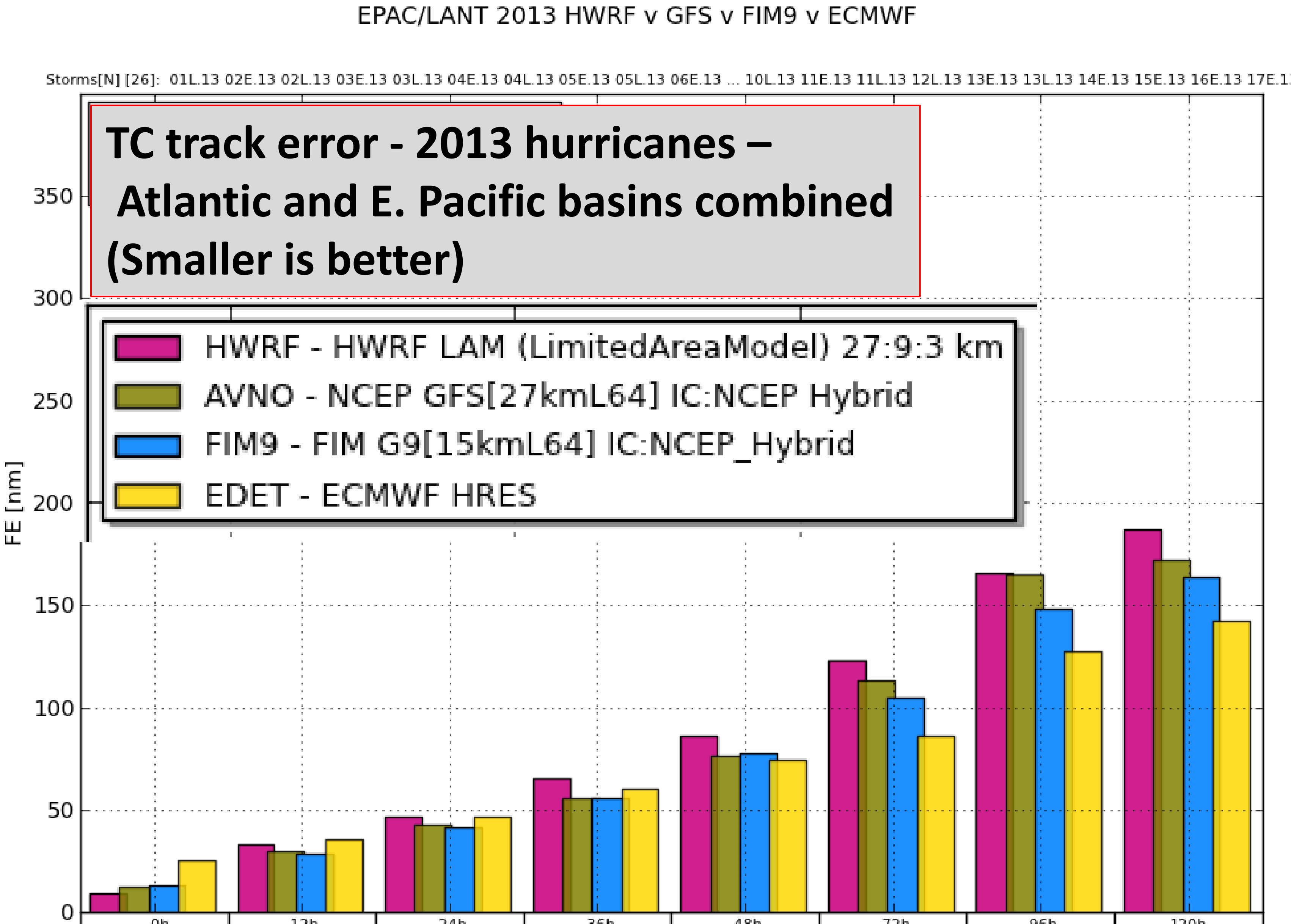
Model

FIM



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

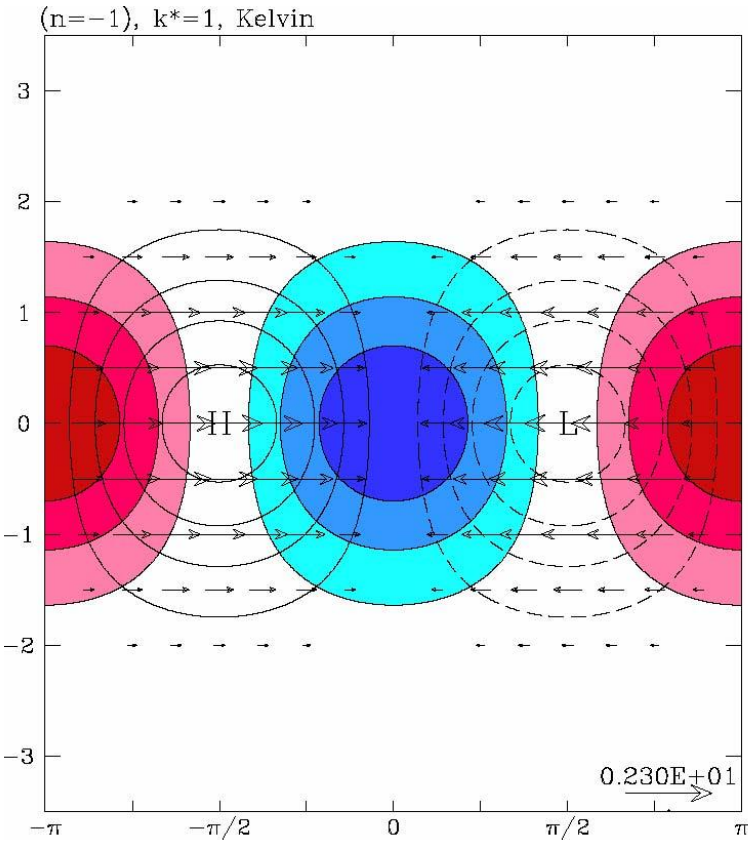
TC track error - 2013 hurricanes – Atlantic and E. Pacific basins combined (Smaller is better)

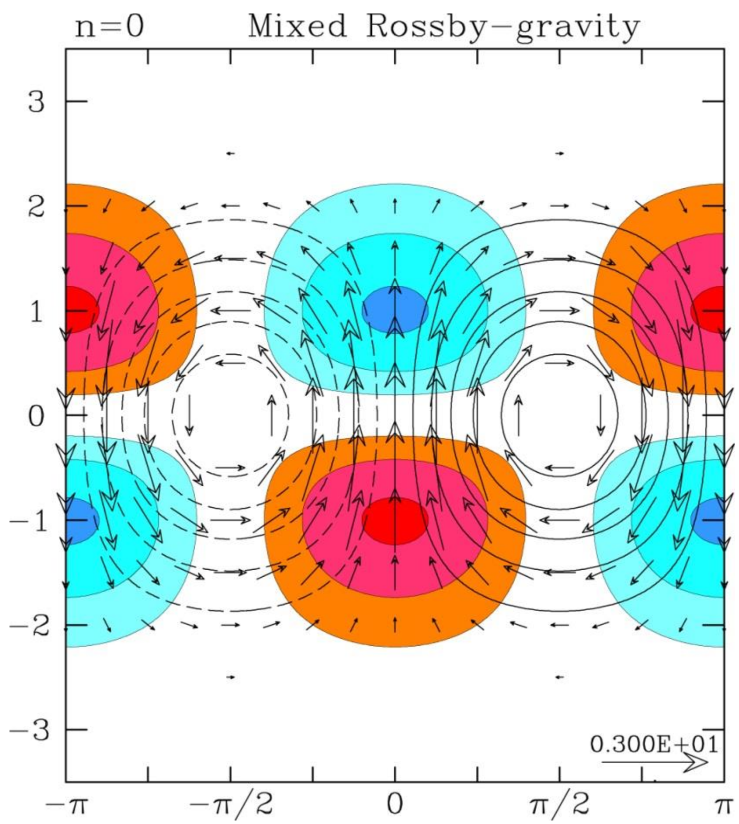


	0h	12h	24h	36h	48h	72h	96h	120h
hwrf	9[196]	33[159]	47[137]	65[117]	86[96]	123[59]	166[42]	187[28]
avno	12[196]	30[159]	43[137]	56[117]	76[96]	113[59]	165[42]	172[28]
fim9	13[196]	28[159]	42[137]	56[117]	78[96]	105[59]	148[42]	164[28]
edet	25[196]	36[159]	47[137]	60[117]	74[96]	86[59]	127[42]	143[28]

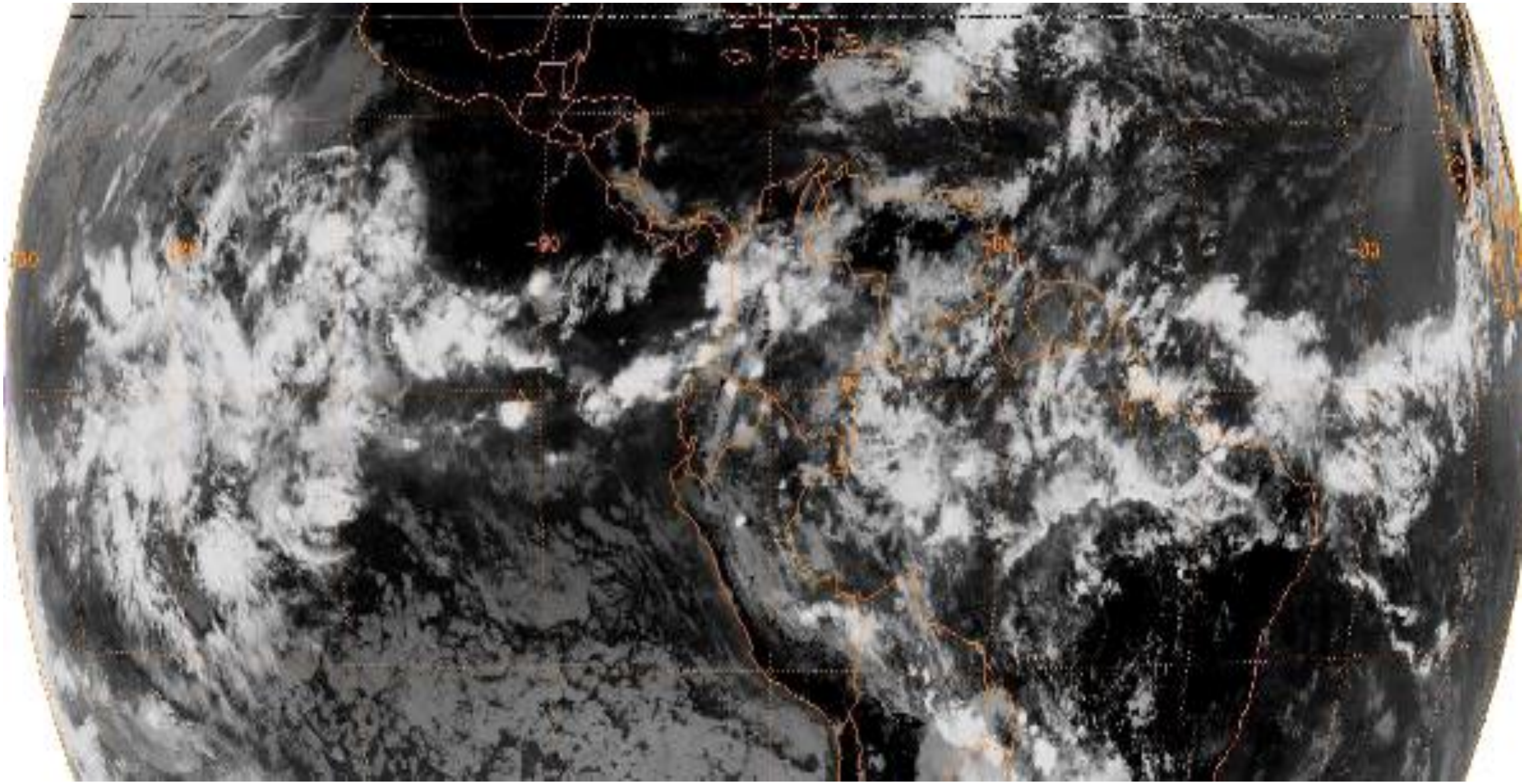
Equatorial Waves
Wavenumber-Frequency Spectral Analysis

- Decompose into Symmetric and Antisymmetric Fields about the Equator





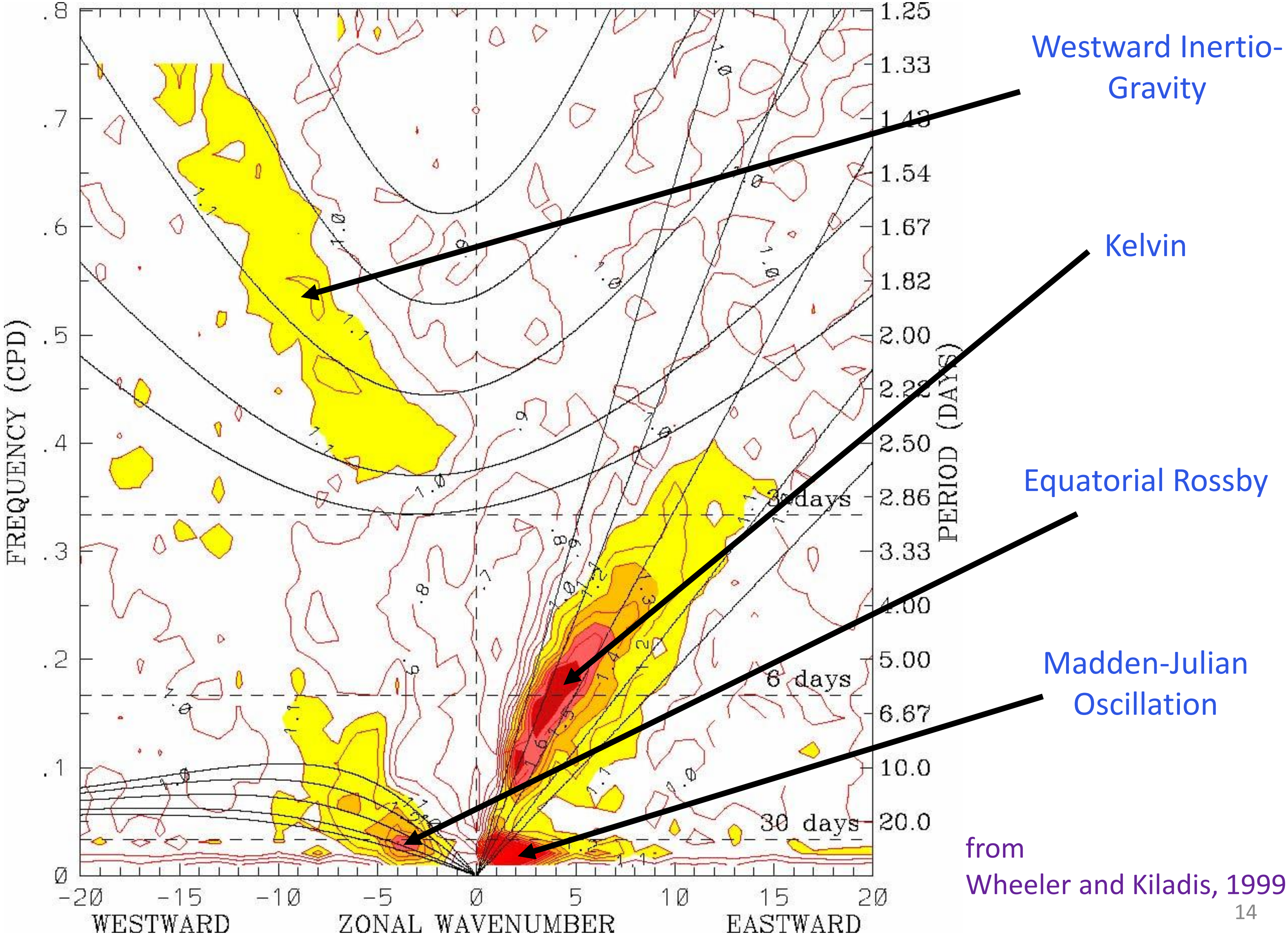
Matsuno, 1967. Could we make the FIM **Matsuno Compliant?**



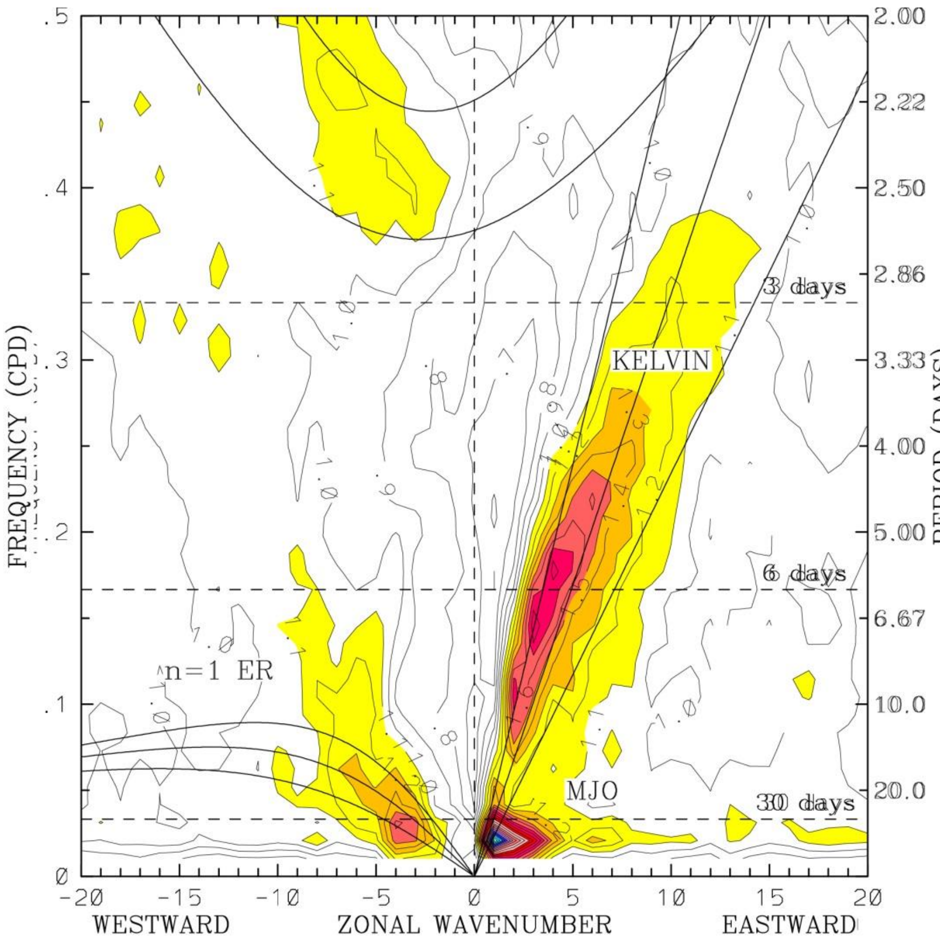
Atmospheric Kelvin Wave/MJO propagates across the American Tropics (blue line).

Our thanks to George Kiladis of ESRL for this analysis.

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

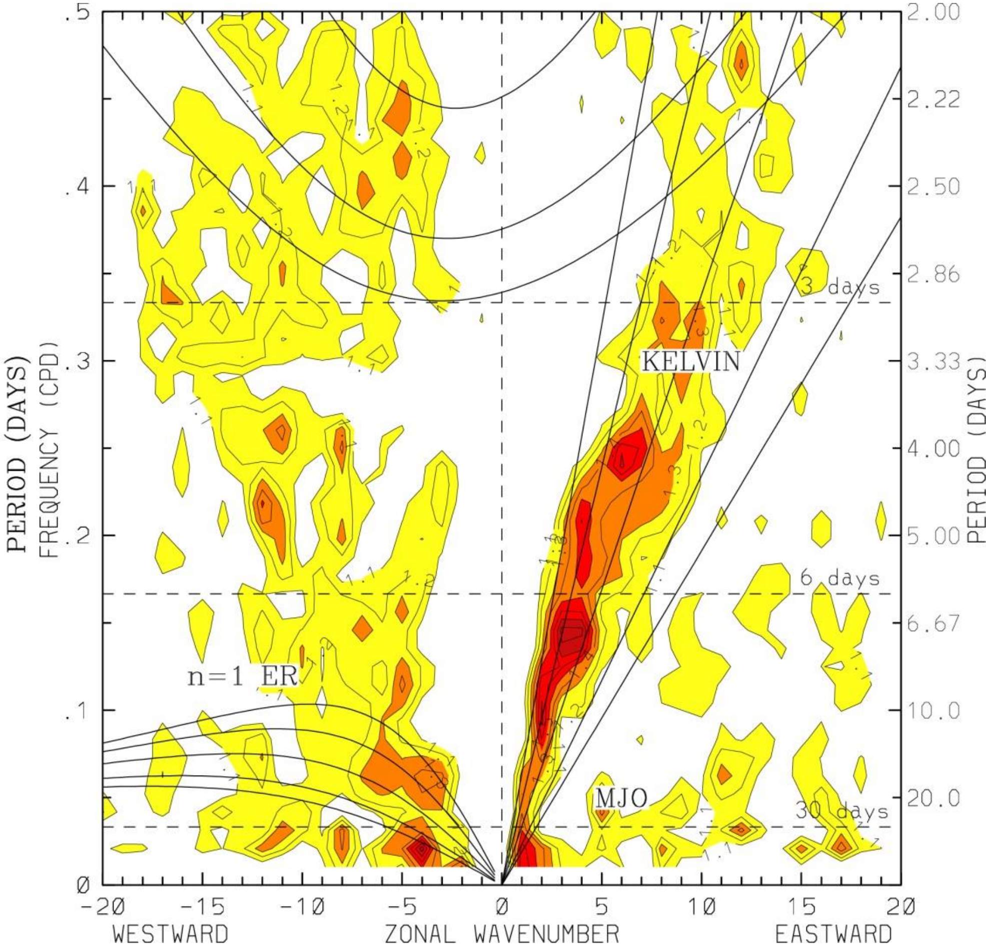


from
Wheeler and Kiladis, 1999



Observed

Outgoing Longwave Radiation



FIM – Grell Physics

Outgoing Longwave Radiation

Nonhydrostatic

Icosahedral

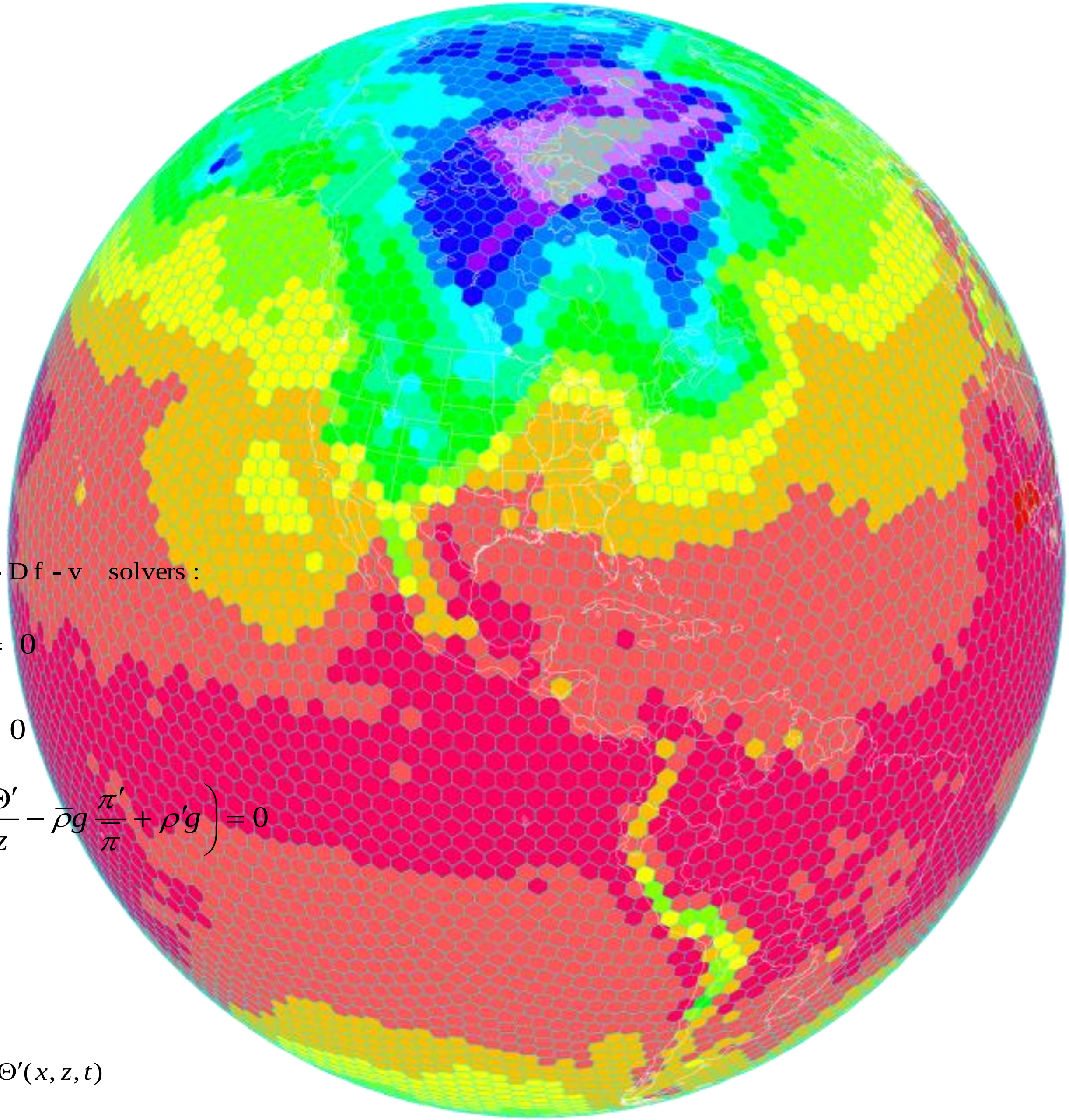
Model

Jin-Luen Lee

Alexander E. MacDonald

Jaques Middlecoff

Esther Kim and others



Nonhydrostatic GEs in flux form on Z-coord with 3-D f-v solvers:

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

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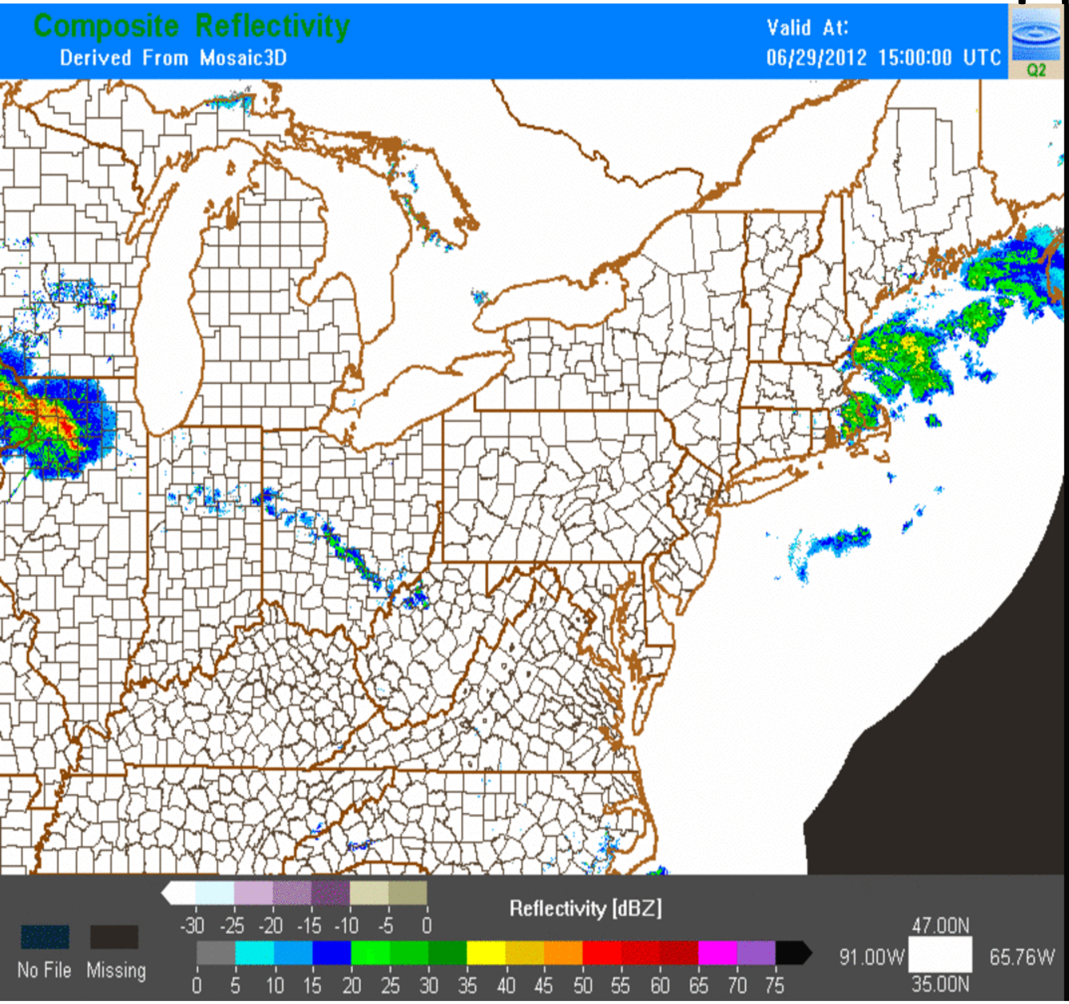
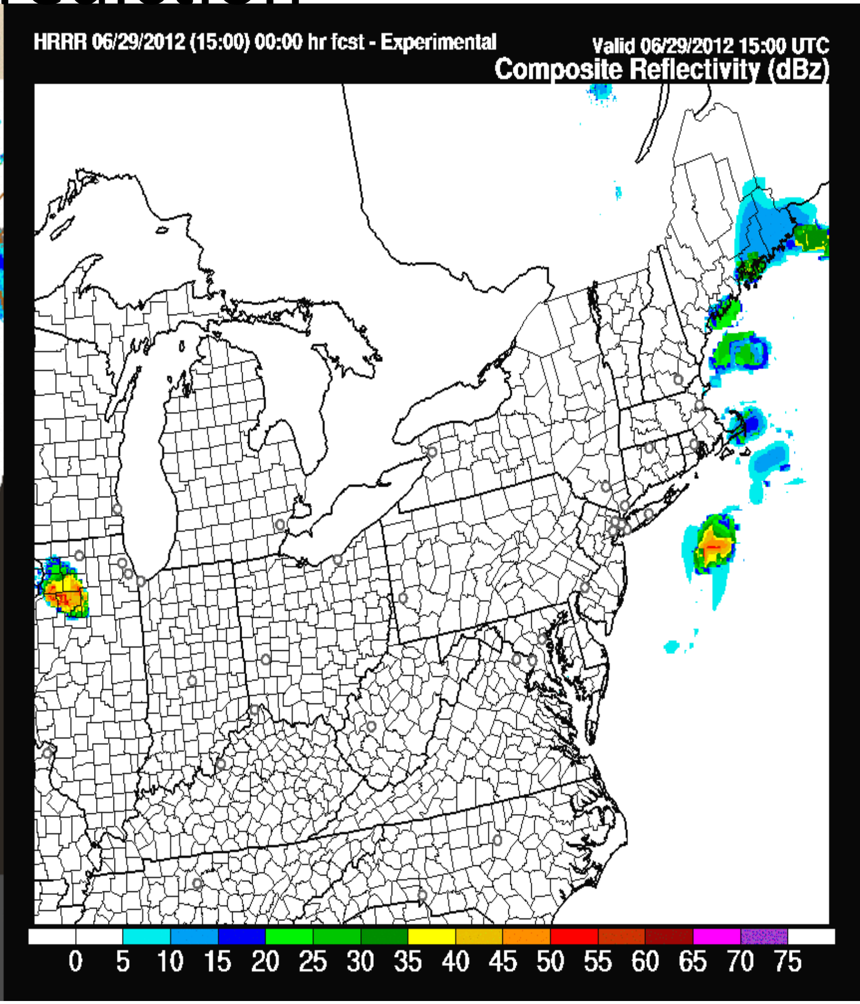
Global Nonhydrostatic models: NIM (ESRL), Cube Sphere (GFDL, NASA), NMM B (NCEP), MPAS (NCAR)

Observed Radar

Model Prediction

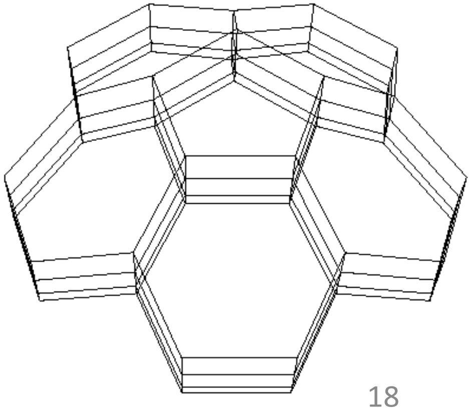




High Resolution Rapid Refresh Model run at ESRL .

NIM Strategy for Don Johnson Compliance

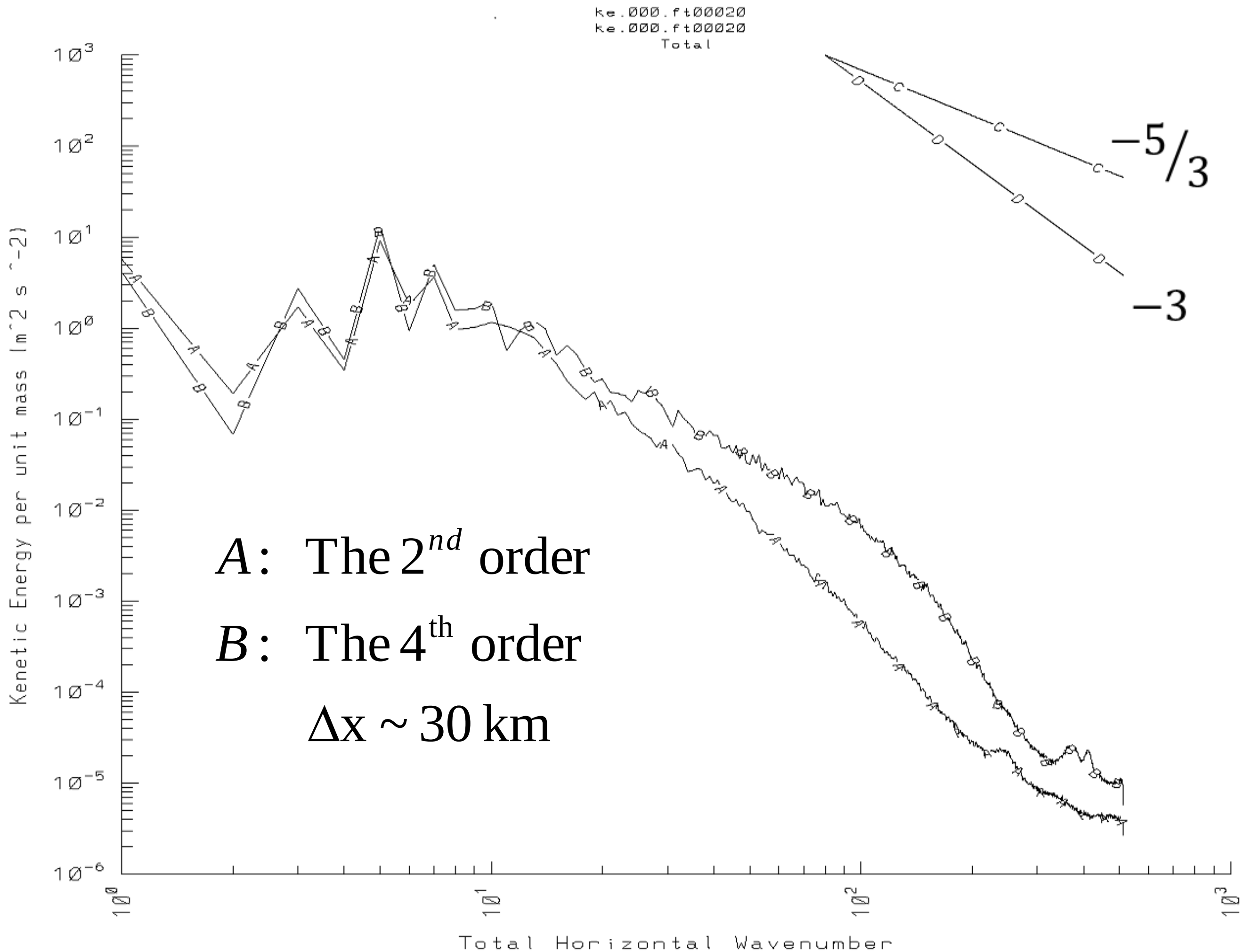
- Use of exact same (divergent) equation form for all variables participating in Reversible Isentropic Processes (Pressure, potential temperature, and water vapor).
- No diffusion for thermodynamic variables.
- Finite volume formulation with fixed control volumes.
- Full three dimensional advection (Gauss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



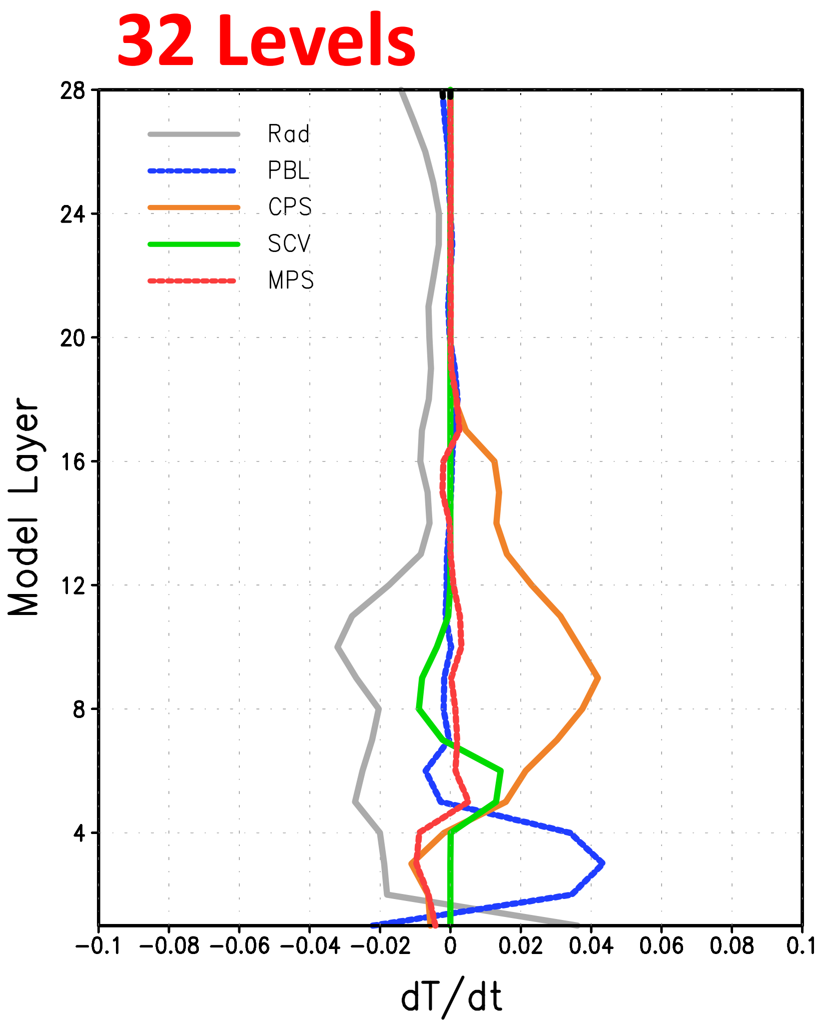
Bill Skamarock Compliant: No divergence damping, high effective resolution.

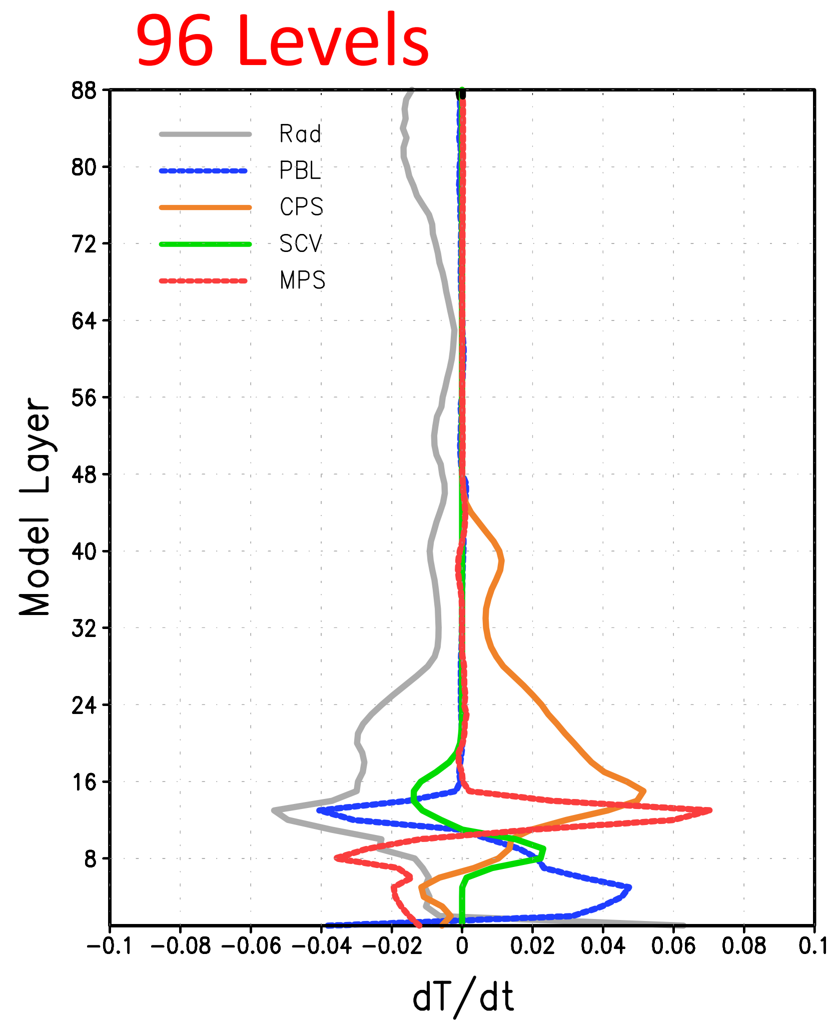
$$2^{nd}:\ \Delta_{\psi}^{2} = \nabla \bullet k_h \nabla \psi, \quad 4^{th}:\ \Delta_{\psi}^{4} = \nabla \bullet k_h \nabla \left(\Delta_{\psi}^{2}\right)$$

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



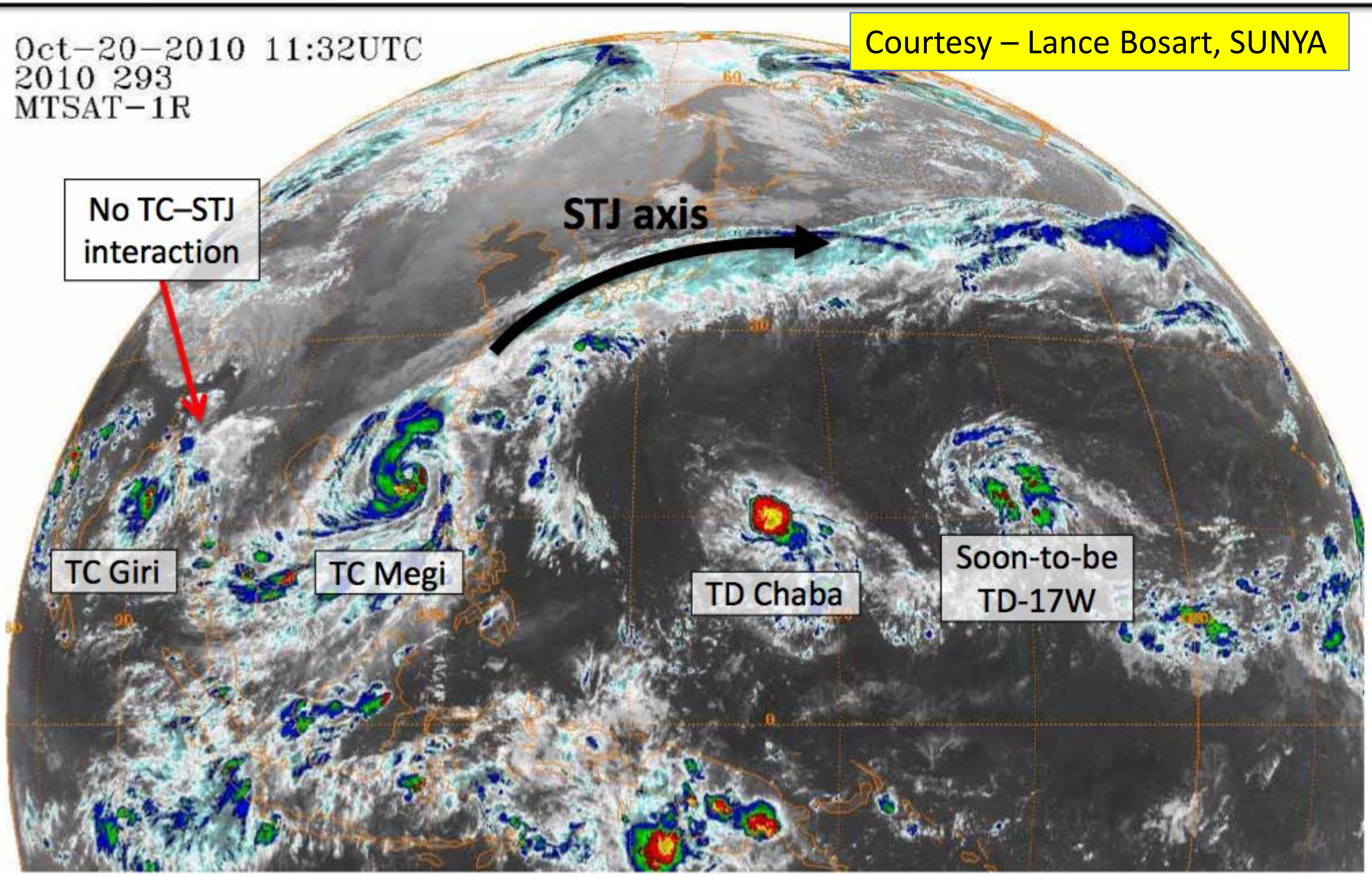
T Tendency from physics (K/6hr)



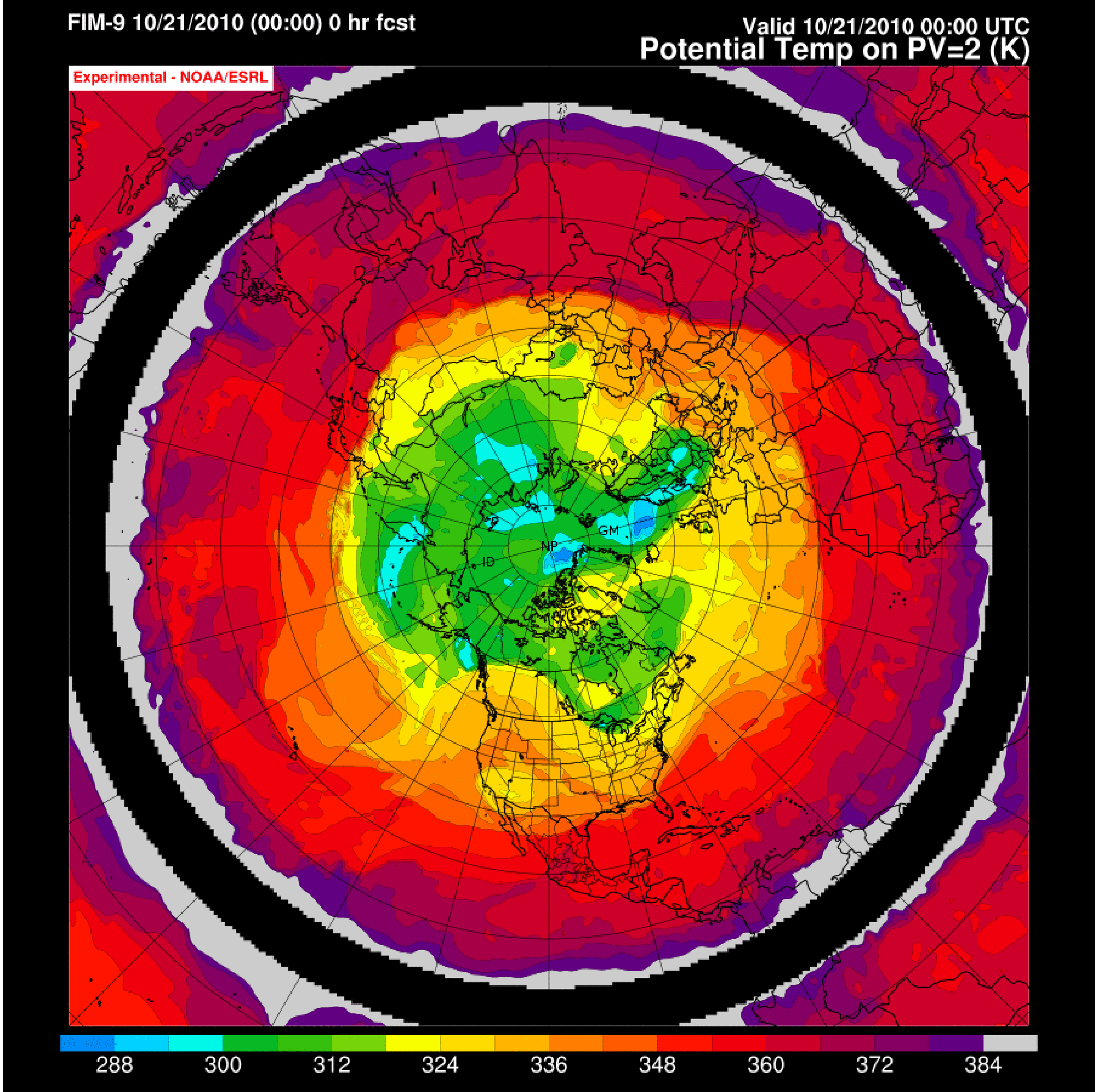


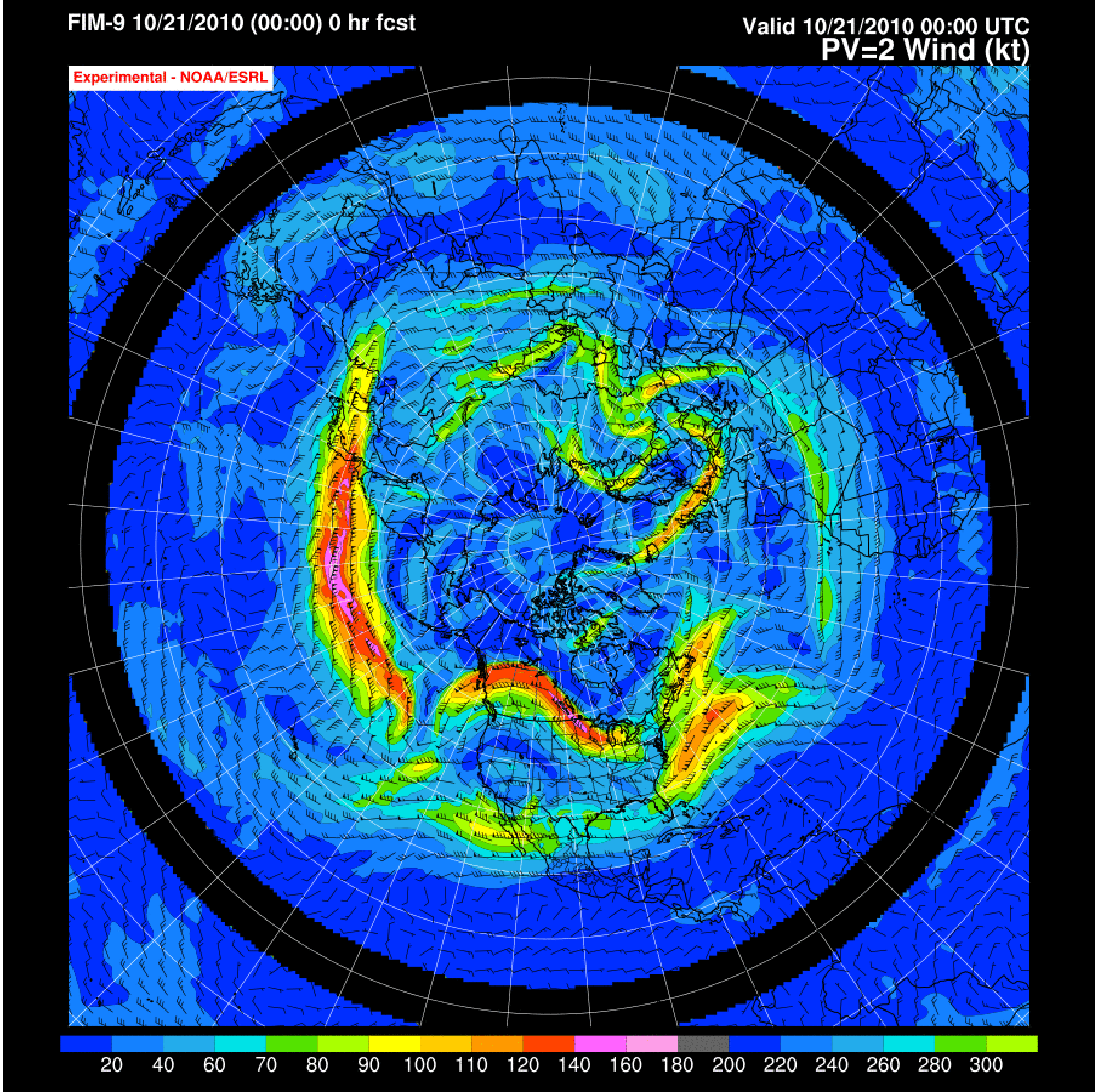
NIM will have 192 layers to resolve thin cloud layers, like western ocean stratus.

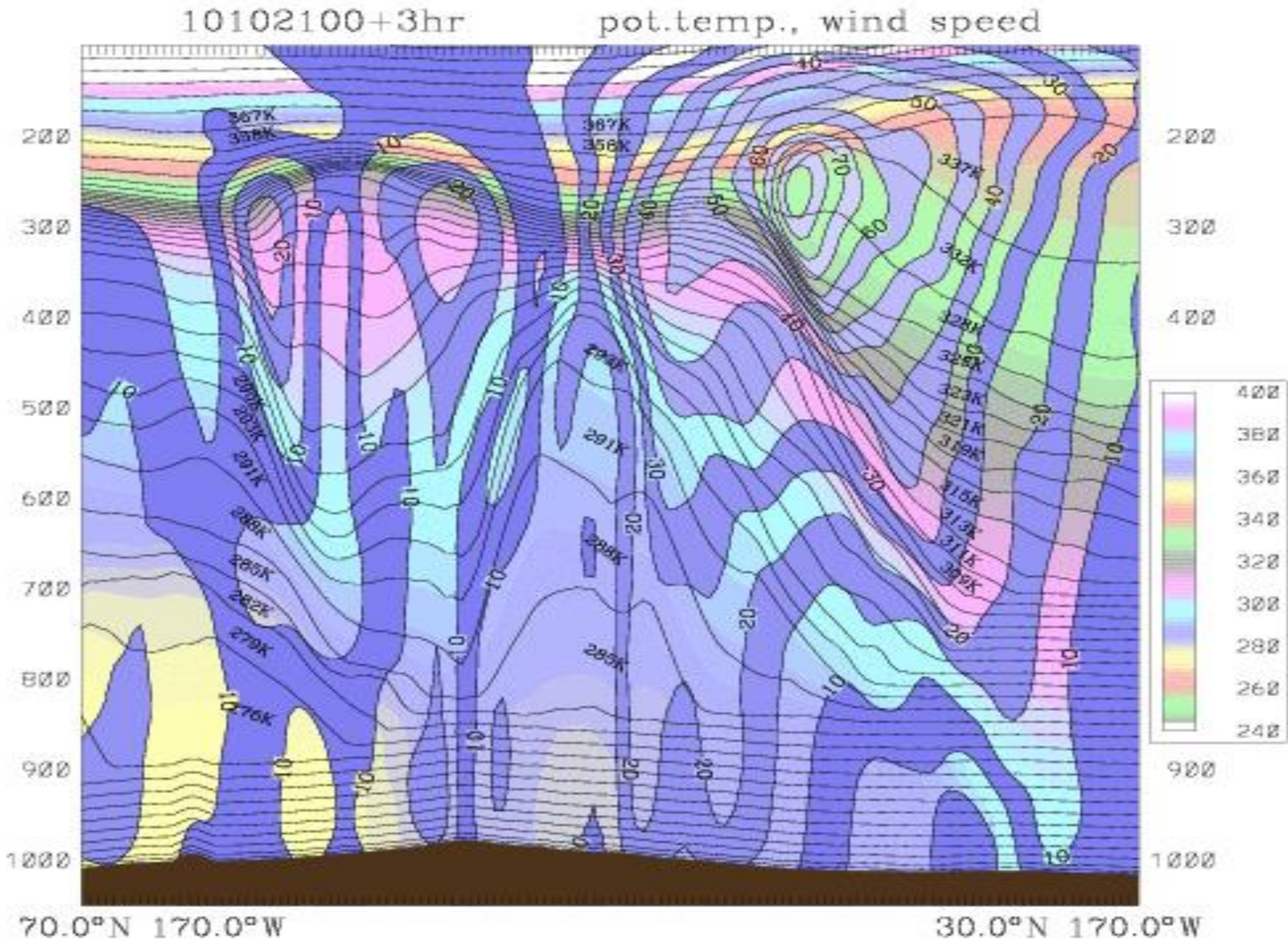
Antecedent conditions: 1200 UTC 20 Oct IR



MTSAT-1R GOES satellite


FIM-9 10/21/2010 (00:00) 0 hr fcst
Valid 10/21/2010 00:00 UTC
Potential Temp on PV=2 (K)
Experimental - NOAA/ESRL
GM
NP
ID
288
300
312
324
336
348
360
372
384

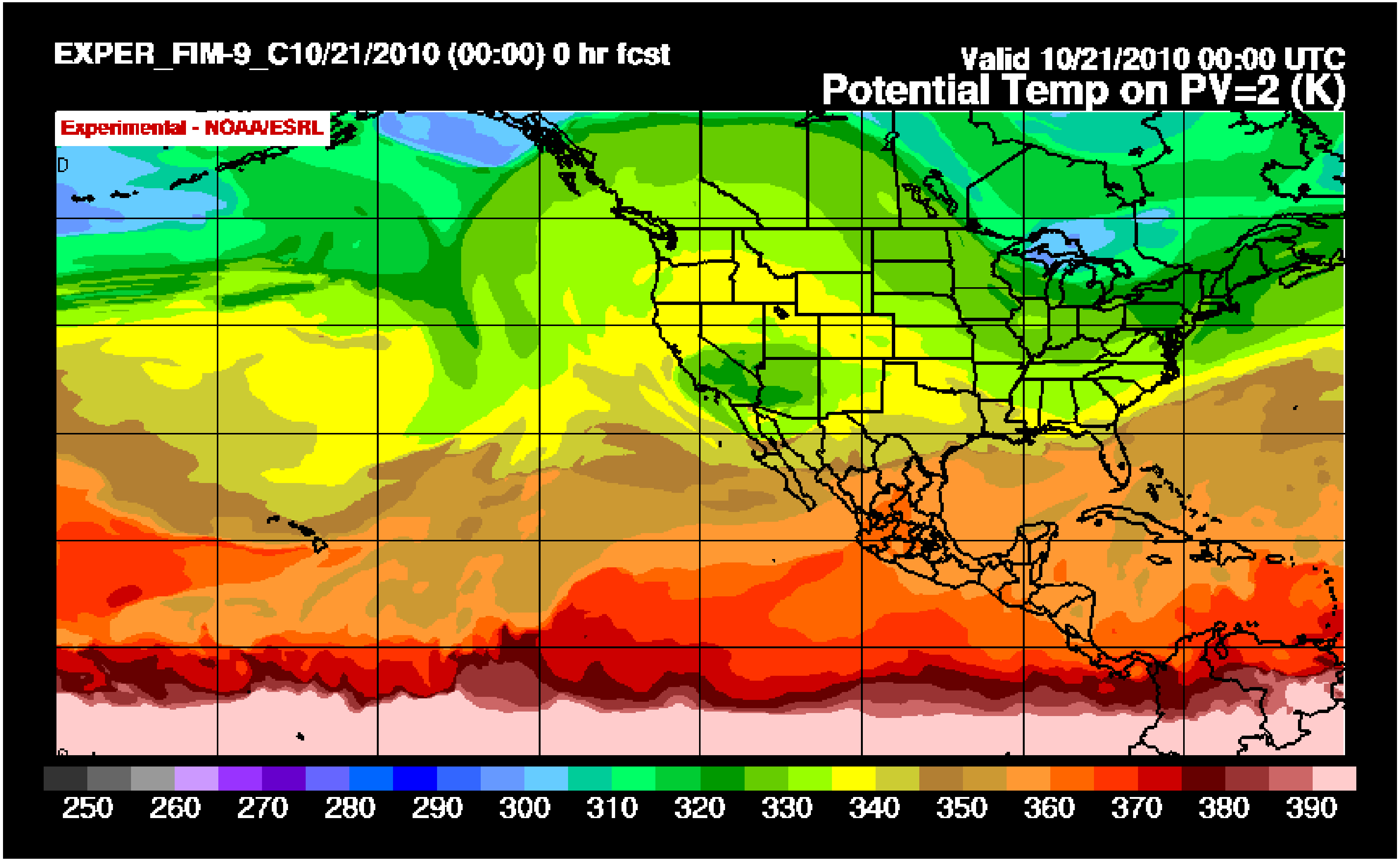

FIM-9 10/21/2010 (00:00) 0 hr fcst
Valid 10/21/2010 00:00 UTC
PV=2 Wind (kt)
Experimental - NOAA/ESRL
20 40 60 70 80 90 100 110 120 140 160 180 200 220 240 260 280 300



fimG9

source: ...jet/FIMRETRO_2010Oct20/FIMrun/fim_9_64_1280_201010210000.5var/fim_C/

21 Oct 2010/00z FIM9 run: loop of Potential Temperature on PV=2 surface.



Comments:

Conclusion: Models get better, and save human lives, because immensely talented people like Don Johnson show us the way forward.

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

Questions . . . .