Future Improvements of Weather and Climate Prediction

Unidata Policy Committee

October 21, 2010

Alexander E. MacDonald, Ph.D.
Deputy Assistant Administrator for Labs
and Cooperative Institutes
& Director, Earth System Research Laboratory
National Oceanic & Atmospheric Administration

Talk Summary

1. Foundations of improvements in prediction.

2. Elements of improving global predictions (both weather and climate).

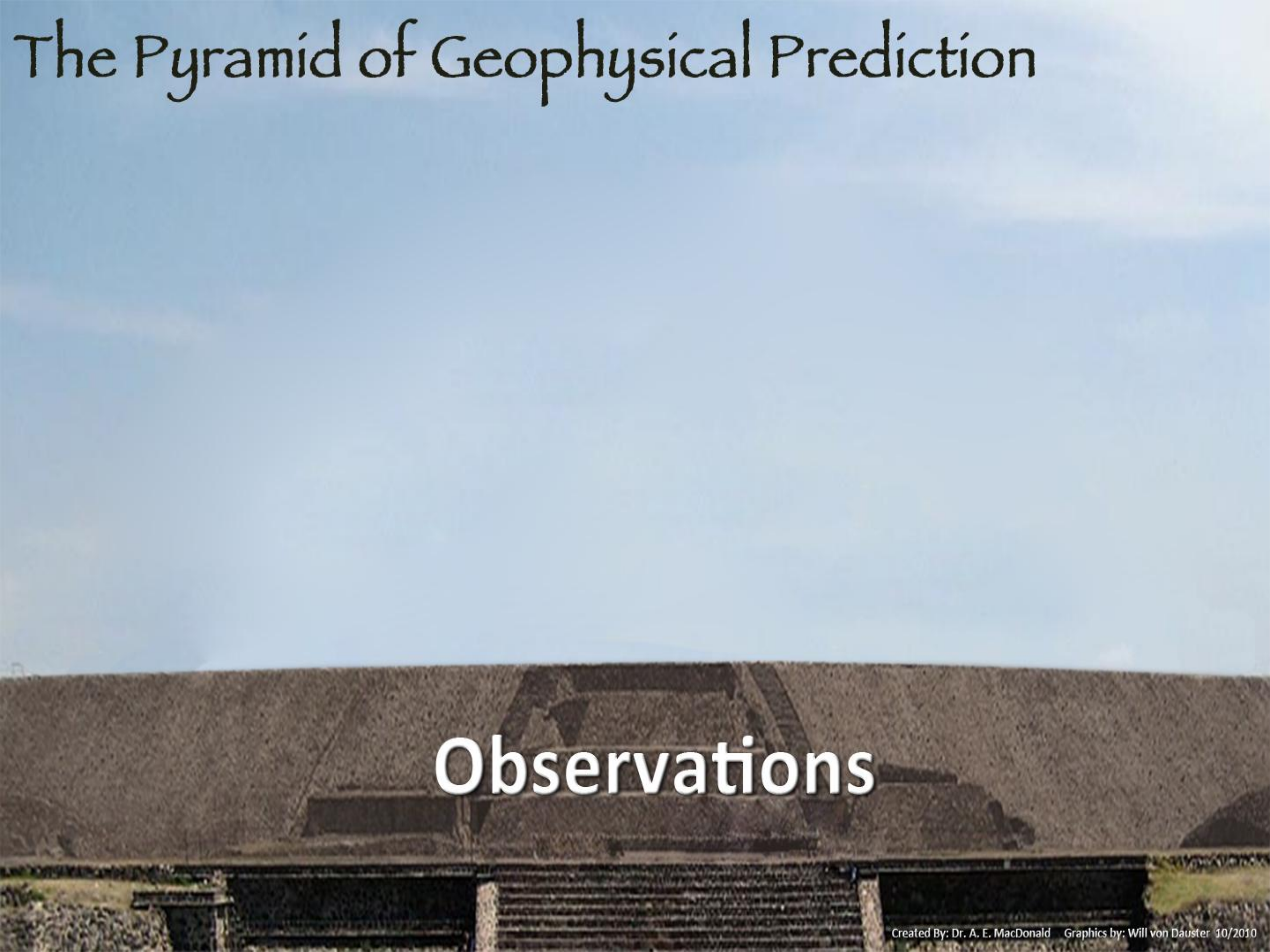
3. Elements of improving regional predictions (mainly weather).

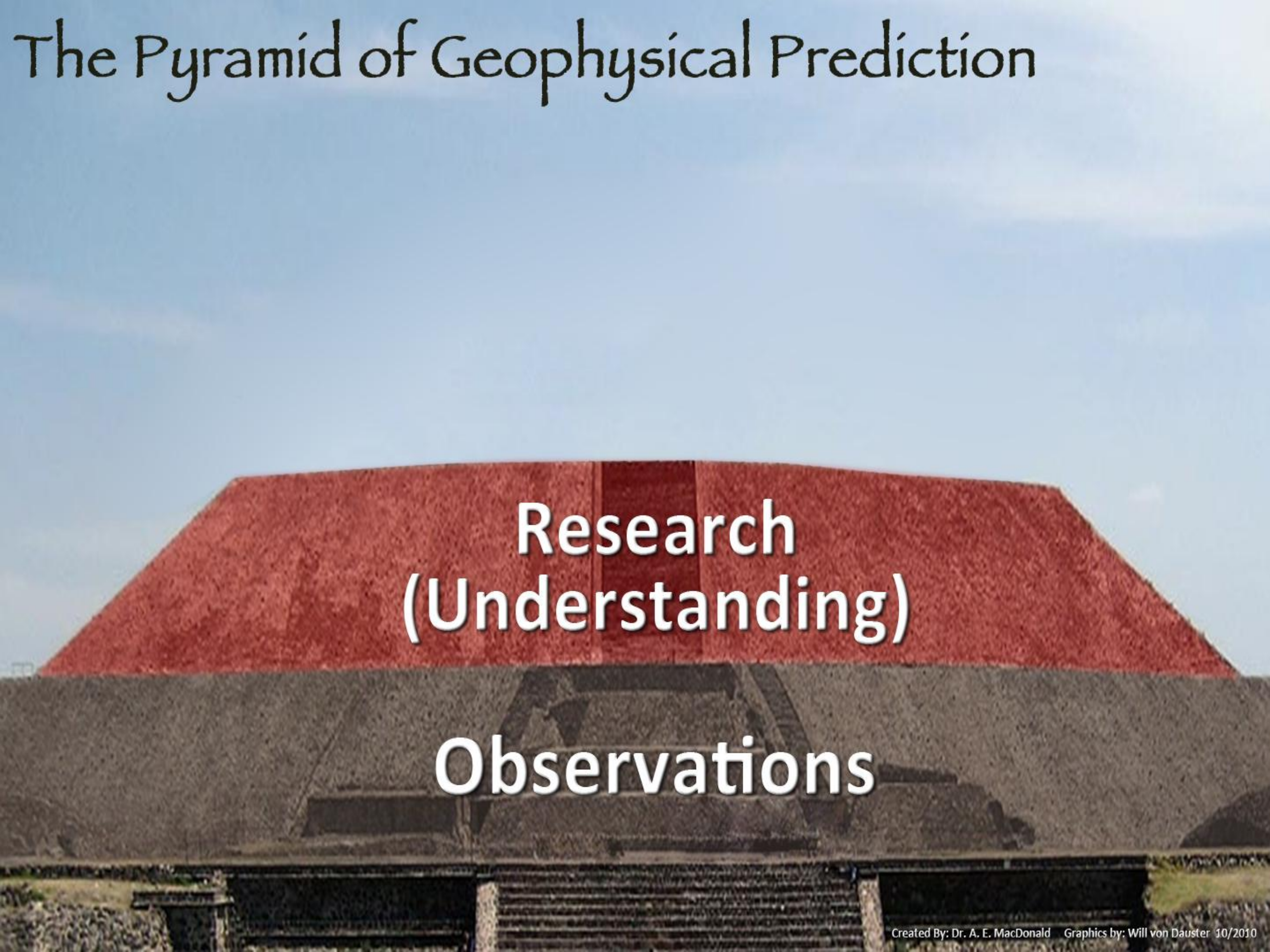
Talk Summary

1. Foundations of improvements in prediction.

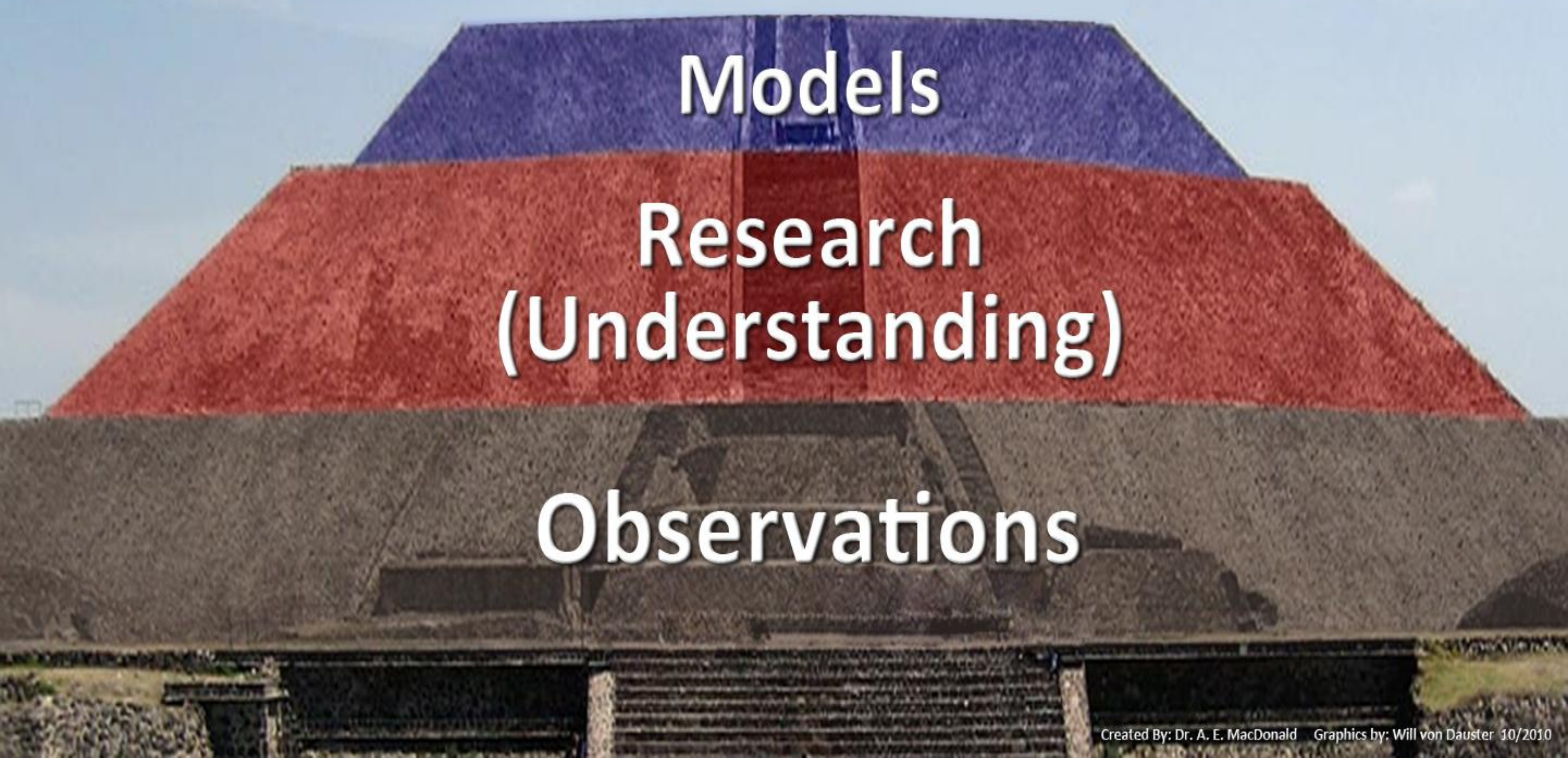
2. Elements of improving global predictions (both weather and climate).

3. Elements of improving regional predictions (mainly weather).

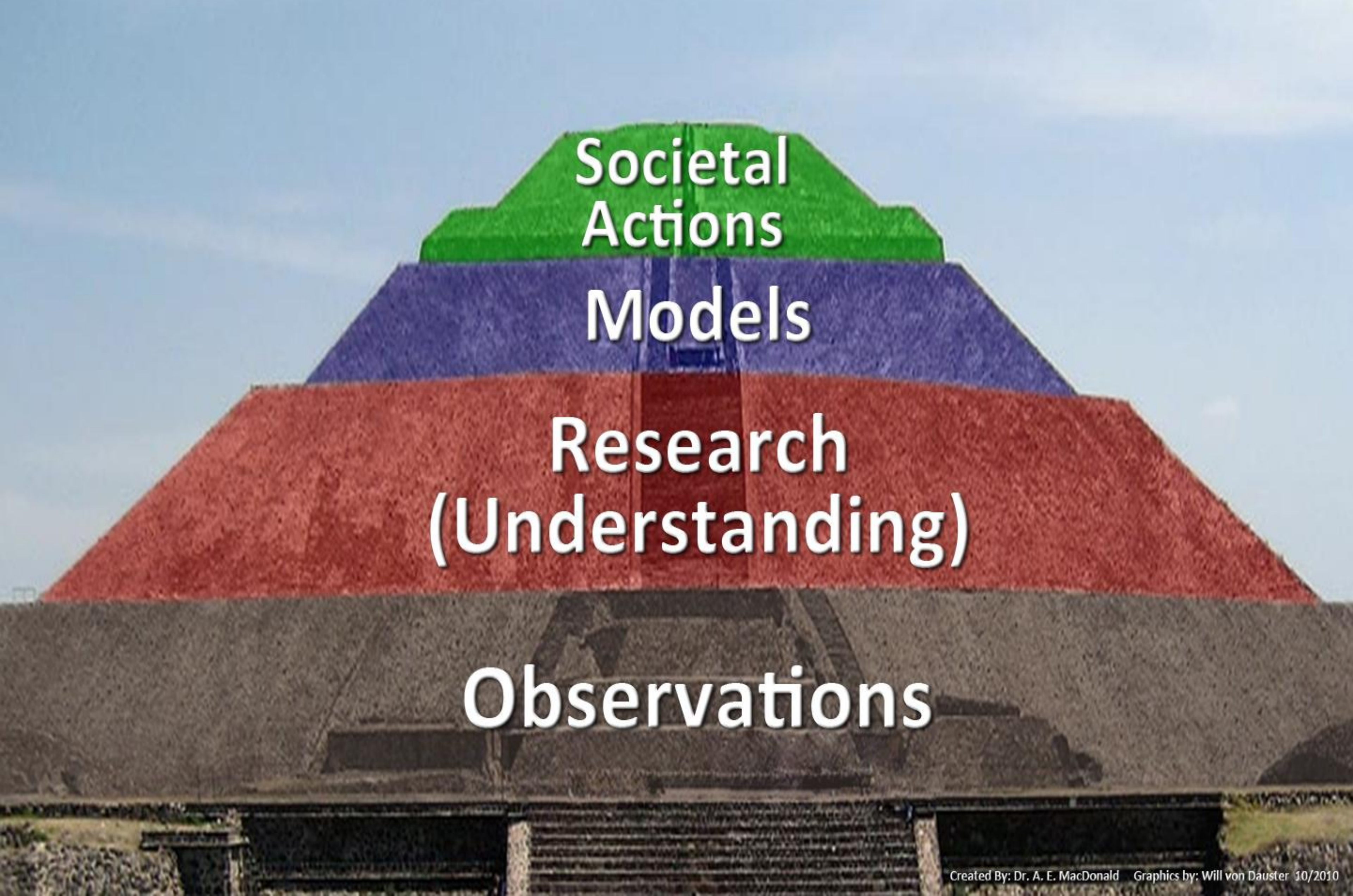

The Pyramid of Geophysical Prediction
Observations
Created By: Dr. A. E. MacDonald Graphics by: Will von Dauster 10/2010


The Pyramid of Geophysical Prediction
Research
(Understanding)
Observations
Created By: Dr. A. E. MacDonald Graphics by: Will von Dauster 10/2010

The Pyramid of Geophysical Prediction



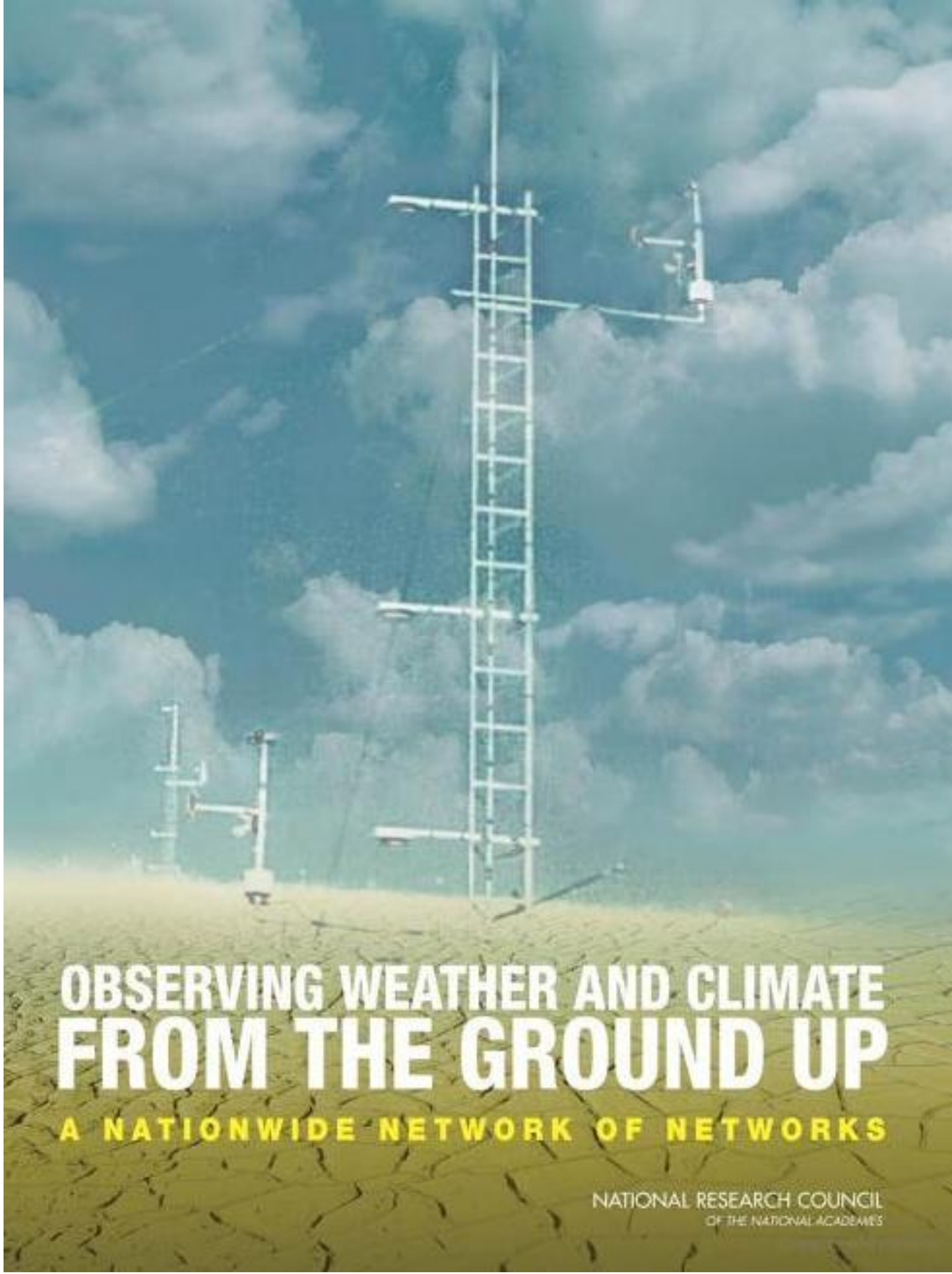
The Pyramid of Geophysical Prediction



A personal opinion:

The US needs a strong program to compare potential observing systems,

And determine which ones are most useful and cost effective.



Earth System Modeling Advances

- Improved numerical formulation of dynamic atmospheric models suitable for resolutions at "cloud permitting scales" globally.
- The ensemble modeling revolution.
- Improved atmospheric assimilation (4DVAR and EnKF).
- Advanced atmospheric physics, with capability of plug compatibility (interoperability).
- Improved ocean observing, assimilation and modeling.
- Advances in computing such as Massively Parallel Fine Grain.

Clouds, according to Professor Bleck:

dx > 4 km:

Cloud Imitating

400 meters < dx < 4 km

Cloud Permitting

dx < 400 meters

Cloud Resolving

The ensemble Kalman Filter (EnKF)

- A method for the initialization of ensemble forecasts that is conceptually appealing for hurricanes
  - "Flow-dependent" background-error covariances may be useful to achieving quality analyses

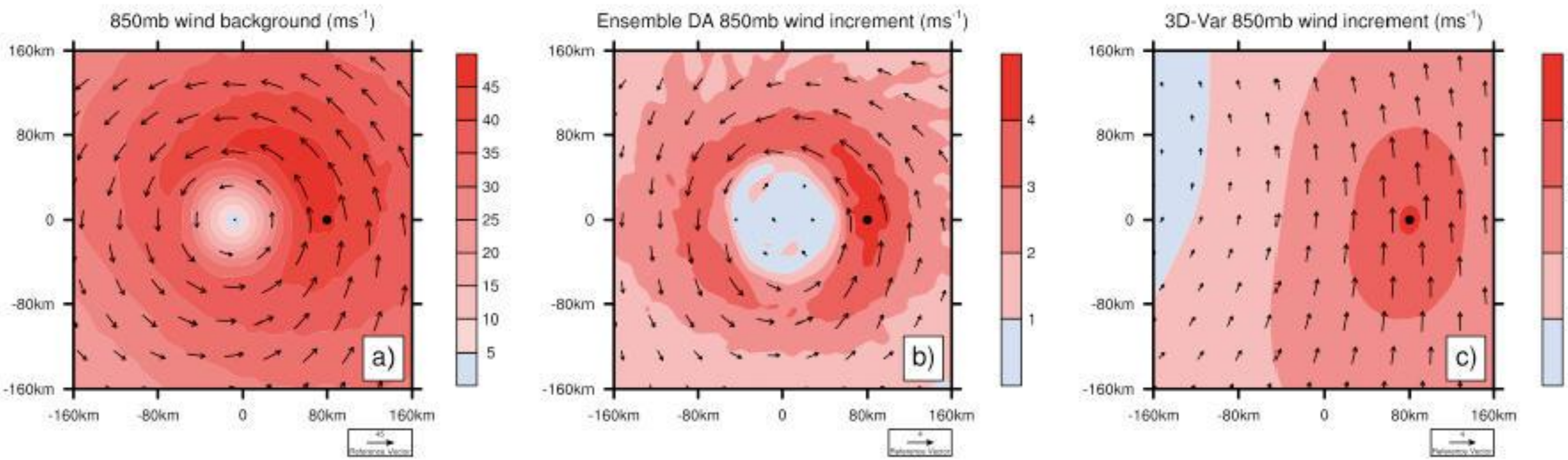
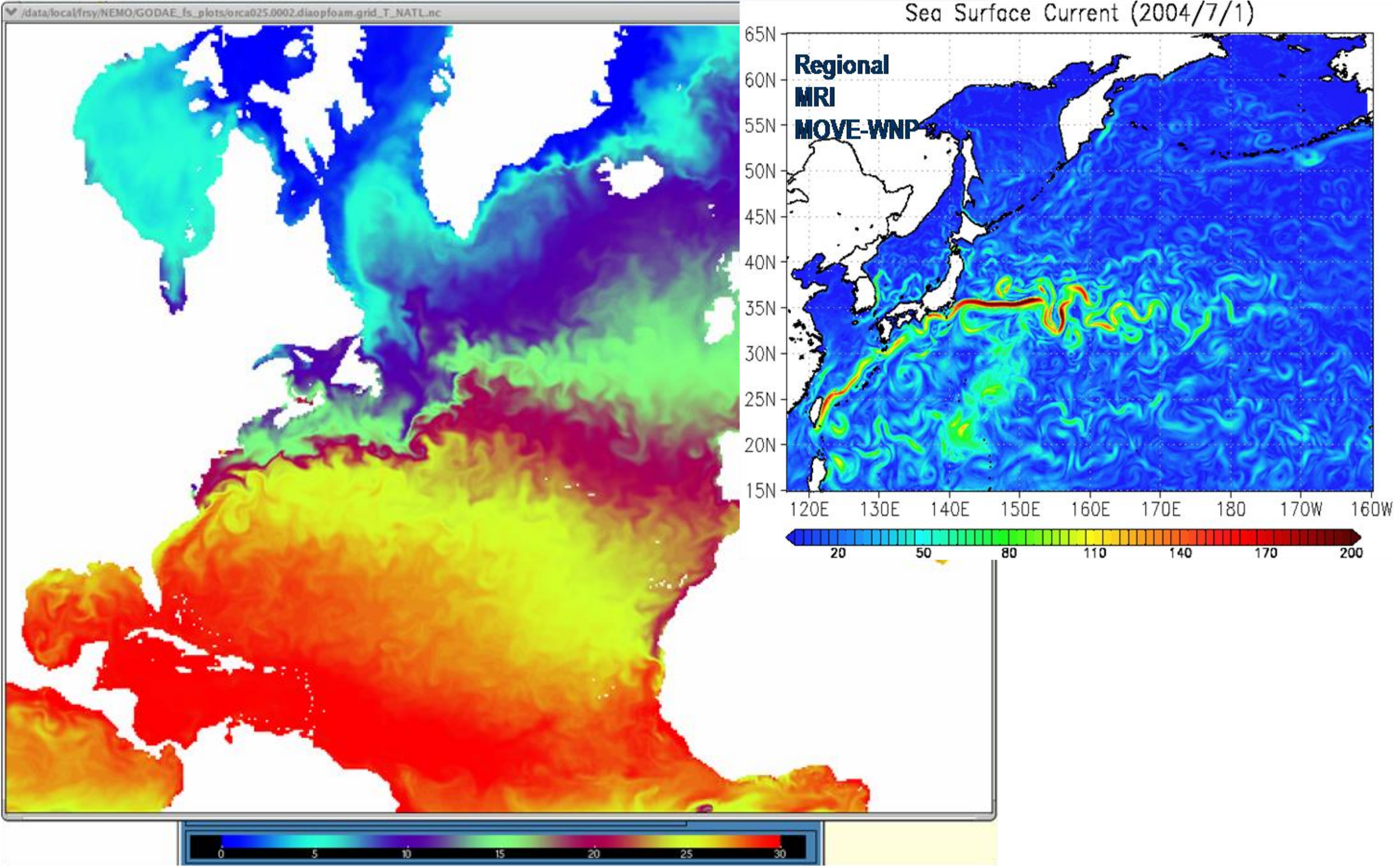


figure c/o Xuguang Wang, University of Oklahoma

Large community effort developing **WRF plug-compatible physics packages**. Example below are new WRF physics:

New Physics Options

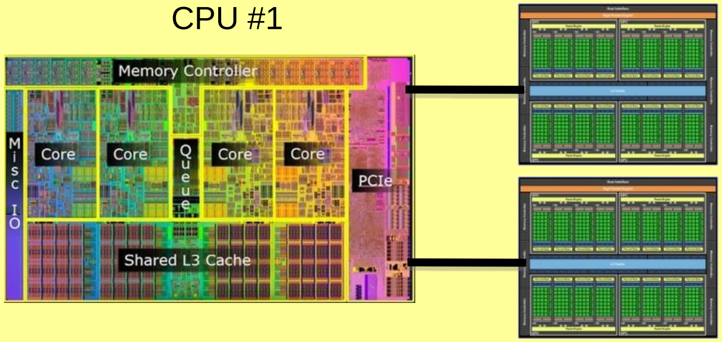
- Goddard microphysics (*mp_physics=7*)
- Morrison 2-moment microphysics (*mp_physics=10*)
- Grell-3 cumulus (*cu_physics=5*, talk 10.2)
- ACM2 PBL and surface layer (Pleim) (*bl_pbl_physics=7*, *sf_sfclay_physics=7*)
- Pleim-Xiu land-surface model (*sf_surface_physics=7*, talk 3.4)



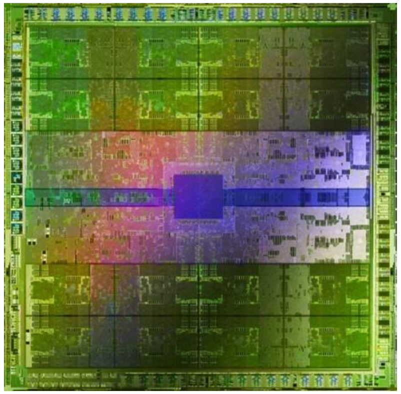
Ocean observing, assimilation and modeling are progressing rapidly.

NVIDIA GPUs

Illustration of two Fermi GPUs attached to a dual-socket Nahalem CPU

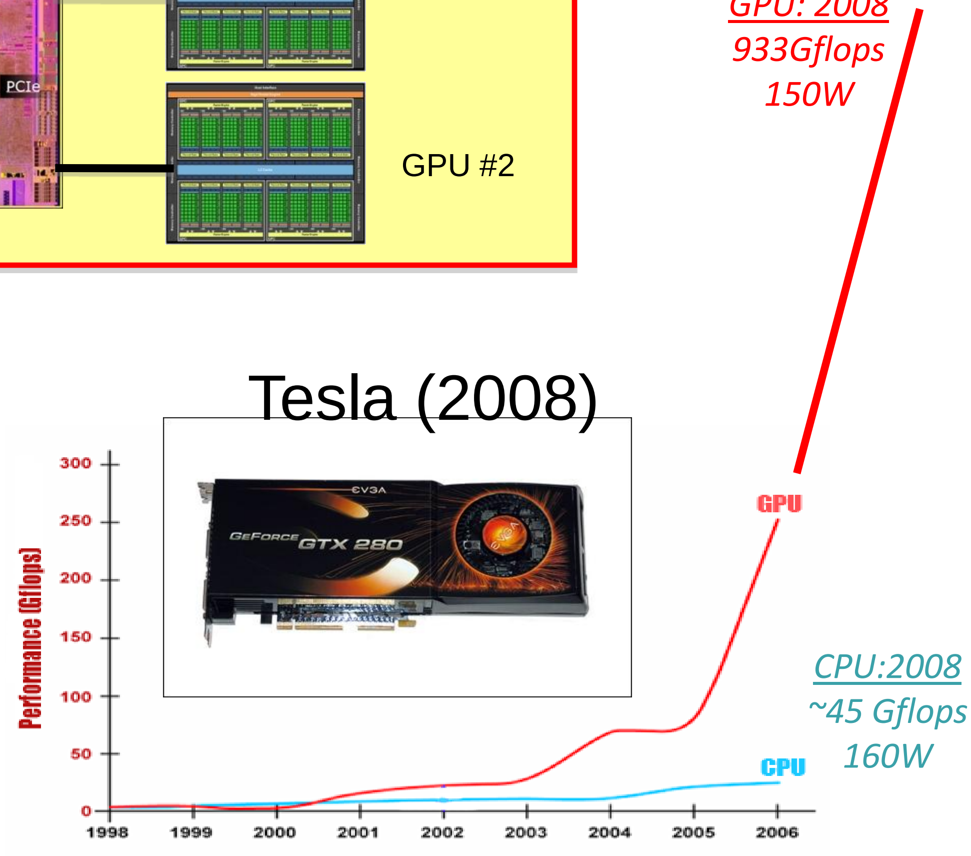


Fermi (2010)



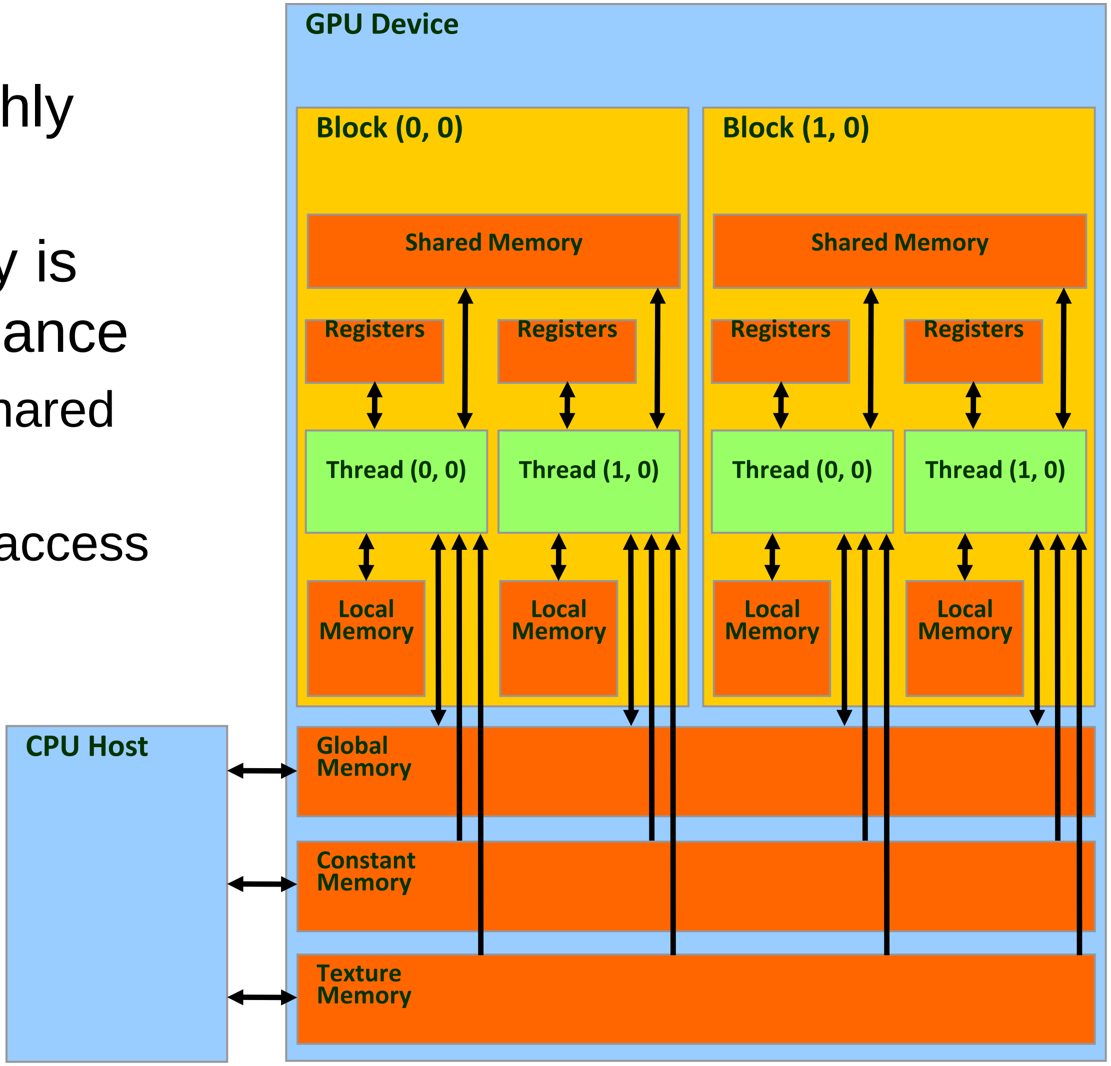
- ✧ 8x increase in double precision
- ✧ 2x increase in memory bandwidth
- ✧ Error correcting memory

Tesla (2008)



GPU Memory Model

- 100x is possible on highly scalable codes
- Efficient use of memory is critical to good performance
  - 1-2 cycles to access shared memory
  - Hundreds of cycles to access global memory

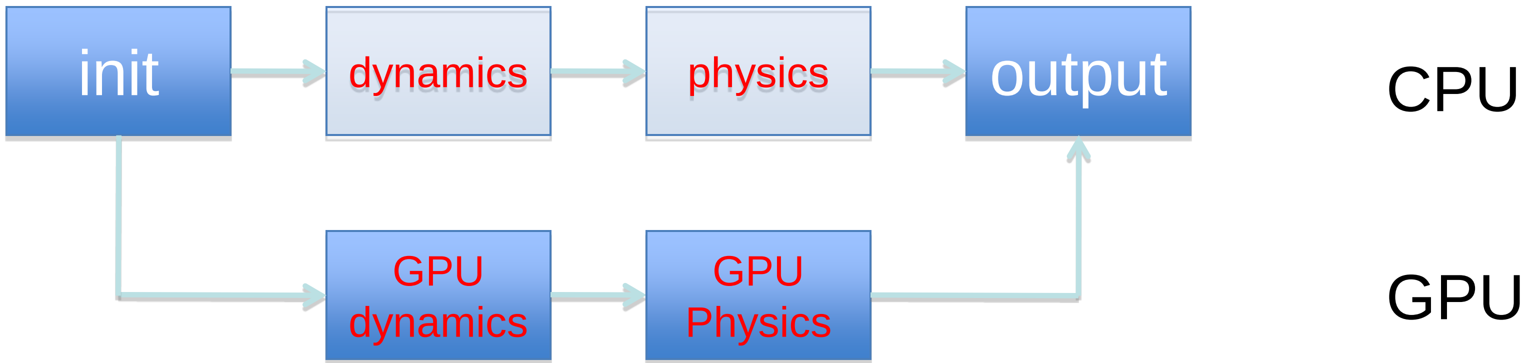


Tesla (2008)

- 16K shared memory
- 16K constant memory
- 2GB global memory

Execution Flow-control

(run mostly on the GPU)



- Eliminates copy every model time step
- CPU-GPU copy only needed for input and output

Talk Summary

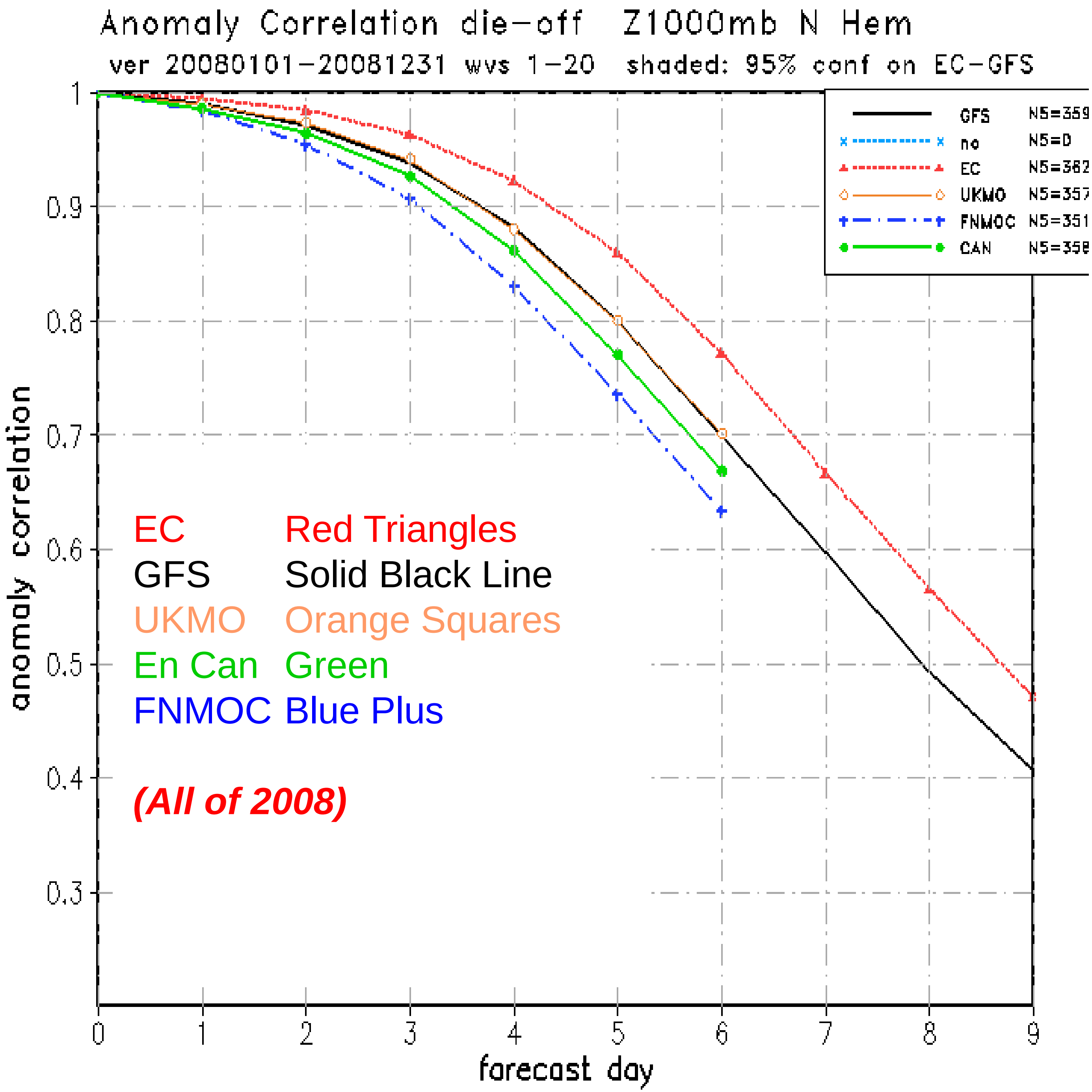
1. Foundations of improvements in prediction.

2. Elements of improving global predictions (both weather and climate).

3. Elements of improving regional predictions (mainly weather).

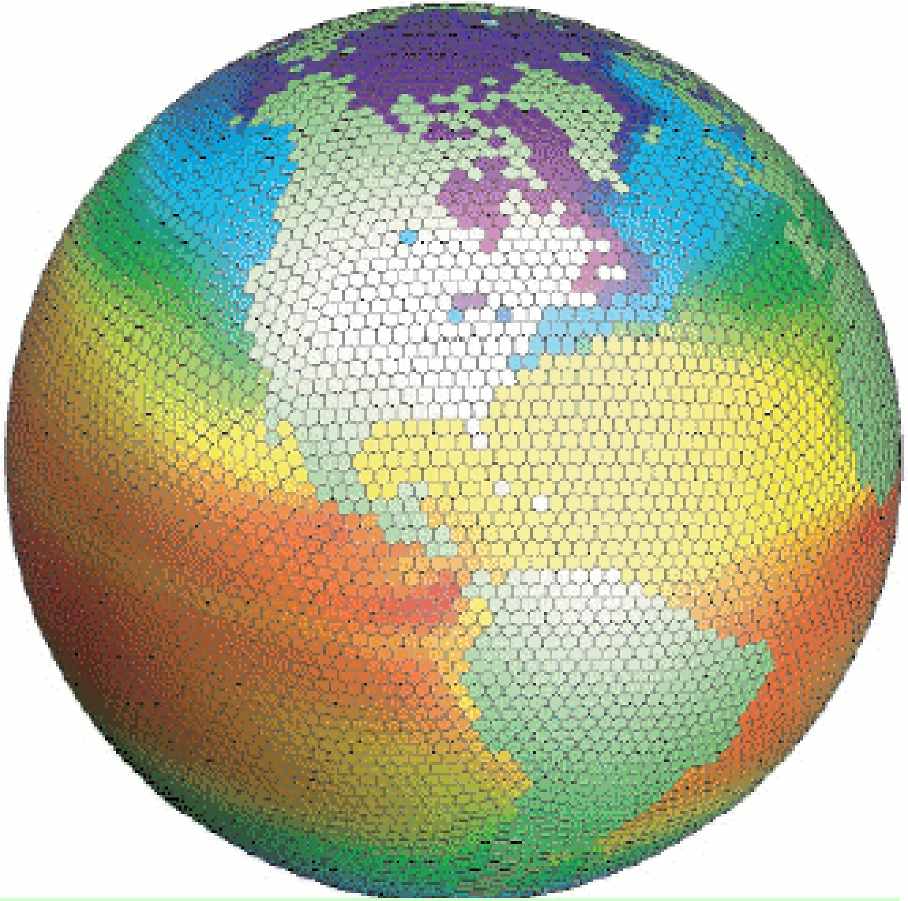
Anomaly Correlation:

A limited measure of global model skill.



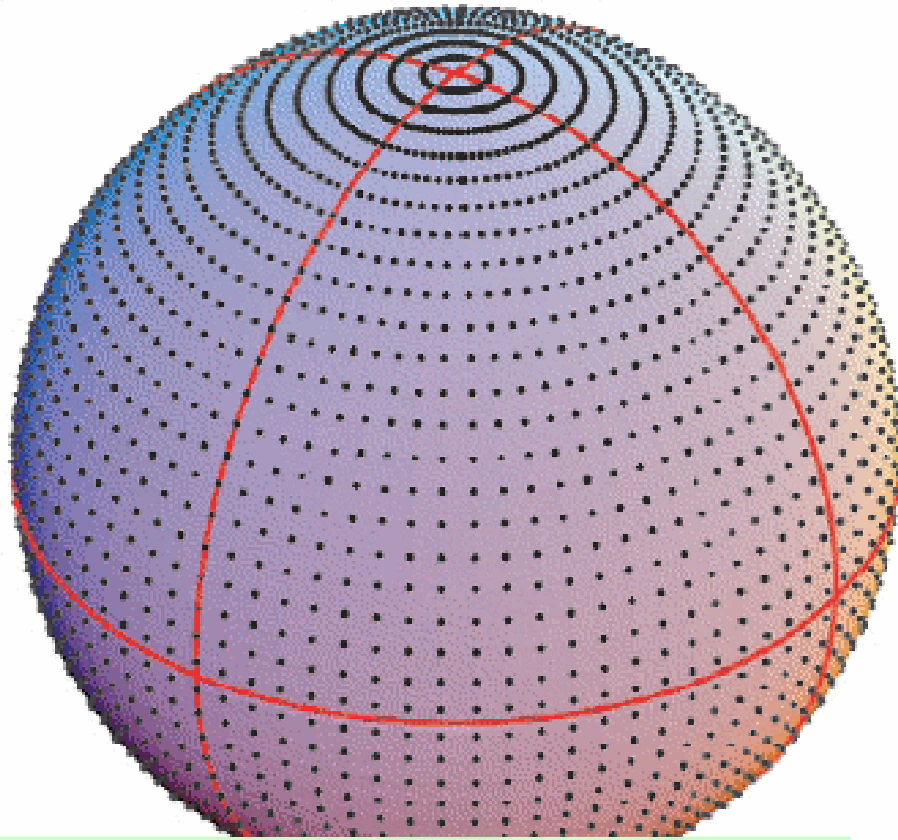
Global discretization for models

Icosahedral grid

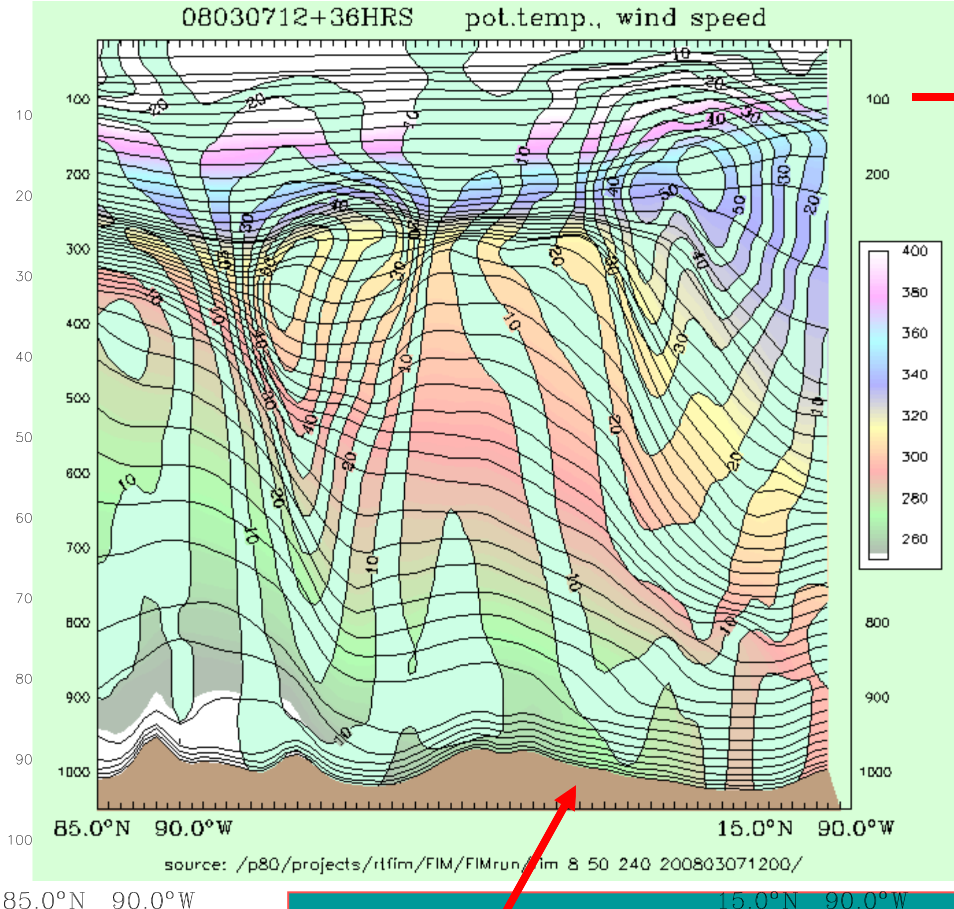


Nearly equal size of grid volumes, including near poles

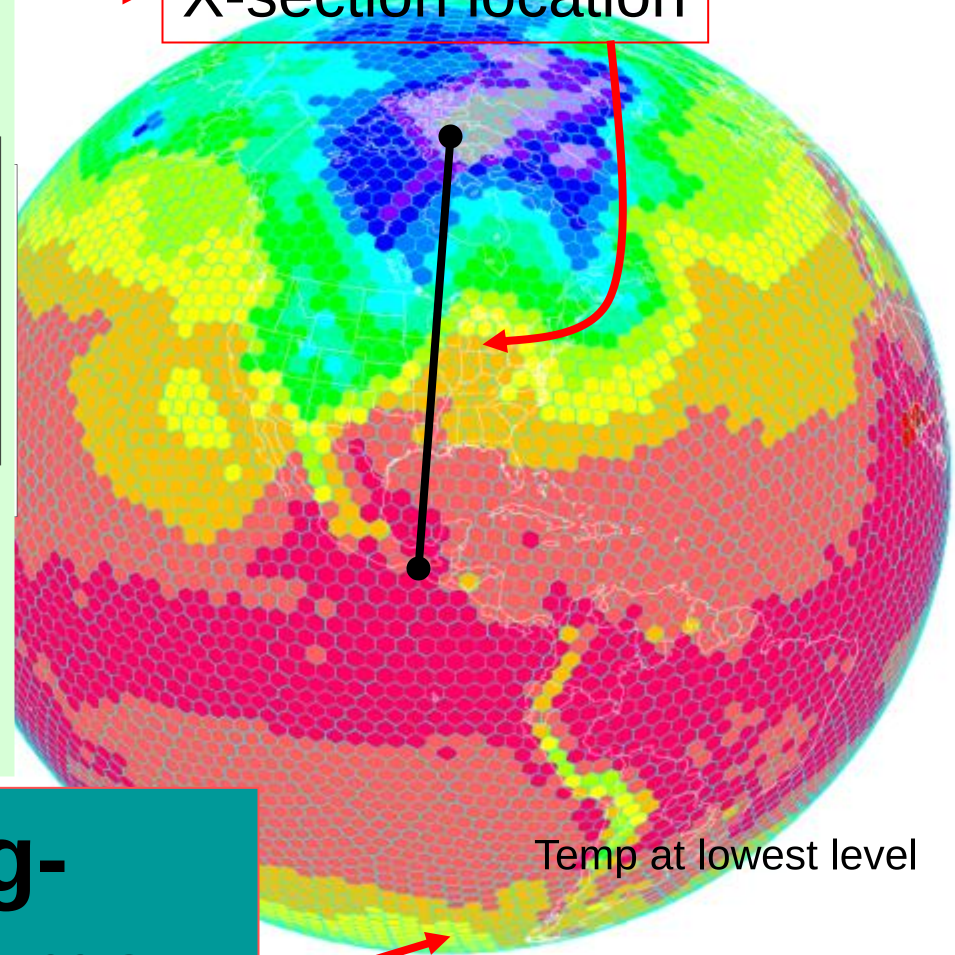
Lat-lon representation
- Basis for GFS, ECMWF, others



- Singularities near poles
- Requires extra diffusion, longer time steps



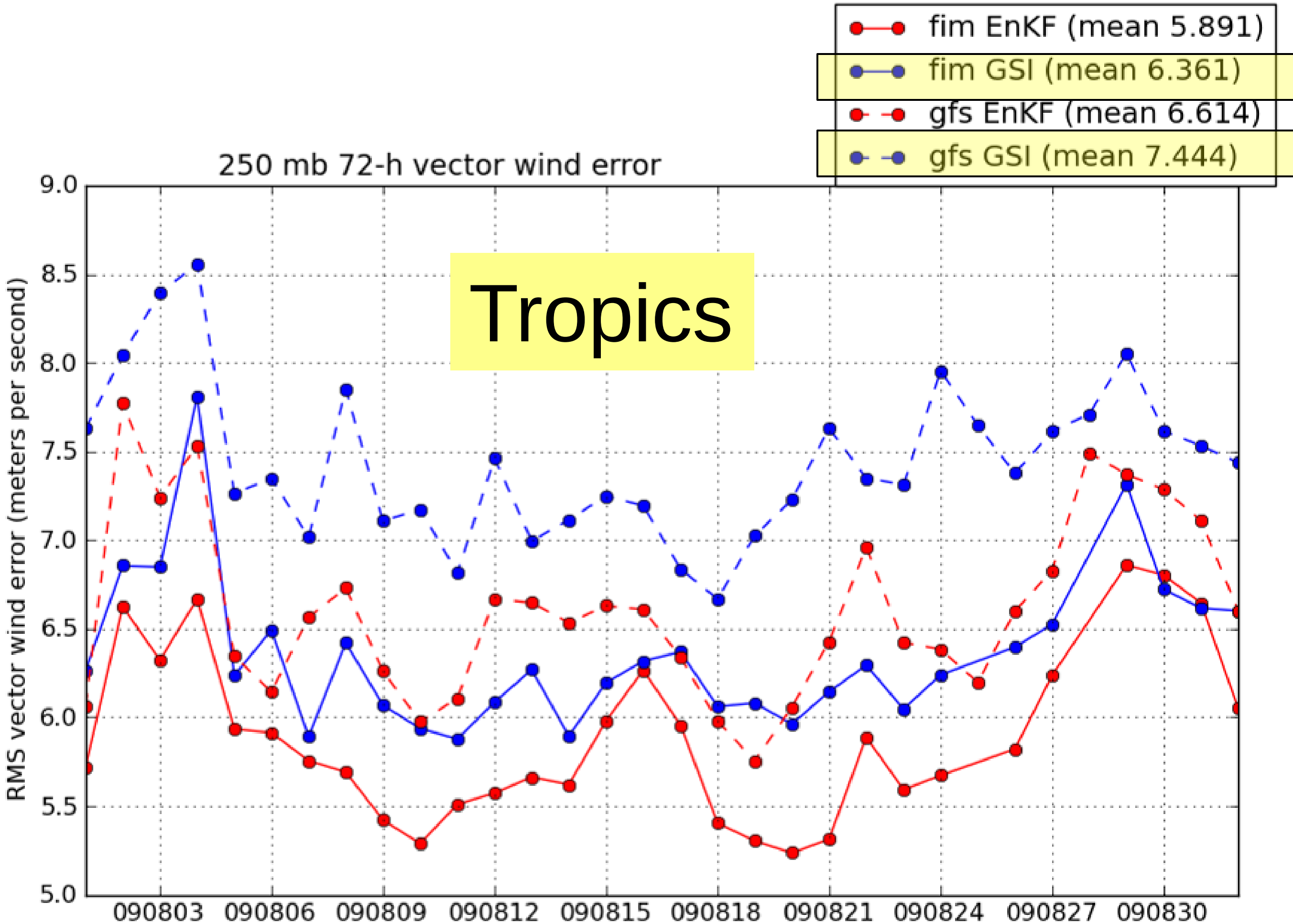
X-section location



Temp at lowest level

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

72-h 250-hPa Wind RMS vector error (vs. analyses) smaller is better Aug 09



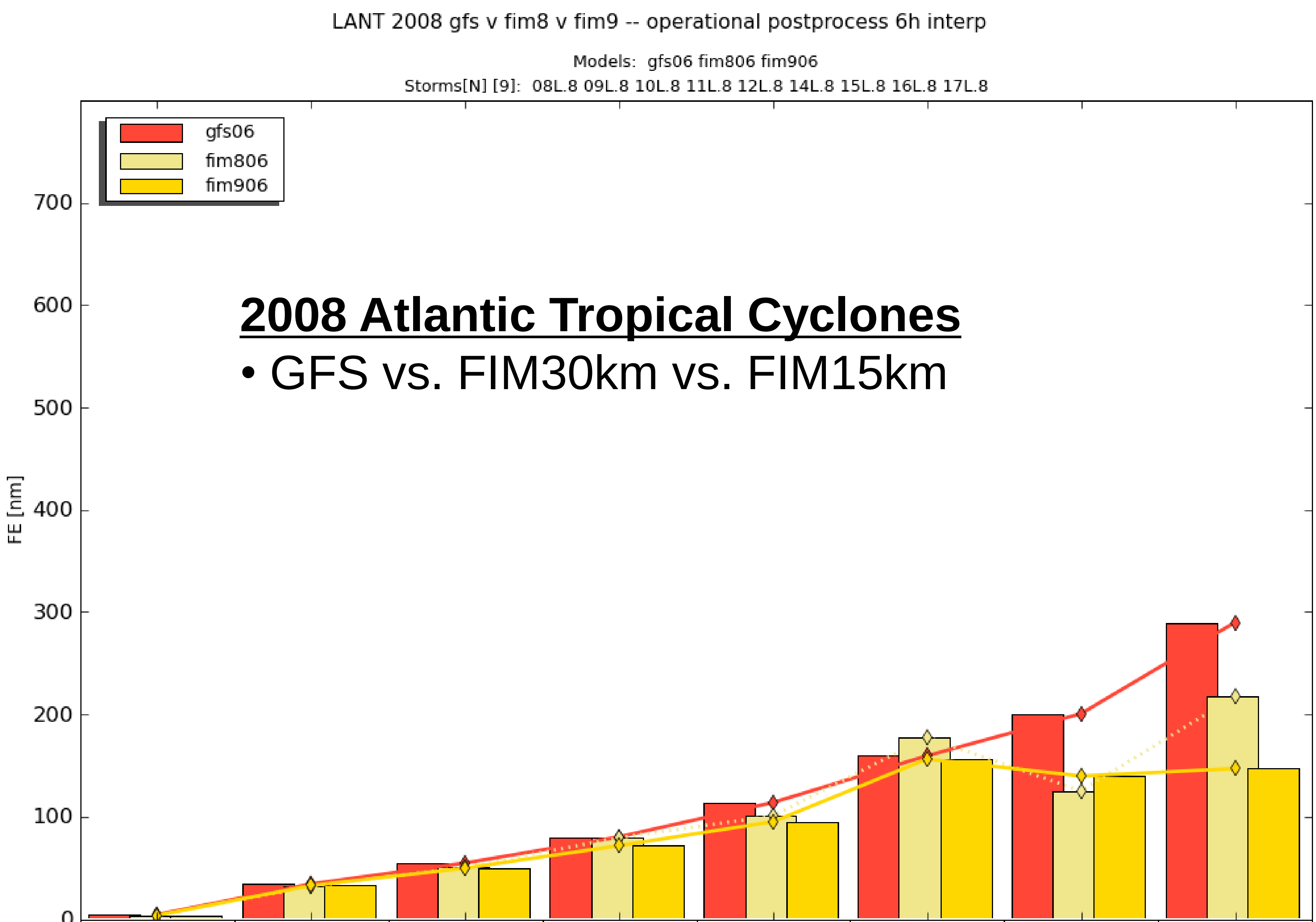
FIM –
GFS -

	Tropics- m/s
FIM	6.36
GFS	7.44

FIM much better than GFS, EnKF IC adds further accuracy

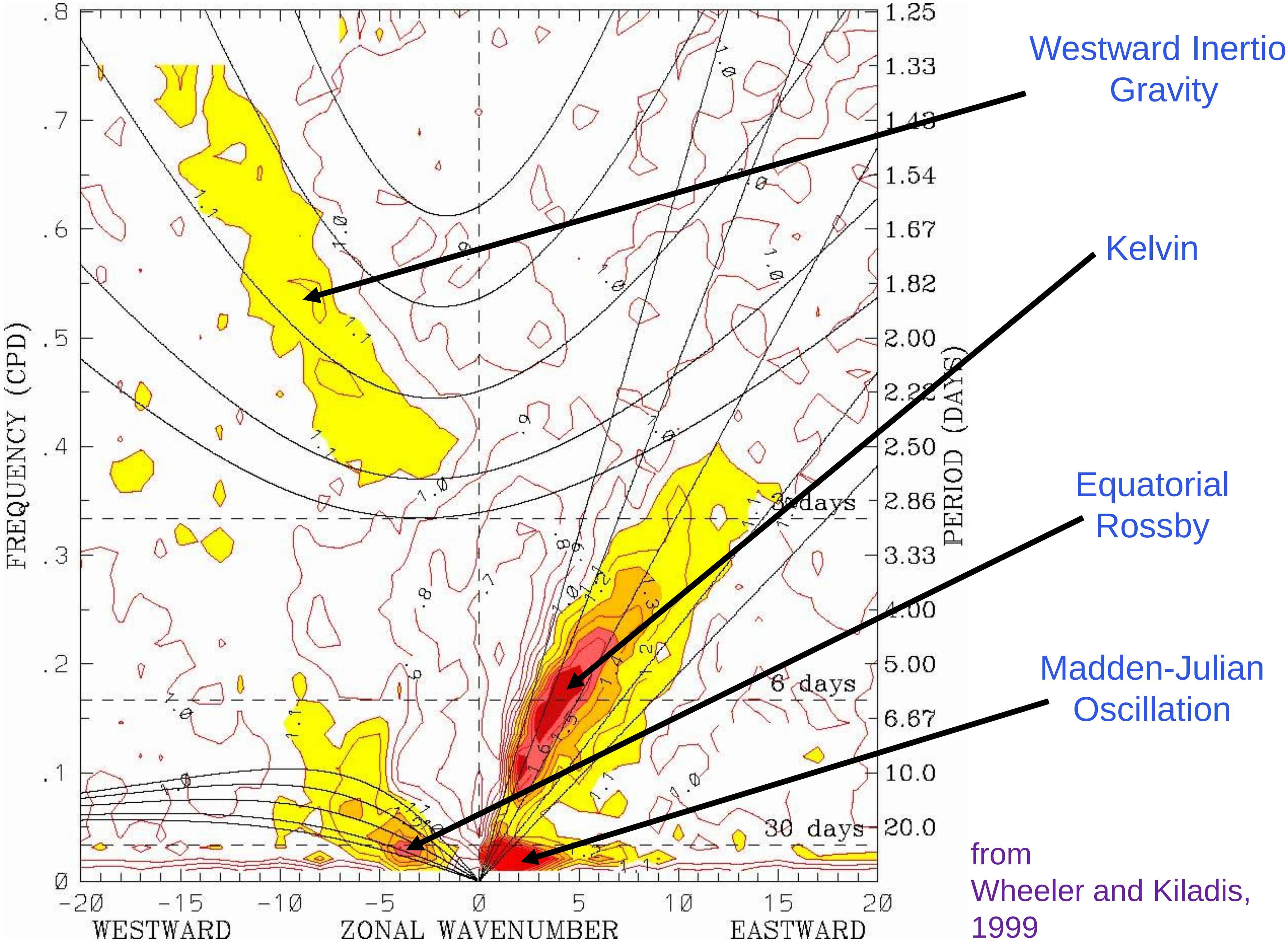
2008 Atlantic Tropical Cyclones

• GFS vs. FIM30km vs. FIM15km



	0h	12h	24h	36h	48h	72h	96h	120h
gfs06	4[19]	34[17]	55[13]	80[12]	114[11]	159[8]	201[6]	290[5]
fim806	4[18]	32[17]	51[13]	79[12]	101[11]	177[8]	125[6]	217[5]
fim906	4[18]	33[17]	50[13]	72[12]	95[11]	156[8]	140[6]	147[5]

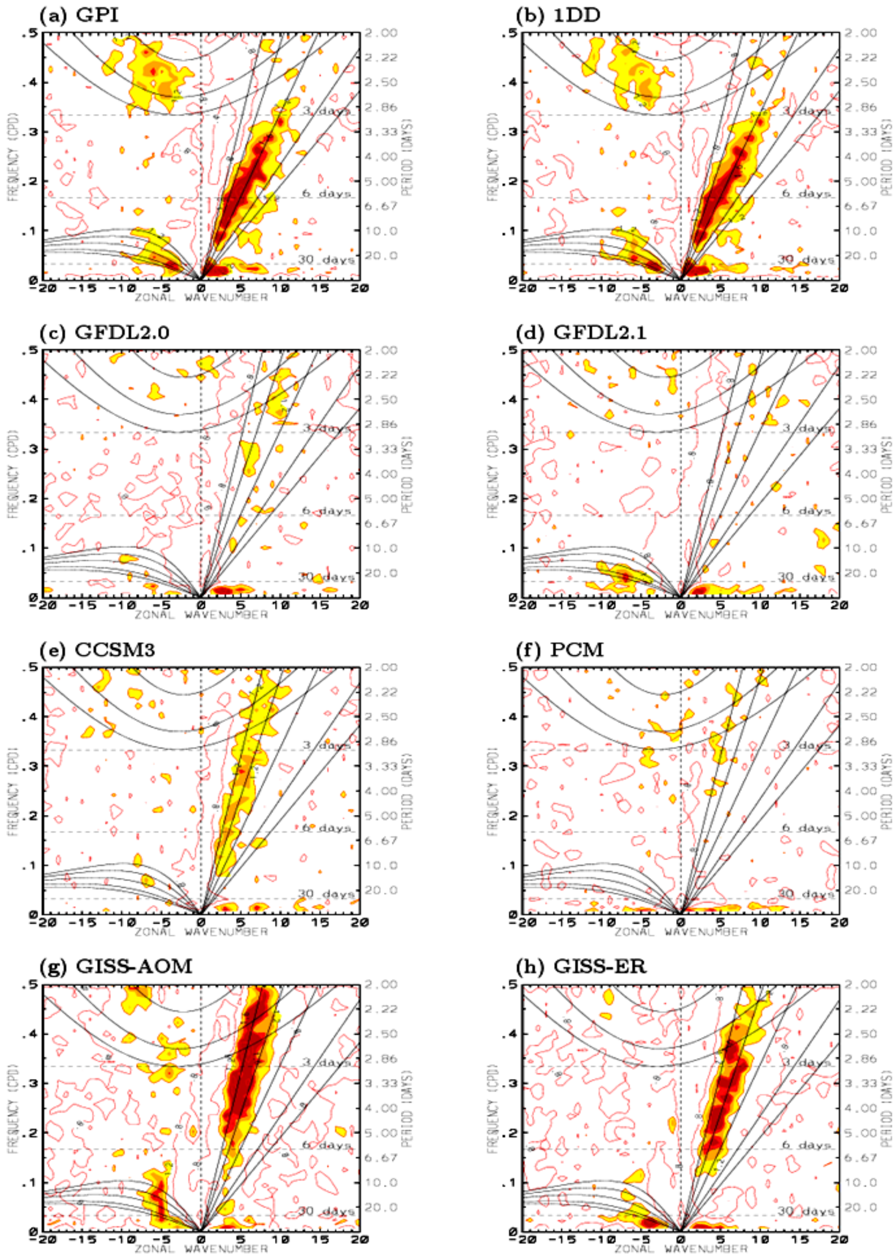
OLR total/background power spectrum, 15ºS-15ºN, 1983–2005 (Symmetric)



from Wheeler and Kiladis, 1999

Rainfall Spectra/Backgr, IPCC AR4 Intercomparison 15S-15N, (Symmetric)

Observations →

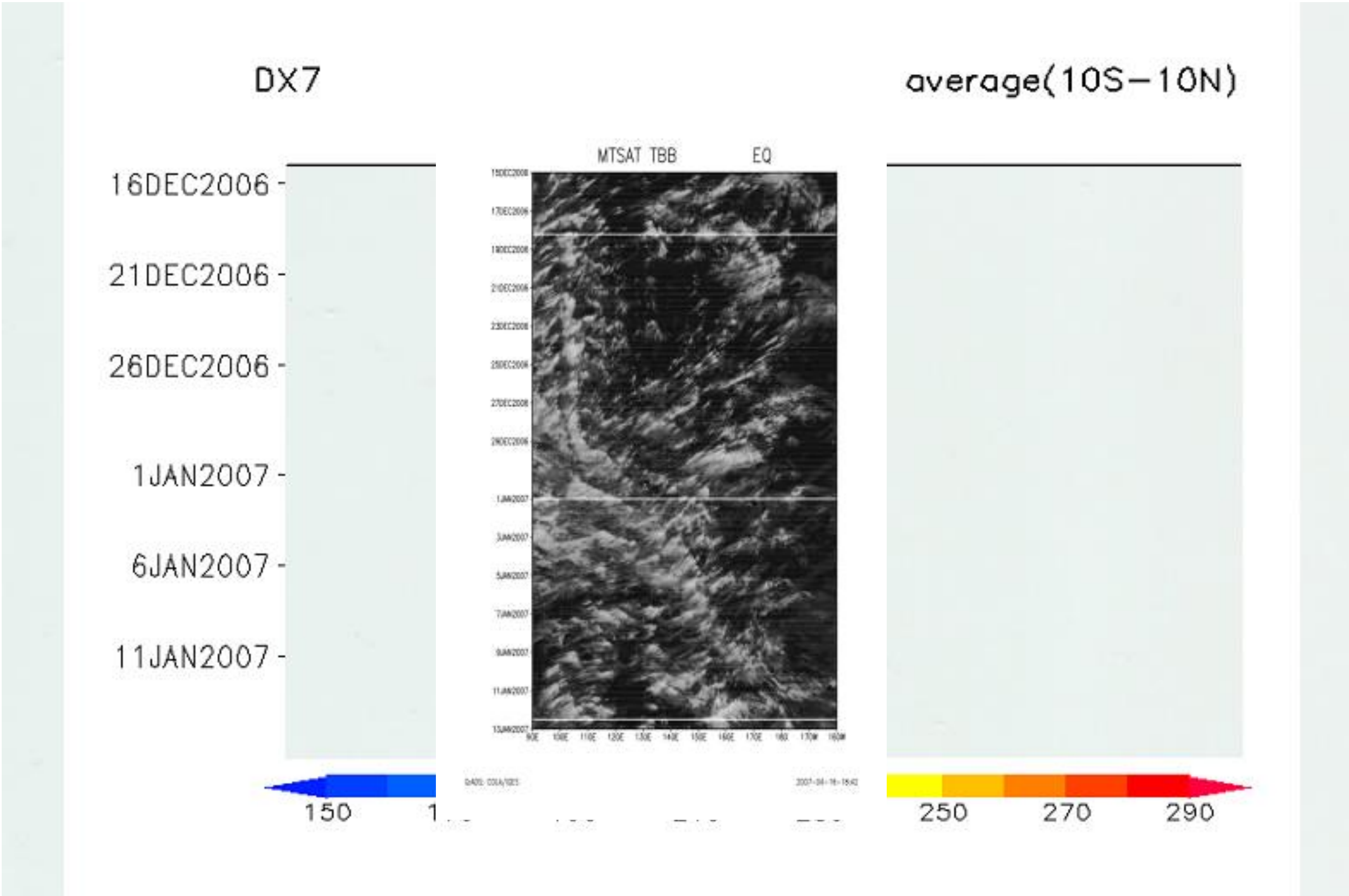


from Lin et al., 2006

OLR Hovmoller showing MJO simulation

NICAM dx=3.5 km

(Non-hydrostatic ICosahedral Atmospheric Model)

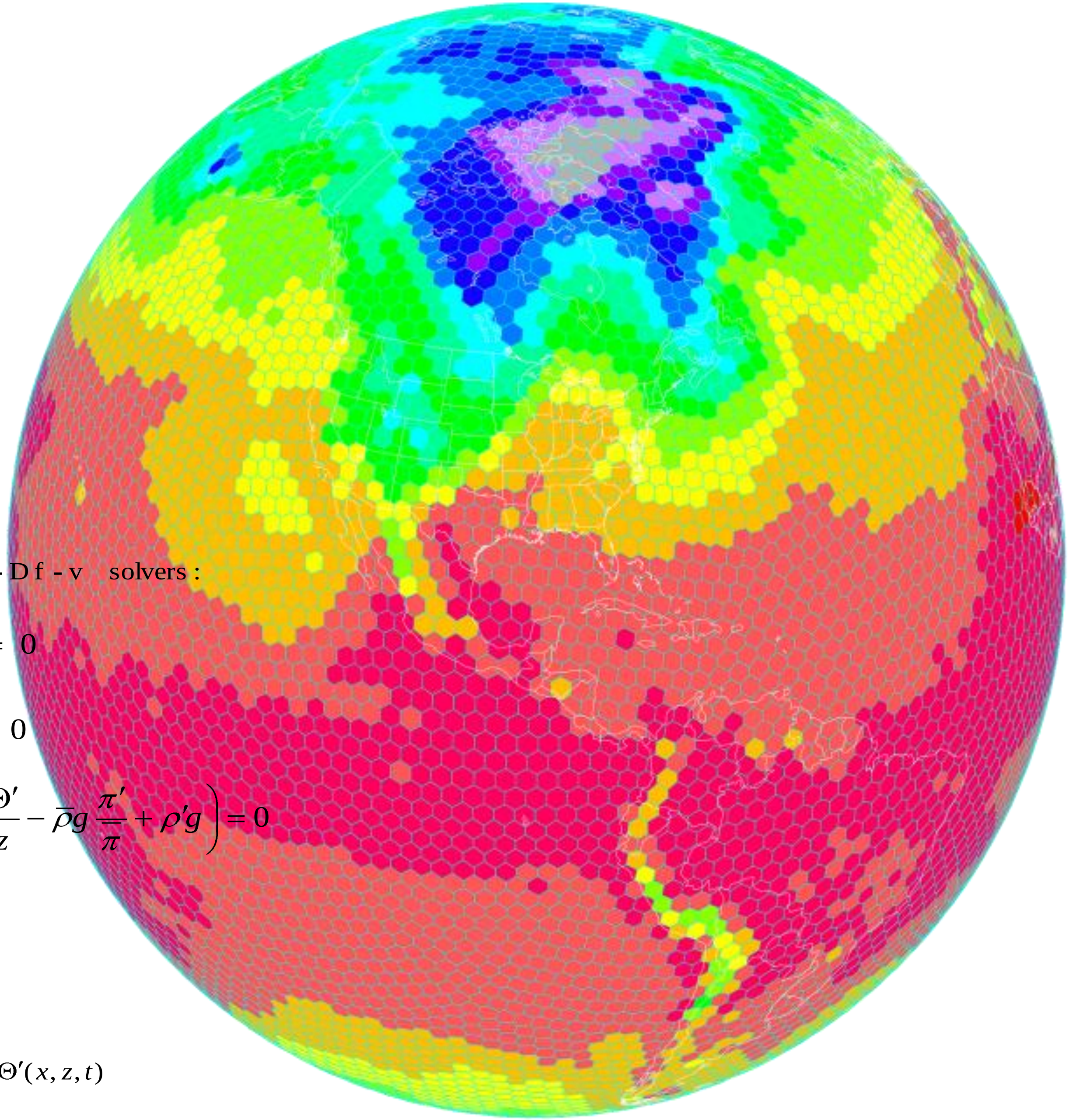


Courtesy of Prof. Satoh *(Science, Dec. 7, 2007)*

Nonhydrostatic Icosahedral Model

Jin-Luen Lee

Alexander E. MacDonald



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

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

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

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

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

ESRL Research Efforts

- Next Generation Weather Models are driving computing requirements
  - NIM Model development (Lee, MacDonald)
- Purchased 16 node NVIDIA Tesla system in 2008 (~31Tflops)
- Developed Fortran to CUDA compiler
- Parallelized NIM model dynamics

2011: GPU 4 KM NIM 1 Day Forecast Projected

Processors	Points per Processor	Time (hours)	Percent of Real Time
1280	32768	1.87	7.8%
2560	16384	.99	4.1%
5120	8192	.56	2.3%
10240	4096	.33	1.3%
20480	2048	.20	.8%
40960	1024	.15	.6%

Talk Summary

1. Foundations of improvements in prediction.

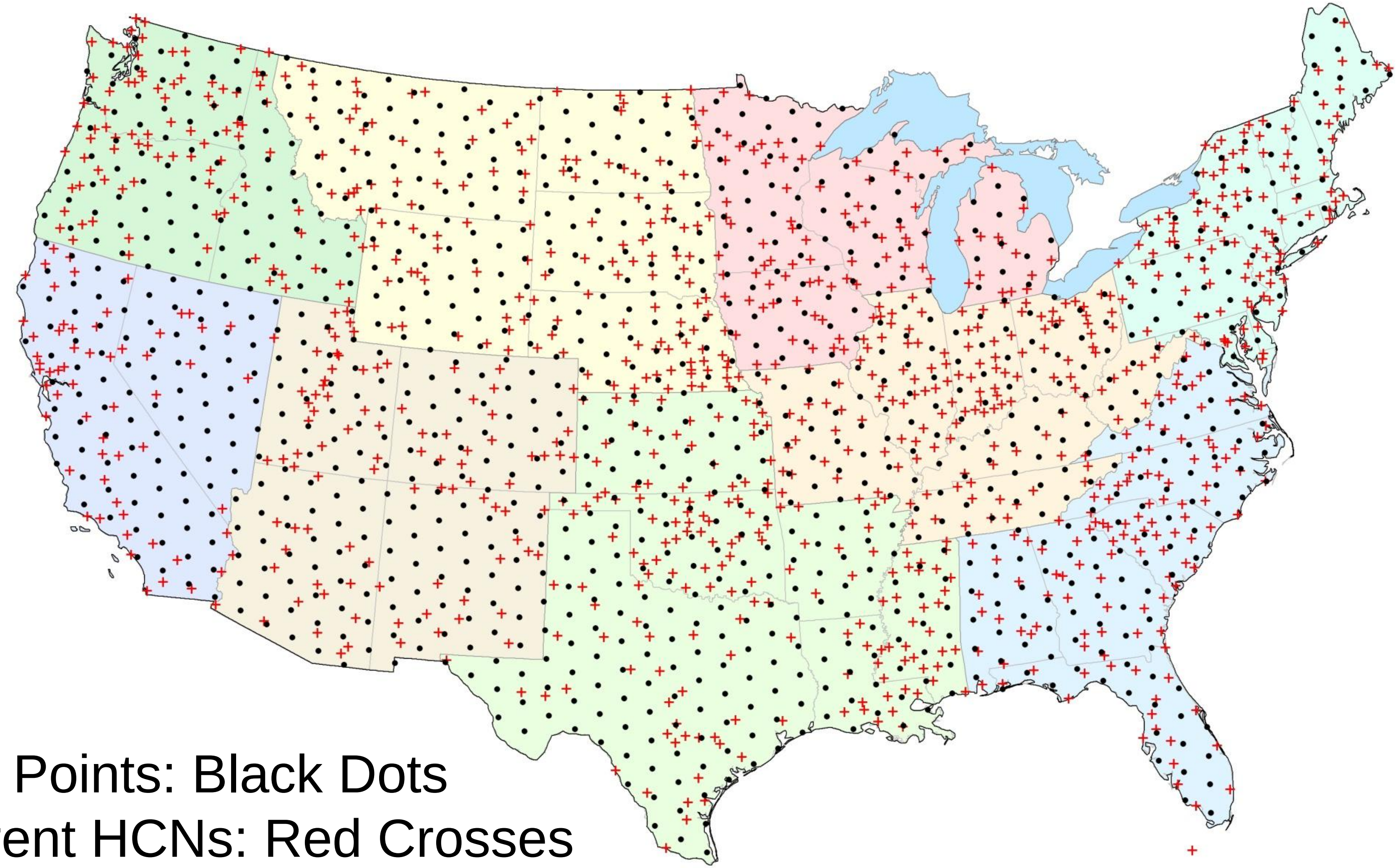
2. Elements of improving global predictions (both weather and climate).

3. Elements of improving regional predictions (mainly weather).

The Next Modernization of the National Weather Service

- Improved aviation prediction (NextGen).
- Warn-On-Forecast (the two hour convective warning).
- Renewable Energy prediction requirements.
- Air quality and homeland security (chem, bio and nuclear threats).

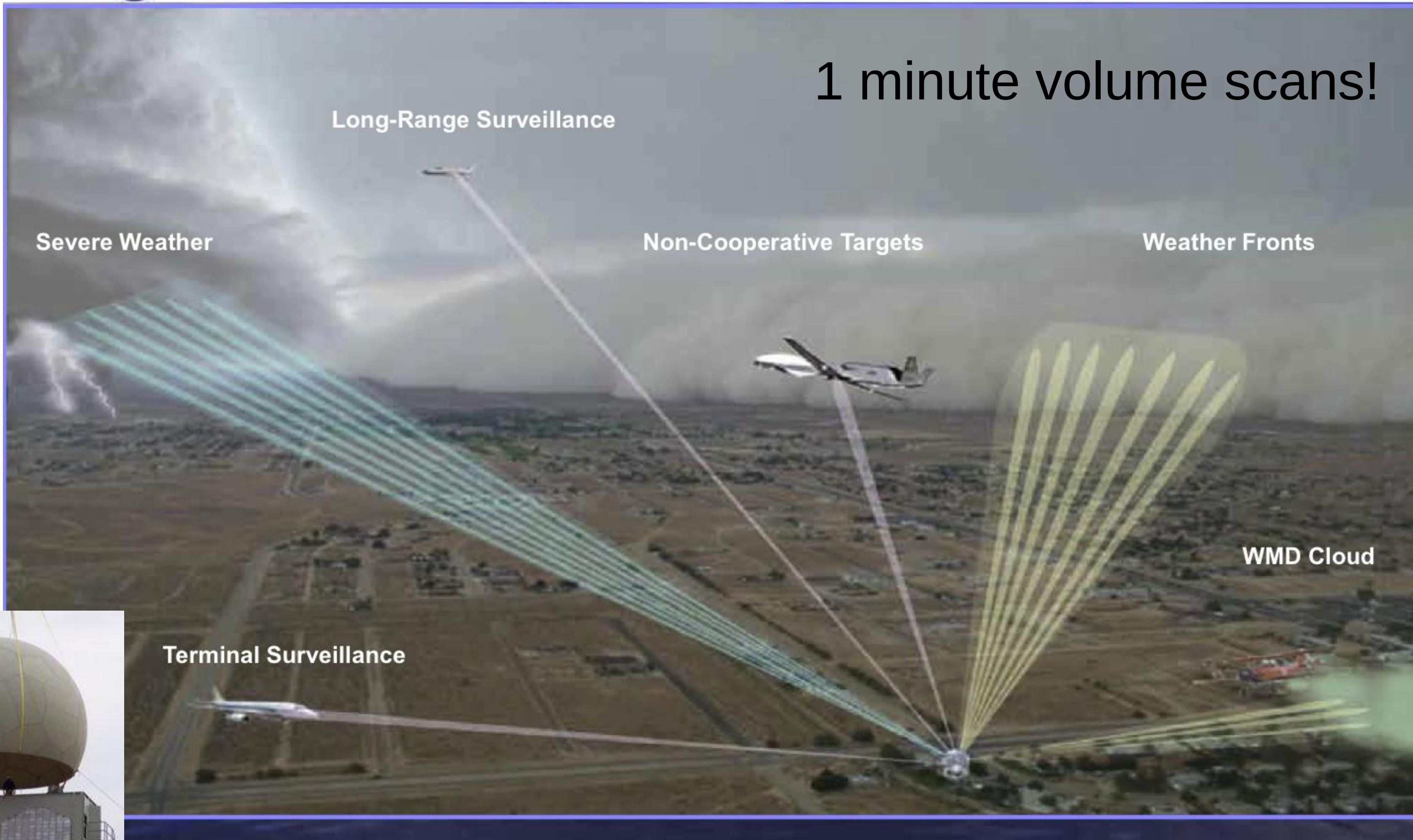
Grid Point (1,000) and Top 1,000 Current HCN Locations



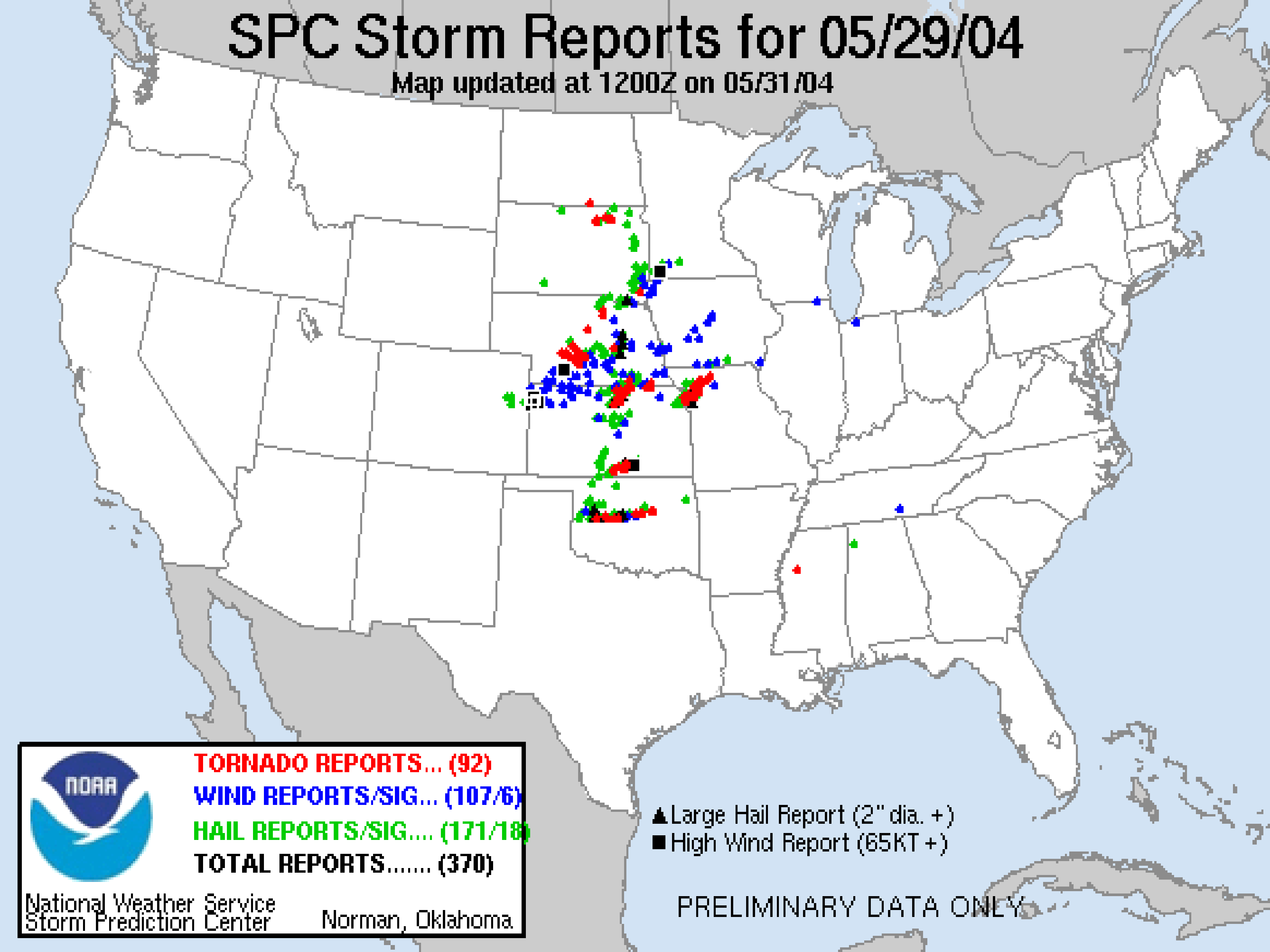
Grid Points: Black Dots
Current HCNs: Red Crosses

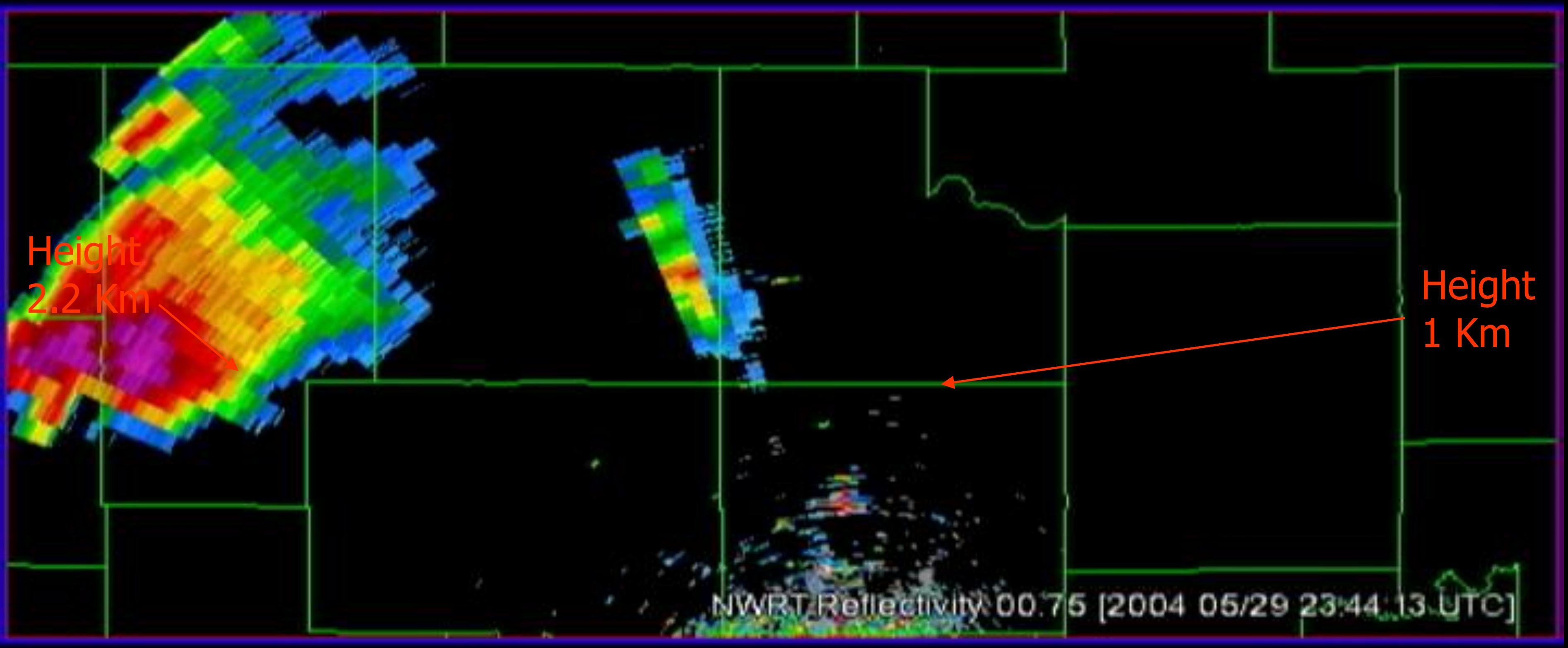
Multi-Function Phased Array Radar (MPAR) Concept

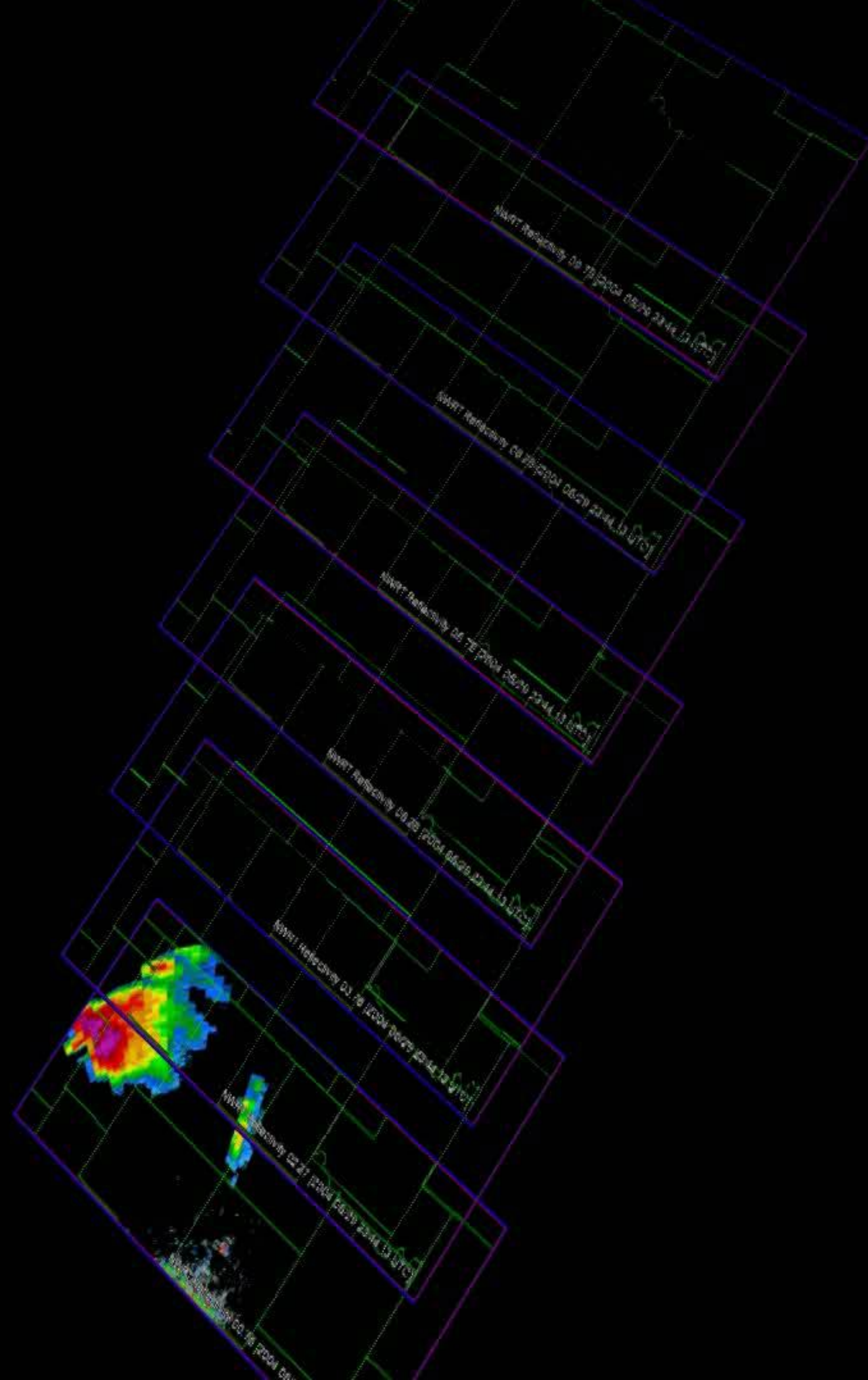
1 minute volume scans!



Weber et al. 2007, Weadon et al. 2009

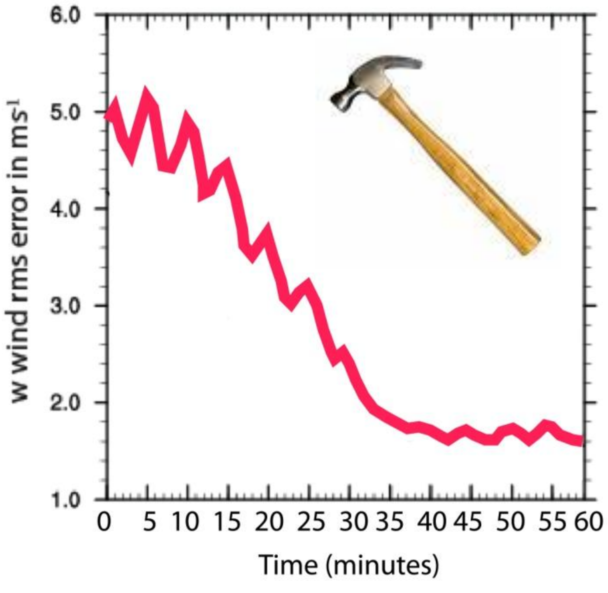

SPC Storm Reports for 05/29/04
Map updated at 1200Z on 05/31/04
TORNADO REPORTS... (92)
WIND REPORTS/SIG... (107/6)
HAIL REPORTS/SIG.... (171/18)
TOTAL REPORTS....... (370)
NOAA
National Weather Service
Storm Prediction Center
Norman, Oklahoma
Large Hail Report (2" dia. +)
High Wind Report (65KT +)
PRELIMINARY DATA ONLY


Height
2.2 Km
Height
1 Km
NWRT Reflectivity 00.75 [2004 05/29 23:44:13 UTC]

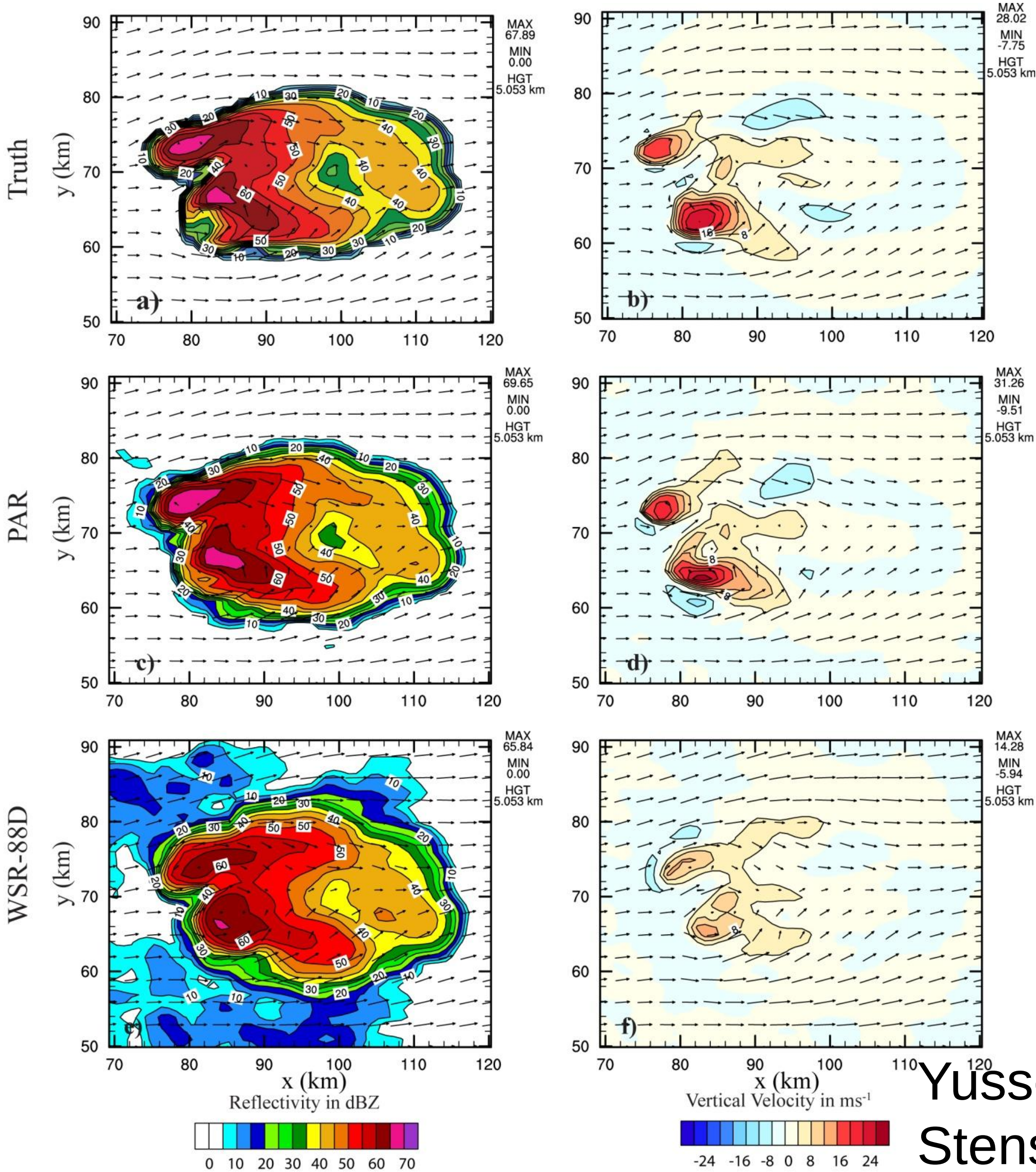


Under-determined Problem

- General consensus is that it takes 8-10 radar volume scans to obtain accurate analyses (~40 min for operational WSR-88D)



Benefits of PAR
15 minutes of assimilation



Truth

PAR Analysis

WSR88D Analysis

Yussouf and Stensrud 2010

NextGen 101

- NextGen is a Congressionally mandated initiative to modernize the U.S. Air Transportation System in order to:
  - Increase capacity and reliability
  - Improve safety and security
  - Minimize the environmental impact of aviation

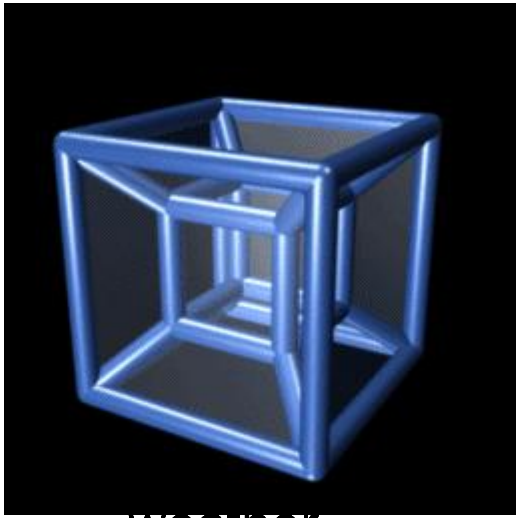
NextGen 101

- Weather accounts for 70% of all air traffic delays within the U.S. National Airspace System (NAS)
  - The Federal Aviation Administration (FAA) has determined two thirds of this is preventable with better weather information

- "A key finding, based on an analysis of several 2005-2006 convective events, is that as much as two-thirds of the weather related delay is potentially avoidable."
  -Research, Engineering and Development Advisory Committee; Report of the Weather-ATM Integration Working Group; Oct3, 2007

Weather Information Data Base

- The WIDB (aka the 4-Dimensional Weather Data Cube) will contain:
  - Continuously updated weather observations (surface to low earth orbit, including space weather and ocean parameters)
  - High resolution (space and time) analysis and forecast information (conventional weather parameters from numerical models)
  - Aviation impact parameters for IOC (2013)
    - Turbulence
    - Icing
    - Convection
    - Ceiling and visibility
    - Winds (surface and aloft)
  - The WIDB of the future will contain "all" weather data, not just aviation parameters.



Questions?

Alexander.E.MacDonald@noaa.gov sandymacd@comcast.net