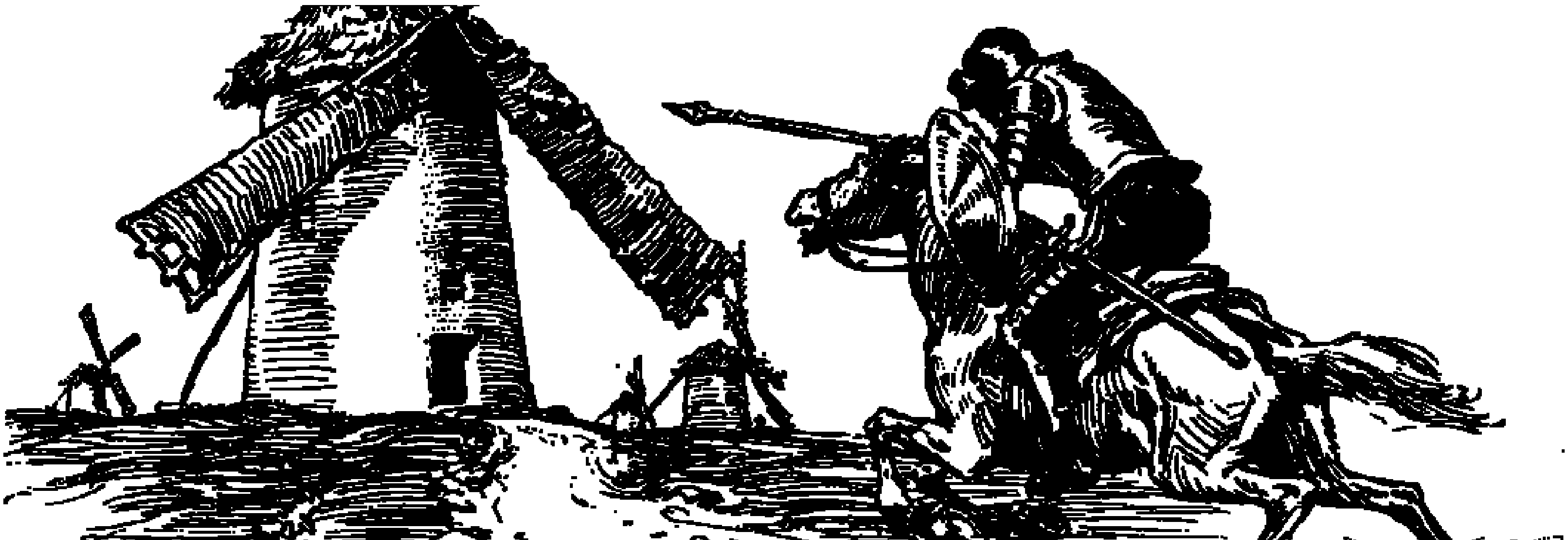
The Guiding Principles, Realities and Future of Cloud Resolving Models



by

G. J. Tripoli

The University of Wisconsin - Madison

Synoptic Paradigm

- NWP was born under the the Synoptic Paradigm:
  - (1903) V. Bjerknes Use natural laws to predict Weather
  - (1922) L. F. Richardson Weather Prediction is an initial value problem
  - (1950) Charney performs 1st NWP integration
  - (1961) Lorenz shows that there are limits to predictability

The last 50 years

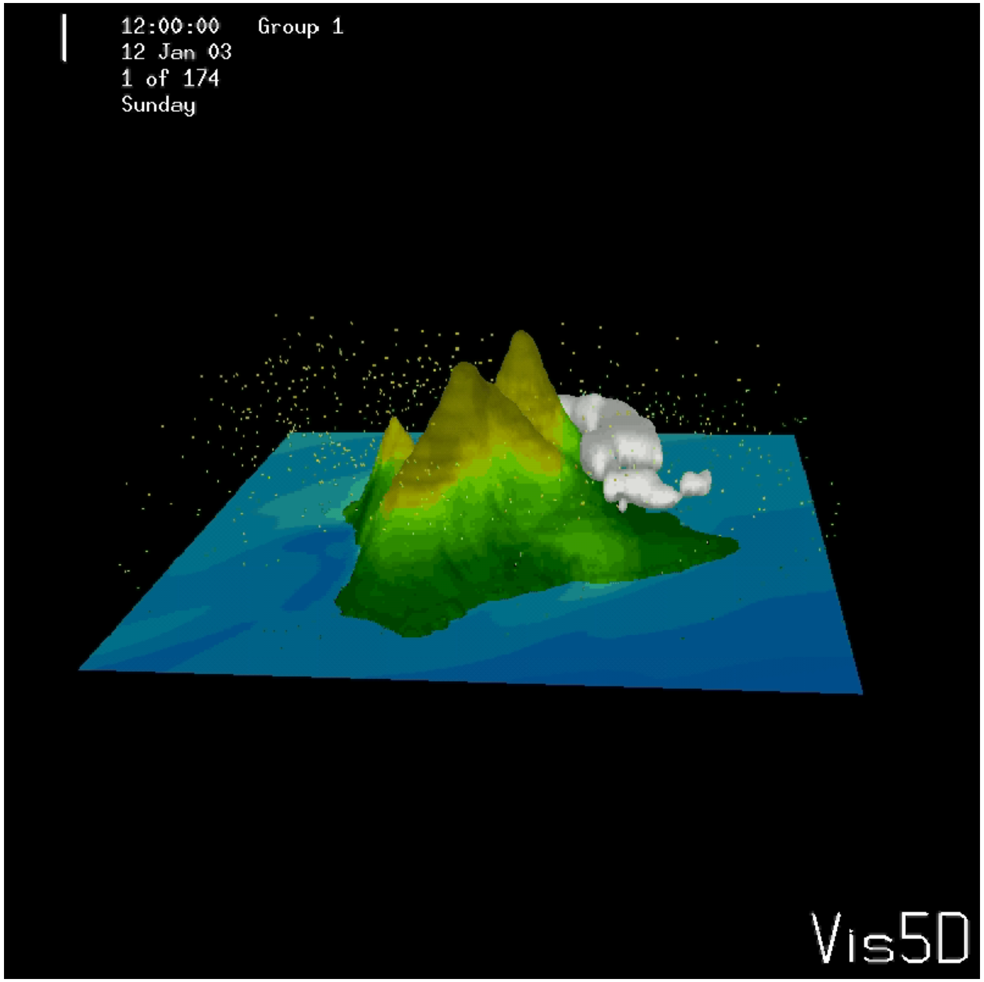
- We developed climate models, GCMs, weather prediction models, cloud models, LES models and more
- We developed multivariate analysis schemes that evolved into data assimilation systems
- Physics representation has steadily improved
- Resolution is increasing with Moores Law
- Weather forecasts have generally improved

But

- There has been a troubling problem with the “QPF” and “Warm Season” prediction in particular, it just hasn’t been improving as much.
- The tropical cyclone problem is similar and is a good manifestation of this problem

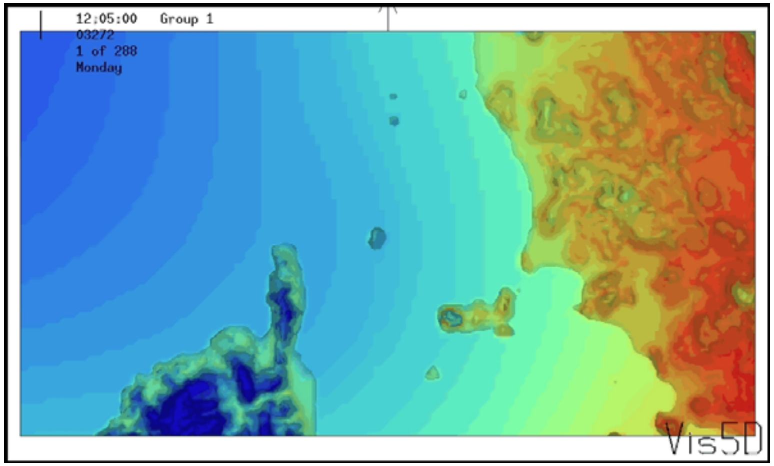
20th Century Paradigm for NWP

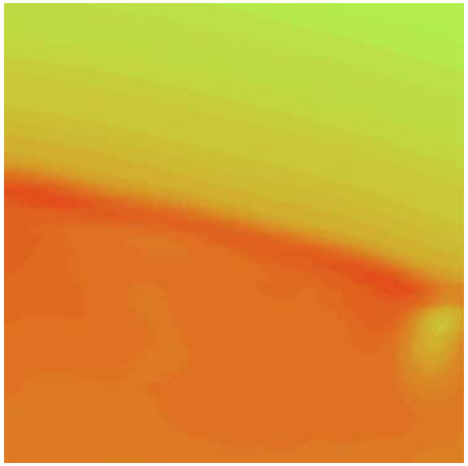
- **Deterministic Prediction of Subordinate Disturbances**
  - Initialize model with deterministic flow
  - Predict mesoscale features created by the interaction of predictable features with definable surface characteristics
  - Mesoscale features take on the predictability of the synoptic scale flw

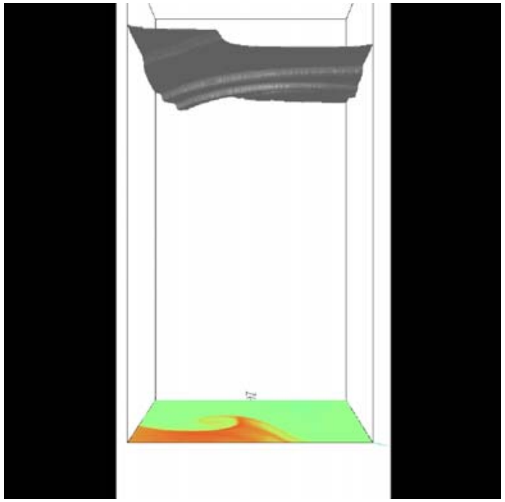


20th Century Paradigm for NWP

- **Simulation of Subordinate Disturbances**
  - Initialize model with deterministic flow
  - Predict mesoscale features created by the interaction of predictable features with definable surface characteristics
  - Simulated mesoscale features have independent behavior, but may be used to explain the behavior of simulated phenomena

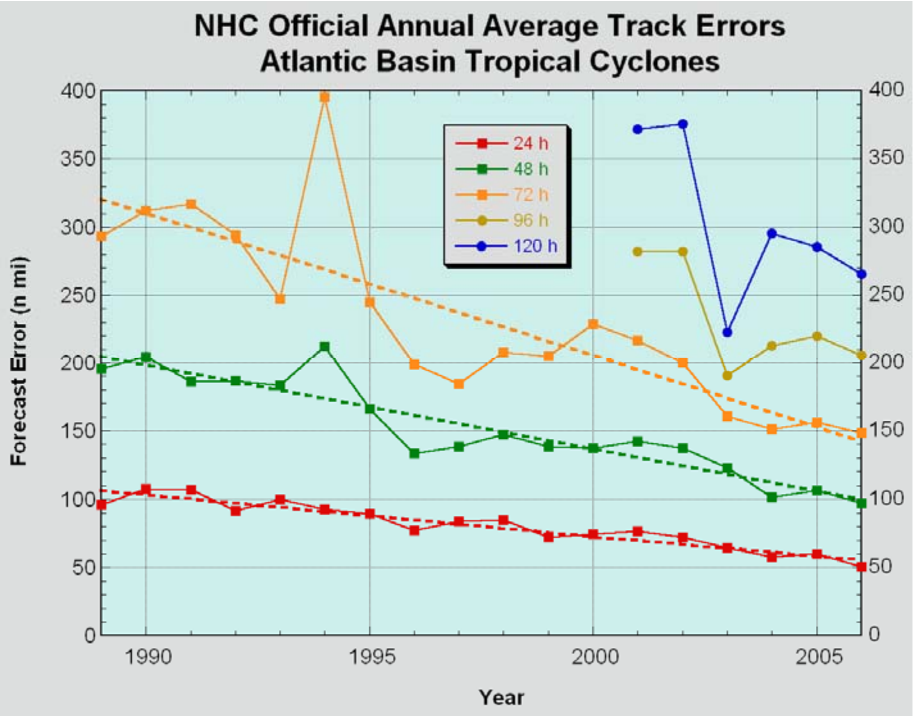


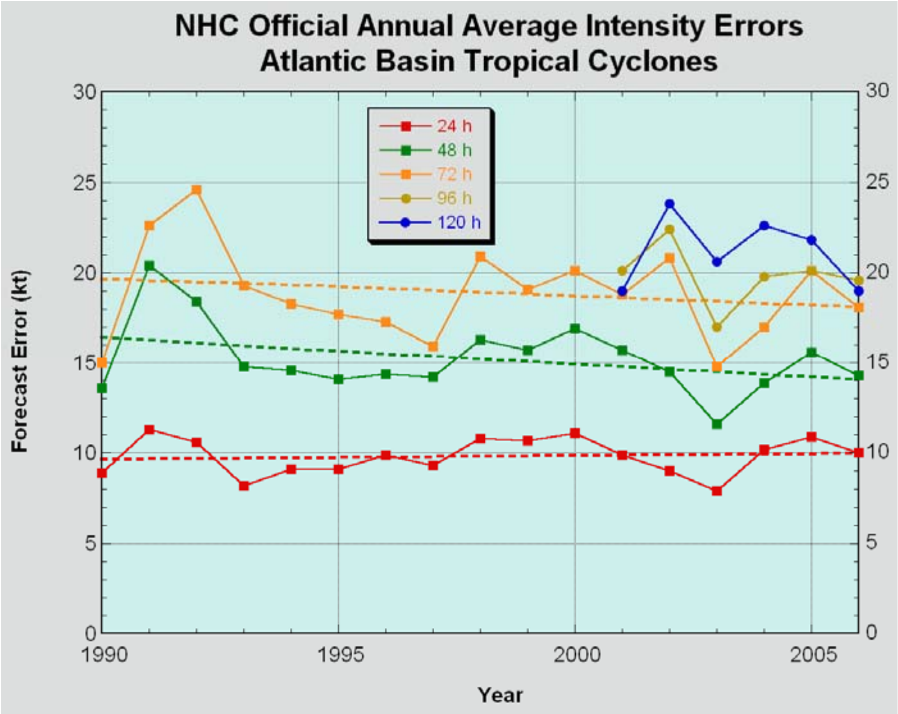




Hurricane Forecast Problem

Track forecast skill is steadily improving while intensity prediction skill is showing little improvement…Why?





Hurricane Forecast Improvement Project

- Established by NOAA in 2007
- 10 year plan to improve 5 day tropical cyclone forecasts
- Strategy includes
  1. Observation and analysis improvement
  2. Basic research on intensity change
  3. Develop advanced hurricane modeling system
     - Several recent studies suggested improved resolution reaching competent cloud resolving scales of 1km horizontal spacing can significantly improve forecasts (Powers and Davis, 2002; Hendricks et al., 2004; Yau et al., 2004, Braun et al.,2006; Vhen et al., 2007; Davis et al., 2008; Rotunno et al., 2009)

The Test

- **Hypothesis:**
  - Given an initial condition of the hurricane vortex defined at 9 km resolution then
    - Decreasing the horizontal numerical model grid spacing from 9 km to 1 km, will result in a **significant increase in the skill of intensity forecasts** in the 5 day time frame
    - The **dependence of intensity forecast accuracy on resolution is a robust** property of all numerical models

The Test

- Control model will be the GFDL hurricane model having nesting resolutions:
  - **Coarse Grid 1**:
    - ~ 75 latitude x 75 longitude degrees (8000 x 8000 km)
    - Delta x = Delta y ~ 9 km (1/12 degree)
  - **Medium Grid 2:**
    - ~ 9 latitude x 9 longitude degrees latitude (1000 x 1000 km)
    - Delta x = Delta y ~ 3 km (1/36 degree)
  - **Fine Grid 3:**
    - ~ 3 latitude x 3 longitude degrees (330 x 330 km)
    - Delta x = Delta y ~ =1 km (1/108 degree)

The Test

- **Test impact of resolution** by 3 part tests for each case:
  a) 5 day forecast, Grid 1 only
  b) 5 day forecast, Grids 1 and 2 only
  c) 5 day forecast, Grids 1, 2 and 3

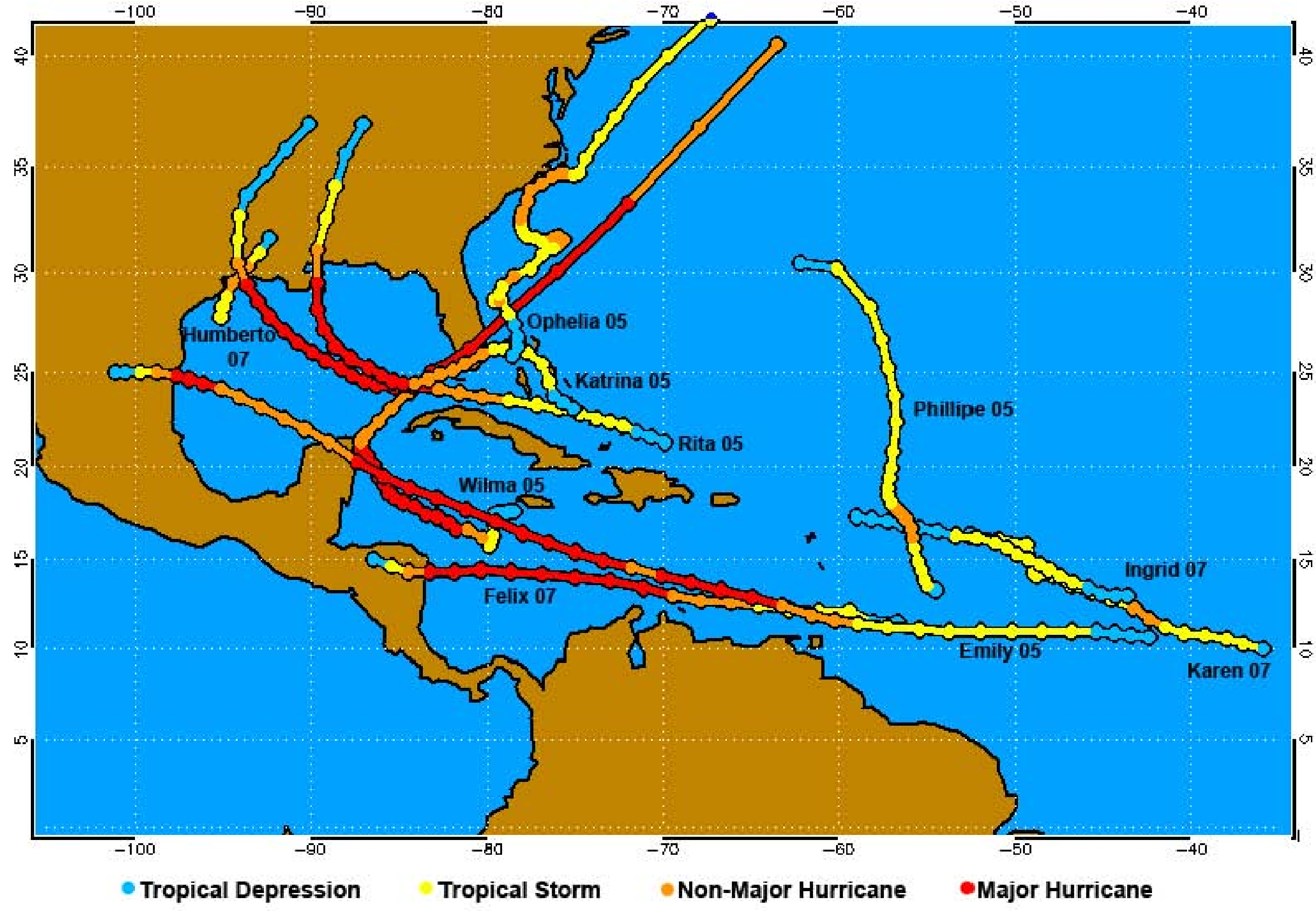
- **Hypothesis verified if**:
  1) significant improvement in track and intensity going from a to b and from b to c
  2) Similar improvements for each model tested

HRH Test Cases

Criteria: diverse set of storms, as well as time periods for each storm

Ten storms from the 2005 & 2007 hurricane seasons

Number of cases: 69



Examples of storms to be run

74 cases in all

Storms Prioritized List of Test Cases

Storm	Forecast Date	Forecast Time	Hours w/track	Hours as TC	RI periods	RW periods
Wilma					5	1
	10/16/2005	0000 UTC	126	126	5	0
	10/17/2005	0000 UTC	126	126	5	0
	10/18/2005	0000 UTC	126	126	4	0
	10/19/2005	0000 UTC	126	126	0	0
	10/19/2005	1200 UTC	126	126	0	0
	10/20/2005	0000 UTC	126	126	0	0
	10/21/2005	0000 UTC	126	114	0	1
	10/22/2005	0000 UTC	114	90	0	1
	10/23/2005	0000 UTC	90	66	0	1
	10/24/2005	0000 UTC	66	42	0	1
	10/25/2005	0000 UTC	42	18	0	0
Philippe					0	0
	9/17/2005	1200 UTC	126	126	0	0
	9/18/2005	1200 UTC	126	120	0	0
	9/19/2005	1200 UTC	126	96	0	0
	9/20/2005	1200 UTC	90	72	0	0
	9/21/2005	1200 UTC	66	48	0	0
	9/22/2005	1200 UTC	42	24	0	0
Felix					8	1
	8/31/2007	1200 UTC	126	114	8	1
	9/1/2007	1200 UTC	126	90	5	1
	9/2/2007	0000 UTC	114	78	3	1
	9/2/2007	0600 UTC	108	72	2	1
	9/2/2007	1200 UTC	102	66	1	1
	9/2/2007	1800 UTC	96	60	0	1
	9/3/2007	0000 UTC	90	54	0	1
	9/3/2007	1200 UTC	78	42	0	0
Rita					6	3
	9/18/2005	0000 UTC	126	126	6	2
	9/19/2005	0000 UTC	126	126	6	3
	9/20/2005	0000 UTC	126	126	6	3
	9/21/2005	0000 UTC	126	120	2	3
	9/22/2005	0000 UTC	102	96	0	3
	9/23/2005	0000 UTC	78	72	0	0

Modeling Groups

- **U. Rhode Island - GFDL Hurricane Model (I. Ginis/ M. Bender)**
  - **Operational** NOAA hurricane model **hydrostatic, compressible, sigma vertical coordinate**
  - GFDL initial vortex (bogused with guidance from reconnaissance)
- **AOML- HWRF-X (S. Gopalakrishnan)**
  - **Research** hurricane model **nonhydrostatic, compressible, sigma vertical coordinate**
  - Adapted WRF model
  - GFDL initial vortex
- **NCAR/MMM- AHWRF (C. Davis/ R. Torn)**
  - **Research** hurricane model **nonhydrostatic, compressible, sigma vertical coordinate**
  - EnKF data assimilation initial vortex
- **PSU - WRF-ARW (F. Zhang)**
  - **Research** mesoscale model **nonhydrostatic, compressible, sigma vertical coordinate**
  - EnKF data assimilation initial vortex
- **NRL - COAMPS - TC (M. Peng/ R. Hodur)**
  - **Operational** NAVY TC **nonhydrostatic model, quasi-compressible**, **sigmaz vertical coordinate**
  - Initial vortex relocated from previous 12 hour forecast
- **U. Wisconsin - NMS - (W.Lewis/ G. Tripoli)**
  - **Research** mesoscale model; **nonhydrostatic Lamb Vector form, quasi-compressible, vertical height coordinate with VST**
  - Uniquely constrained dynamics core
  - GFDL initial vortex

Developmental Testbed Center (DTC) Team

- Louisa Nance
- Ligia Bernardet
- Barb Brown
- Jamie Wolff
- Chris Harrop
- Laurie Carson
- Tara Jensen
- John Halley Gotway
- Shaowu Bao
- Jian-Wen Bao

Honorary Member - Tim Marchok
Extensive assistance wrt GFDL Vortex Tracker!

HRH Teams

Verification

Barb Brown (NCAR)

James Franklin (NHC)

Mike Fiorino (NHC)

Mark DeMaria (CIRA)

Tim Marchok (GFDL)

Case Selection

Jack Beven (NHC)

Mark DeMaria (CIRA)

Results

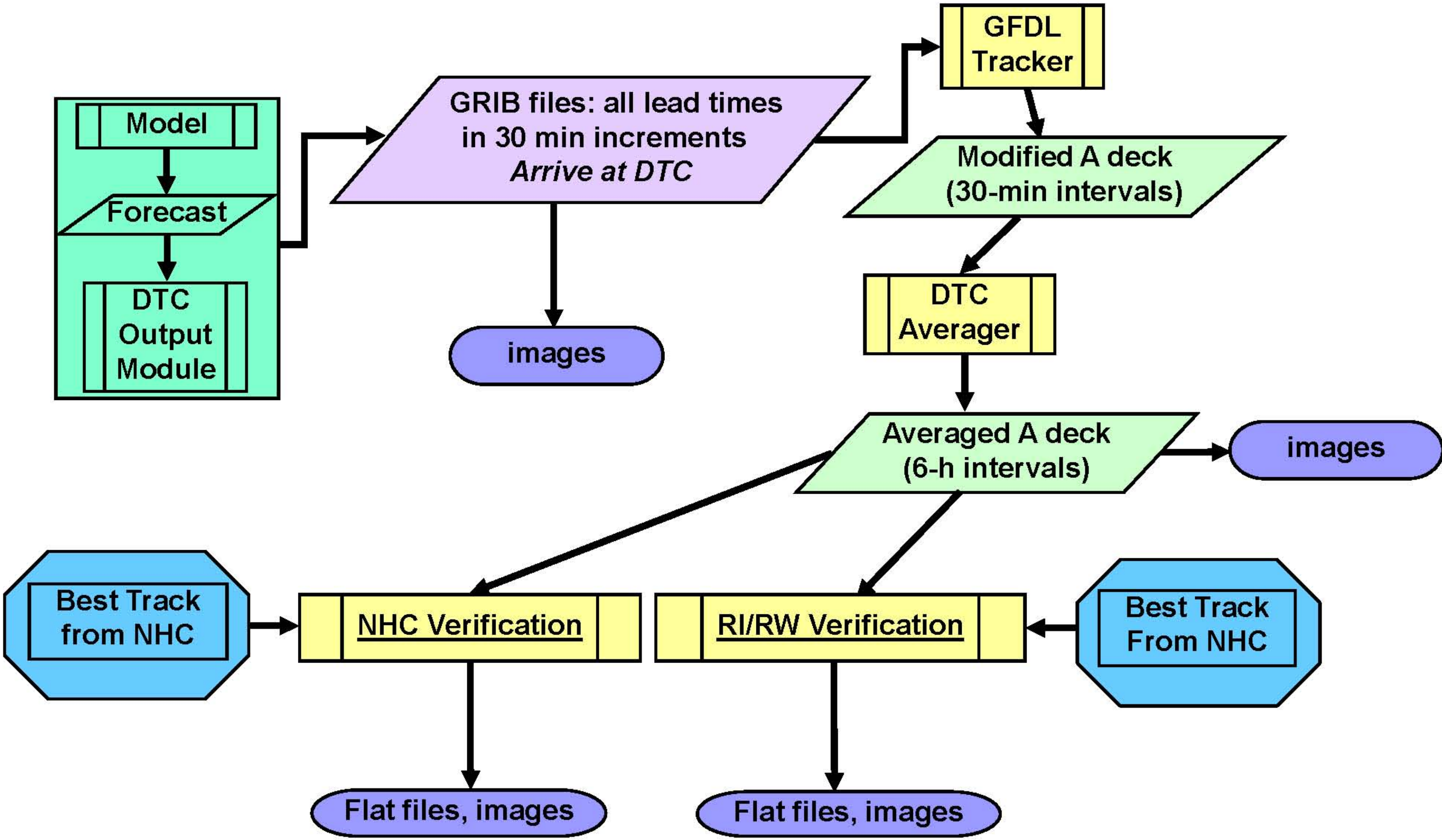
- Web Site Featuring Graphical Outputs:

  http://www.dtcenter.org/plots/hrh_test/graphics/

- Web site where one can download final DTC report:

http://www.dtcenter.org/plots/hrh_test/HRH_Report_30Sept.pdf

DTC Evaluation System for HRH

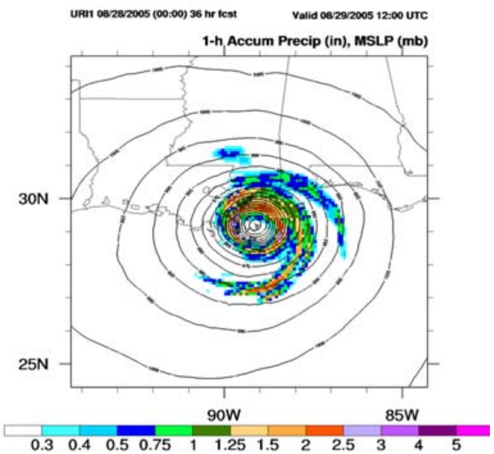


Evaluation

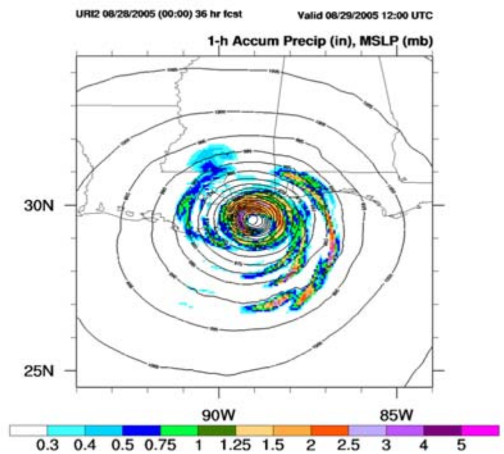
- Track Error (nm) vs lead time
- Intensity Error (kt) vs lead time
- Absolute Intensity Error (kt) vs lead time
- Wind radii error (nm) (34,50, 64 kt) SS improvement
- Rapid Intensification and Rapid Weakening using event and episode methodologies SS improvement with resolution?
- Consistency --subjective inspection or 10 difference measurements
- Overall evaluation

URI GFDL

1 grid

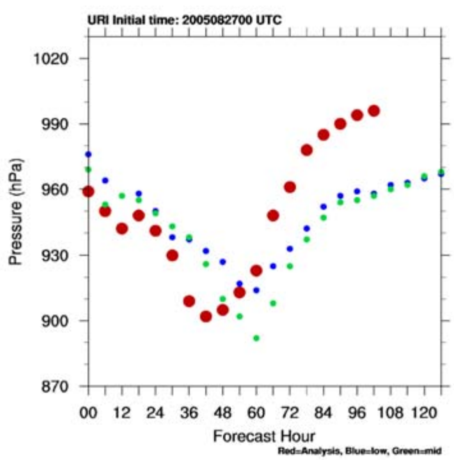


2 grids

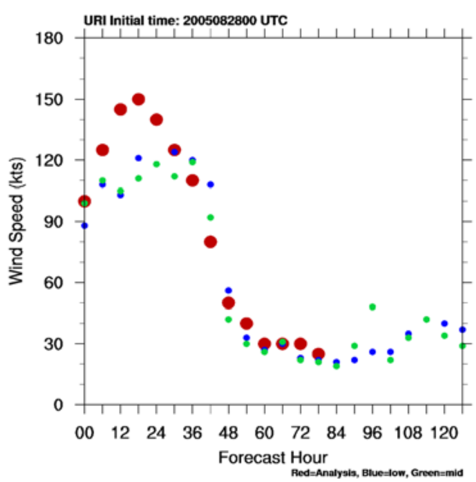


3 grids

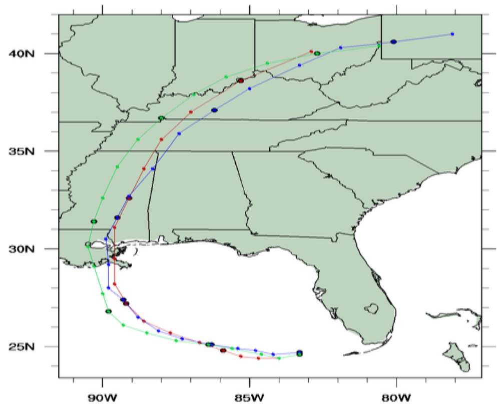
Not available



Pressure trace



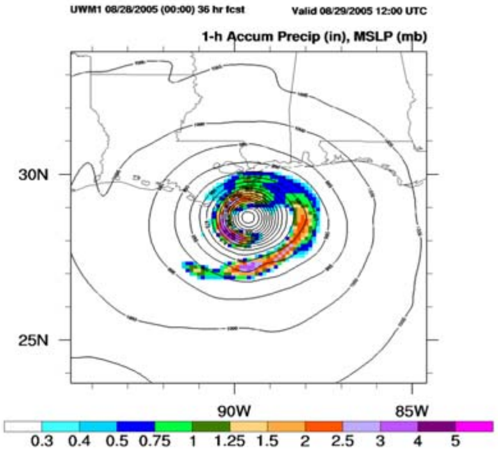
Peak wind trace



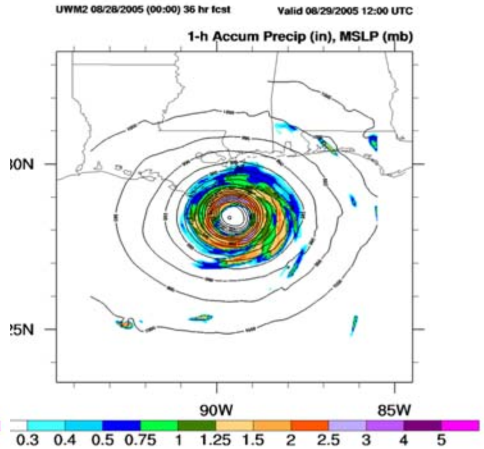
Track

UW NMS

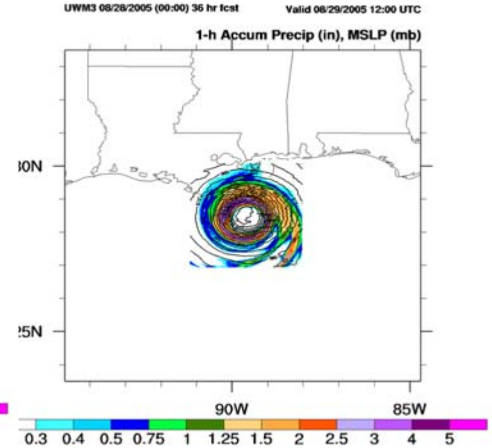
1 grid

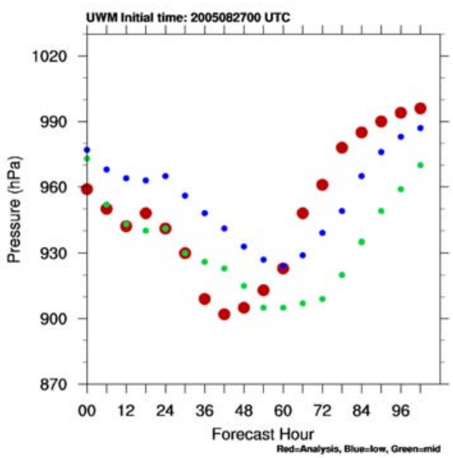


2 grids

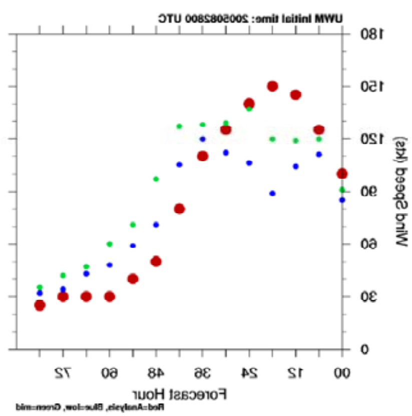


3 grids

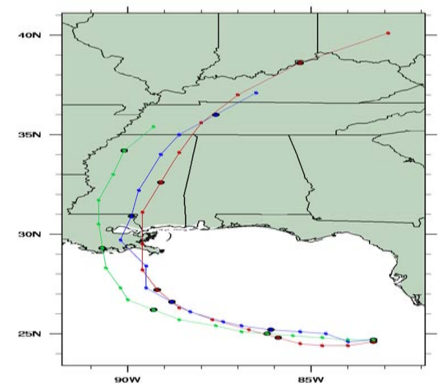




Pressure trace



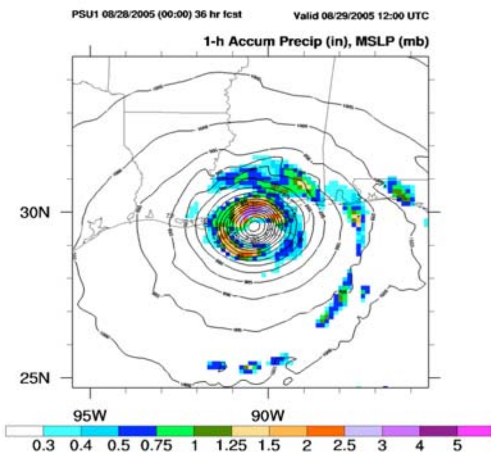
Peak wind trace



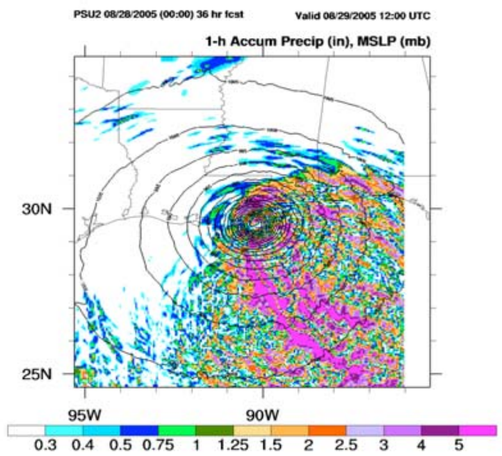
Track

PSU WRF-ARW

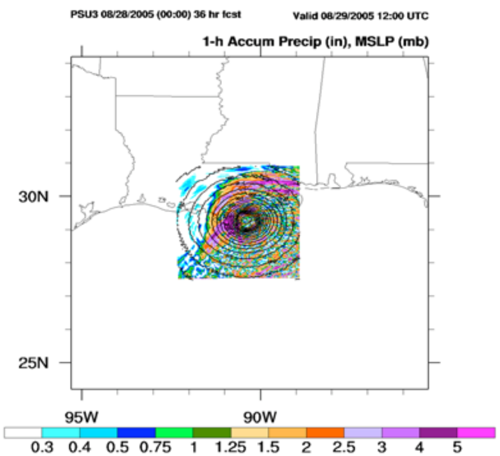
1 grid

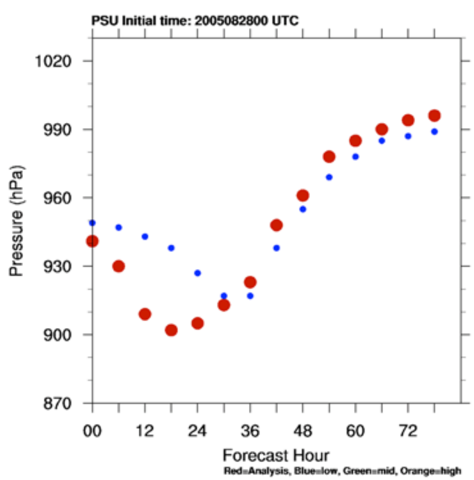


2 grids

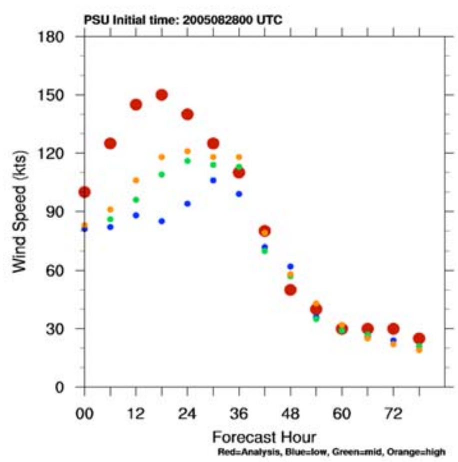


3 grids

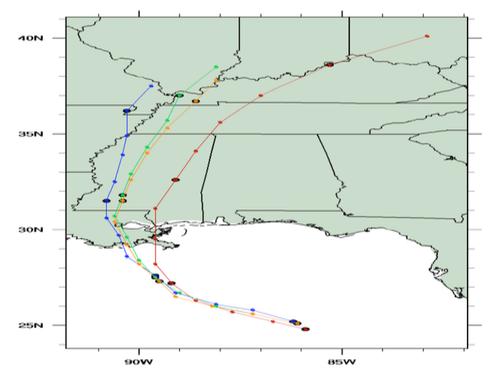




Pressure trace



Peak wind trace



Track

AOML HWRF-X

1 grid

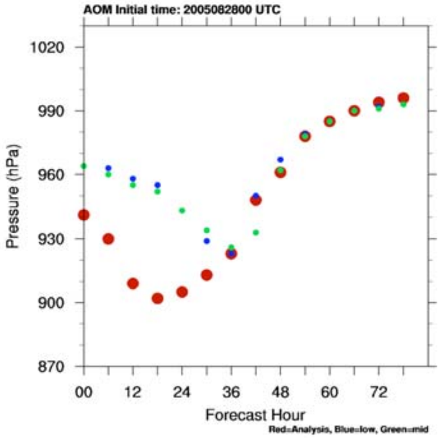
2 grids

3 grids

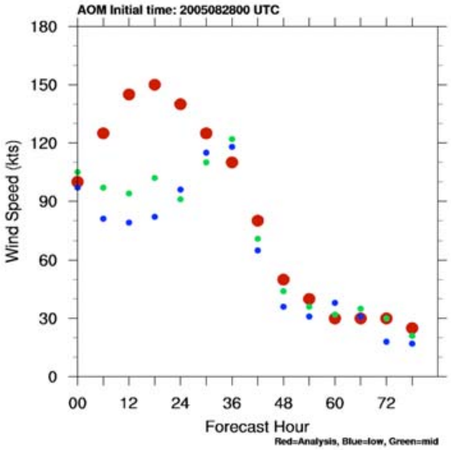
Not available

Not available

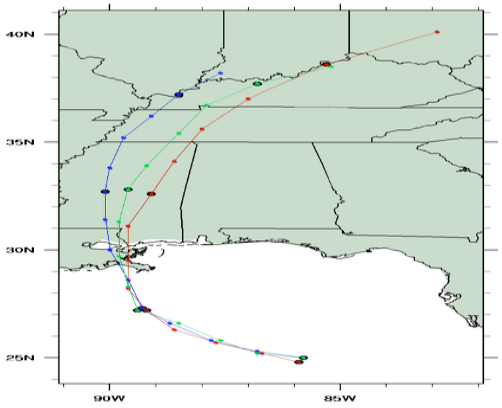
Not available



Pressure trace



Peak wind trace



Track

NRL COAMPS-TC

1 grid

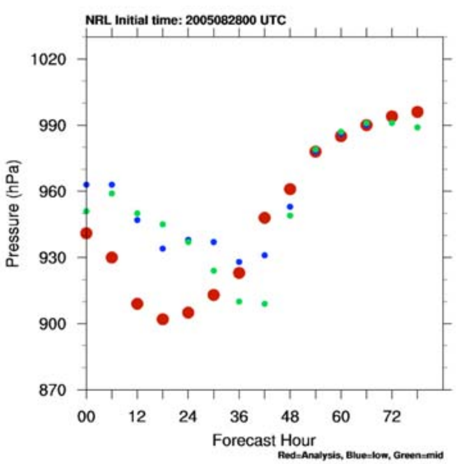
2 grids

3 grids

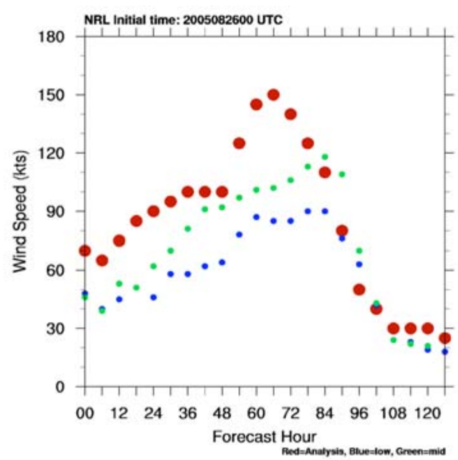
Not available

Not available

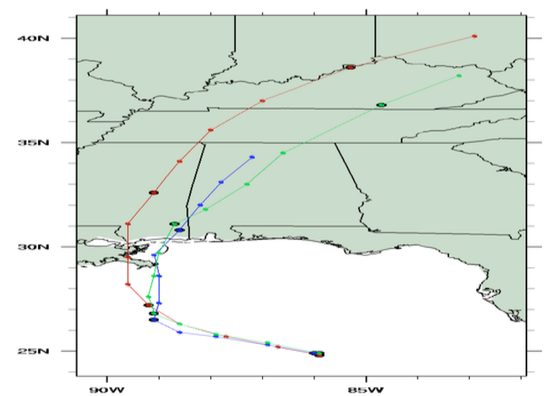
Not available



Pressure trace



Peak wind trace



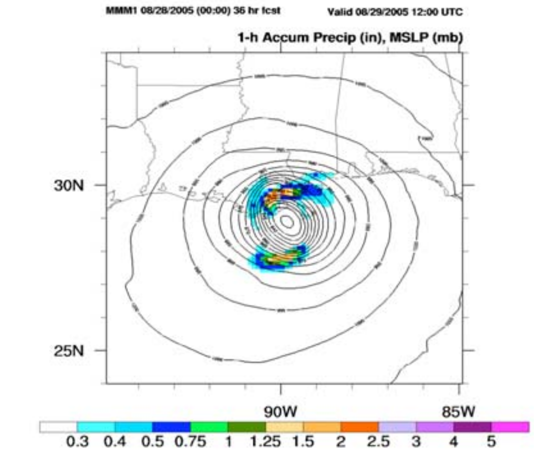
Track

MMM-AHW

1 grid

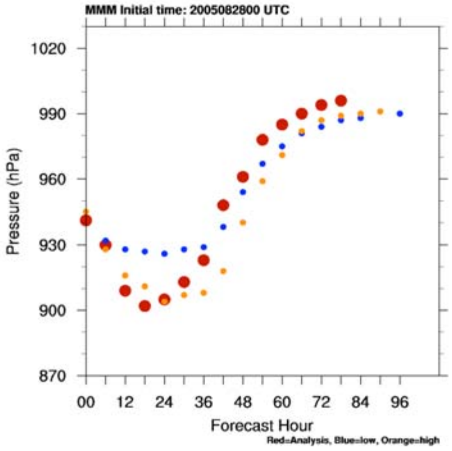
2 grids

3 grids

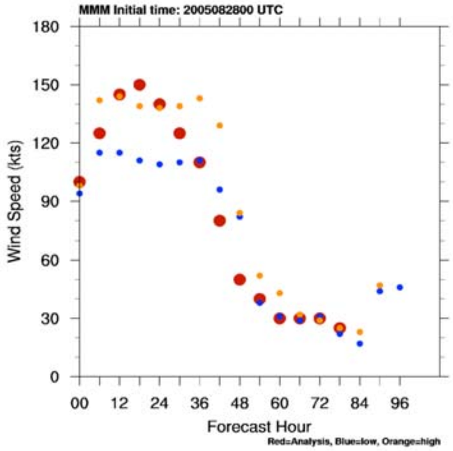


Not available

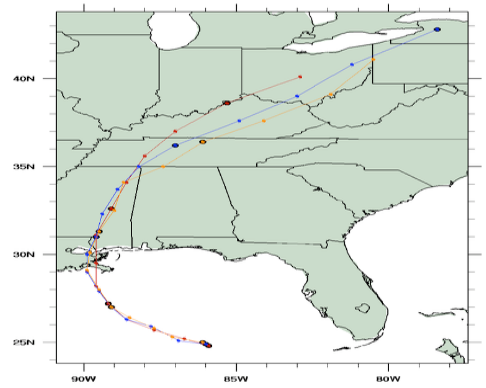
Not available



Pressure trace

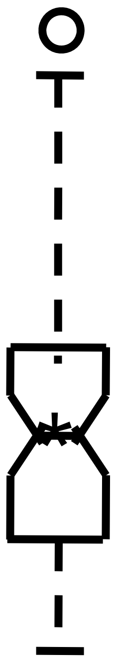


Peak wind trace



Track

Box Plots



Median: bold waist

Mean: star

95% CI on median: notch

Sample size: width of box

25% and 75% quartiles: bottom and top of box

Length of whiskers: furthest point from median that is not an outlier.

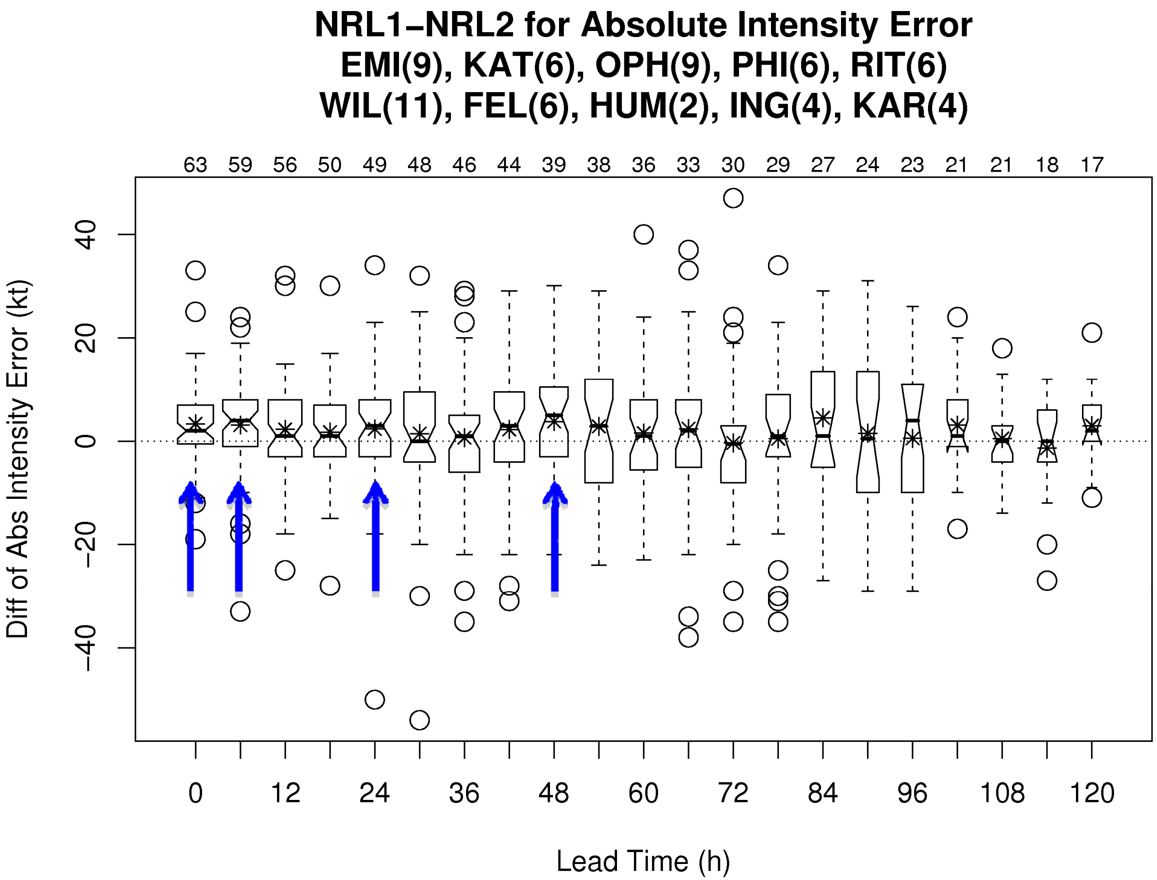
Outliers: points further away from median than 1.5 * IQR (circles)

NRL

NRL1 = 9 km

NRL2 = 3 km

NRL1 - NRL2 abs intensity error diff



- NRL2 produces a better intensity forecast than NRL1 at lead times 0, 6, 24, and 48 h.

- However, some track degradation was observed

AOML HRWF-X Summary

- Improves track and intensity forecast in 1st 30 hours
- Improves RI events in 1st 30 hours
- Consistent degradation of wind radii errors with high resolution and too frequent RI episodes **suggest that the “apparent” improvements are misleading and not real!**

MMM AHWRF Summary

- Higher resolution :
  - Improves track error in long time frame
  - **No improvement to intensity forecast**
  - Improves RI events
  - Consistent degradation of wind radii errors with high resolution and too frequent RI episodes suggest that the “apparent” improvements are misleading!

NRL Summary

- Resolution had positive impact on intensity error for a few lead times
- Caused degradation in track forecasting and wind radii
- **Conclusion: Increase in resolution did not improve intensity prediction overall**

PSU Summary

- Completed too few cases for conclusive results

URI GFDL Model Summary

- **Higher resolution did not substantially improve track or intensity error**

UW NMS
Summary

- Some decrease in intensity error at several lead times
- Some increase in ability to capture RI at several led times
- **Decreases in intensity prediction error were not significant enough (given number of completed cases) for higher resolution to verify hypothesis**

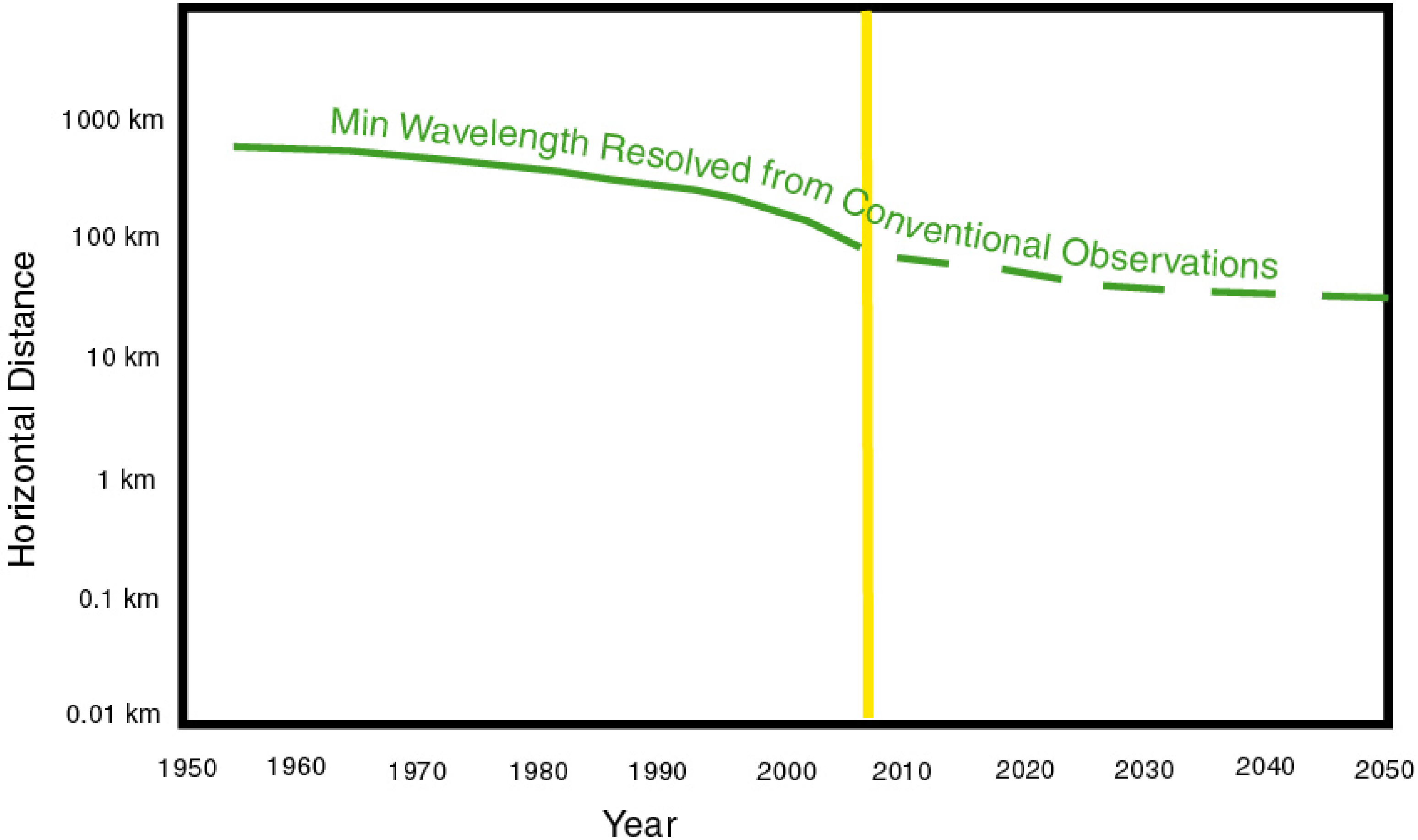
Final Conclusions of HRH Test

- **Results are suggesting that the hypothesis is NOT verified!**
- Less than significant and less than robust improvements found.
- In a few cases, increased resolution led to degraded results
- No apparent increase in skill for those employing 4DVAR (NRL) or EnKF (PSU, MMM) data assimilation systems

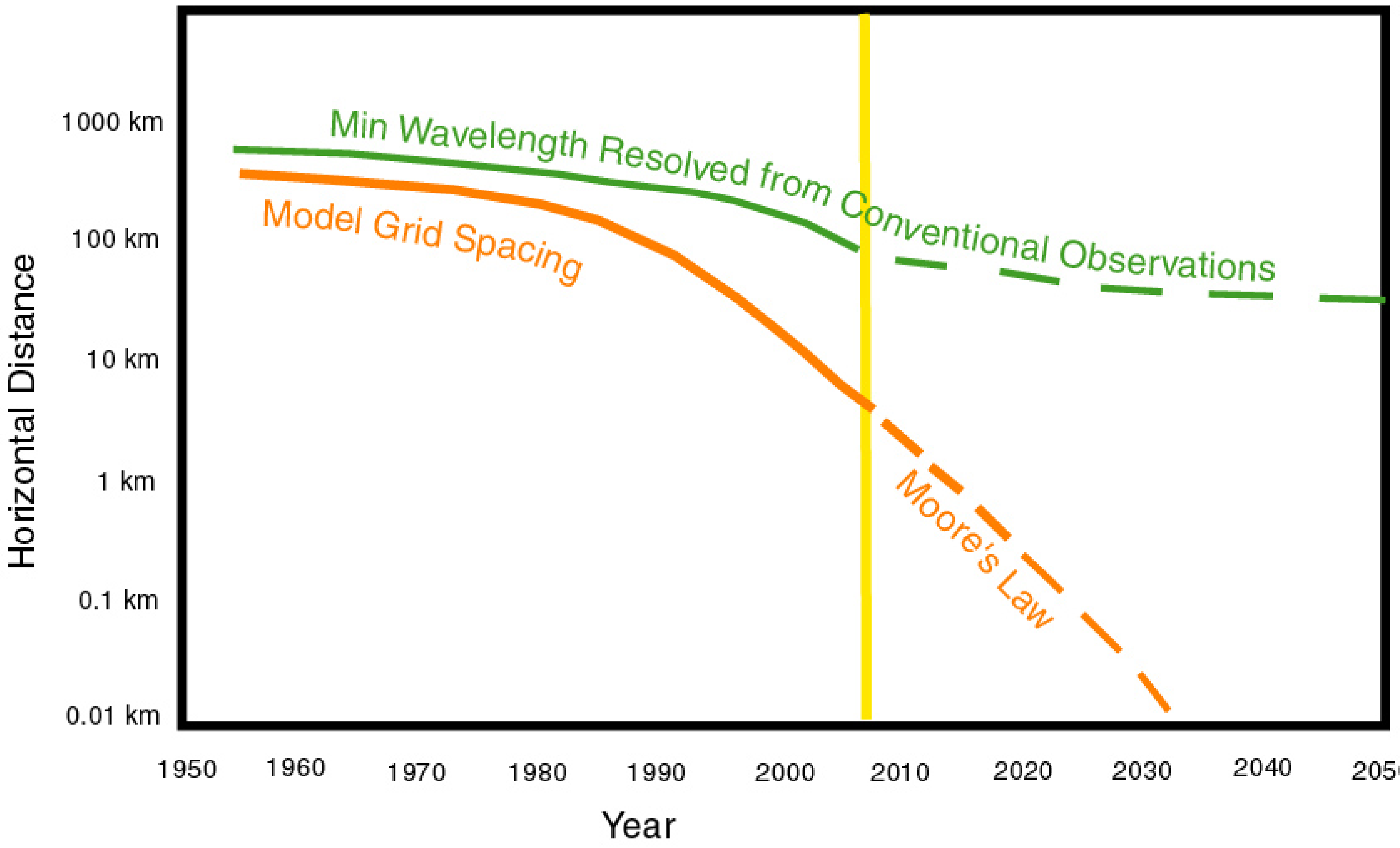
Bottom Line

THE SYNOPTIC PARADIGM HAS HIT THE WALL

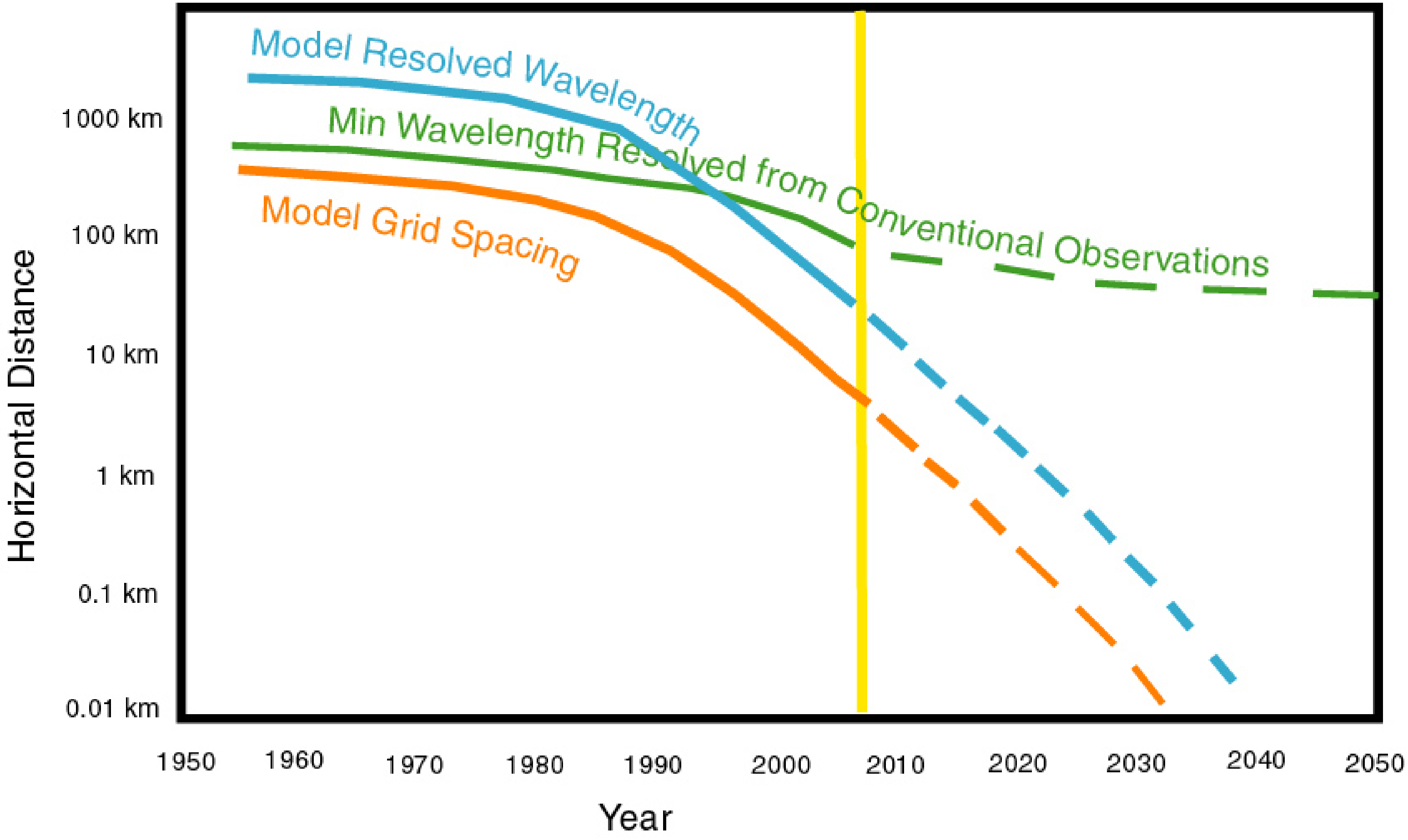
Conventional "Synoptic" Observations



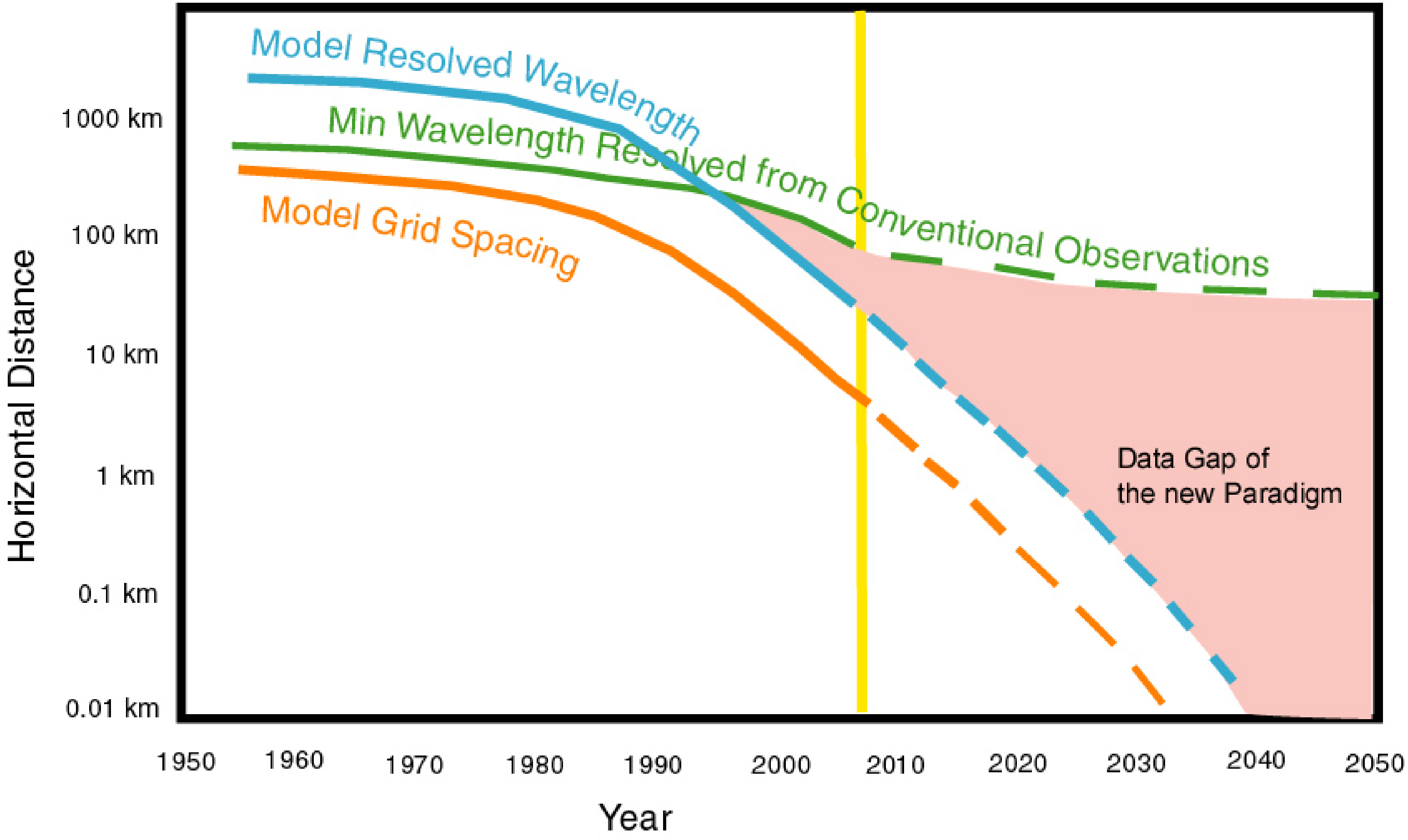
Model Grid Spacing



Model Resolution



Gap between conventional "synoptic" observations and model resolution



Can we overcome the gap?

- “we can just fill it with satellite data?”
- “ we just need more satellite resolution to match the model scales, right?”

- Or is the existence of a simple resolution gap “problem” really just good old time “synoptic” thinking?

Filling the Gap

- The only option to fill this continually widening gap is through remote sensing, i.e. satellite, radar, lidar, E-M signals, specialized aircraft
  - But remotely sensed weather analysis is indirect, under-specified and dependent on models to make a connection with state measurement.

Predictability Issues in Age of Cloud Resolving Models

- Deterministic predictability is practically confined to time scales less than 1 lifecycle period of the energy containing disturbance, i.e. linear time scales
  - Things we can do
    - Baroclinic Cyclone ~ 6 - 7 days (classic synoptic problem)
  - Things we have trouble with
    - Eye Wall ~ 20 - 40 hours
    - Rainband, MCS ~ 4-20 hours
    - Cumulus cloud ~ 20 - 60 minutes
- Perhaps **probabilistic predictability** of certain small space-time scale features can be attained from the predictability of their sustaining environment
  - Most typically, this will be the slow manifold, balanced portion of the flow field…but not always

Can we initialize cloud scales with Cloud Resolving Data?

- How much data resolution does it take to define a feature?
  - Dependent on spatial scales
  - Dependent on time scales
- We were raised with the “synoptic” paradigm, but recall the classic “synoptic” disturbance has a lifecycle of 6-7 days.
- It is no accident that we typically take 3D observations 1-2 times a day, because that is about 6-12 observations pre lifecycle…of the “synoptic” wave with which we have had some success with prediction
- Most of us who have worked with numerical systems know the 2^{nd} order numerical representation of a simple sine wave yields 28 % error when defined by 6 points and 8% phase error when represented by 10 points etc.

The Space-Time Problem

- We have had success with the “synoptic” paradigm until now because
  - multivariate observations have adequately defined the “synoptic” problem in both space and time.
- We now resolve with models features we cannot define adequately by observations
- We must build observation systems to optimally equip our prediction systems with the S-T observations they need

How can we move forward?

- Remote sensing based data assimilation
  - Goals of data collection and modeling must be modified to reflect the new S-T paradigm, i.e. optimizing S-T definition
  - To define these entities, we need a minimum of 6-10 observations per S-T dimension
  - Models must ultimately merge with data collection to:
    - Optimize interpretation of radiance in the context of these mixed S-T entities
    - Form a probabilistic analysis , such as an ensemble analysis
    - The optimal analysis must select the S-T model physics and evolution at space and time scales that support the observed behavior of radiance over time.

Expectations and Goals

- Expectations should be for probabilistic forecasts, where uncertainty becomes an expected and necessary part of a forecast.
- The goal of NWP should not be for a most likely atmospheric state, but for a range of possibilities articulated electronically in a standardized probabilistic format.