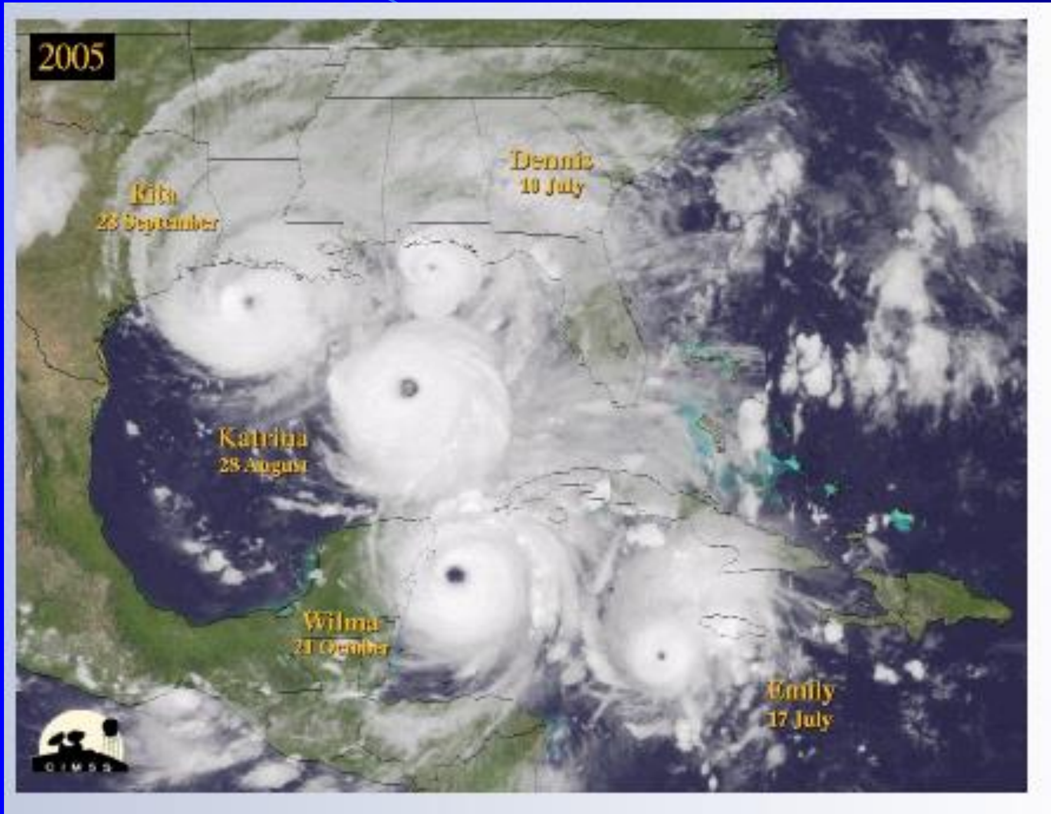
Ch. 1 Introduction and Historical Review of Numerical Weather Prediction



AST853 (NWP)

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1.1 Introduction to Numerical Weather Prediction

- NWP models use numerical methods to make approximations of a set of partial differential equations (PDEs) on discrete grid points in a finite area to predict weather systems in a finite area for a certain time in the future.

- Mathematically, NWP is equivalent to solving an *initial- and boundary-value problem*.

Thus, the accuracy of NWP depends on the accuracies of the i.c. & b.c. of the governing PDEs.

Procedure of NWP

Observations

Analysis

Running a NWP Model

Postprocessing Model Data

Forecasters

Users

Preprocessing (i.c. & b.c. for the model; IVP & BVP)

NWP Model

Numerical Weather Prediction System

(Adapted after Uccellini 2006)

Physically, the Newton's second law is applied to describe air motion in x, y, and z directions:

$$F = ma \quad => \quad a = \frac{F}{m}; \quad => \quad a_x = \frac{du}{dt} = \frac{F_x}{m}$$

$$\frac{du}{dt} = \frac{F_x}{m}; \qquad \frac{dv}{dt} = \frac{F_y}{m}; \qquad \frac{dw}{dt} = \frac{F_z}{m}$$

The above 3 equations give the momentum equations.

The conservation of mass is then applied to derive the continuity equation.

The conservation of energy and ideal gas law are applied to derive the thermodynamics equation.

Mathematically, a NWP model solves an initial- and boundary-value problem (IVP & BVP) in a rotating frame of reference: (Primitive Equations)

$\dfrac{du}{dt} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x} + fv + F_{rx}$	x-momem. eq.	(1)
$\dfrac{dv}{dt} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial y} - fu + F_{ry}$	y-momem. eq.	(2)
$\dfrac{dw}{dt} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial z} - g + F_{rz}$	z-momem. eq.	(3)
$\dfrac{d\rho}{dt} = -\rho\left(\dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z}\right)$	Continuity eq.	(4)
$\dfrac{dT}{dt} = Q$	Thermo. energy eq.	(5)
$p = \rho RT$	Eq. of state	(6)

NWP Model Development: A numerical model based on the above primitive equations may be developed step by step.

For example, the inviscid nonlinear Burger equation can be solved numerically using finite difference method, even though it can be solved analytically.

$$\frac{\partial u'}{\partial t} + (U + u')\frac{\partial u'}{\partial x} = 0$$

Apply a finite difference method at discrete points in *x* and *t*

$$\frac{u_i^{\tau+1} - u_i^{\tau-1}}{2\Delta t} + (U + u_i^{\tau})\frac{u_{i+1}^{\tau} - u_{i-1}^{\tau}}{2\Delta x} = 0$$

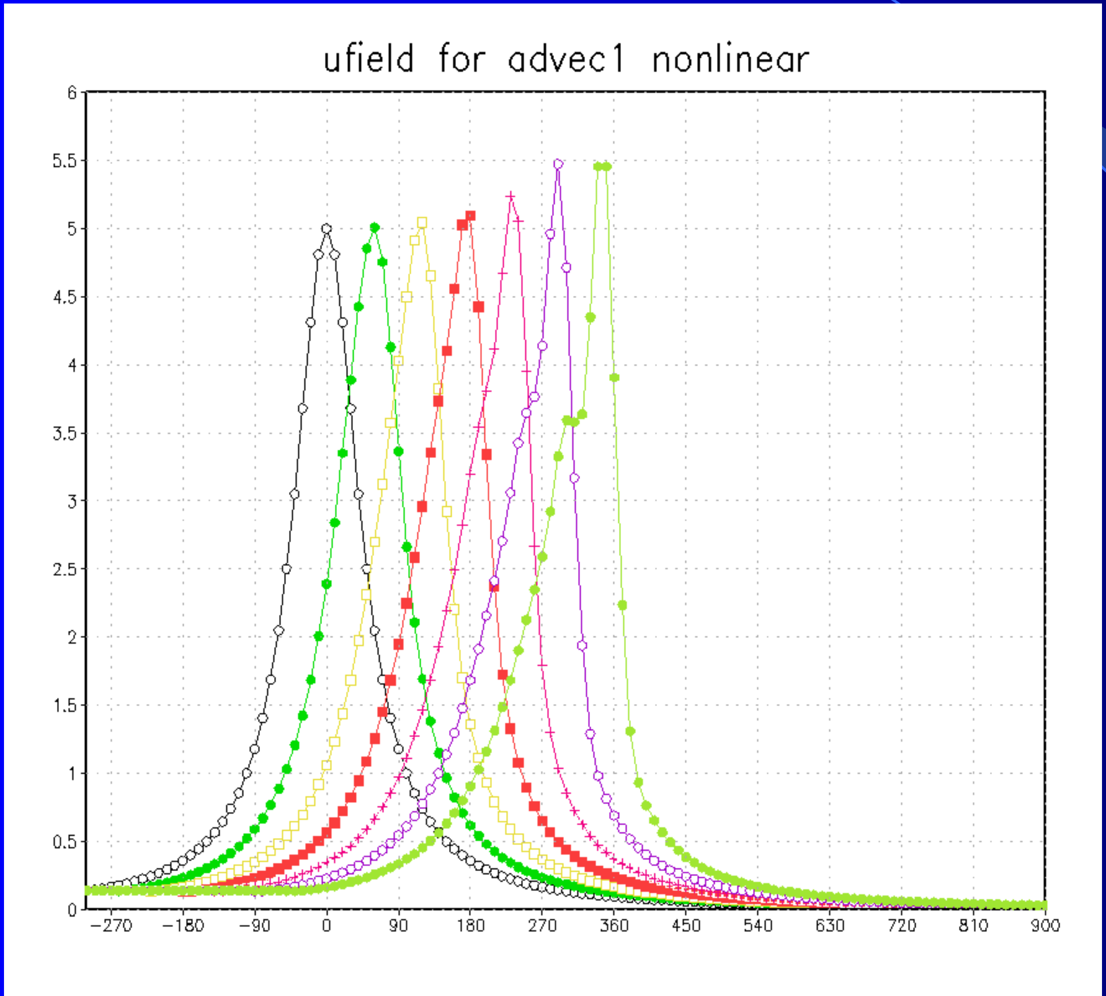
Solve for $u_i^{\tau+1}$

$$u_i^{\tau+1} = u_i^{\tau-1} - \frac{\Delta t}{\Delta x}(U + u_i^{\tau})\left(u_{i+1}^{\tau} - u_{i-1}^{\tau}\right)$$

1D Burger equation

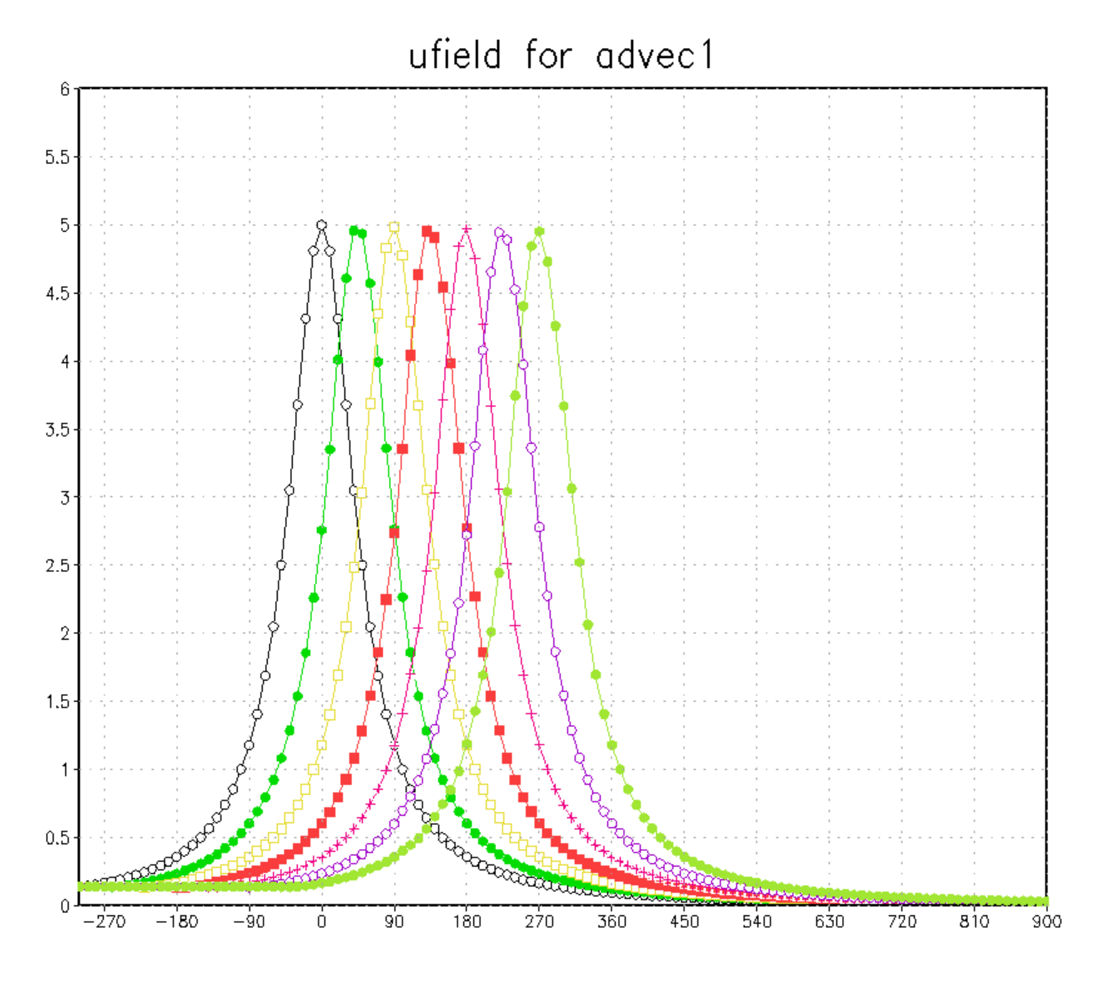
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \nu\frac{\partial^2 u}{\partial x^2}$$

The Advection Model may be used as a powerful way to study some basic wave properties and extend to more complicated models.



$$\frac{\partial u'}{\partial t} + (U + u')\frac{\partial u'}{\partial x} = 0$$

The nonlinearity term can be deactivated to become the Linear Advection Model to study nonlinear effect.

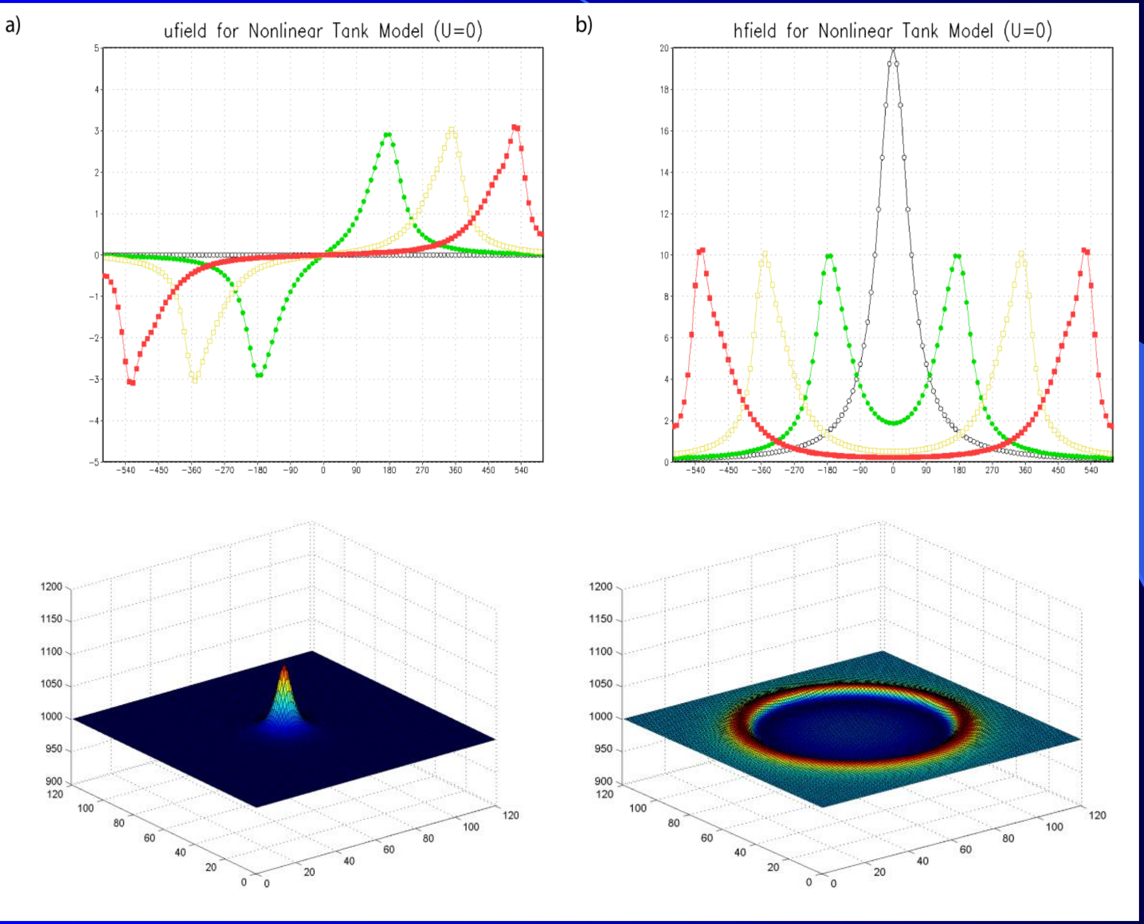


$$\frac{\partial u'}{\partial t} + U\frac{\partial u'}{\partial x} = 0$$

The above advection model can be modified to build a 2D and then extend to a 3D shallow-water tank models, based on shallow-water systems:

2D Tank Model

3D Tank Model



The 3D Tank Model can then be further extended to build a model based on the primitive equations (1)–(6).

- A simple NWP model based on Eqs. (1) – (6) may be extended from the above Tank Model.
- In 1922, Lewis Richardson, did the very first numerical weather prediction based on a simple primitive equation model. He made a 6-h forecast with hand calculators which took more than 6 weeks.
- The first successful NWP was performed using the ENIAC digital computer in 1950 by Charney, Fjotoft, von Neumann et al.
- Today's NWP: (NOAA NCDC)

Mathematically, we are facing lots of challenges, some of them have been resolved, but some not:

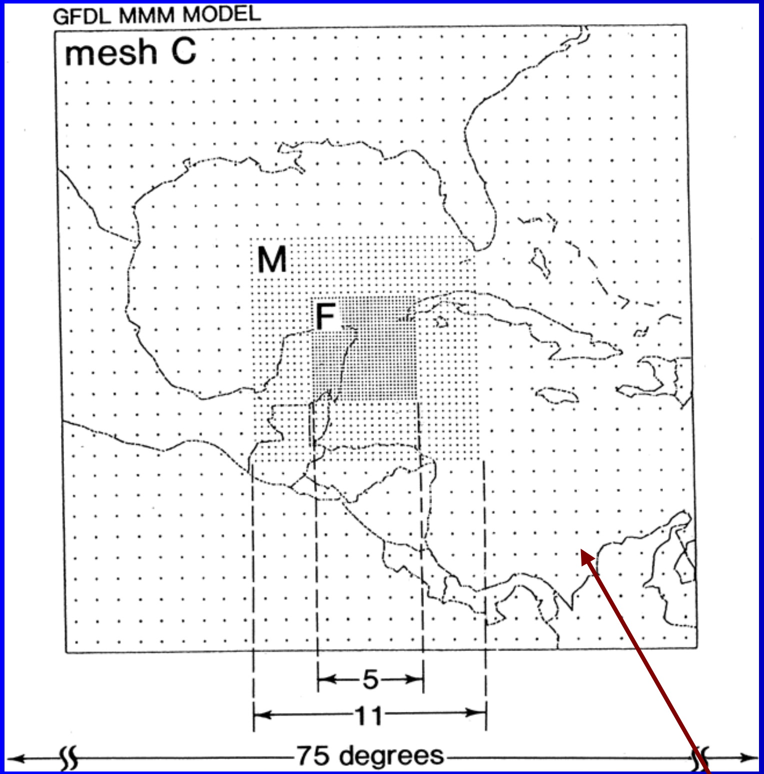
1. IVP: lack of i.c., obs. data not on grid points, inconsistency with governing equations, etc. => a need of initialization
2. Incorporation of obs. data into model => data assimilation
3. BVP:
   - Lower b.c. problem => terrain-following coordinates or finite element method
   - Upper b.c. problem => radiative or sponge layer approaches
   - Lateral b.c. problem => open b.c. to advect energy out of the domain
4. Requirement of conservation of mass => leads to the development of staggered grids.
5. Non-unique numerical solutions => development of Ensemble forecasting technique
6. The number of primitive equations grows when more physical processes are involved, such as moist convection.
7. Then, came the big question of the predictability of the atmosphere, as proposed by Lorentz.

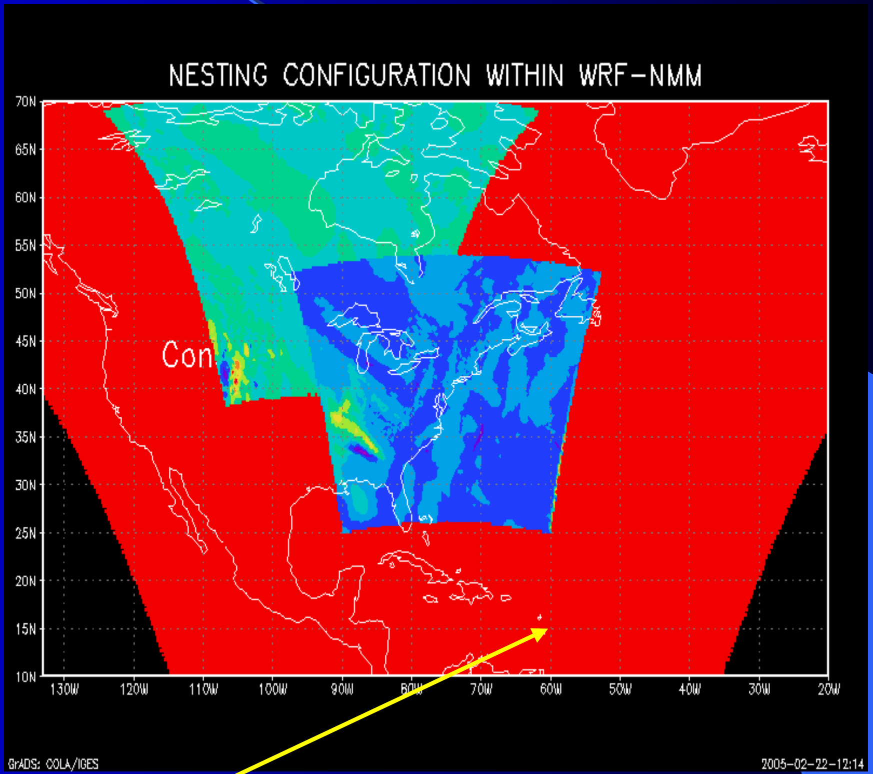
Physically, we are also facing lots of challenges, e.g.:

1. To satisfy the CFL criterion for a fully-compressible system which includes sound waves => leads to the development of the time-splitting scheme
2. To represent subgrid physical processes, such as planetary boundary layer, cumulus and cloud microphysics, radiation, air-sea interaction, etc. => a need of physical parameterization schemes
3. Inclusion of moisture => Need to add 6 – 7 additional equations, based on conservation of mass for each hydrometeor species.
4. The need to verify NWP results requires field experimenst (campaigns) which are very expensive.
5. NWP models rely on global models to provide i.c. and b.c., thus inherit errors from global models.
6. Need more powerful supercomputers for real-time forecasting.

Examples of Special Techniques used in NWP Models:

Using a moving, nested grid domain with higher resolution to follow a hurricane:

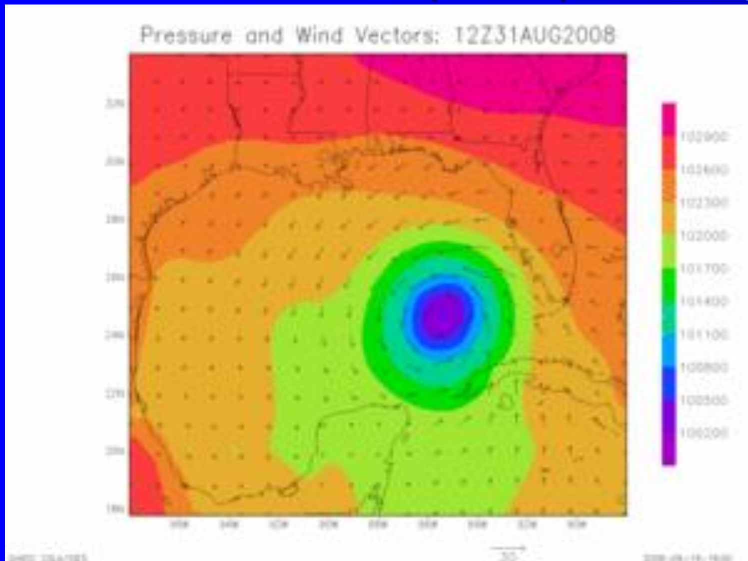




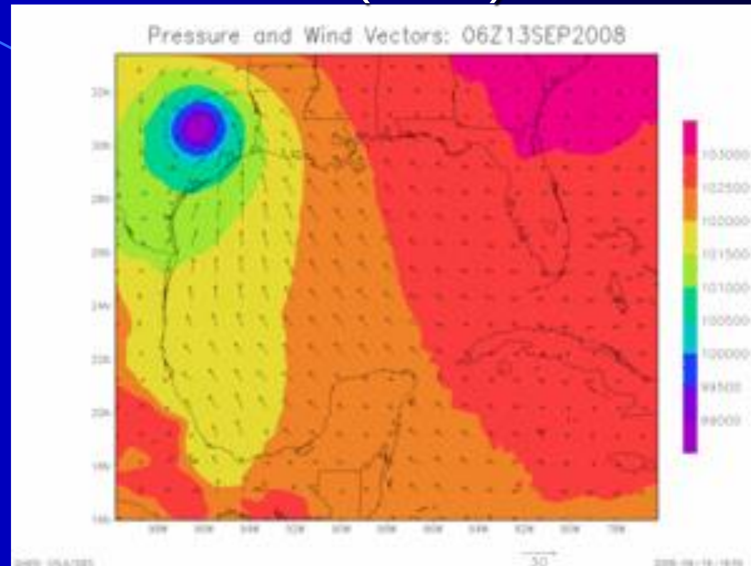
Note that there is not much data over the ocean, which is one major source of forecast errors!

A grid mesh moving with hurricanes

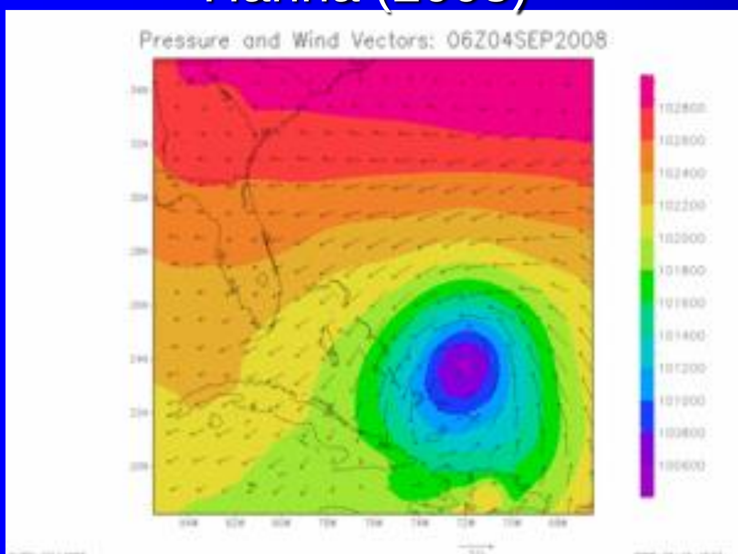
Gustav (2008)



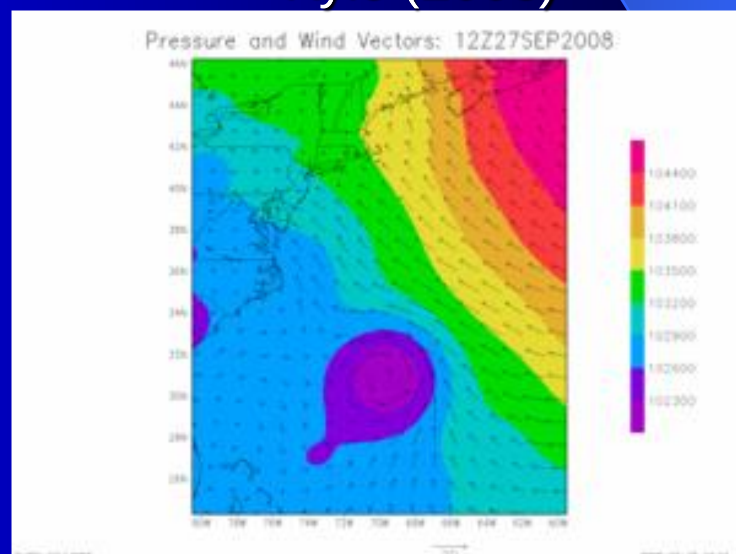
Ike (2008)



Hanna (2008)



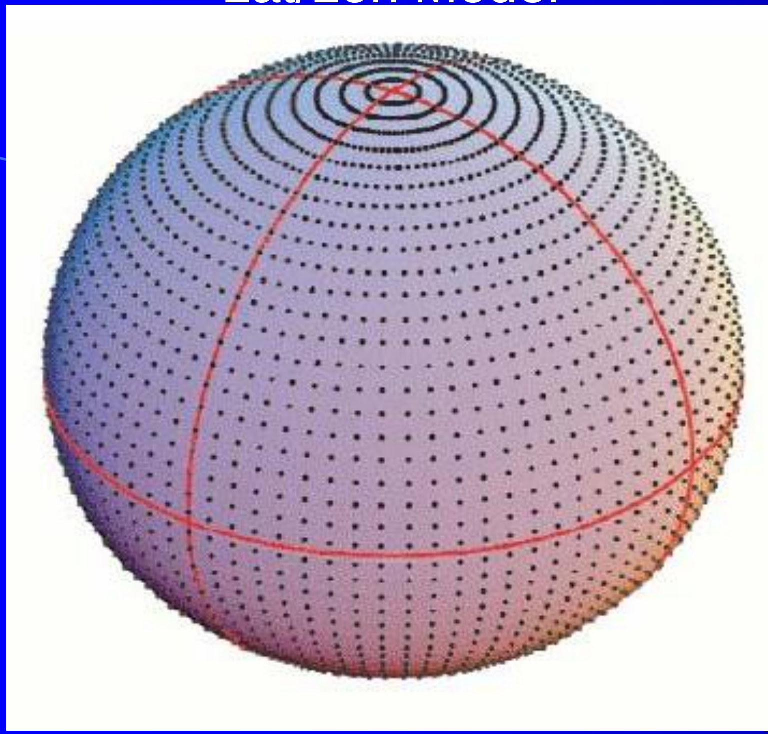
Kyle (2008)



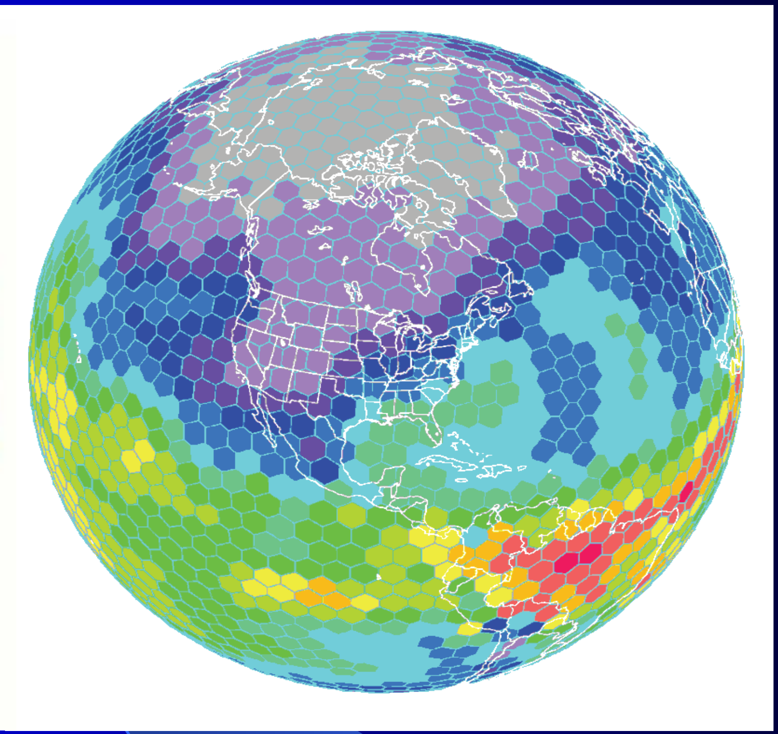
Roop, Lin, Tang (2008)

Using Global Models for NWP

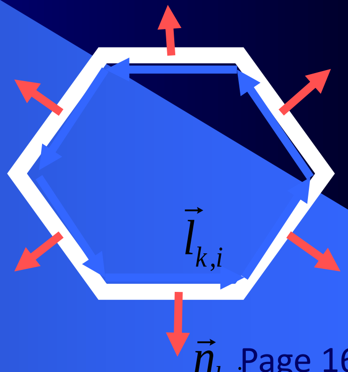
Lat/Lon Model



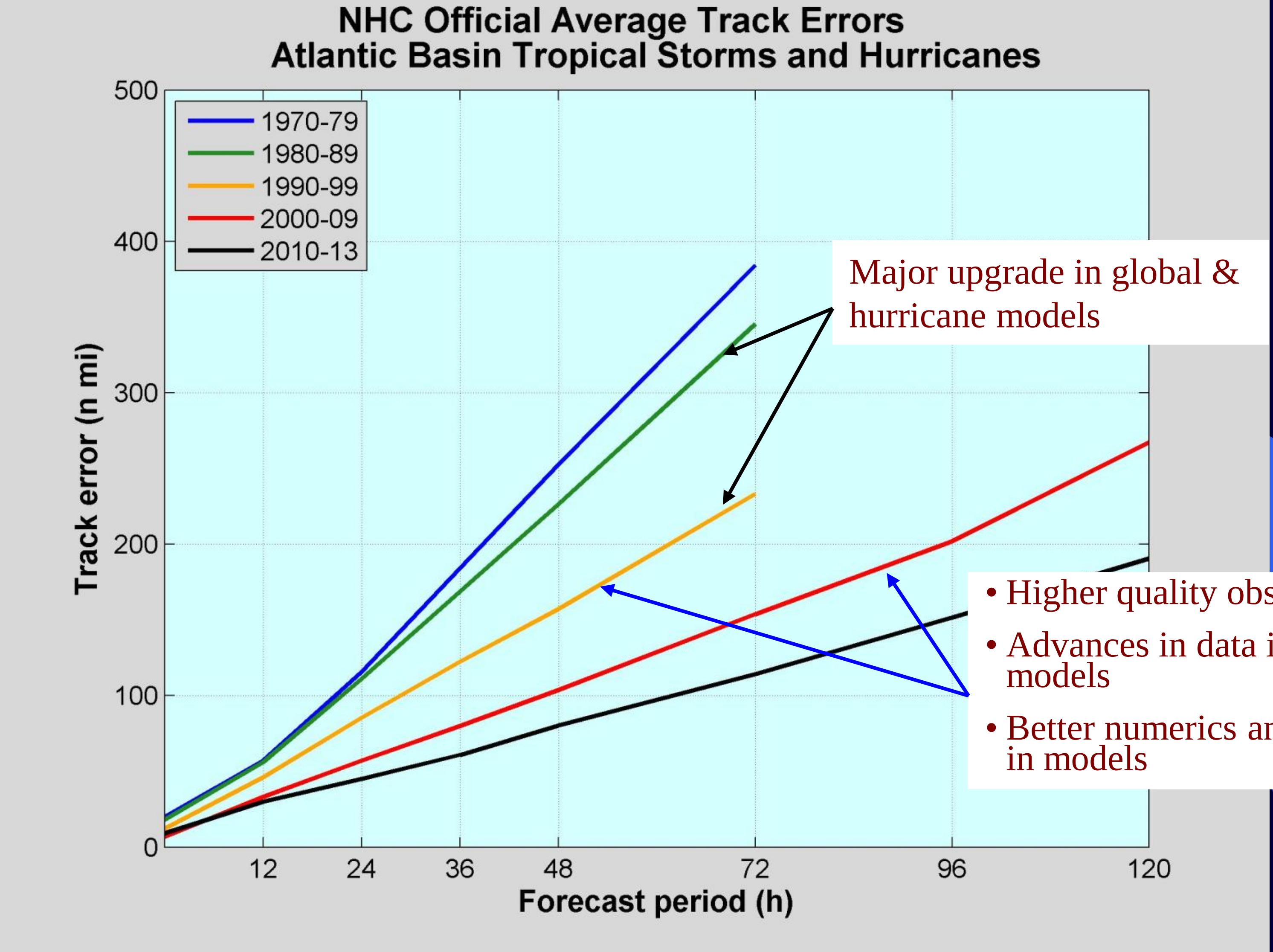
Icosahedral Model



- No singularity at poles
- Near constant resolution over the globe
- Efficient high resolution simulations
- NOAA ESRL FIM model; NIM model
- NCAR MPAS model



Challenges in NWP: TC Track Forecasting



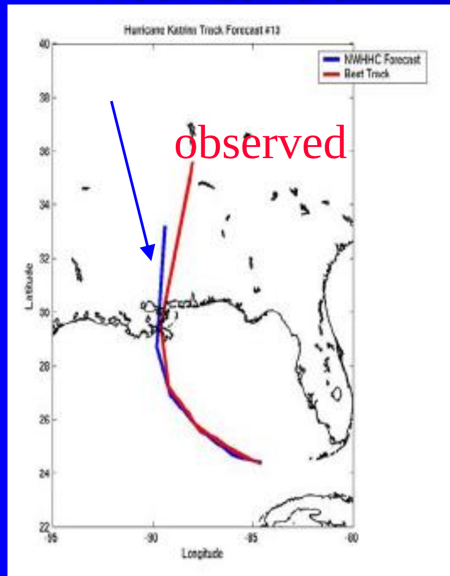
Major upgrade in global & hurricane models

- Higher quality observations
- Advances in data input into models
- Better numerics and physics in models

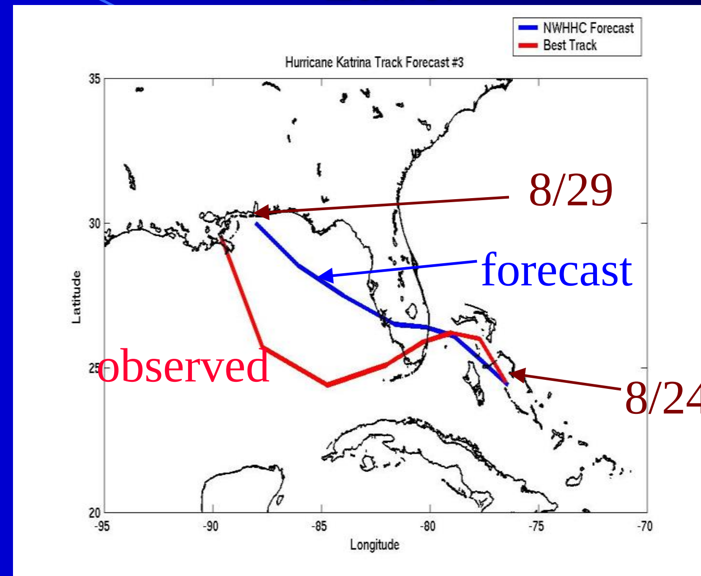
National Hurricane Center

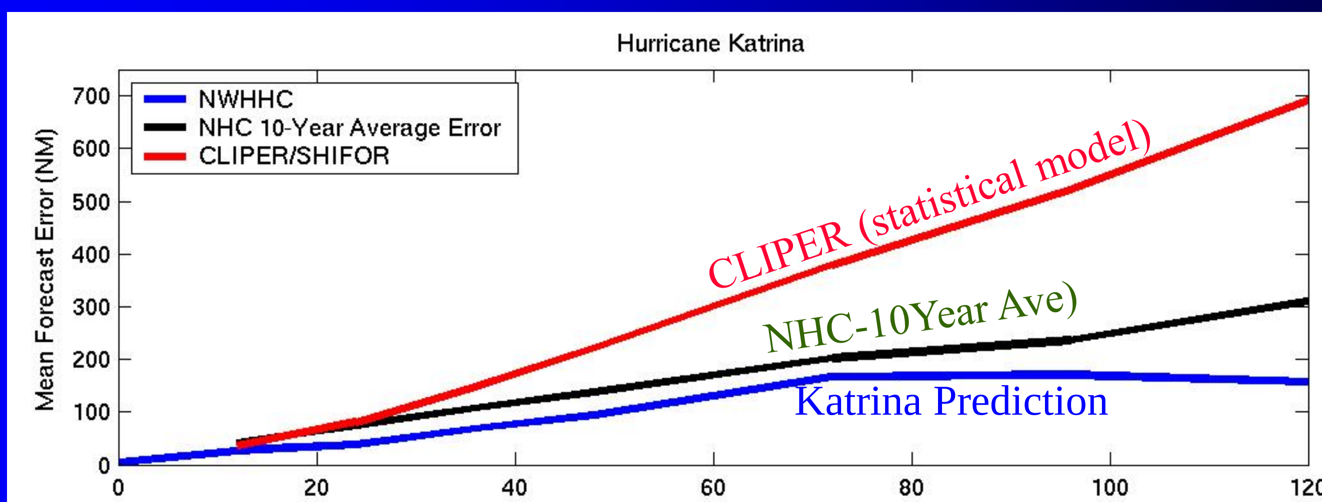
Example: Hurricane Katrina (2005) Prediction

Near Landfall



Earlier



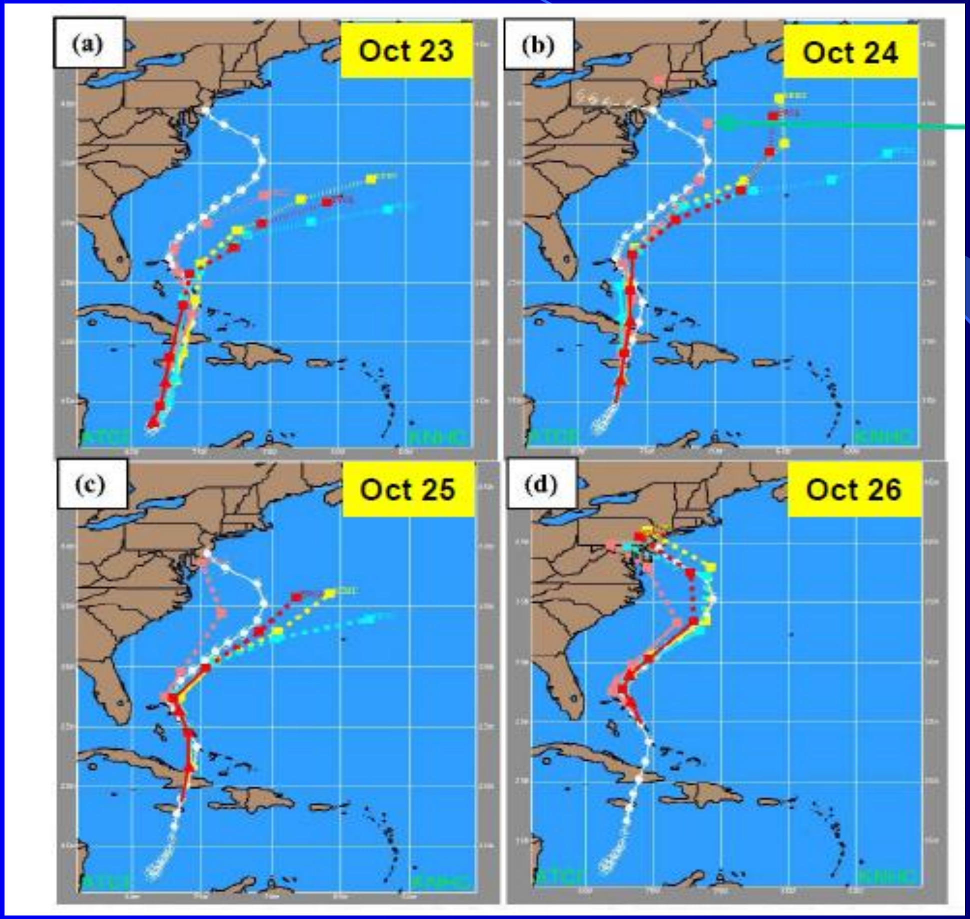


Hour

Simulation of Hurricane Katrina (2005) by a Mesoscale Global Model

(Courtesy of Dr. Bo-Wen Shen NASA/GSFC)

Many models had missed forecasting the unusual inland track deflection 5 days before Sandy's (2012) landfall



Forecasts of Sandy (2012) began at 00Z Oct. 23, 24, 25, and 26 for every 12 h by GFDL, HWRF, ECMWF, and GFS (Blake et al. 2013). The NHC best track is denoted by the hurricane symbol.

The offshore forecast error may be due to the Ω block

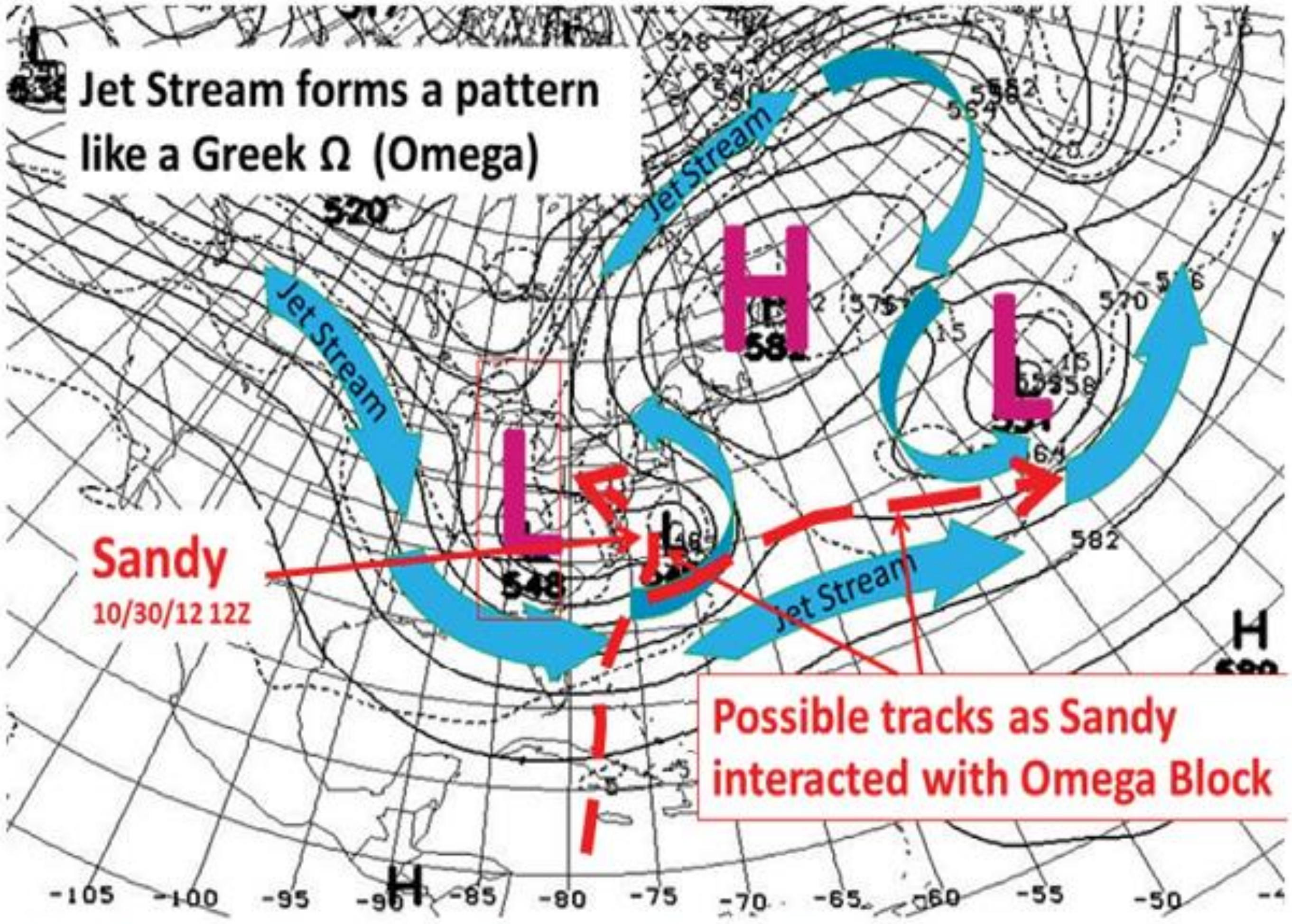
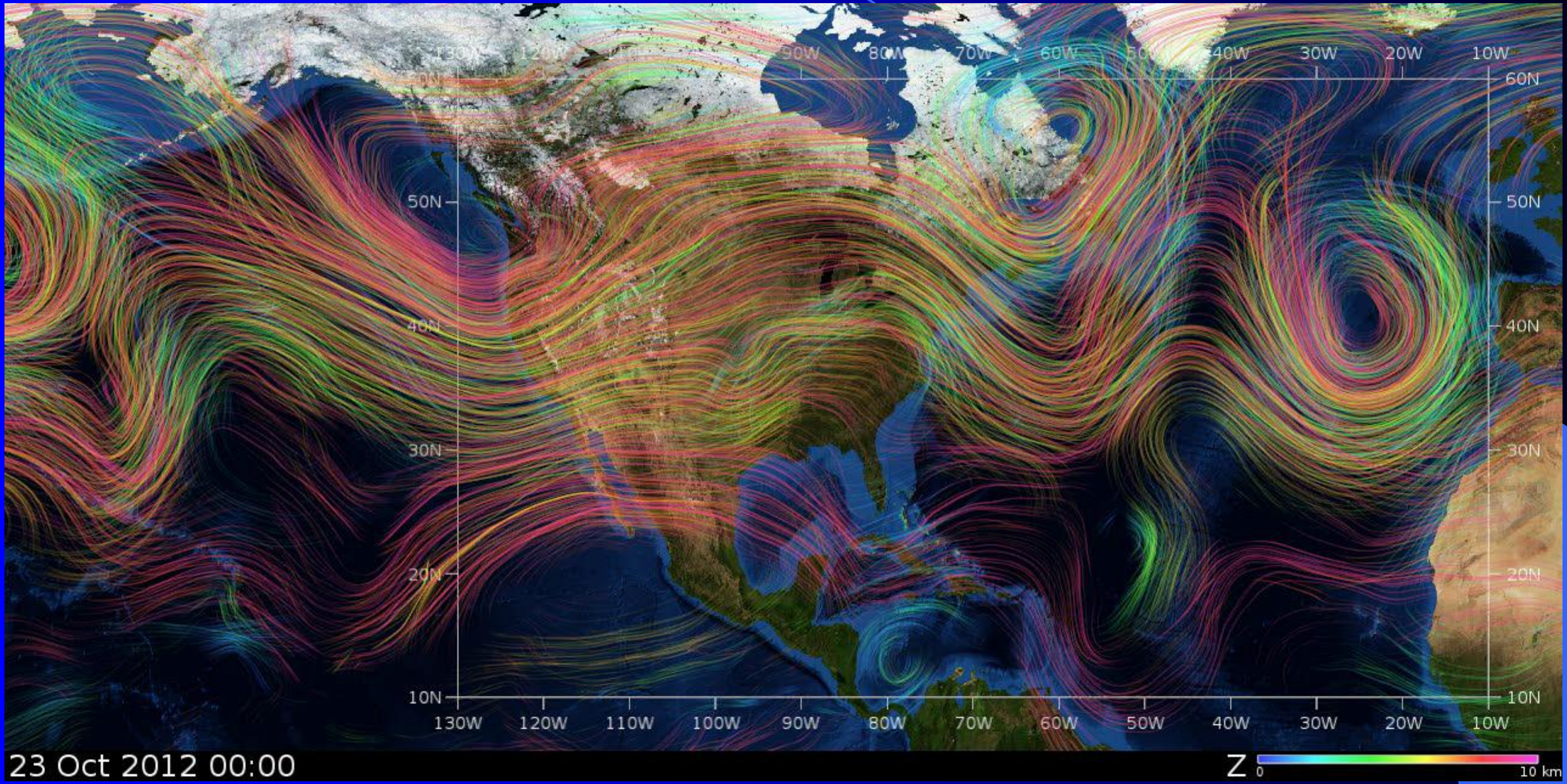


Figure 3. A cartoon illustrating possible tracks that Sandy could have taken as it interacted with the developing Omega Block over the Atlantic. See text for more discussion. The cartoon is overlaid on the 500 mb geopential height map for 10/30/12 at 12Z.

Gall et al. (2013)

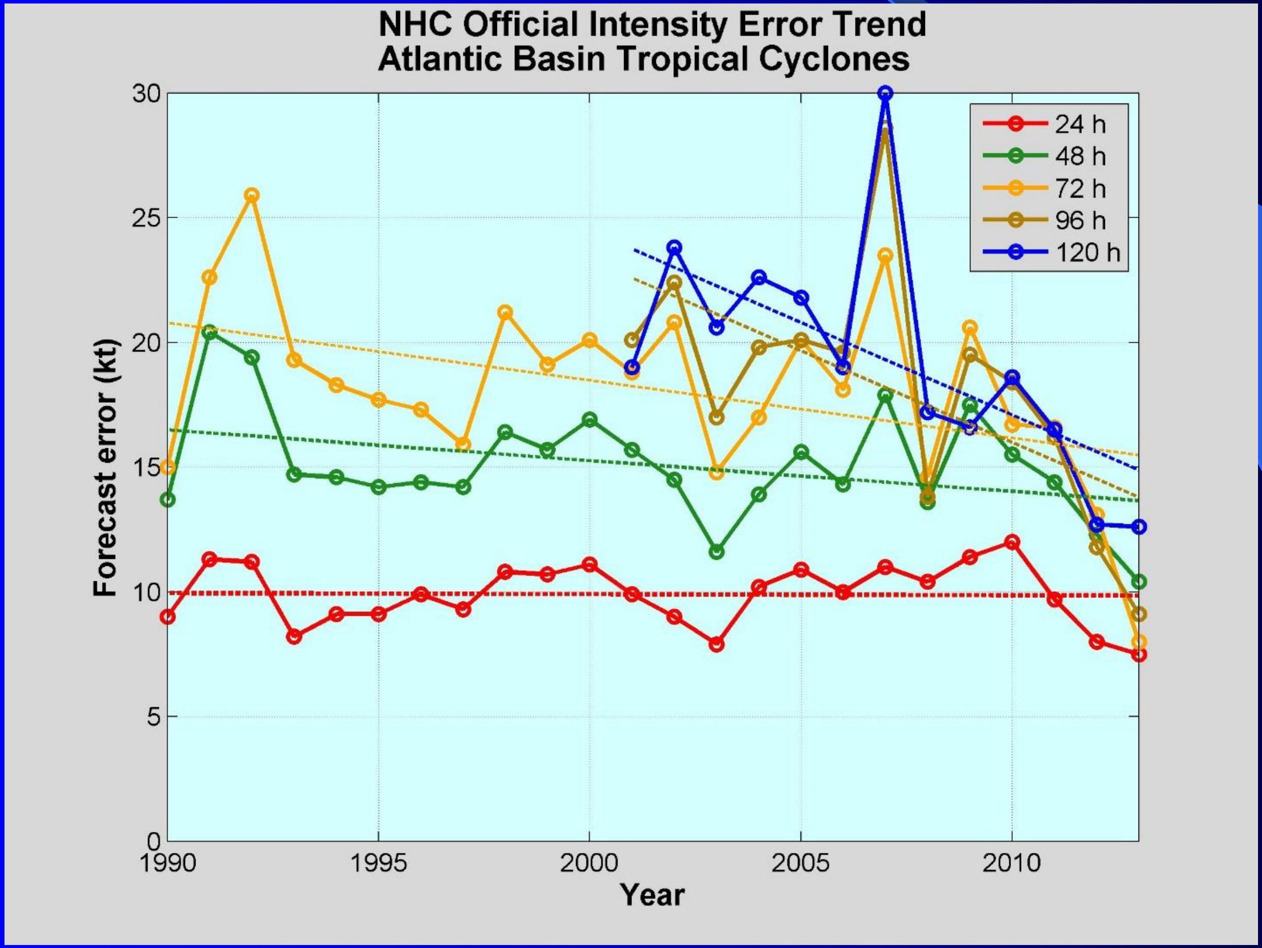
Interaction of Sandy (2012) and a Trough simulated by the NASA Global Mesoscale Model



(Courtesy of Dr. Bo-Wen Shen, University of Maryland and NASA)

Challenges in NWP: Hurricane Intensity and Rainfall Prediction

Not much progress in short-term intensity prediction!



Inner core and rainbands need to be well observed and represented in the model

Hurricane Core Structure