WRF Modeling System: Overview

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Courtesy to NCAR

Current Focus in NWP

1.Initial Condition and Boundary Condition

- observations
- Data quality control
- Assimilation

2.Dynamics and Physics

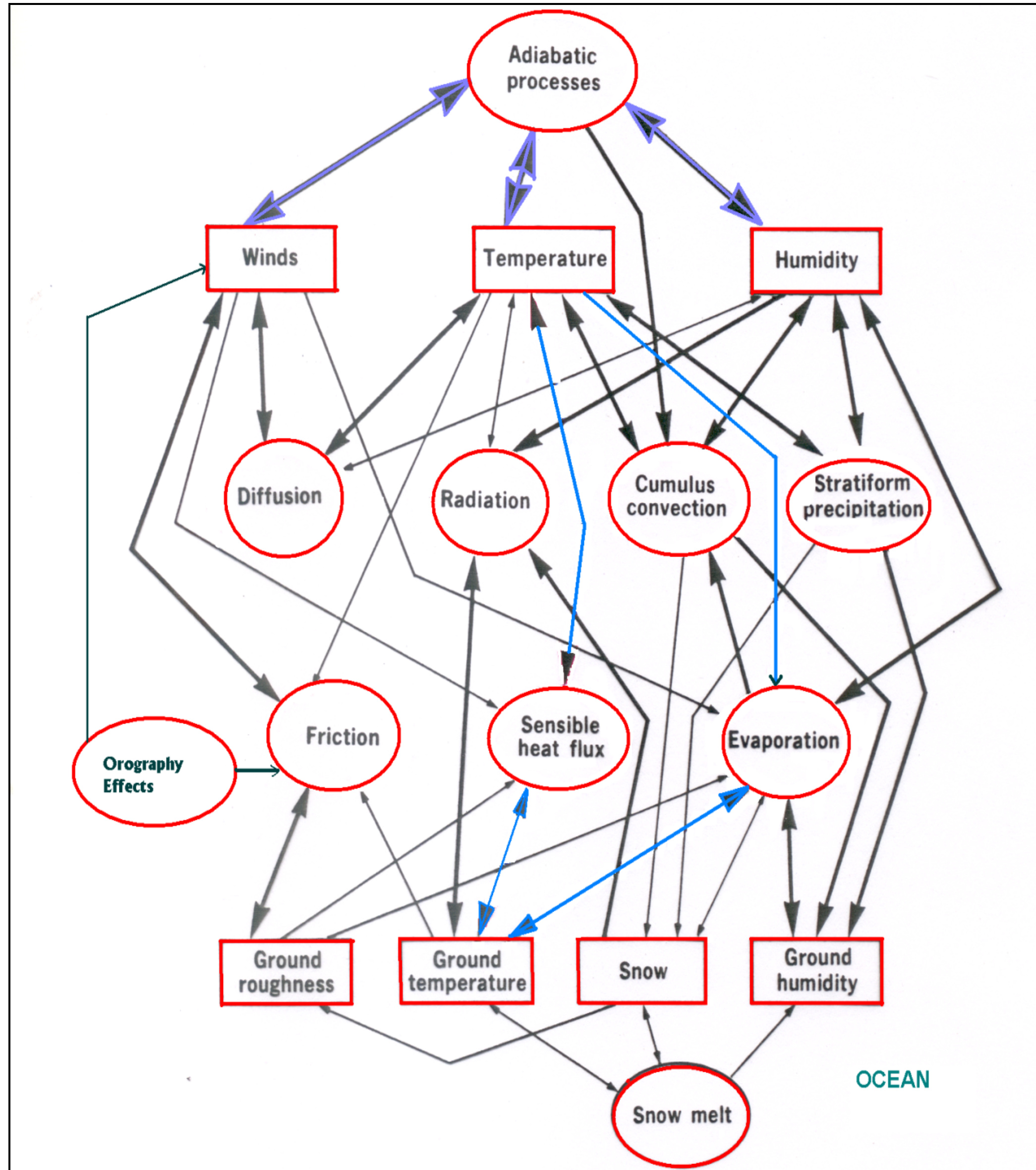
- Model framework and resolution
- Representation of physical processes through appropriate physics parameterization

3.Post-processing

- System Diagnosis.
- Bias Correction.
- Location specific forecast
- Probabilistic prediction

Complex interactions of dynamics and physics

The thickness of the arrows represented qualitatively the importance of the interactions.
Any close loop indicates a feed-back phenomenon.
(ED: Temp → Evp → Ground Temp → Sen Heat Flux → Temp).
The physical processes and the feedback mechanisms to be incorporated
in a numerical model.



What is WRF?

- WRF: Weather Research and Forecasting Model
  Used for both research and operational forecasting

- It is a supported "community model".

- Its development is led by NCAR, NOAA/ESRL (ARW) and NOAA/NCEP/EMC (NMM) with partnerships at AFWA, FAA, and collaborations with universities and other government agencies in the US and overseas

What are ARW and NMM?

- The Advanced Research WRF (ARW) and Non-hydrostatic Meso-scale Model (NMM) are dynamical cores

  Dynamical core includes mostly advection, pressure-gradients, Coriolis, buoyancy, filters, diffusion, and time-stepping

- Both are Eulerian mass dynamical cores with terrain-following vertical coordinates
- ARW support and development are centered at NCAR/MMM
- NMM development is centered at NCEP/EMC and support is provided by NCAR/DTC
- Both are downloadable in the same WRF tar file
- *This tutorial is for ARW core only*
- Physics, the software framework, and parts of data pre- and post-processing are shared between the dynamical cores

What can WRF be used for?

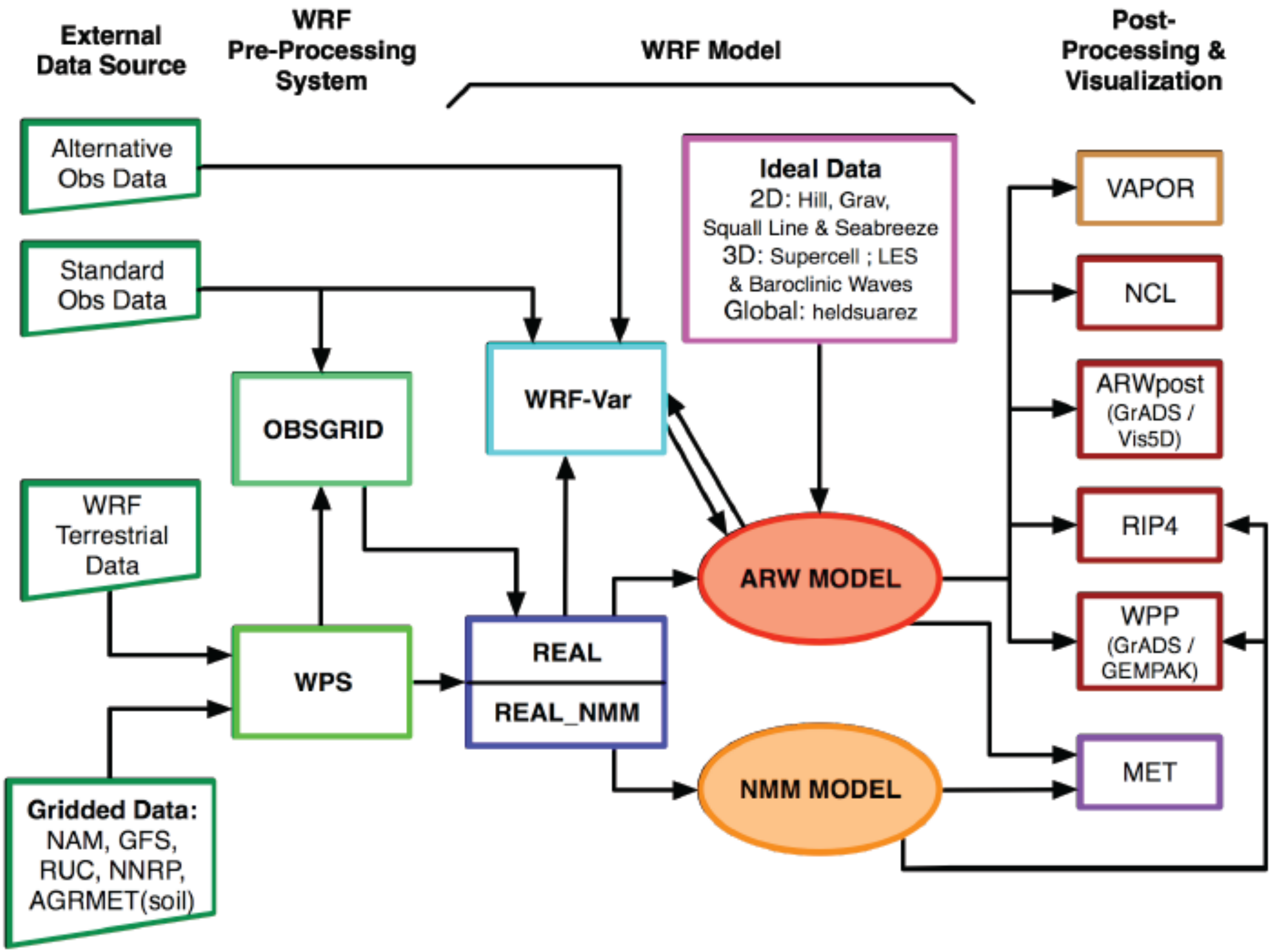
- ARW and NMM
  - Atmospheric physics/parameterization research
  - Case-study research
  - Real-time NWP and forecast system research
  - Data assimilation research
  - Teaching dynamics and NWP

- ARW only
  - *Regional climate and seasonal time-scale research*
  - *Coupled-chemistry applications*
  - *Global simulations*
  - *Idealized simulations at many scales (e.g. convection, baroclinic waves, large eddy simulations)*

WRF user interface

- Research and Development in dynamics, physics of severe weather events
- Weather and climate Research
- Air quality and hydrology studies
- Operational endeavor

WRF modeling system Flow Chat



*First need to compile WRF and then WPS

Modeling System Components

- WRF Pre-processing System (WPS)
  - Real-data interpolation for NWP runs
  - New obsgrid program for adding more obs to analysis
- WRF Model (ARW and NMM dynamical cores)
  - Initialization programs for (ARW) real and idealized data (real.exe / ideal.exe)
  - Numerical integration program (wrf.exe)
- WRFDA (ARW)
  - Pre-processing of observational data (obsproc.exe)
  - WRF-VAR analysis executable (wrfvar.exe)
  - Updating boundary conditions (bc_update.exe)
- Graphics and verification tools including MET

Graphics and Verification Tools

- ARW and NMM
  - RIP4 (Read, Interpolate and Plot)
  - *WRF Post-Processor (WPP)*
- ARW
  - NCAR Graphics Command Language (NCL)
  - ARWPost
  - Conversion program for GrADS and Vis5D

MET (Model Evaluation Toolkit)

Portability

- Runs on Unix single, OpenMP and MPI
- Platforms:
  - IBM SP AIX (xlf)
  - Linux (PGI, Intel and GNU compilers)
  - SGI Altix (Intel)
  - Cray XT (PGI, Pathscale)
  - Mac Darwin (xlf, PGI, Intel, g95 compilers)
  - Others (HP, Sun, SGI Origin, Compaq)

Basic Software Requirement

- FORTRAN 90/95 compiler
- C compiler
- Perl
- NETCDF library
- NCAR Graphics (optional, but recommended – used by graphical utility programs)
- Public domain mpich for MPI

Optional libraries for GRIB2 support (in WPS):*

- *JasPer (JPEG 2000 "lossy" compression library)*
- *PNG ("lossless" compression library)*
- *zlib (compression library used by PNG*

ARW Modeling System

WRF model Program Flow

If you are only planning to run ***Idealized*** Cases, you would need:

WRF ARW Model + Post Processing

If you are planning on running ***Real*** Cases, you would need:

WPS + WRF ARW Model + Post Processing

If you are planning on running ***Real Cases with Variational Analysis***, you would need:

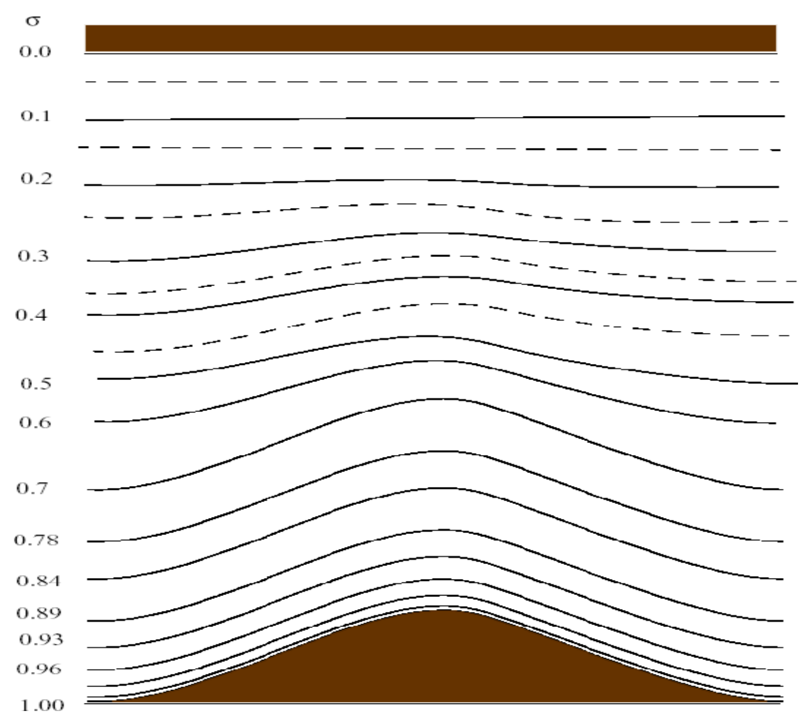
WPS + WRF-Var + WRF ARW Model + Post Processing

WRF Model Key features

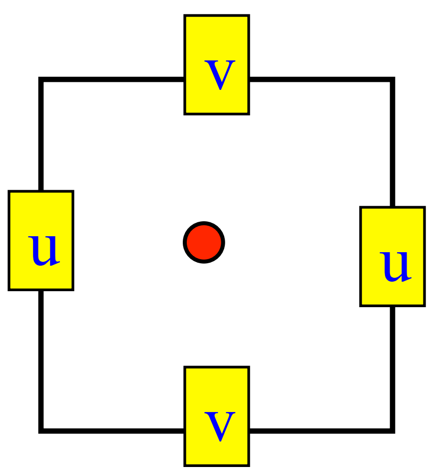
• Fully compressible, non-hydrostatic (with hydrostatic option)

• Mass-based terrain following coordinate, η
where π is hydrostatic pressure, μ is column mass

$$\eta = \frac{(\pi - \pi_t)}{\mu}, \qquad \mu = \pi_s - \pi_t$$



• Arakawa C-grid staggering



Scalars: $\Theta, \delta p$

WRF Model Key features ….cntd

- 3rd-order Runge-Kutta time integration scheme
- 5th-order upwind advection scheme
- Scalar-conserving (positive definite option)
- Complete Coriolis, curvature and mapping terms
- Two-way and one-way nesting

WRF Model Key features ….cntd

- Choices of lateral boundary conditions suitable for real-data and idealized simulations

– Specified, Periodic and Nested

- Full physics options to represent atmospheric radiation, surface and boundary layer, and cloud and precipitation processes

- Grid and observational nudging (FDDA)

- New Digital Filter Initialization option

WRF Model Key features ….cntd

- Two executable stages with namelist input

– real.exe: set up vertical model levels for model input and boundary files

– wrf.exe: Integration model

ARW real and ideal functions

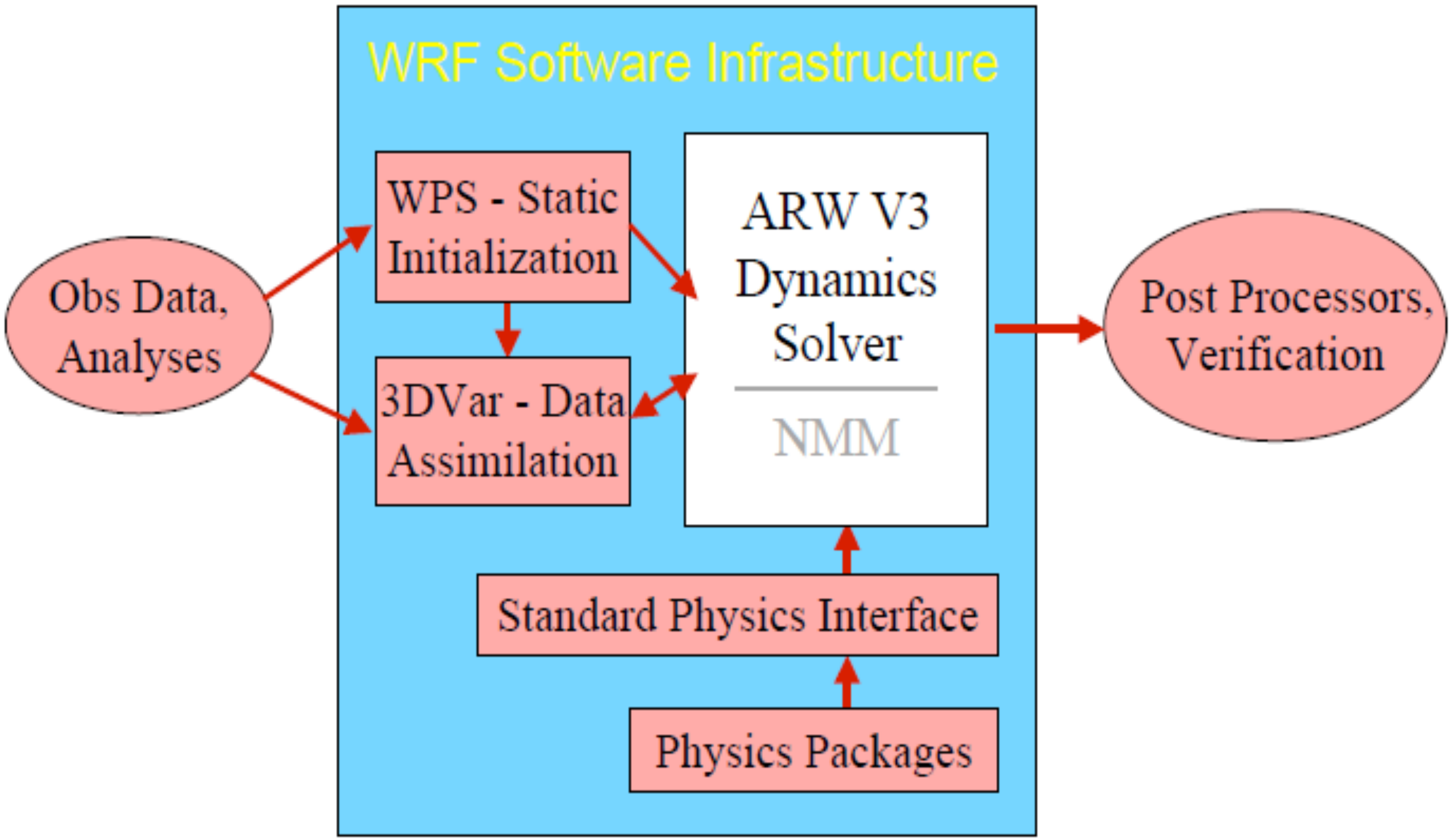
- REAL

– Creates initial and boundary condition files for real-data cases
– Does vertical interpolation to model levels (when using WPS)
– Does vertical dynamic (hydrostatic) balance
– Does soil vertical interpolations and land-use mask checks

- IDEAL

– Programs for setting up idealized case
– Simple physics and usually single sounding
– Initial conditions and dynamic balance

ARW Dynamics


WRF Software Infrastructure
Obs Data, Analyses
WPS - Static Initialization
3DVar - Data Assimilation
ARW V3 Dynamics Solver
NMM
Post Processors, Verification
Standard Physics Interface
Physics Packages

ARW Solver

- ***Equations:*** **Fully compressible ,**
  - **Euler non-hydrostatic**
  - **hydrostatic option also available.**
- ***Prognostic Variables:***
  - **Velocity components *u, v and w***
  - **perturbation potential temperature,**
  - **perturbation geopotential,**
  - **perturbation surface pressure**
- ***Vertical Coordinate:*** **Terrain-following hydrostatic-pressure, with vertical grid stretching permitted. Top of the model is a constant pressure surface.**
- ***Horizontal Grid:*** **Arakawa C-grid staggering.**

- ***Time Integration:*** **Time-split integration using a 2nd- or 3rd-order Runge-Kutta scheme with smaller time step for acoustic and gravity-wave modes.**

- ***Spatial Discretization:*** **2nd- to 6th-order advection options in horizontal and vertical.**

- ***Initial Conditions:*** **Three dimensional for real-data, and one-, two- and three-dimensional for idealized data. Digital filtering initialization (DFI) capability available (real-data cases).**

- ***Lateral Boundary Conditions:*** **Periodic, open, symmetric, and specified options available.**

- ***Earth's Rotation:*** **Full Coriolis terms included.**

- ***Mapping to Sphere:*** **Four map projections are supported for real-data simulation (Curvature terms included):**
    - **polar stereographic,**
    - **Lambert conformal,**
    - **Mercator,**
    - **latitude-longitude (allowing rotated pole).**

- ***Nesting:*** **One-way interactive, two-way interactive, and moving nests. Multiple levels and integer ratios.**

- ***Nudging:*** **Grid (analysis) and observation nudging capabilities available.**

- ***Global Grid:*** **Global simulation capability using polar Fourier filter and periodic east-west conditions.**

Different Vertical Coordinate Systems

- Sigma coordinate
- Eta Coordinate
- Theta Coordinate
- Hybrid Coordinate
- Isentropic-sigma hybrid

Comparison between Different vertical coordinates

Vertical Coordinate	Models	Primary Advantage	Primary Limitation
Eta ( )	Eta, WRF	Allows for large local differences in terrain from one grid point to another	May not represent the boundary layer with sufficient resolution over elevated terrain
Generic hybrid	ECMWF, NOGAPS	Combines strengths of several coordinate systems	Difficult to properly interface across coordinate domains
Isentropic-sigma hybrid ( )	RUC	Naturally increases resolution in baroclinic regions, such as fronts and tropopause	Incompletely depicts important low-level adiabatic flow
Sigma ( )	AVN/MRF, NGM, MM5, RAMS	Surfaces are terrain-following and therefore resolve the boundary layer well	May not correctly portray weather events in lee of mountains (downwind)

Vertical Coordinate

- **The ARW equations are formulated using a terrain-following hydrostatic-pressure vertical coordinate denoted by η (ETA) and defined as**

$\eta=(P_h-P_{ht})/\mu$ where $\mu=P_{hs}-P_{ht}$

P_h=hydrostatic component of the pressure

P_{hs} and P_{ht} refer to values along the surface and top boundaries, respectively.

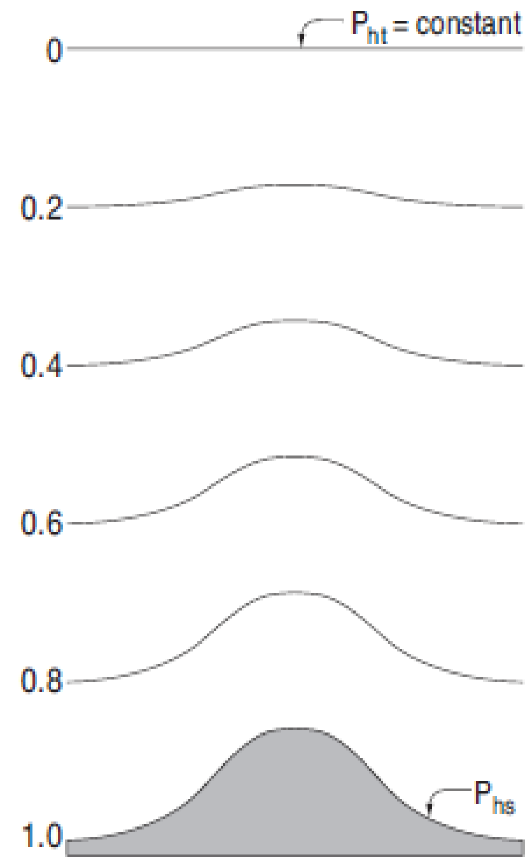


Figure 2.1: ARW η coordinate.

- **The ARW dynamics solver integrates the compressible, non-hydrostatic Euler equations.**

- **The equations are cast in flux form using variables that have conservation properties, following the philosophy of mass and entropy by Ooyama (1990).**

- **The equations are formulated using a terrain-following mass vertical coordinate (Laprise, 1992).**

- **Define μ(x, y) represents the mass per unit area within the column in the model domain at (x, y), the appropriate flux form variables are**

$$\mathbf{V} = \mu \mathbf{v} = (U, V, W),\quad \Omega = \mu \acute{\eta},\quad \Theta = \mu\theta$$

where v = (u, v,w) are the covariant velocities in the two horizontal and vertical directions, respectively,

while ω= ή (dη/dt) is the contravariant 'vertical' velocity.

θ is the potential temperature. Also appearing in the governing equations of the ARW are the non-conserved variables φ= gz (the geopotential).

p is the pressure.

Flux-Form Euler Equations

U-equation	$\frac{\partial U}{\partial t} + (\nabla . Vu) - p\left(\frac{\partial \phi}{\partial x}\right) + p\left(\frac{\partial_x \phi}{\partial \eta}\right) = F_U$	**1**
V-equation	$\frac{\partial V}{\partial t} + (\nabla . Vv) - p\left(\frac{\partial \phi}{\partial y}\right) + p\left(\frac{\partial_y \phi}{\partial \eta}\right) = F_V$	**2**
W-equation	$\frac{\partial W}{\partial t} + (\nabla . Vw) - g\left(\frac{\partial p}{\partial \eta} - \mu\right) = F_W$	**3**
Energy Eqn.	$\frac{\partial \Theta}{\partial t} + (\nabla . V\theta) = F_\theta$	**4**
Continuity Eqn.	$\frac{\partial \mu}{\partial t} + (\nabla . V) = 0$	**5**
Eqn. of Moisture	$\frac{\partial q}{\partial t} + (\nabla . Vq) = 0$	**6**
Geopotential Eq.	$\frac{\partial \phi}{\partial t} + \mu^{-1}\left[(\nabla . V\phi) - gW\right] = 0$	**7**

Diagnostic relations:

$$\frac{\partial \phi}{\partial \eta} = -\mu\alpha, \qquad p = \left(\frac{R\theta}{p_0 \alpha}\right)^{\gamma}, \qquad \Omega = \mu\dot{\eta}$$

- The right-hand-side (RHS) terms F_U, F_V , F_W, and F_θ represent forcing terms arising from model physics, turbulent mixing, spherical projections, and the earth's rotation.
- The prognostic equations (1 – 7) are cast in conservative form except for Eq^n (7) which is the material derivative of the definition of the geopotential.
- The Eq^n (7) could be cast in flux form but we find no advantage in doing so since $\mu\varphi$ is not a conserved quantity.
- Prognostic pressure equation is used in the place of Eq^n (7) (Laprise, 1992).

Inclusion of Moisture

- **In formulating the moist Euler equations, dry air mass is added to the prognostic variables.**

- **On these principles, the vertical coordinate can be written as**

$$\eta = (p_{dh} - p_{dht})/\mu_d$$

where μd represents the mass of the dry air in the column

p_{dh} represent the hydrostatic pressure of the dry atmosphere

p_{dht} the hydrostatic pressure at the top of the dry atmosphere.

- **The coupled variables are defined as**

$$\mathbf{V} = \mu_d \mathbf{v} = (U, V, W), \quad \Omega = \mu_d \acute{\eta}, \quad \Theta = \mu_d \theta$$

We follow this approach because μ_d is a conserved quantity that can be used to formulate flux-form equations for other conserved variables that do not contain additional terms accounting for sources and sinks of liquid water.

The moist Euler equations can be written as:

$$\partial_t U + (\nabla . \mathbf{V} u) - \mu_d \alpha \, \partial_x p + (\alpha / \alpha_d) \;\; \partial_\eta p \partial_x \phi \quad = \quad F_U$$

$$\partial_t V + (\nabla . \mathbf{V} v) - \mu_d \alpha \, \partial_y p + (\alpha / \alpha_d) \;\; \partial_\eta p \partial_y \phi \quad = \quad F_V$$

$$\partial_t \mathbf{W} + (\nabla . \mathbf{V} w) - g \; [(\alpha / \alpha_d) \;\; \partial_\eta p - \mu_d] \quad = \quad F_W$$

$$\partial_t \Theta + (\nabla . \mathbf{V} \theta) \quad = \quad F_\theta$$

$$\partial_t \mu_d + (\nabla . \mathbf{V}) \quad = \quad 0$$

$$\partial_t \phi + \mu_d{}^{-1} [(\mathbf{V} . \nabla \phi) - g \mathbf{W}] \quad = \quad 0$$

$$\partial_\eta Q_m + (\nabla . \mathbf{V} q_m) \quad = \quad F Q_m$$

$$\partial_\eta \phi \quad = \quad - \alpha_d \mu_d$$

$$p \quad = \quad p_0 (R_d \theta_m \div p_0 \alpha_d)^\gamma$$

$\theta m = \theta(1 + (R_v/R_d)q_v) \approx (1 + 1.61q_v)$, and

$Q_m = \mu_d \, q_m$; $q_m = q_v, q_c, q_i, \ldots$.

After that the map projections, coriolis and curvature terms are also included in the moist Eulerian equations.

Then the final equations are written in perturbation form for all variables before solving.

Final form of the equations in the ARW solver

The momentum equations

$$\partial_t U + m_x[\partial_x(Uu) + \partial_y(Vu)] + \partial_\eta(\Omega u) + (\mu_d \alpha \partial_x p' + \mu_d \alpha' \partial_x \bar{p}) + (\alpha/\alpha_d)(\mu_d \partial_x \phi' + \partial_\eta p' \partial_x \phi - \mu_d' \partial_x \phi) = F_U$$

$$\partial_t V + m_y[\partial_x(Uv) + \partial_y(Vv)] + (m_y/m_x)\partial_\eta(\Omega v) + (\mu_d \alpha \partial_y p' + \mu_d \alpha' \partial_y \bar{p}) + (\alpha/\alpha_d)(\mu_d \partial_y \phi' + \partial_\eta p' \partial_y \phi - \mu_d' \partial_y \phi) = F_V$$

$$\partial_t W + (m_x m_y/m_y)[\partial_x(Uw) + \partial_y(Vw)] + \partial_\eta(\Omega w) - m_y^{-1} g(\alpha/\alpha_d)[\partial_\eta p' - \bar{\mu}_d(q_v + q_c + q_r)] + m_y^{-1}\mu_d' g = F_W ,$$

The mass conservation equation and geopotential equation

$$\partial_t \mu_d' + m_x m_y[\partial_x U + \partial_y V] + m_y \partial_\eta \Omega = 0$$

$$\partial_t \phi' + \mu_d^{-1}[m_x m_y(U\partial_x \phi + V\partial_y \phi) + m_y \Omega \partial_\eta \phi - m_y g W] = 0.$$

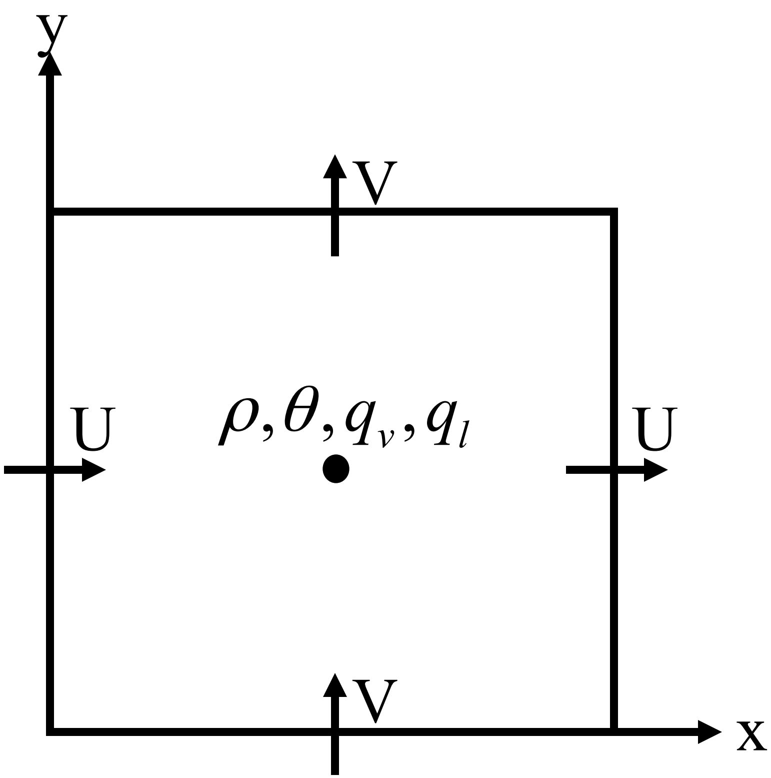
The conservation equations for the potential temperature and scalars

$$\partial_t \Theta + m_x m_y[\partial_x(U\theta) + \partial_y(V\theta)] + m_y \partial_\eta(\Omega\theta) = F_\Theta$$

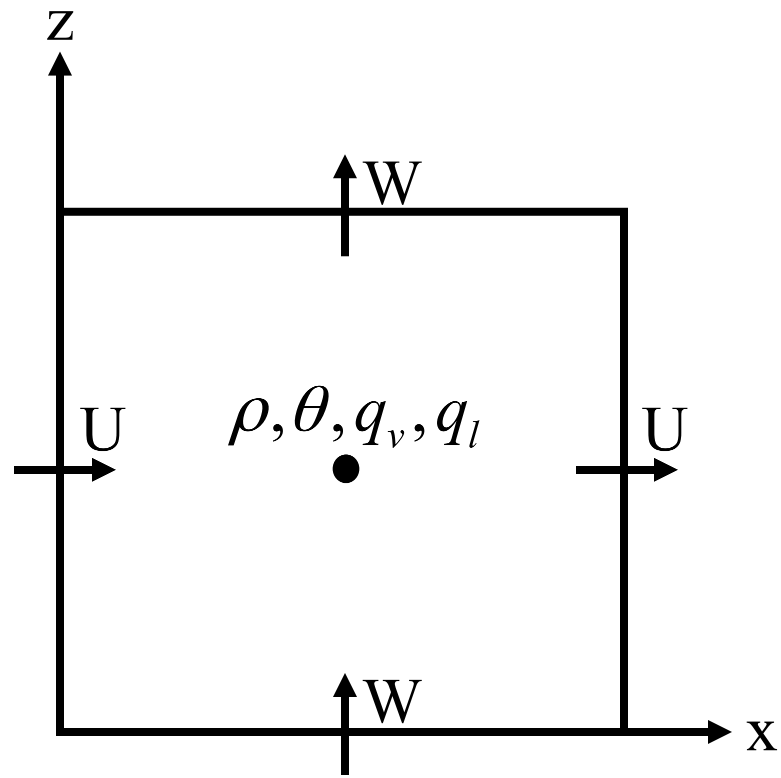
$$\partial_t Q_m + m_x m_y[\partial_x(Uq_m) + \partial_y(Vq_m)] + m_y \partial_\eta(\Omega q_m) = F_{Q_m}.$$

ARW model, grid staggering

C-grid staggering



horizontal



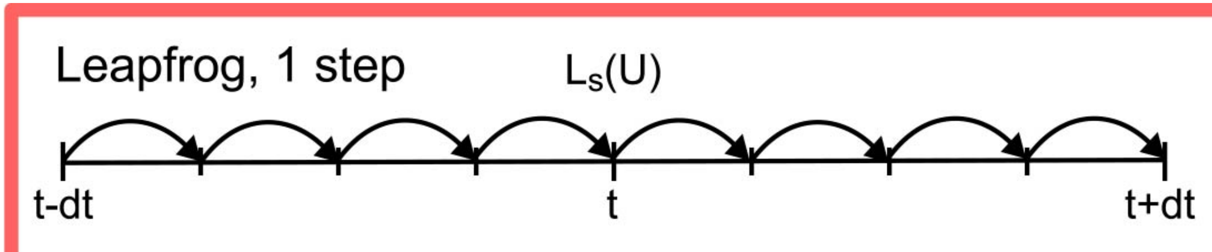
vertical

Time Integration in ARW

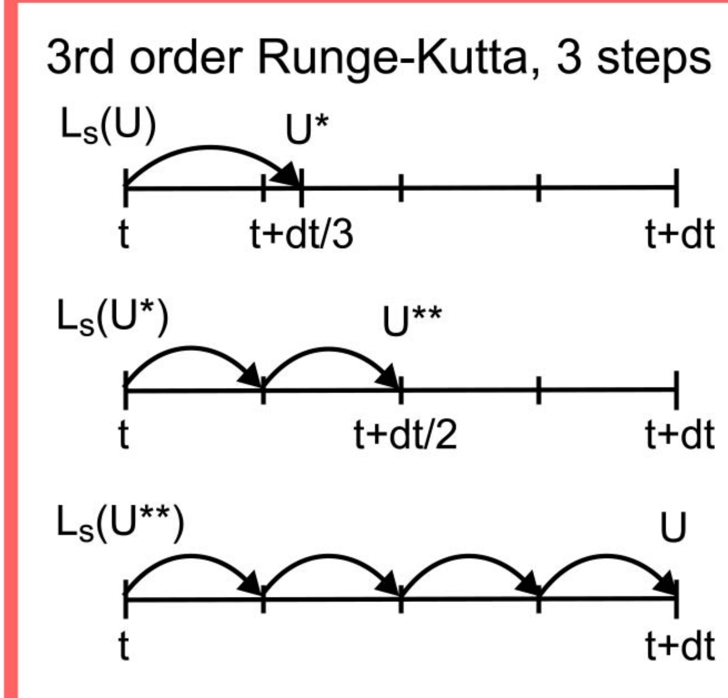
3rd Order Runge-Kutta time integration

Integrate

$U_t = L_f(U) + L_s(U)$



- LF is formally 1st order accurate, RK3 is 3rd order accurate
- RK3 stable for centered and upwind advection schemes, LF only stable for centered schemes.
- RK3 is stable for timesteps 2 to 3 times larger than LF.
- LF requires only one advection evaluation per timestep, RK3 requires three per timestep.



Time Integration in ARW

3rd Order Runge-Kutta time integration

advance $\phi^{t} \rightarrow \phi^{t+\Delta t}$

$$\phi_t = R(\phi)$$

$$\phi^{*} = \phi^{t} + \frac{\Delta t}{3} R\left(\phi^{t}\right)$$

$$\phi^{**} = \phi^{t} + \frac{\Delta t}{2} R\left(\phi^{*}\right)$$

$$\phi^{t+\Delta t} = \phi^{t} + \Delta t\, R\left(\phi^{**}\right)$$

Amplification factor $\phi_t = i\, k\phi; \quad \phi^{n+1} = A\,\phi^{n}; \quad |A| = 1 - \frac{(k\Delta t)^4}{24}$

Time Integration in ARW

Example:

The flux form of the scalar advection equation in one dimension

$$\frac{\partial q}{\partial t} = -\frac{\partial (uq)}{\partial x}. \qquad (1)$$

Using forward-in-time finite difference representation

$$\frac{(q_i^{n+1} - q_i^n)}{\Delta t} = -\frac{(F_{i+1/2}^n - F_{i-1/2}^n)}{\Delta x}, \qquad (2)$$

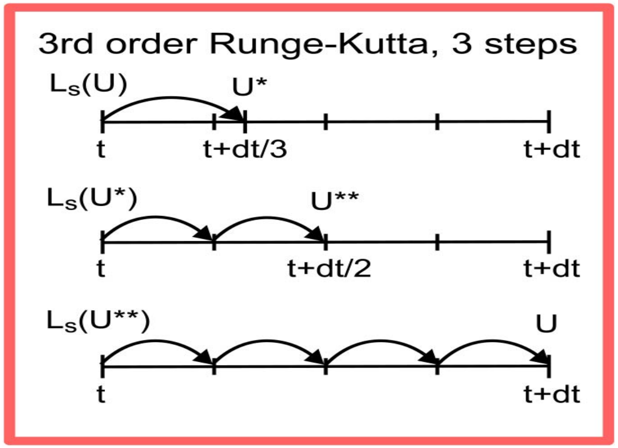
where ${F^n}_{i+1/2}$ is the flux through the edge of the grid zone at time step "*n*."

Using Taylor's expansion, the third-order RK time integration algorithm using the flux differencing (2) is

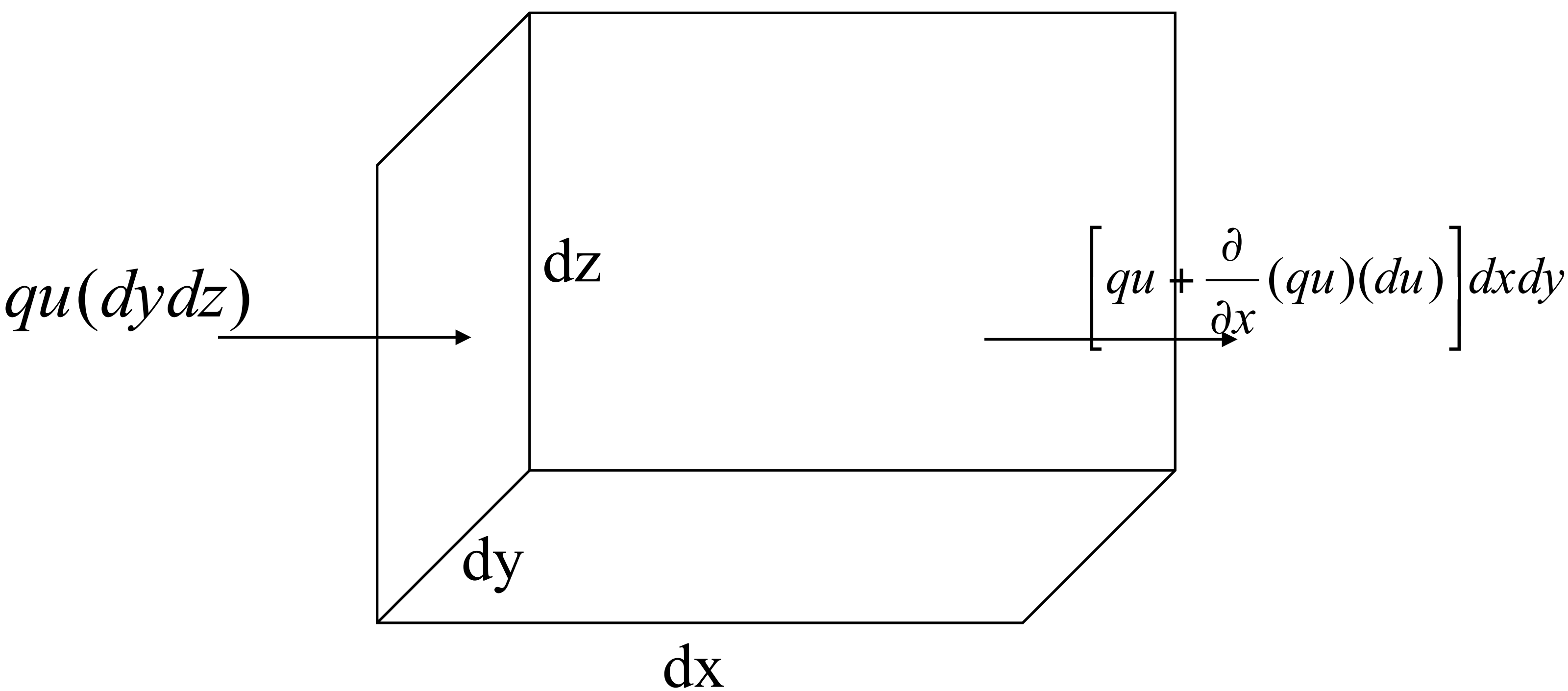
$$q_i^* = q_i^n - \frac{\Delta t}{3\Delta x}(F_{i+1/2}^n - F_{i-1/2}^n) \qquad (3a)$$

$$q_i^{**} = q_i^n - \frac{\Delta t}{2\Delta x}(F_{i+1/2}^* - F_{i-1/2}^*) \qquad (3b)$$

$$q_i^{n+1} = q_i^n - \frac{\Delta t}{\Delta x}(F_{i+1/2}^{**} - F_{i-1/2}^{**}). \qquad (3c)$$



Formulation of Mass Conservation



Change in x-direction $\left[qu+\frac{\partial}{\partial x}(qu)(du)\right](dxdz)-qu(dydz)$

$$-\left[\frac{\partial}{\partial x}(qu)\right](dxdxdz)$$

Formulation of Mass Conservation

Change in y-direction $$-\left[\frac{\partial}{\partial y}(qv)\right](dxdxdz)$$

Change in z-direction $$-\left[\frac{\partial}{\partial z}(qw)\right](dxdxdz)$$

Net Change in total volume $$-\left[\frac{\partial(qu)}{\partial x}+\frac{\partial(qv)}{\partial y}+\frac{\partial(qw)}{\partial z}\right](dxdxdz)$$

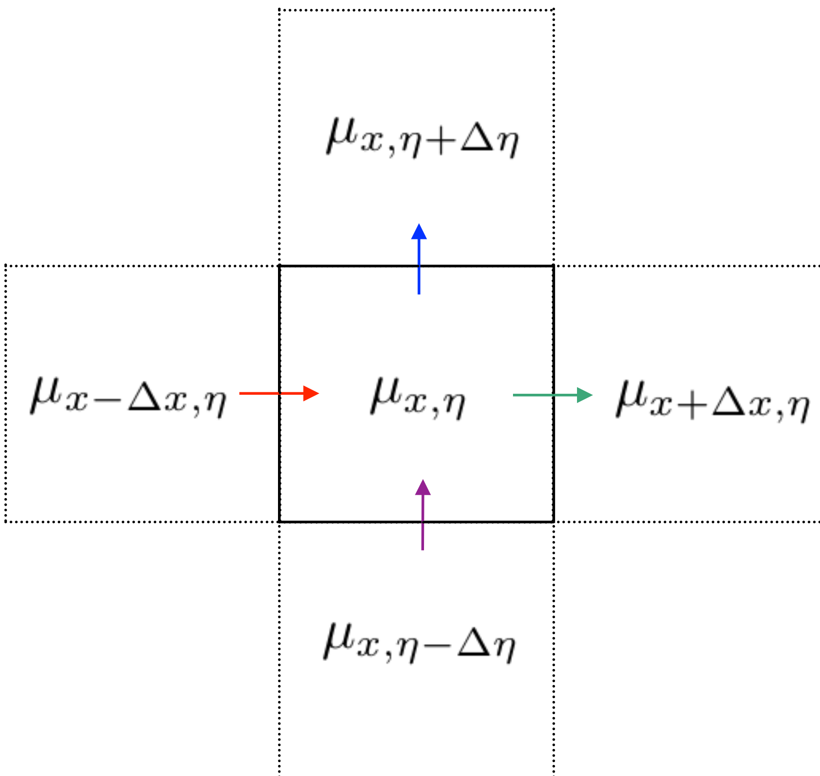
The rate of change of mass in total volume $$\left[\frac{\partial q}{\partial t}\right](dxdxdz)$$

$$\left[\frac{\partial q}{\partial t}\right](dxdxdz) \quad = \quad -\left[\frac{\partial(qu)}{\partial x}+\frac{\partial(qv)}{\partial y}+\frac{\partial(qw)}{\partial z}\right](dxdxdz)$$

$$\left[\frac{\partial q}{\partial t}\right]+\nabla .q = \quad 0 \quad ; \quad \frac{dq}{dt}=0 \quad \Rightarrow \quad q = const.$$

Mass Conservation in the ARW Model

The same mass fluxes are used for neighboring grid cells - hence mass is conserved locally and globally.



Advection in the ARW Model

2nd, 3rd, 4th, 5th and 6th order centered and upwind-biased schemes are available in the ARW model.

The 3rd, 4th, 5th and 6th order flux-form spatial approximations from Taylor expansion of equation (1) $\frac{\partial q}{\partial t} = -\frac{\partial (uq)}{\partial x}$. are as follow:

$$F^{3rd}_{i-1/2} = F^{4th}_{i-1/2} - \frac{|u_{i-1/2}|}{12}[3(q_i - q_{i-1}) - (q_{i+1} - q_{i-2})], \tag{4a}$$

$$F^{4th}_{i-1/2} = \frac{u_{i-1/2}}{12}[7(q_i + q_{i-1}) - (q_{i+1} + q_{i-2})], \tag{4b}$$

$$F^{5th}_{i-1/2} = F^{6th}_{i-1/2} - \frac{|u_{i-1/2}|}{60}[10(q_i - q_{i-1}) - 5(q_{i+1} - q_{i-2}) + (q_{i+2} - q_{i-3})], \tag{4c}$$

$$F^{6th}_{i-1/2} = \frac{u_{i-1/2}}{60}[37(q_i + q_{i-1}) - 8(q_{i+1} + q_{i-2}) + (q_{i+2} + q_{i-3})] \tag{4d}$$

Wicker, L. J. and W. C. Skamarock, 2002: Time splitting methods for elastic models using forward time schemes, Mon. Wea. Rev., 130, 2088–2097.

WRF model Installation

Download ARW system

- Download WRF (unified ARW + NMM) source code from
  http://www.mmm.ucar.edu/wrf/users/downloads.html

- Choose the link of latest version,

- What you will get is
  WRFV3.6.1.TAR.gz
  WPSV3.6.1.tar.gz
  WRFDAV3.6.1.TAR.gz

Flow of model installation

- WRF source code is need to be installed prior to installation of any other components of WRF modeling system (like Preprocessor, post processor).

  [Note: ARWpostV3 and above does not required prior installation of WRF source code]

Unzip and Untar Downloaded Files

`cd to_where_you_want_the_source`

- **`gzip -cd WRFV3.6.1.TAR.gz | tar -xf -`**

- After **`gunzip`** and **`untar`**, you should see a directory **`WRFV3/`**

`cd WRFV3`

WRF Top-Level Directory

Unified ARW/NMM

`Makefile`	
`README`	
`README_test_cases`	

`clean`
`compile`
`configure`
	build scripts

`Registry/`	CASE input files
`arch/`	machine build rules

`dyn_em/`
`dyn_nnm/`
`external/`
`frame/`
`inc/`
`main/`
`phys/`
`share/`
`tools/`
	source code directories

`run/` `test/`	execution directories

WRF modeling Installation and Functions

- First set ***one*** core environment variable to 1:

setenv WRF_EM_CORE 1

Note: The default is to compile ARW.

- Then set PATH environment variables for NETCDF, JASPER, PNG and ZLIB as:

setenv NETCDF /usr/local/netcdf	*- C shell*
setenv JASPERLIB /usr/local/jasper/lib/	*- C shell*
setenv ZLIB /usr/local/zlib	*- C shell*

export NETCDF= /usr/local/netcdf	*- B shell*
export JASPERLIB=/usr/local/jasper/lib/	*- B shell*
export ZLIB=/usr/local/zlib	*- B shell*

WRF model Installation

- To create a WRF configuration file for your computer, type:
  ./configure

- This script checks the system for hardware, software and libraries, and then offers the user choices for configuring WRF:
  Type of compiler,
  Serial, OpenMP, or MPI;
  Type of nesting (basic, preset moves, vortex following)

  On successful, it creates configure.wrf

- Type the following command to install the code

./compile *test_case* ***>& compile_wrf.log***

WRF Executables and Functions

- If the compilation is successful:

– ARW: creates four executables in the ***main/*** directory:

  - ***real.exe***: used for initialization of real data cases.
  - ***ideal.exe***: used for initialization of Idealized cases.
  - ***wrf.exe***: used for model integration.
  - ***ndown.exe:*** used for one-way nesting
  - ***nup.exe*** (not used much)

- These executables will be linked to either ***test/em_real*** or ***test/nmm_real*** and ***run/*** directories.

WRF Pre-processing System

WPS Compilation

Required libraries (WRF and WPS):

Reminder: A successful compilation of WRF is required prior to WPS compilation!

To create a WPS configuration file for your computer, type:

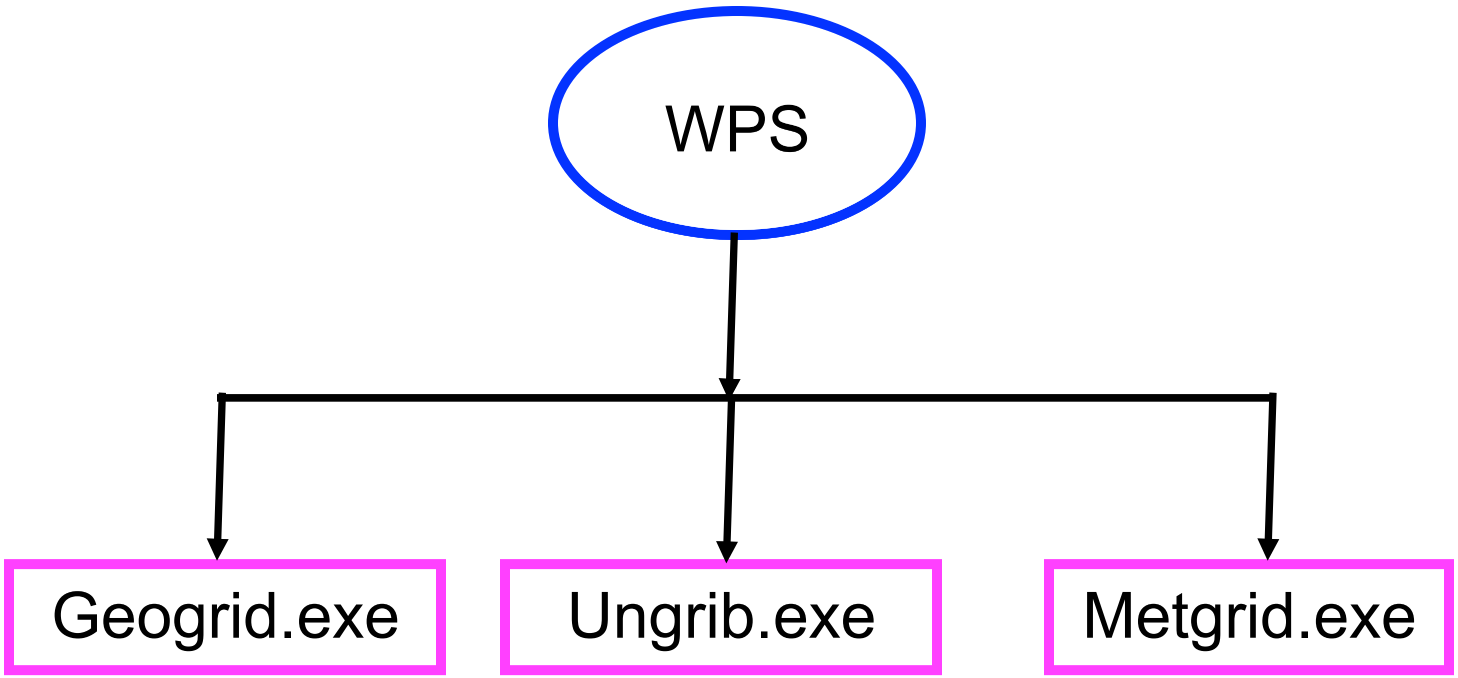
./configure

This script offers the user choices
-Type of compiler
- Serial or Distributed memory
- GRIB1 or GRIB2

If configuration was successful, compile WPS:

./compile >& compile_wps.log

On successful WPS Compilation



Produce terrain, landuse, soil type etc. on the simulation domain ("static" fields)

De-grib GRIB files (of both GRIB1 and GRIB2) for meteorological data (u, v, T, q, Ps, soil data, snow data, SST, etc.)

Interpolate meteorological data to WRF model grid (horizontally)

WPS Functions

- Support WRF nesting
- Three map projections:
  - *Lambert conformal (mid-latitude applications)*
  - *Polar stereographic (high-latitude applications)*
  - *Mercator (low-latitude applications, Tropical belt)*
- GUI for running the program
  - Domain Wizard (both on Linux and AIX)

Running WPS

- Running WPS has 3 executable stages with namelist input

– geogrid.exe (interpolate maps and time-independent fields):
can run on multiple processors

– ungrib.exe (convert time-dependent Grib-formatted data to simple binary format):
can run on single processor

– metgrid.exe (interpolate time-dependent initial and boundary data):
can run on multiple processors

WPS does only horizontal interpolation. The vertical interpolation comes in real program

It provides number of utilities and full details in the next lecture

Running Real Data Case

On successful run of WPS, it creates **met_em.*** files for all the time periods.

met_em.2011-11-26_00:00:00
met_em.2011-11-26_03:00:00
met_em.2011-11-26_06:00:00
met_em.2011-11-26_09:00:00
met_em.2011-11-26_12:00:00

• Link or copy these WPS output files to the run directory of WRFV3:

cd /WRF_directory/test/*em_real*

ln -sf WPS_directory/met_em.d01.* .

Running Real Data Case

- Edit **namelist.input** file for runtime options

  &time_control for start, end and integration times, and

  &domains for grid dimensions)

- Run the real-data initialization program:

  ./real.exe, if compiled serially / SMP, or

  mpirun -np *N* ./real.exe, or

  mpirun -machinefile *file* -np *N* ./real.exe **-----** for a MPI job

where ***N*** is the number of processors requested, and ***file*** has a list of CPUs for the MPI job

Running Real Data Case

Successfully running this program will create model initial and boundary files:

wrfinput_d01
wrfbdy_d01

Single time level data at model's start time

N-1 time-level data at the lateral boundary, and only for domain 1

N: the number of time periods processed

Running Real Data Case

- Run the model executable by typing:

./wrf.exe >& wrf.out &

To see the running process   tail –f wrf.out

- Successfully running the model will a create:

wrfout_d01_2011-11-26_00:00:00

And a *restart* file if **restart_interval** is set to a time within the range of the forecast time:

wrfrst_d01_2011-11-27_12:00:00

WRF-3DVAR System

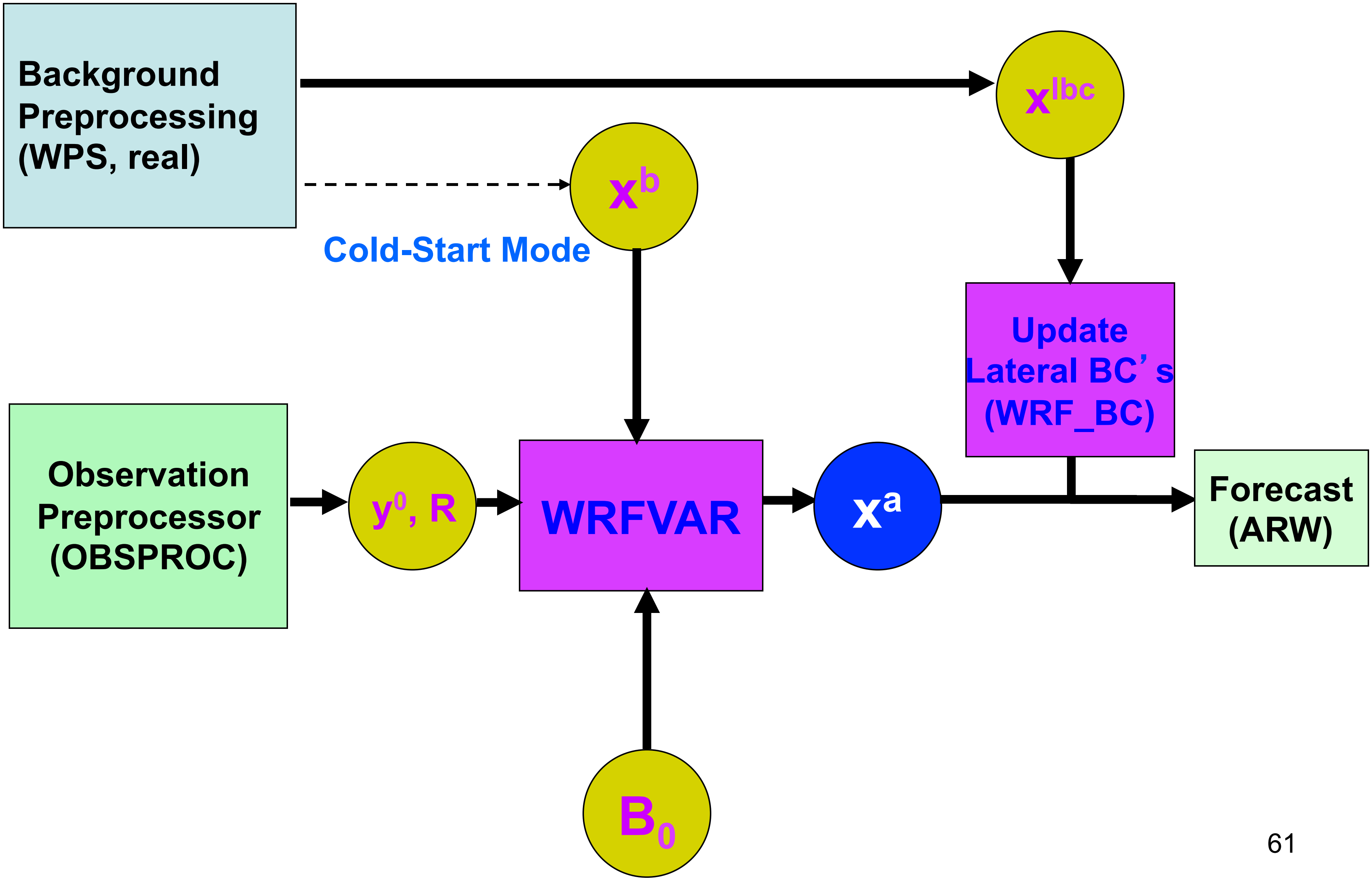
WRFDA (Data Assimilation)

- Variational data assimilation (3D-Var and 4D-Var)
- Ensemble DA
- Hybrid variational/ensemble DA

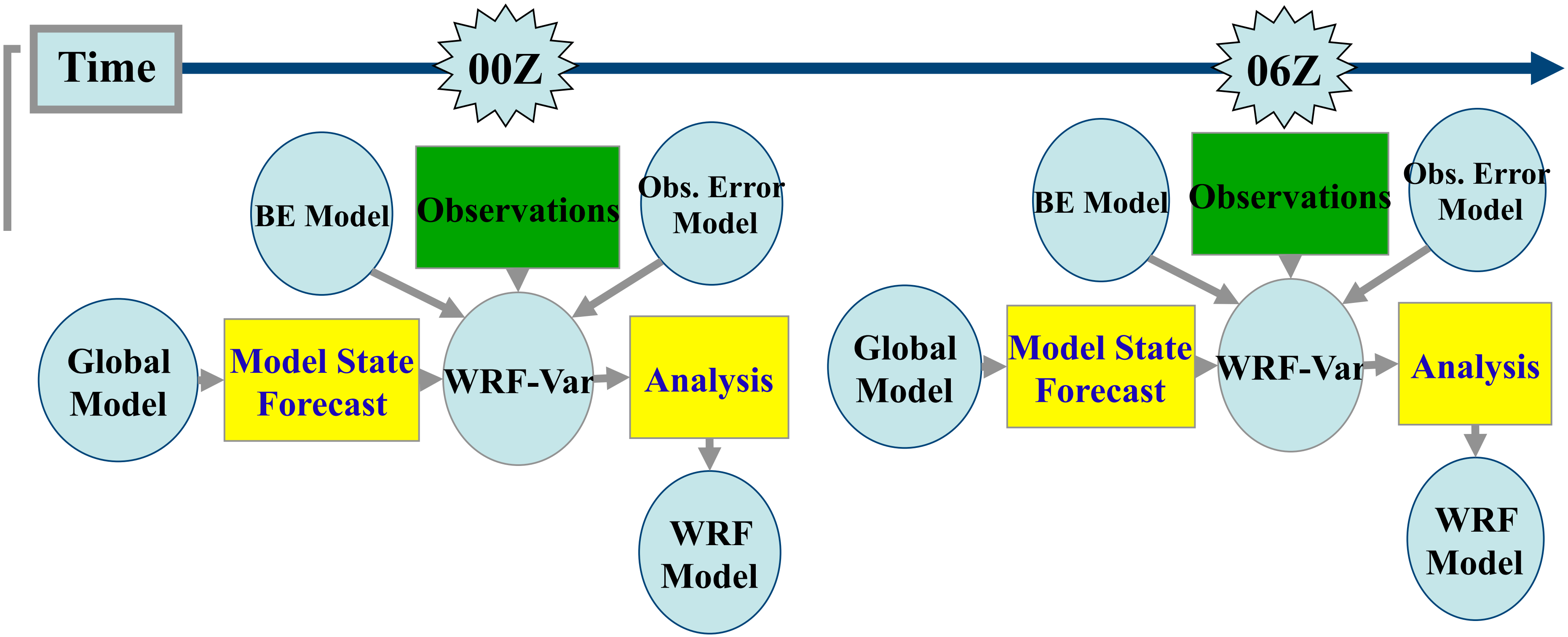
Function

- Ingest observations to improve WRF input analysis from WPS
- May be used in cycling mode for updating WRF initial conditions after WRF run
- Also used for observation impact data studies

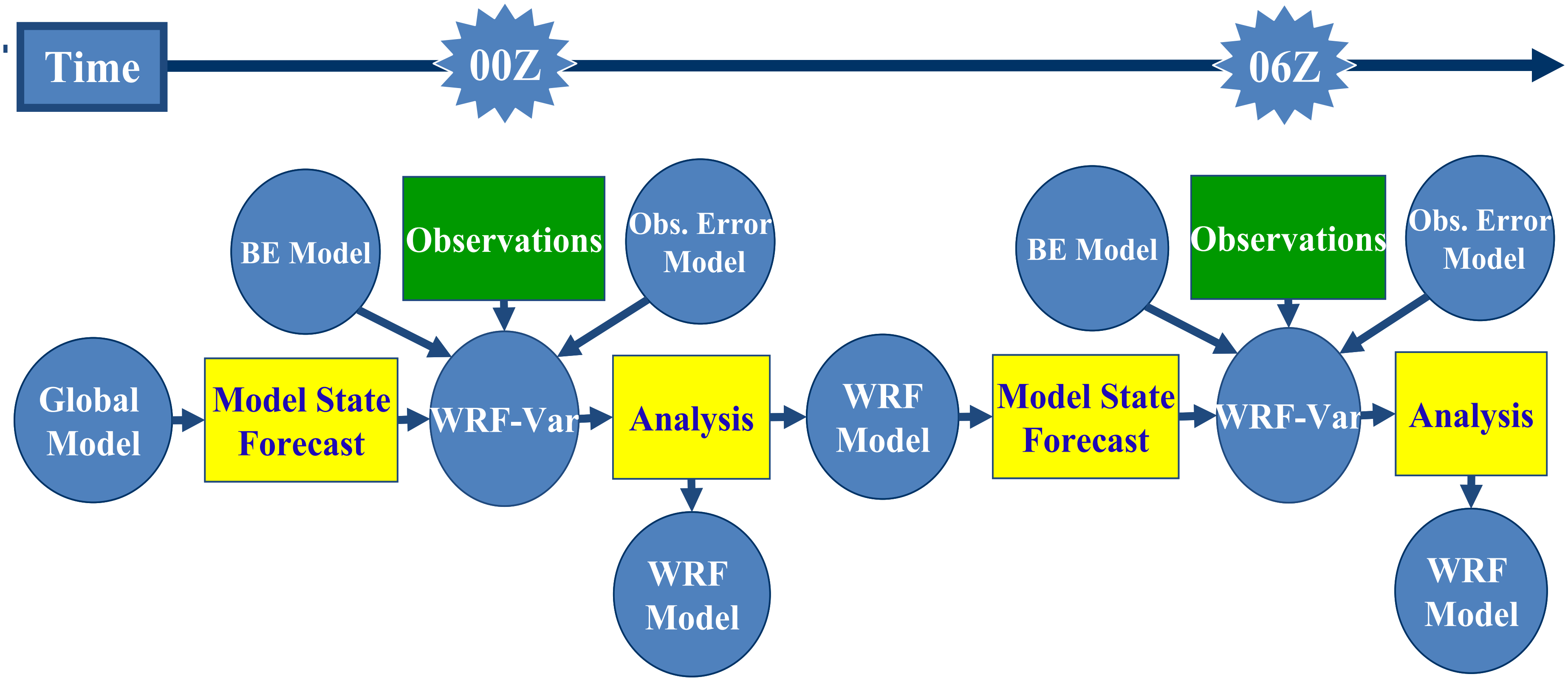
Overview of WRF-VAR System



Cold-start Mode



CYCLING MODE



WRFDA

- Supported data types
- Conventional surface and upper air, wind profiler, aircraft Remote sensing data: Cloud-tracked winds, satellite-retrieved profiles, ground-based/satellite GPS, scatterometer ocean surface winds, radar radial velocity and reflectivity, satellite radiance

- Background error covariance for ARW from
- – NMC method
- – Ensemble method

Building the WRFDA Code

WRFDA uses the same build mechanism as WRF

Get the WRFDA zipped tar file, WRFDAV3.TAR.gz, from

http://www.mmm.ucar.edu/wrf/users/download/get_source.html

Unzip and untar the WRFDA code **gzip -cd WRFDAV3.TAR.gz | tar -xf –**

This will create a directory, **WRFDA**

cd WRFDA

In addition to NETCDF, set up environment variables pointing to additional libraries required by WRFDA.

Please note: only NETCDF library is mandatory to compile basic WRFDA system, all other libraries are optional.

Only if you intend to use PREPBUFR observation, Radiance data data,
The environment variable BUFR and CRTM has to be set with

setenv BUFR 1

setenv CRTM 1

./configure wrfda   and select the appropriate options

./compile all_wrfvar

If the compilation was successful,

ls -l var/build/*.exe

da_wrfvar.exe, **da_update_bc.exe**, and other executables should be found in the var/build directory and their links are in var/da directory; **obsproc.exe** should be found in the var/obsproc/src directory

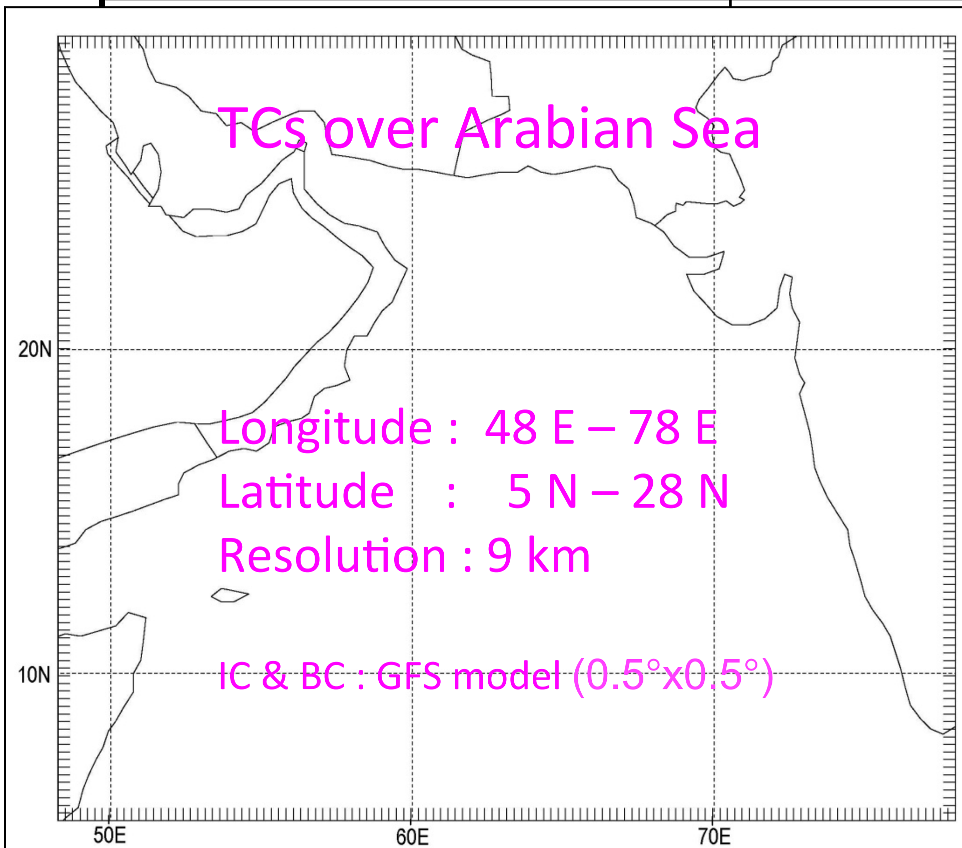
Real time prediction of Tropical cyclones over North Indian Ocean

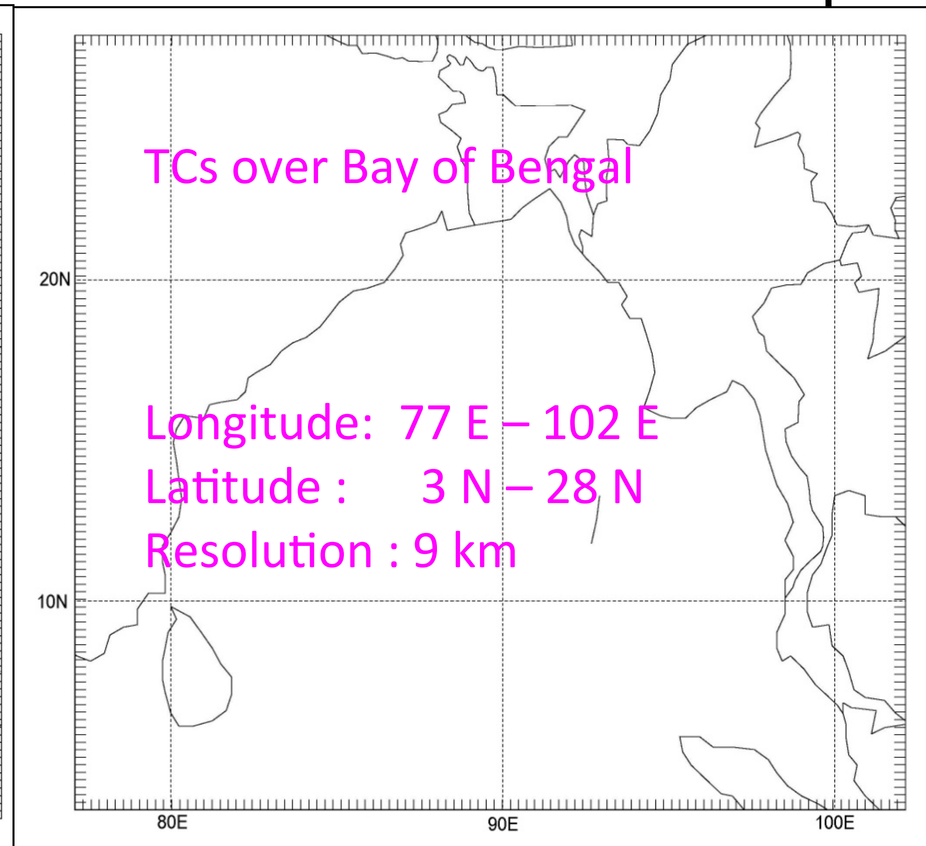
TCs during 2007 – 2014 (Total 172 cases)

Basin	Name (Intensity)	Simulations period in 12-hr interval	Observed Landfall	No. of forecasts
Arabian Sea Cyclones (5 TCs)	Gonu (SuCS)	00 UTC 2 – 12 UTC 5 June 2007	03UTC 6 June (over Oman)	8
	Yemyin (CS)	00 and 12 UTC 25 June 2007	03 UTC 26 June	2
	Phyan (CS)	12 UTC 9 – 00 UTC 11 Nov 2009	Between 10-11 UTC 11 Nov	4
	Phet (VSCS)	12 UTC 31 May – 00 UTC 6 June 2010	12 UTC 6 June (LF-2)	12
	Murjan (CS)	00 UTC 23 – 25 October 2012	18 UTC 25 October 2012	5
Bay of Bengal cyclones (20 TCs)	Akash (CS)	12 UTC 13 – 12 UTC of 14 May 2007	00 UTC 15 May	3
	Sidr (VSCS)	12 UTC 11 – 00 UTC 15 Nov 2007	15 UTC 15 Nov	8
	Nargis (VSCS)	12 UTC 27 April – 00 UTC 2 May 2008	12 UTC 2 May	10
	Rashmi (CS)	00 UTC 25 – 12 UTC 26 Oct 2008	00 UTC 27 Oct	4
	KhaiMuk (CS)	12 UTC 13 – 12 UTC 15 Nov 2008	00 UTC 16 Nov	5
	Nisha (CS)	12 UTC 25 – 26 Nov 2008	00 UTC 27 Nov	3
	Bijli (CS)	12 UTC 14 – 00 UTC 17 Apr 2009	15 UTC 17 April	6
	Aila (SCS)	12 UTC 23 – 00 UTC 25 May 2009	9 UTC 25 May	4
	Ward (CS)	12 UTC 10 – 12 UTC 13 Dec 2009	9 UTC 14 Dec	7
	Laila (VSCS)	12 UTC 17 – 19 May 2010	12 UTC 20 May	5
	Giri (VSCS)	12 UTC 20 – 00 UTC of 22 Oct 2010	14 UTC 22 Oct	4
	Jal (VSCS)	00 UTC of 4 – 7 Nov 2010	16 UTC 7 Nov	7
	Thane (VSCS)	00 UTC 26 – 12 UTC 29 Dec 2011	00 UTC 30 Dec	8
	Nilam (CS)	00 UTC 28 – 12 UTC 31 Oct 2012	15 UTC 31 Oct 2012	6
	Mahasen (CS)	00 UTC 10 – 12 UTC 16 May 2013	9UTC 16 May 2013	13
	PHAILIN (VSCS)	7-12 Oct 2013	17 UTC 12 Oct 2013	9
	(SCS) Helen	19 – 22 Nov 2013	9 UTC 22 Nov 2013	6
	Lehar (VSCS)	25 – 28 Nov 2013	9 UTC 28 Nov 2013	6
	HudHud (VSCS)	7 – 12 Oct 2014	9 UTC 12 Oct 2014	10
Total Number of cyclones during 2007 – 13				164

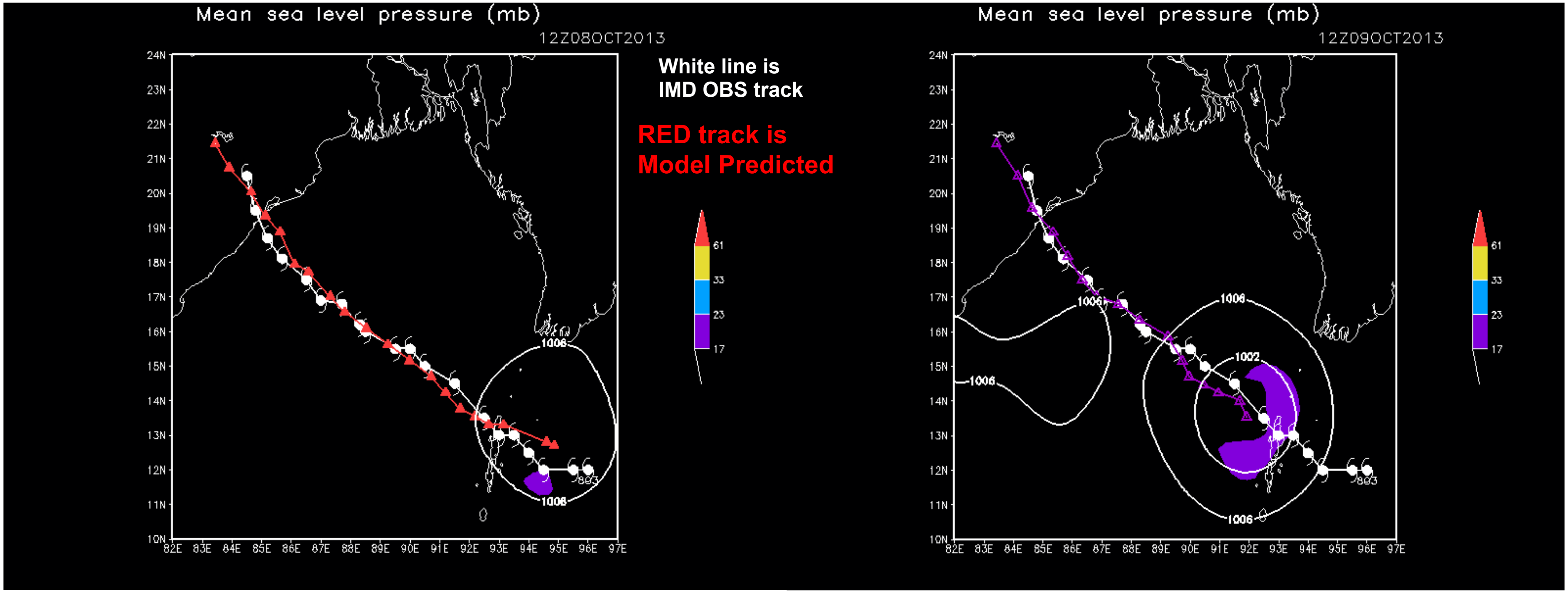
WRF model configuration for cyclone prediction

Model	WRF model configuration
Dynamics	Non-hydrostatic
Horizontal Resolution	27 km / 18 km / 9 km
Micro physics	WSM-3
Initial and boundary conditions	GFS model analysis and forecast fields (0.5° × 0.5° resolution)





TC Phailin (08 – 12 October 2013)



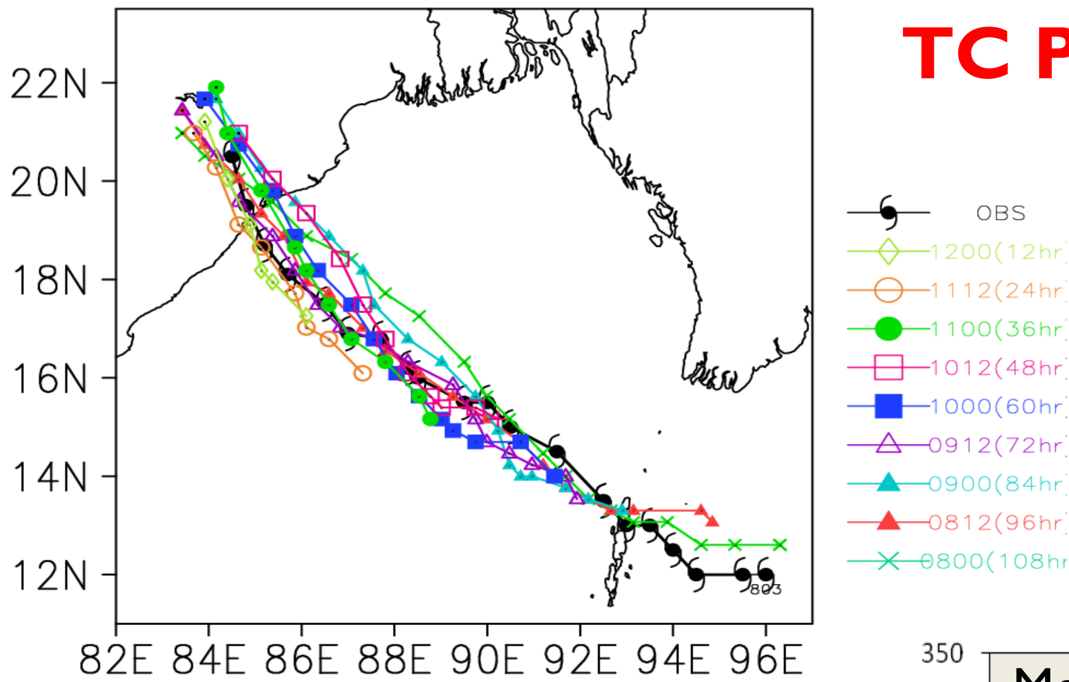
TC Phailin **(96 hour)** Forecast
based on 12 UTC of 8 October 2013

TC Phailin **(72 hour)** Forecast
based on 12 UTC of 9 October 2013

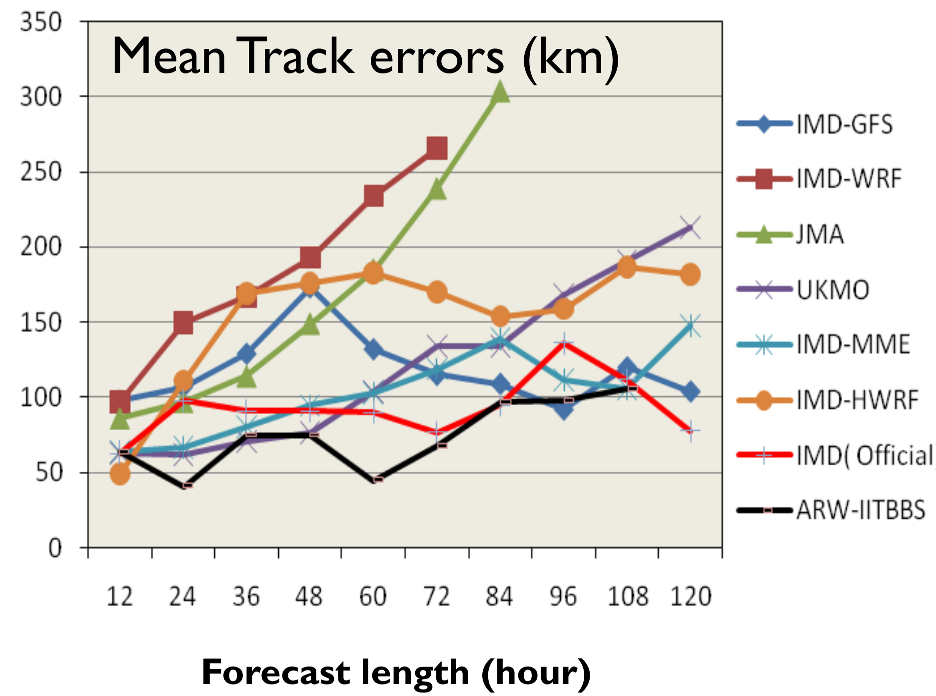
Landfall point error is 29 km
Time error 5 hrs ahead

Landfall point error is 16 km
Time error 2 hrs ahead

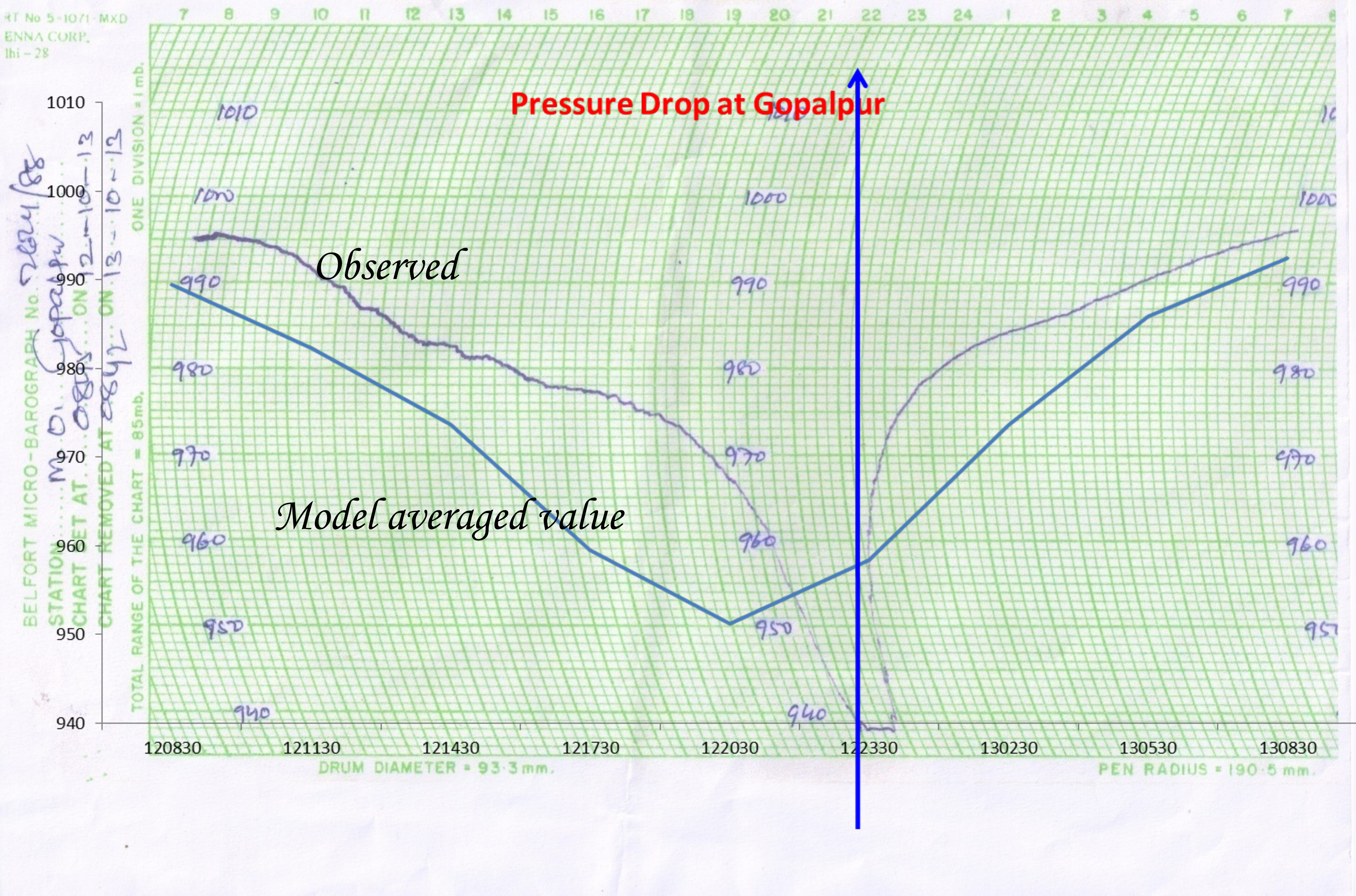
TC PHAILIN with different initial conditions



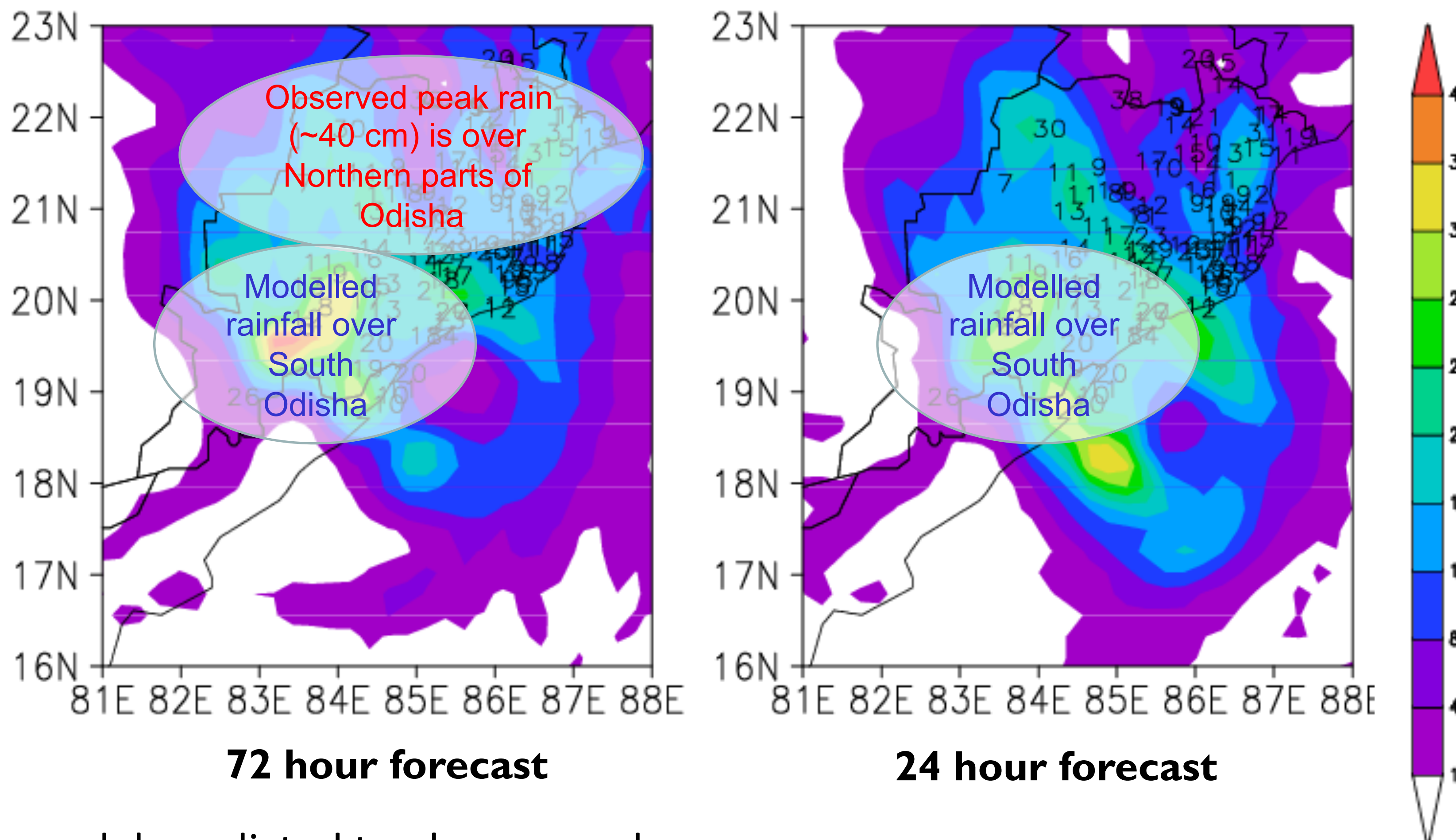
Comparison of Track Prediction of TC **PHAILIN** With Different operational Models



Time series of pressure drop at Gopalpur (landfall point)



24-hr accumulated rainfall (cm) during landfall day for TC PHAILIN (Number represents IMD OBSERVED RAINFALL at 108 stations)



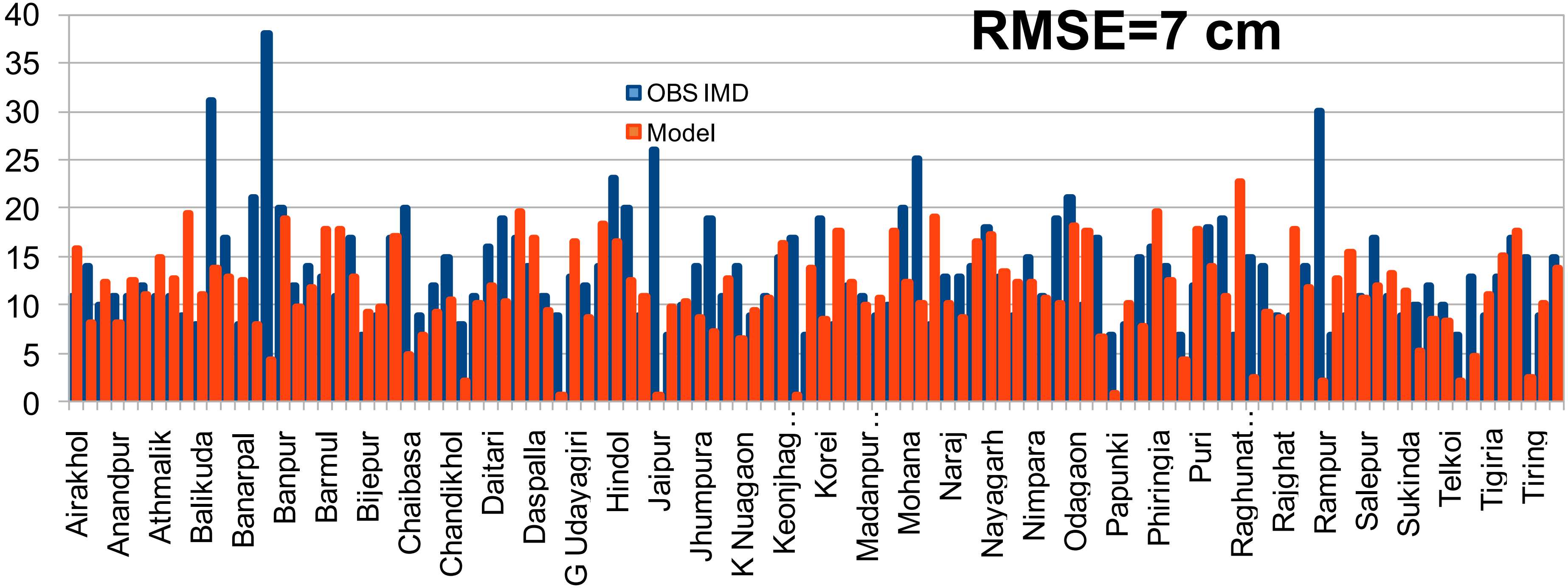
72 hour forecast

24 hour forecast

Though model-predicted track was good,
rainfall distribution and intensity is not realistic.

Model showed peak rainfall over South Odisha and Andhra Pradesh

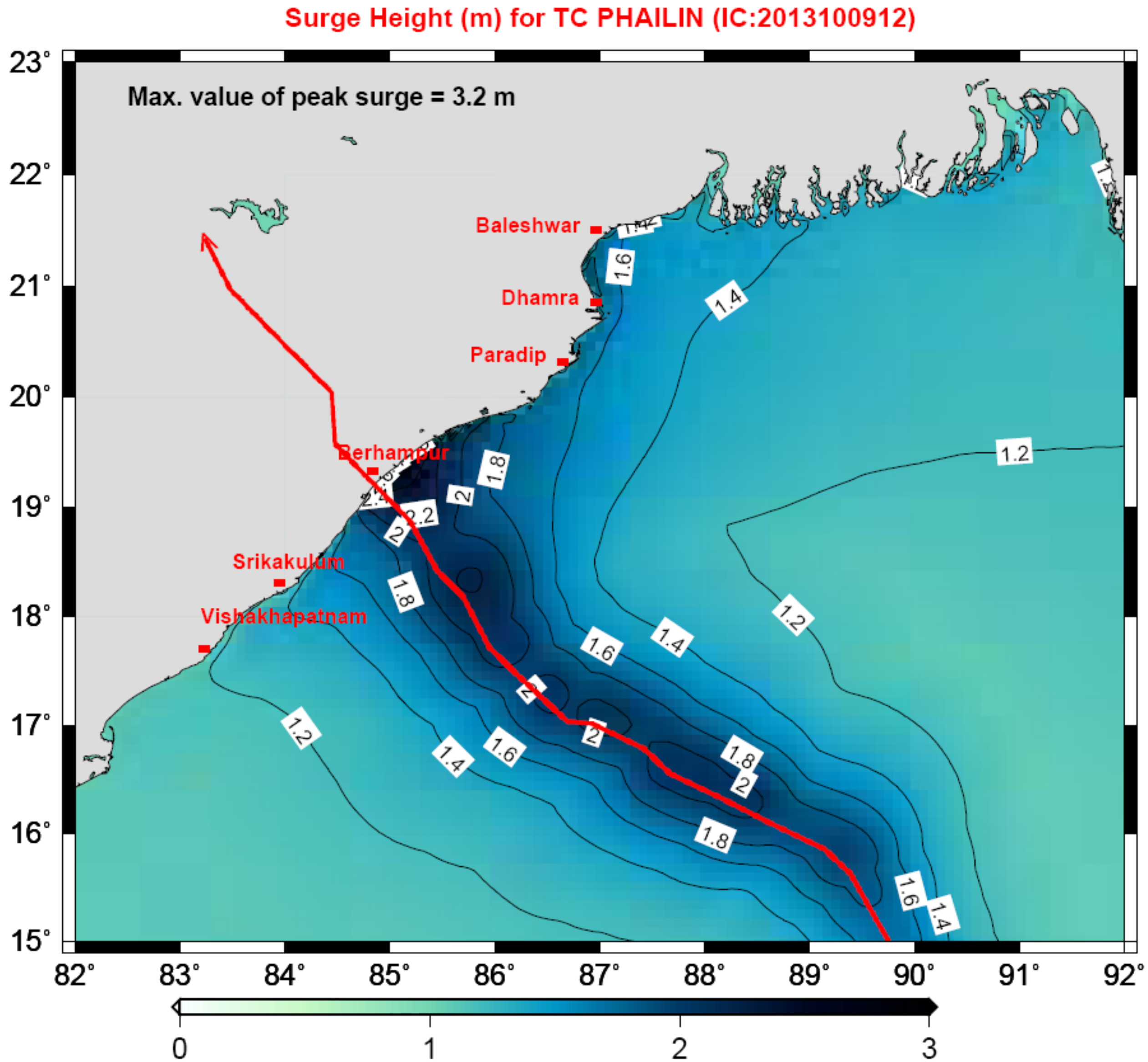
24-hr accumulated rainfall (cm) during landfall day for TC PHAILIN (Verification at 108 stations)



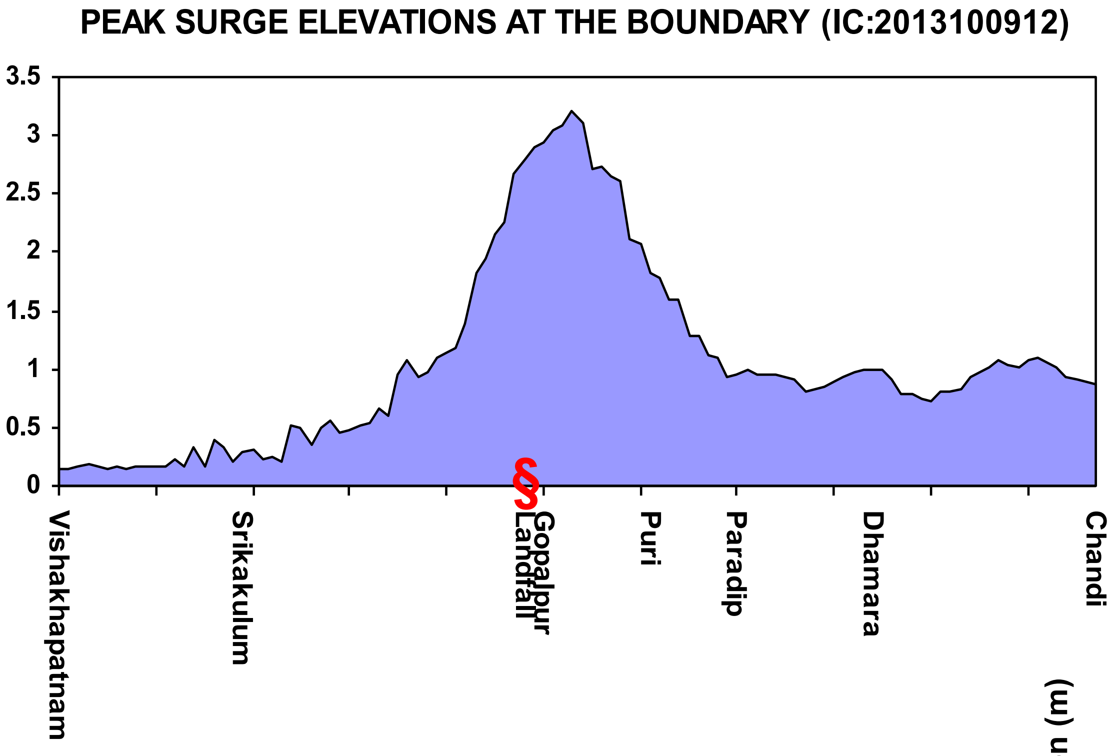
At most of the stations, model underestimated the rainfall.

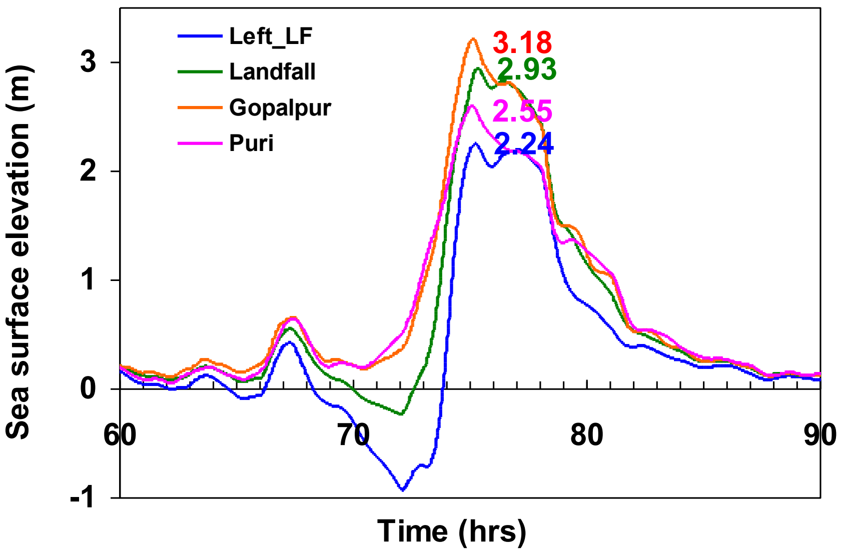
When compared with TRMM rainfall, Model overestimates the rainfall

IIT-BBS Storm Surge Prediction for TC PHAILIN (84 Hours in Advance of Landfall)



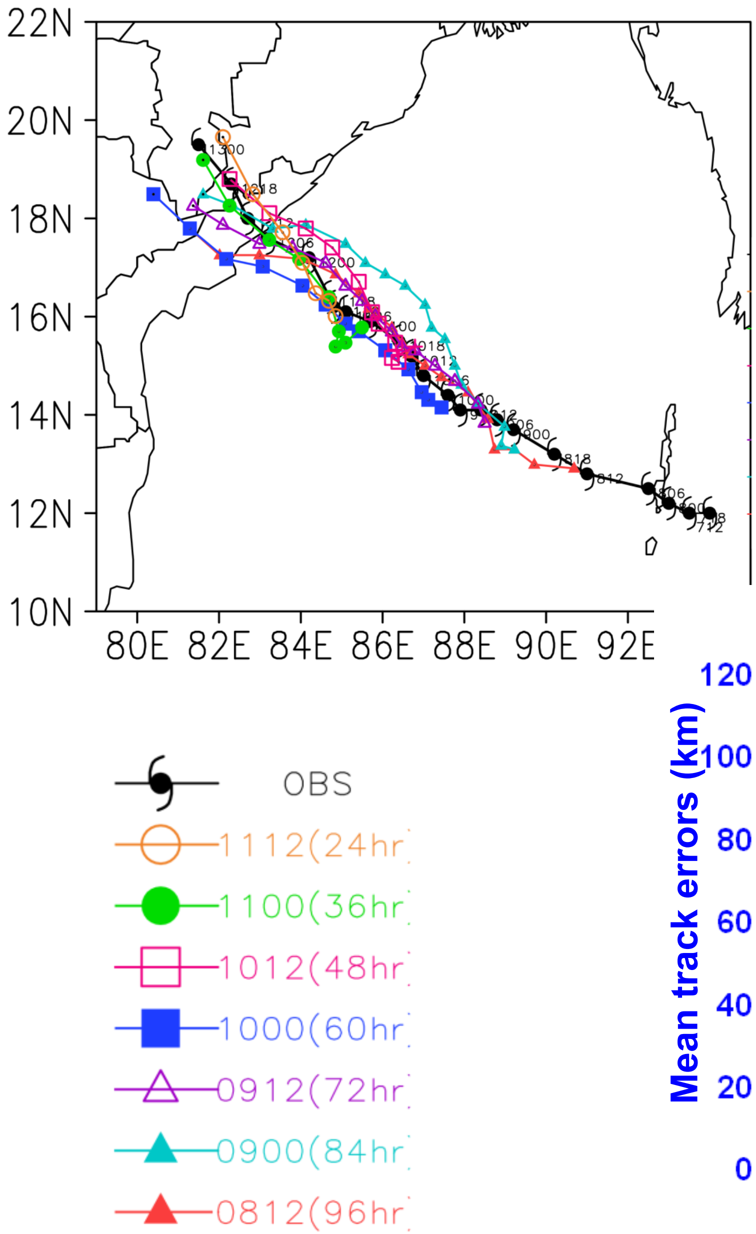
Time series of Surge at different location along the coast (TC PHAILIN)





Disaster of "TC Hudhud" in Visakhapatnam, India

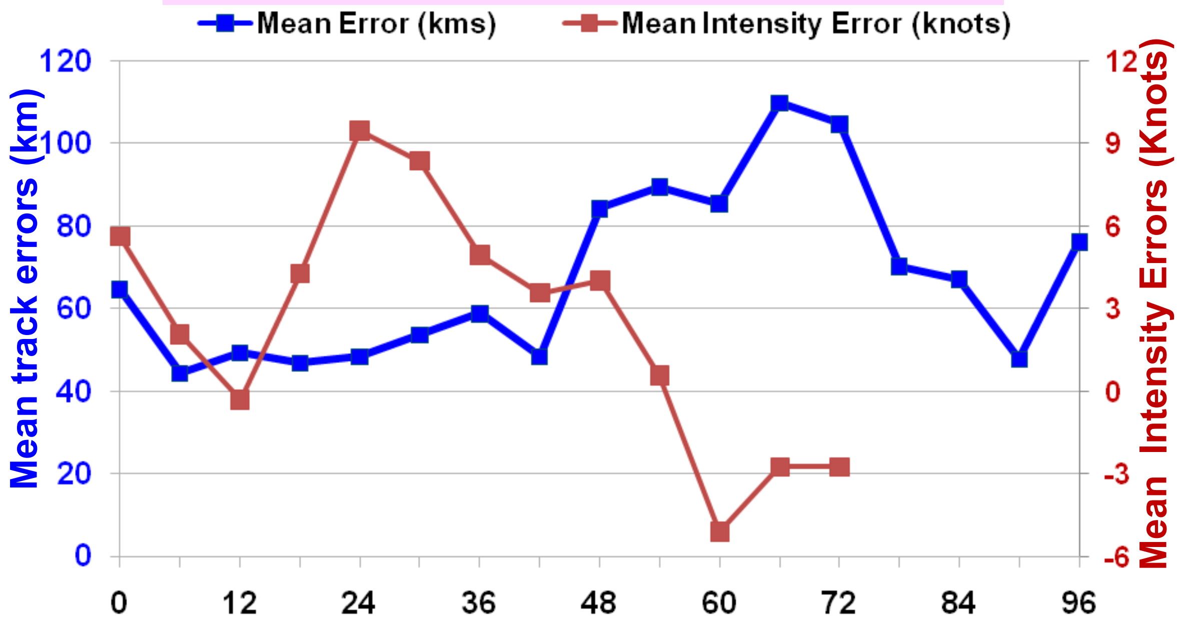
HUDHUD Forecast (12 UTC 8 – 12 UTC 11 Oct 2014)



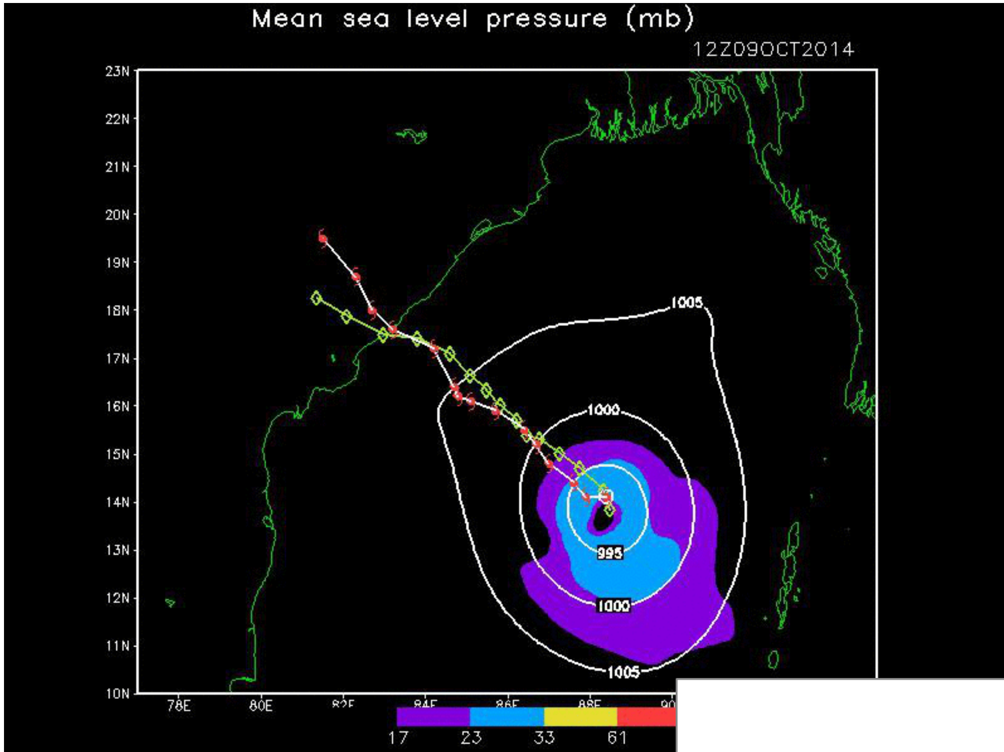
Landfall between 6-9 UTC 12 Oct 2014 with intensity of very severe cyclonic storm (100 knots)

source: IMD

Mean Track (km) and Intensity (Knots) Errors

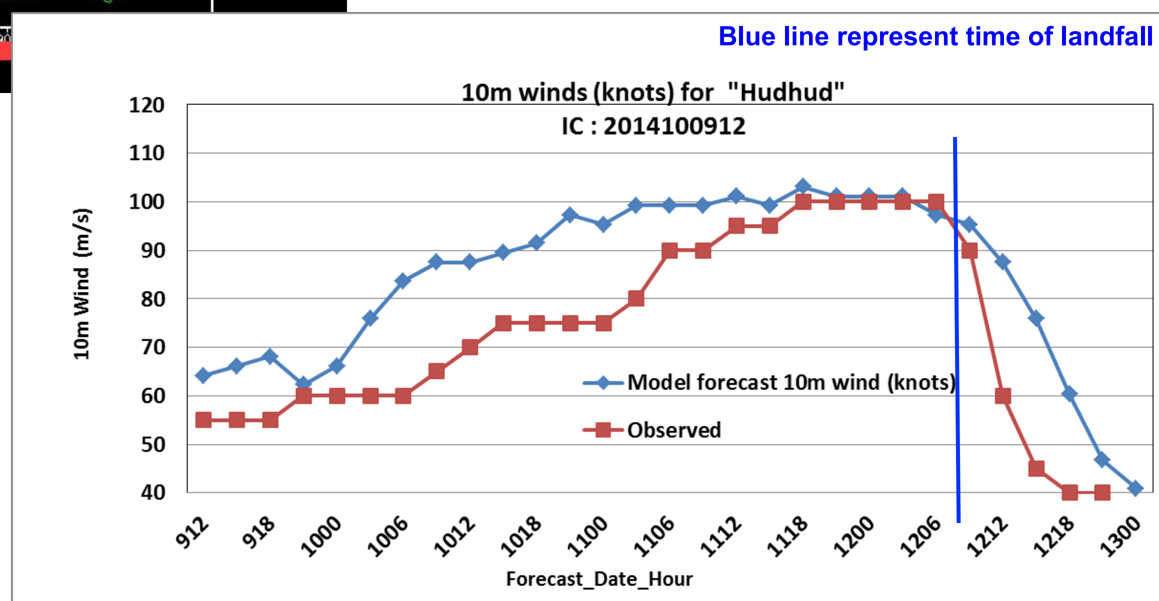


Based on IC: 12 UTC 09 Oct 2014 (96 hr forecast)

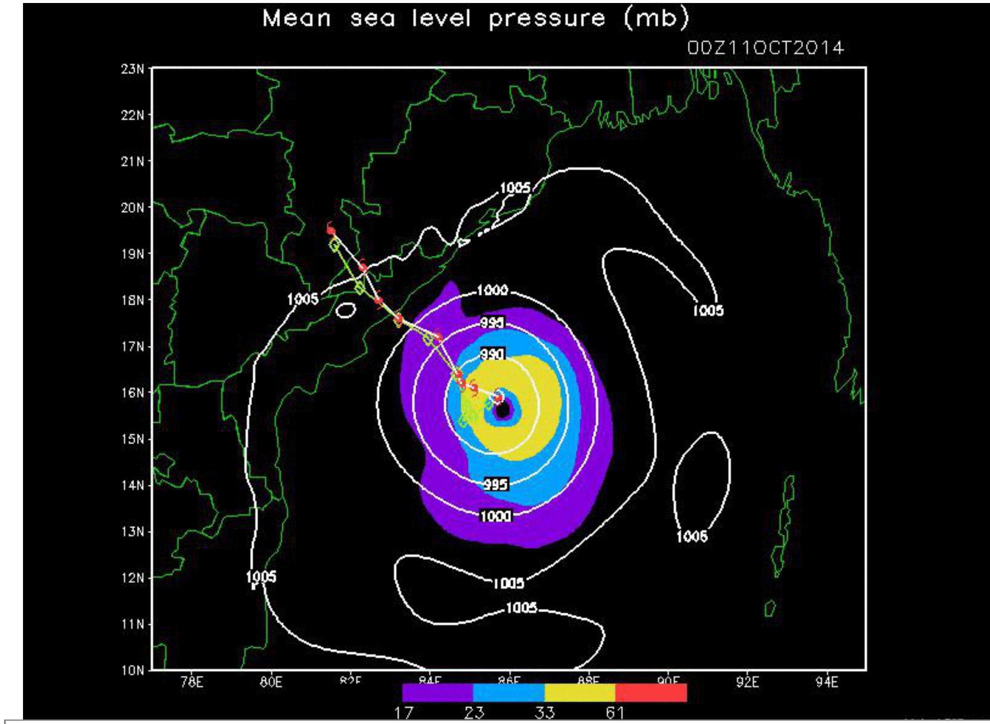


Landfall between 6-9 UTC 12 Oct 2014 with intensity of very severe cyclonic storm (100 knots)

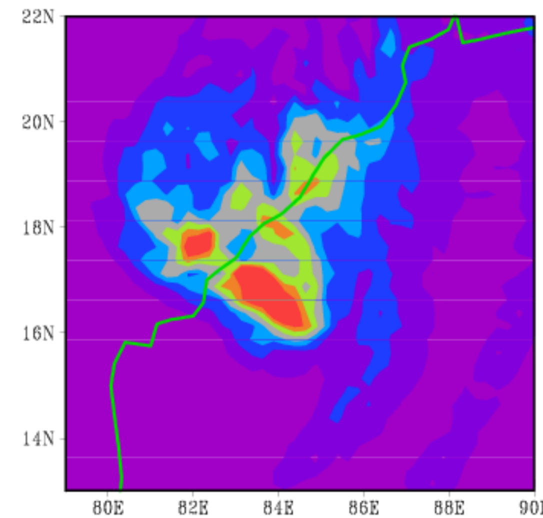
source: IMD



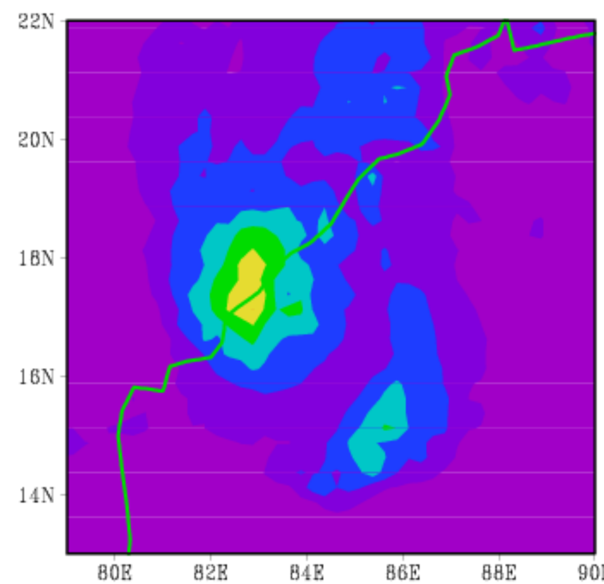
based on IC: 00 UTC 11 Oct 2014 (36 hr forecast)

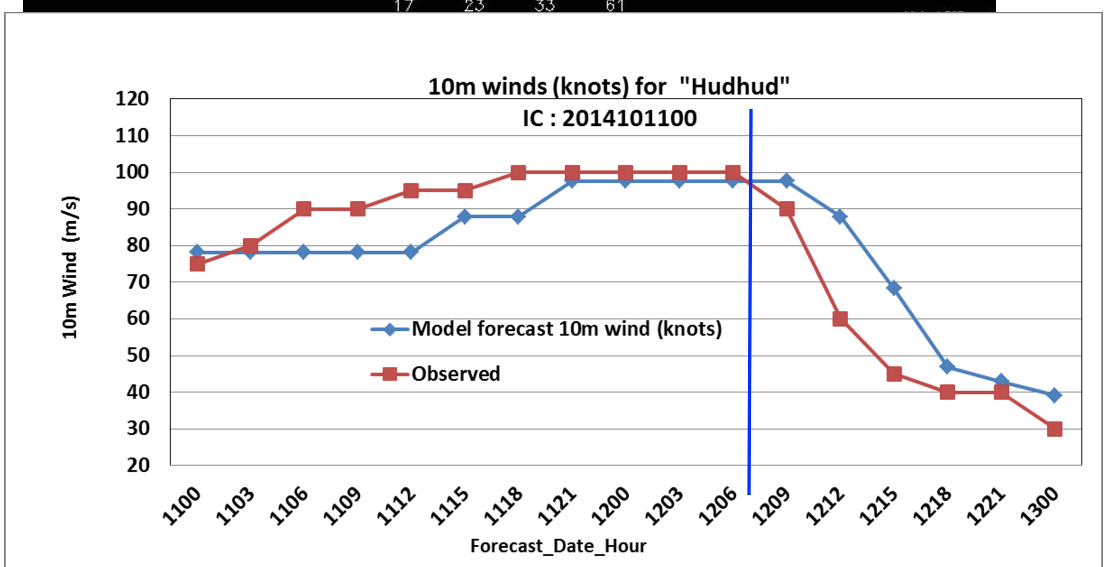


h) 1100 (00UTC 12–13 Oct)



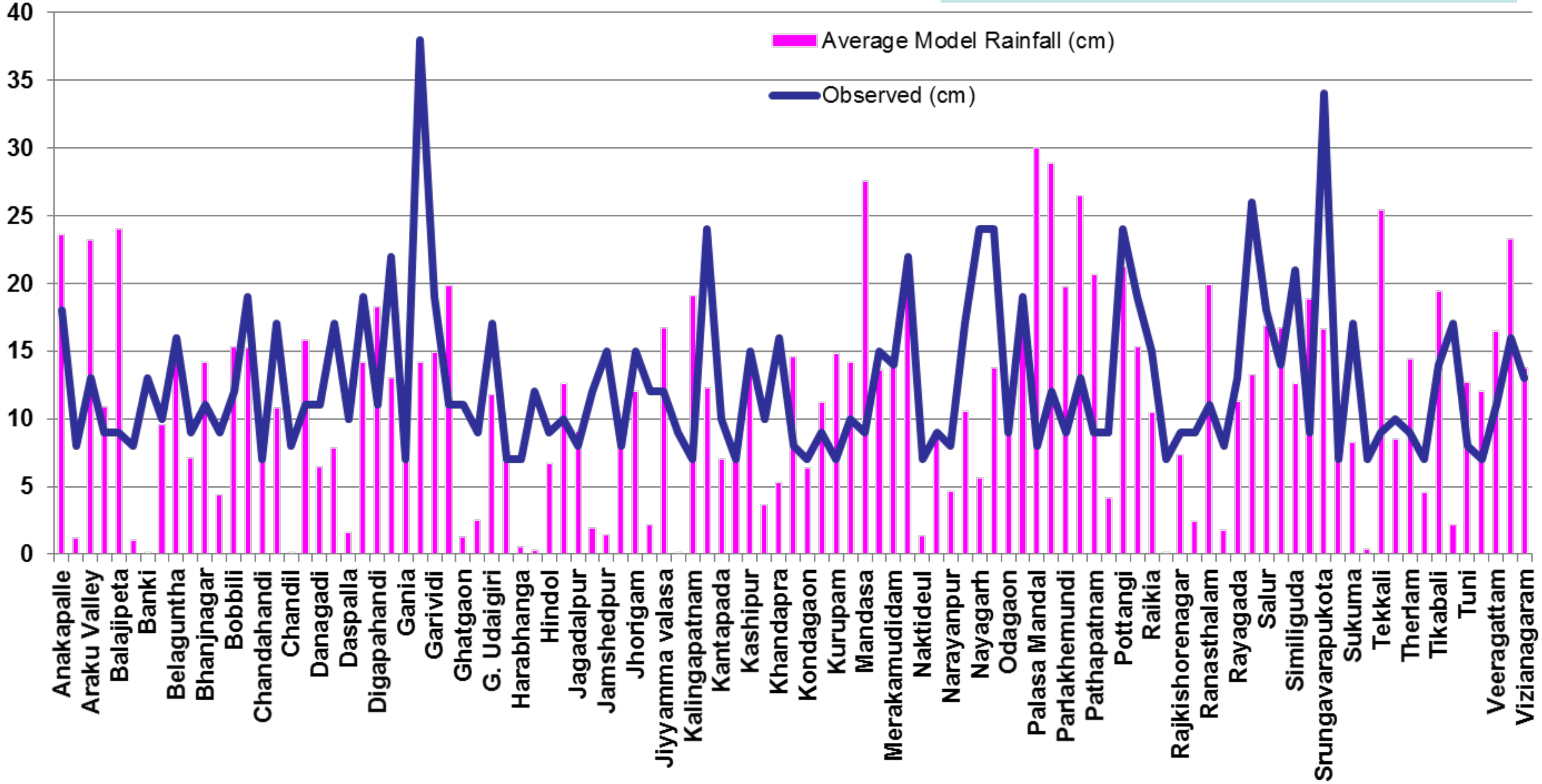
a) TRMM (00UTC 12–13 Oct)



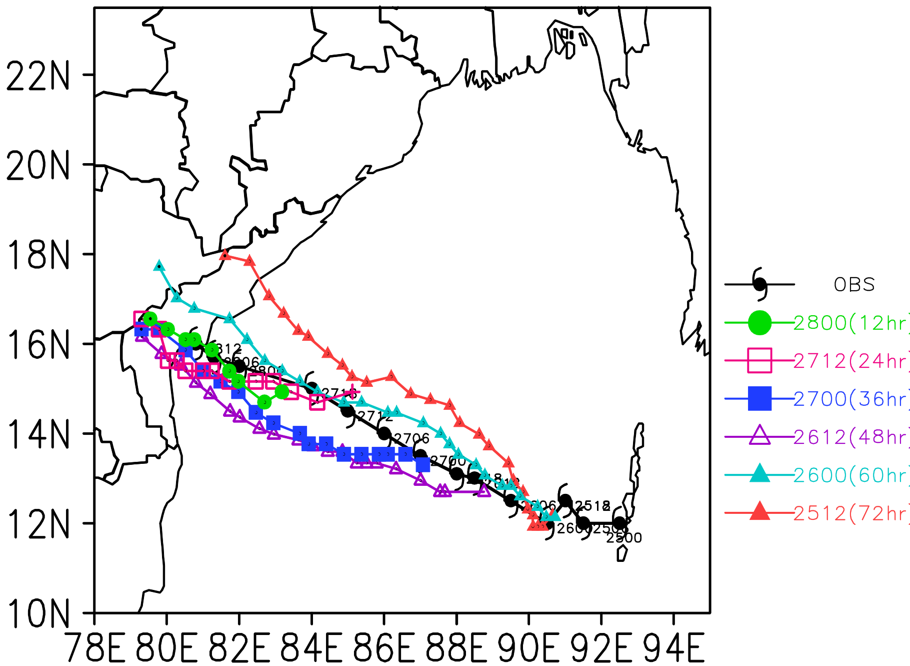


24-hr accumulated rainfall (cm) during landfall day for HudHud (Verification at 103 stations)

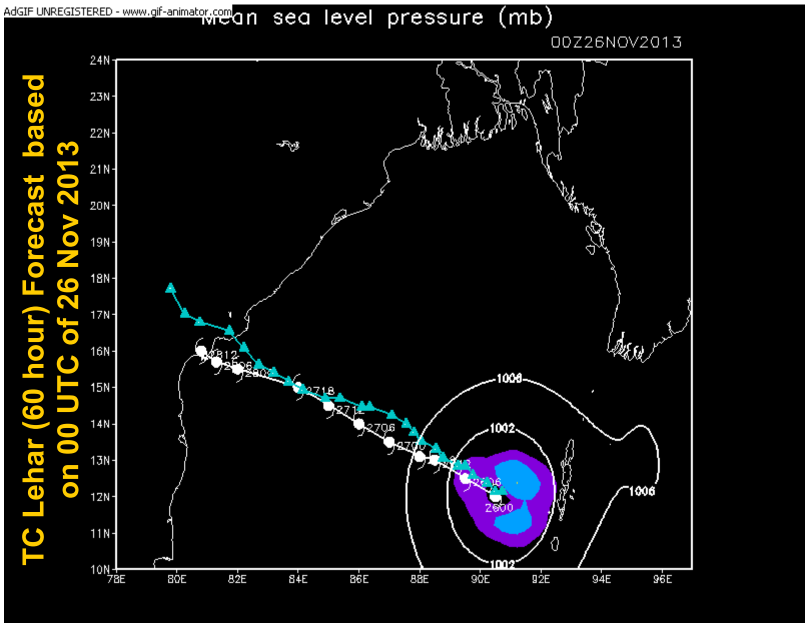
Maximum Rainfall: 38 cm
RMSE: 8 cm
CC : 0.25



Track prediction from different initial conditions for TC LEHAR



TC Lehar (60 hour) Forecast based on 00 UTC of 26 November 2013

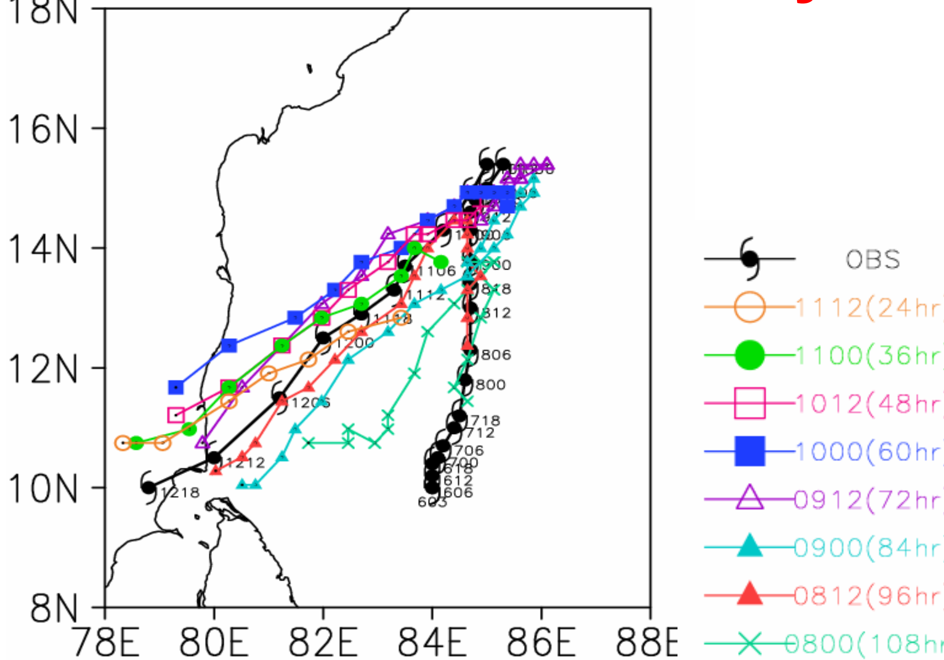


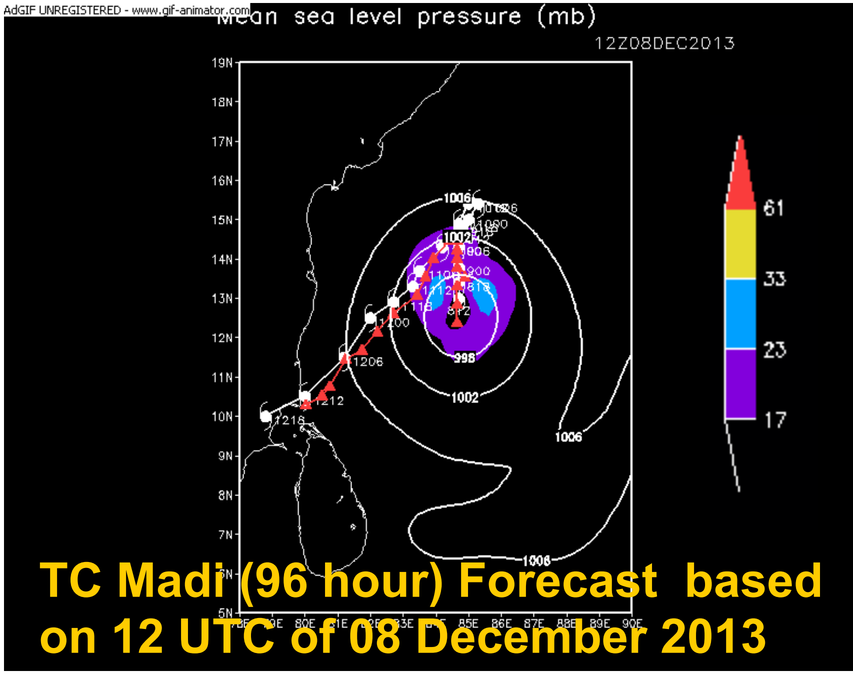
Model predicted weakening of Lehar into depression when approaching land as observed. Model simulated showers/low rainfall as observed.

Possible reasons are

1. **Dry air incursion along the southwestern periphery of the low level circulation (SSMIS 91 GHZ MICROWAVE IMAGE)**
2. **Cooler sea surface (passage of prior cyclone, Helen)**
3. **Increased vertical wind shear**

VSCS "Madi" over Bay of Bengal (8 – 12 Dec 2013)





TC Madi (96 hour) Forecast based on 12 UTC of 08 December 2013

OBSERVATIONAL facts

Madi's pole ward track was explained by the strong subtropical ridge located to the east of the system.

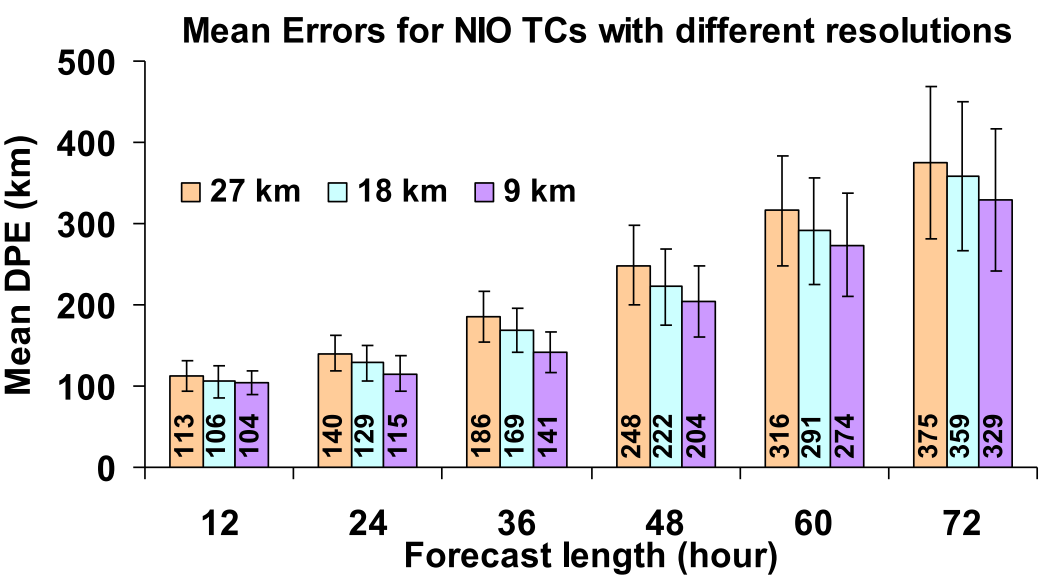
Another subtropical ridge located over India had steered the system southwestward. On December 11, Madi's LLCC became clearly exposed after dry air wrapped around the southern part of the system. This weakened Madi into a Cyclonic Storm

Model predicted sudden return and weakening of Madi. It intensified to very severe cyclonic storm stage (64 – 119 knots) while moving northward till 12UTC 10 Dec.2013

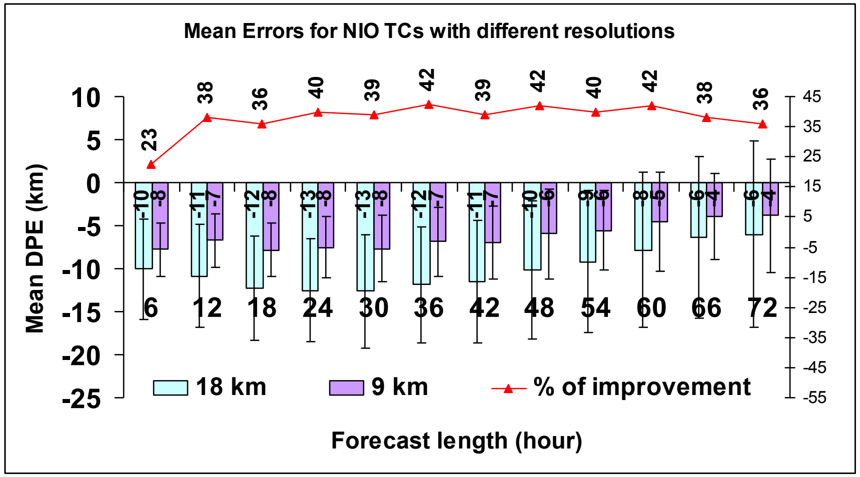
After that, it suddenly returned back and started moving in southwest ward. It started loosing its intensity and reached to depression stage (<33knots) within one day.

Mean track errors for NIO cyclones during 2007 - 2011 (under operational setup)

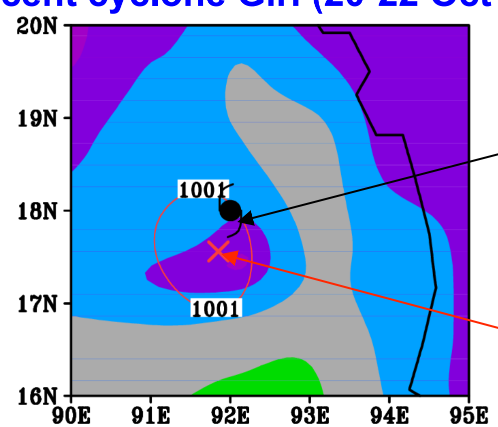
These error statistics are based on 100 TC cases



Mean Intensity Errors (10m winds m/s)



Recent cyclone Giri (20-22 Oct 2010)

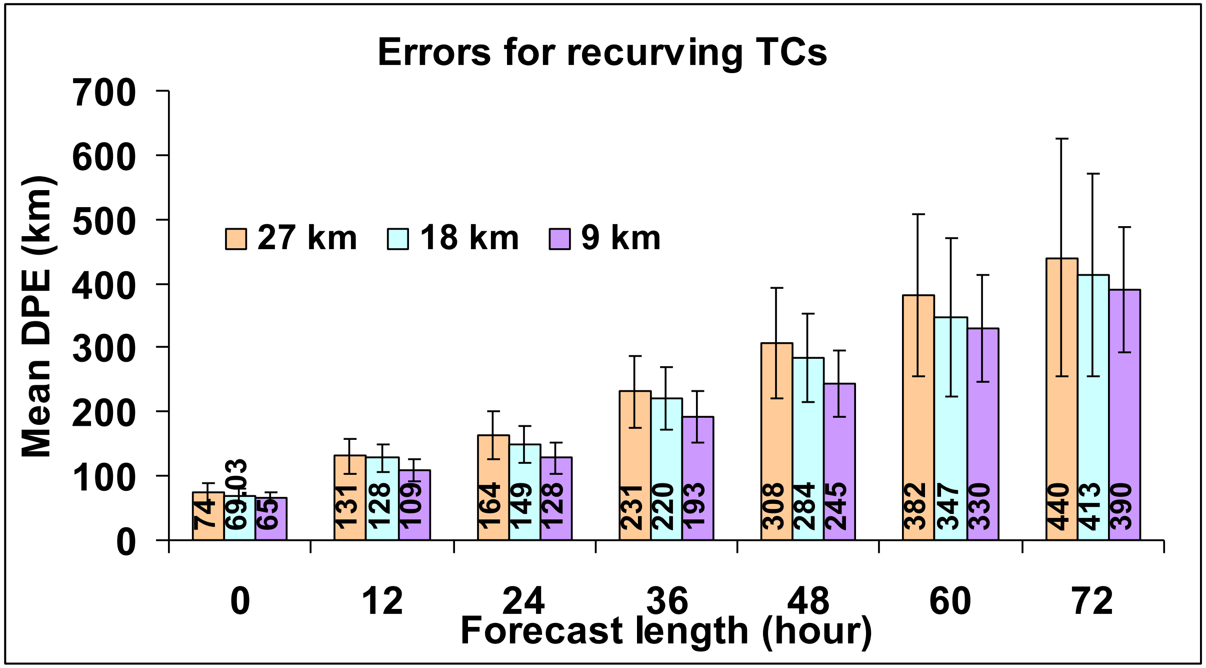


Observed TC Location

Initial cyclone vortex position error is about 60 km

Model TC Location

Osuri et al. 2013, JAMC

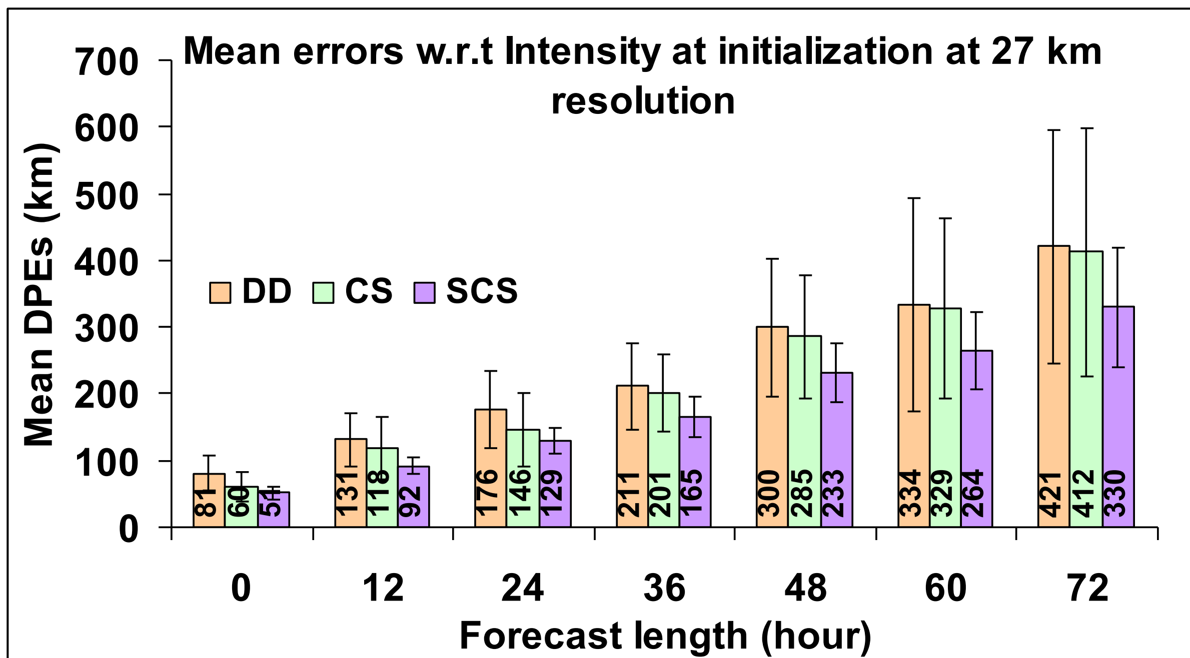


Mean errors for recurving TCs

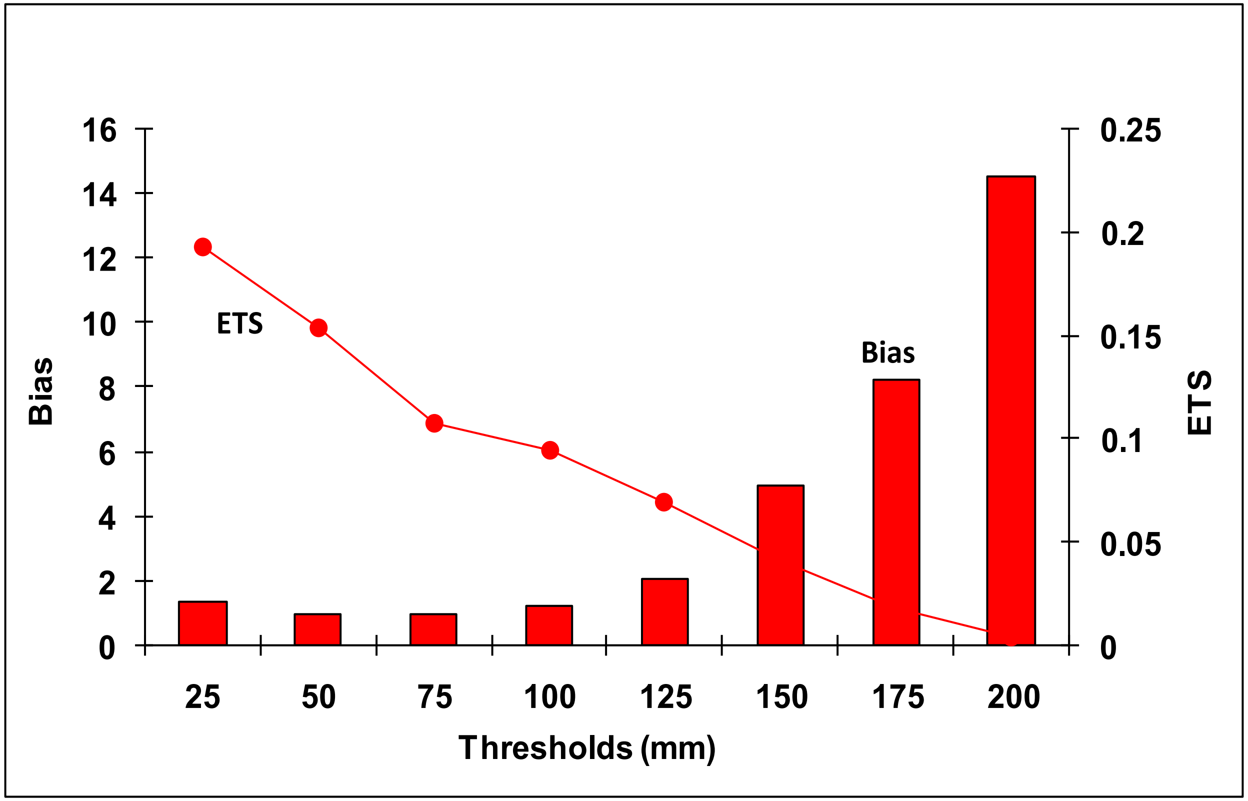
Improvement is significant with high resolution for recurving TCs.

Mean track errors w.r.t intensity at initialization

Stronger cyclones can be tracked with minimum errors compared to marginal cyclones or depressions.



Mean ETS and Bias of 24-hr accumulated rainfall during landfall day (in real time)



Model is overestimating rainfall (comparing with TRMM observations).

Skill (ETS) is good up to 5 cm rainfall, thereafter decreasing sharply.

Thanks

Objective Analysis (OBSGRID)