Impact studies of Data Assimilation using Nudging and 3D VAR for a few atmospheric systems

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Introduction

- Modelling / forecasting of Tropical cyclones requires accurate initial/ boundary conditions to precisely forecast the intensity and movement of the developing storm and its landfall point

- 3-DVAR and Newtonian Nudging are widely used assimilation techniques to incorporate observations in to a dynamical model

- However they require to be evaluated for different sources of data, observational error coeffients (3dvar), period and strength of nudging to assess their potential in data assimilation

- Satellite Scatterometer wind observations, temperature/ humidity profiles and conventional land based observations are potential sources of data for prediction of various atmospheric systems.

Objectives

- To study the impact of vector wind observations from QuickSCAT (Quick Scatterometer) and ASCAT (Advanced Scatterometer) at 25 km resolution using Four Dimensional Data Assimilation (FDDA) analysis nudging technique in WRF ARW nested mesoscale model on simulation of wind field (for dispersion) and Tropical Cyclones.

- To assess the effect of nudging on the intensity and movement with respect to period of nudging and strength of nudging

- To study the effect of assimilating different data sets (QucikSCaT/ SSMI winds, conventional observations) on cyclone simulations using 3D-Var

Newtonian Relaxation or Nudging

The widely used method for data assimilation is *Newtonian relaxation or nudging w*hich consists of adding an empirical term to the prognostic equations that nudges the solution towards the observations

$$\frac{\partial \alpha}{\partial t} = F + G_\alpha W(x, y, \sigma, t) \cdot (\alpha_0 - \alpha),$$

Where **F** = All model's Physical Processes

G_α = Positive relaxation term which determines relative weight of the relaxation term for a given parameter

W = Four dimensional weighing Function

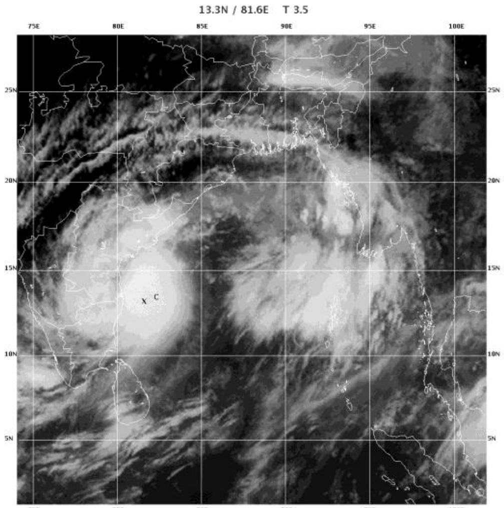
α_o = Gridded field of **α** obtained from objective Analysis of Observations

Questions

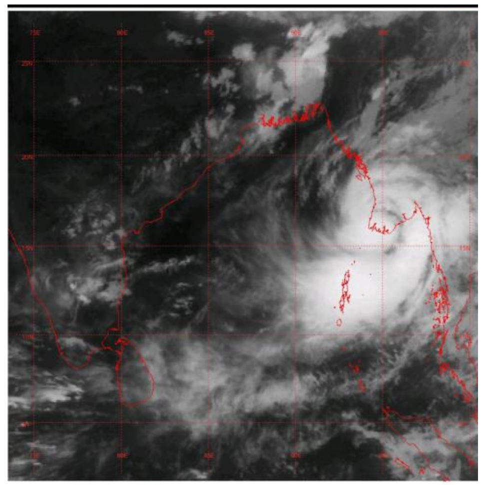
- Which data are useful ? i.e., Impact of different kinds of observations
- How much period is sufficient to obtain better initial condition ?
- What strength of nudging to be applied ?

A few cyclonic systems in the present study….

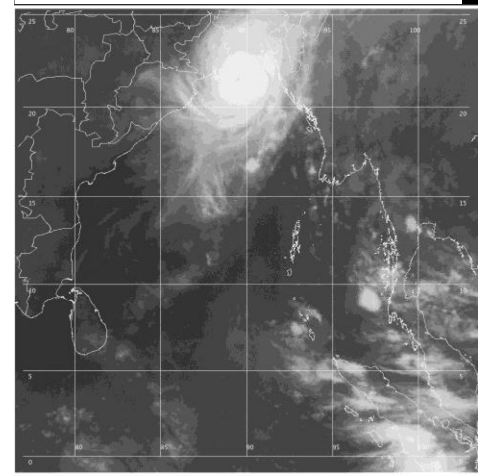
LAILA (18 –21 May 2010)



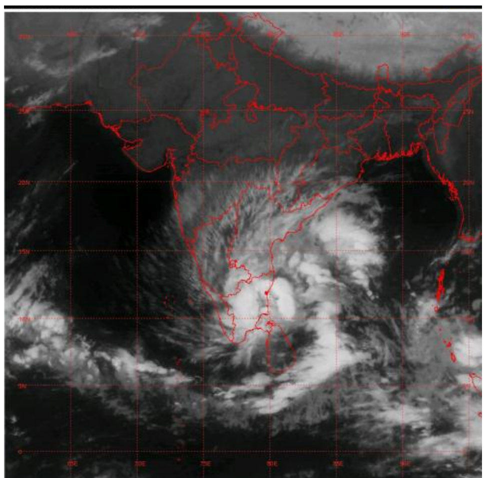
NARGIS (27Apr–2May 2008)



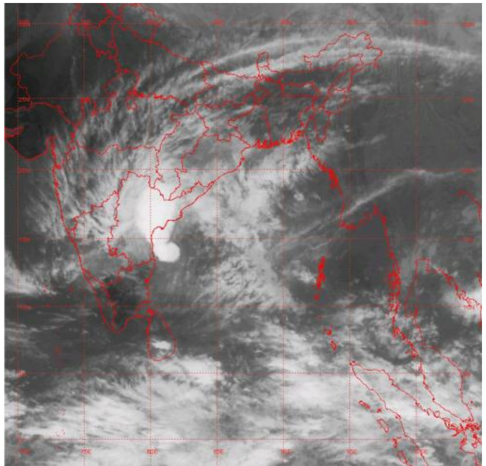
SIDR (11-16 Nov 2007
CSLP – 944 hPa;
Max winds – 115 knots



NISHA (24-28 Nov 2008)
CSLP – 996 h Pa
MSW – 22.5 ms-1



KAIMUKH (15-15 Nov 2008)

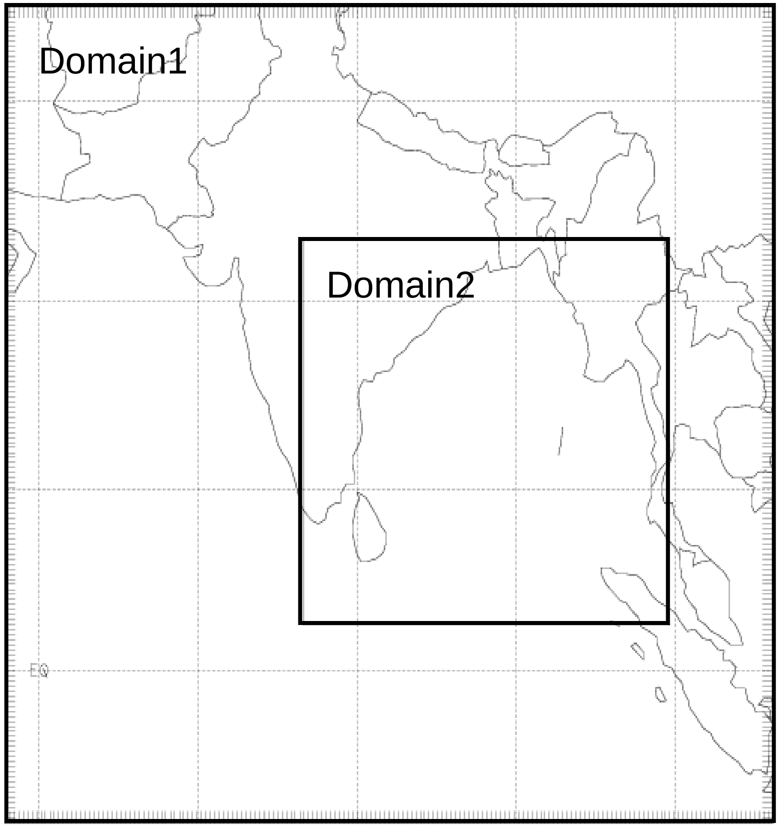


Land fall

Laila – Near Machilipatnam
Nargis – Mynmar
Sidr – Bangladesh
Nisha – Near Chennai
Kaimukh – Near Machilipatnam

Model Configuration

Dynamics	Primitive equation, non-hydrostatic	
Vertical resolution	28 levels	
Domains	Domain1	Domain2
Horizontal resolution	27 km	9km
Grid points	173 x 162	249 x 239
Domains	58.02-105.97 E; -8.26 - 34.31 N;	77.9-99.40 E; 4.49-23.60 N
Radiation	Dudhia scheme for shortwave and RRTM for long wave processes	
SST	NCEP FNL analysis data	
Convection	Kainfritch Scheme	
Explicit moisture	Lin et al	
PBL turbulence	YSU PBL	
Surface processes	NOAH LSM scheme	



Simulations

- Model integrated for 72 hours using the NCEP GFS analysis as first guess for initial/ boundary conditions
- Control run uses NCEP GFS data alone for IC/BC, in assimilation runs the first guess is modified with various observations
- In nudging experiments observations are combined with background first guess fields using objective interpolation / SCM methods (viz.,Cressman).
- Nudging experiments are conducted with respect to period of nudging (6 hour, 12 hour, 18 hour, 24 hour) during pre-forecast period
- Strength of nudging for winds (1.0e-4, 2.0e-4, 3.0e-4, 4.0e-4, 5.0e-4)

Sources of Data

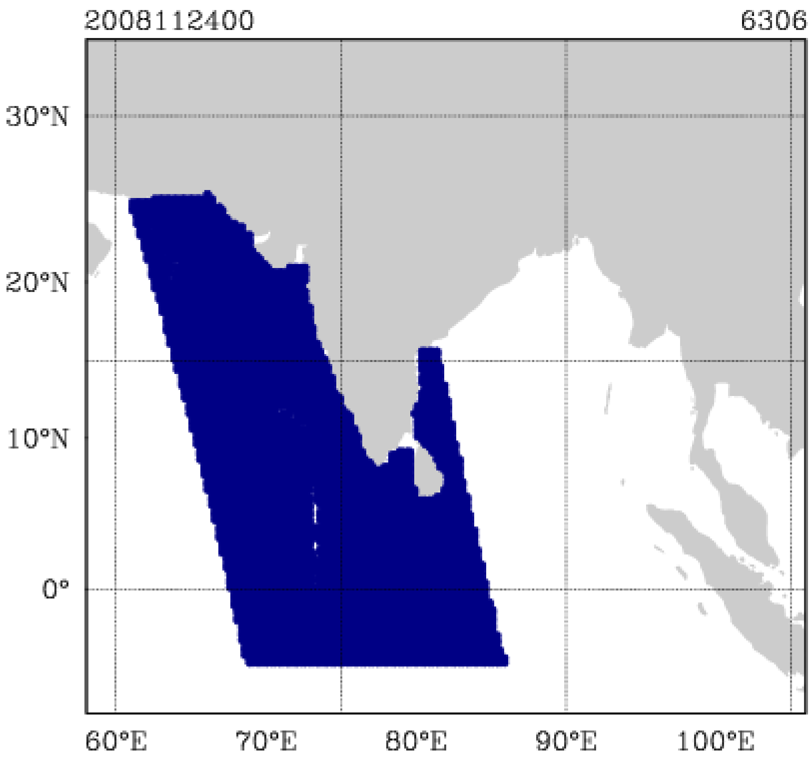
- Conventional (surface, upper air Radiosonde)
- Satellite (QSCAT, SSM/I, ASCAT winds, MODIS temperature, humidity profiles)
- ISRO Automated Weather Stations

- QSCAT is NASA’s scatterometer operates with frequency of 13.4GHZ and provides wind vector with resolution of 25KM at 10m level
- QSCAT has a swath width of 18000KM and measures wind speed with in the range of 3 to 20m/s
- The products of QSCAT are wind speed , wind direction at 10mlevel total columnar water vapor and rain rate estimates

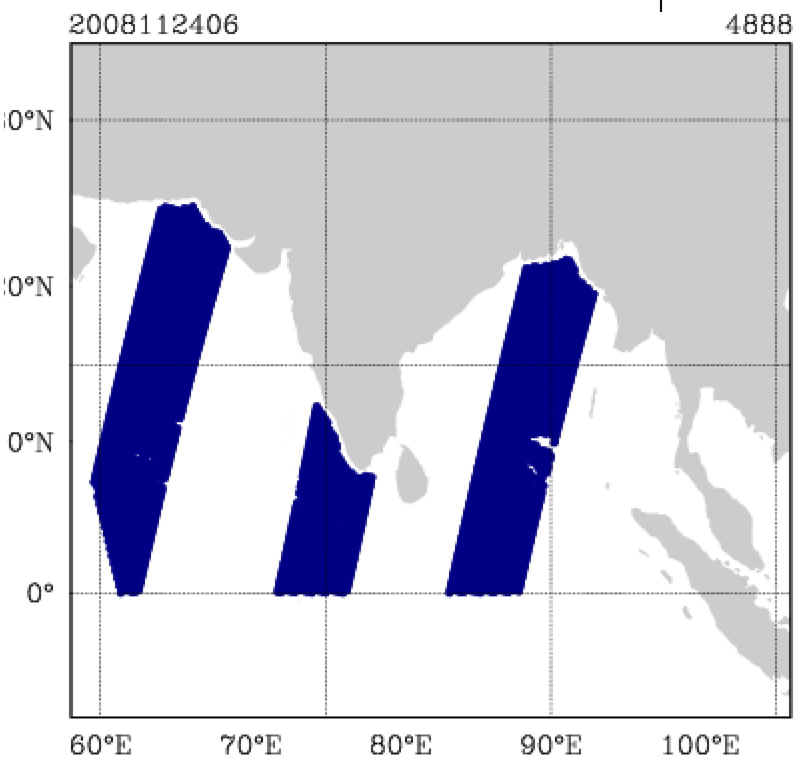
- Advanced scaterometer is EURUMETSAT’s scaterometer operates with frequency of 13.4GHZ and provides wind vector with resolution of 25KM at 10m level
- ASCAT has a swath width of 9000KM and measures wind speed with in the range of 3 to 25m/s
- The products of ASCAT are wind speed , wind direction at 10mlevel and soil moisture estimates

Typical QuickSCAT / ASCAT passes

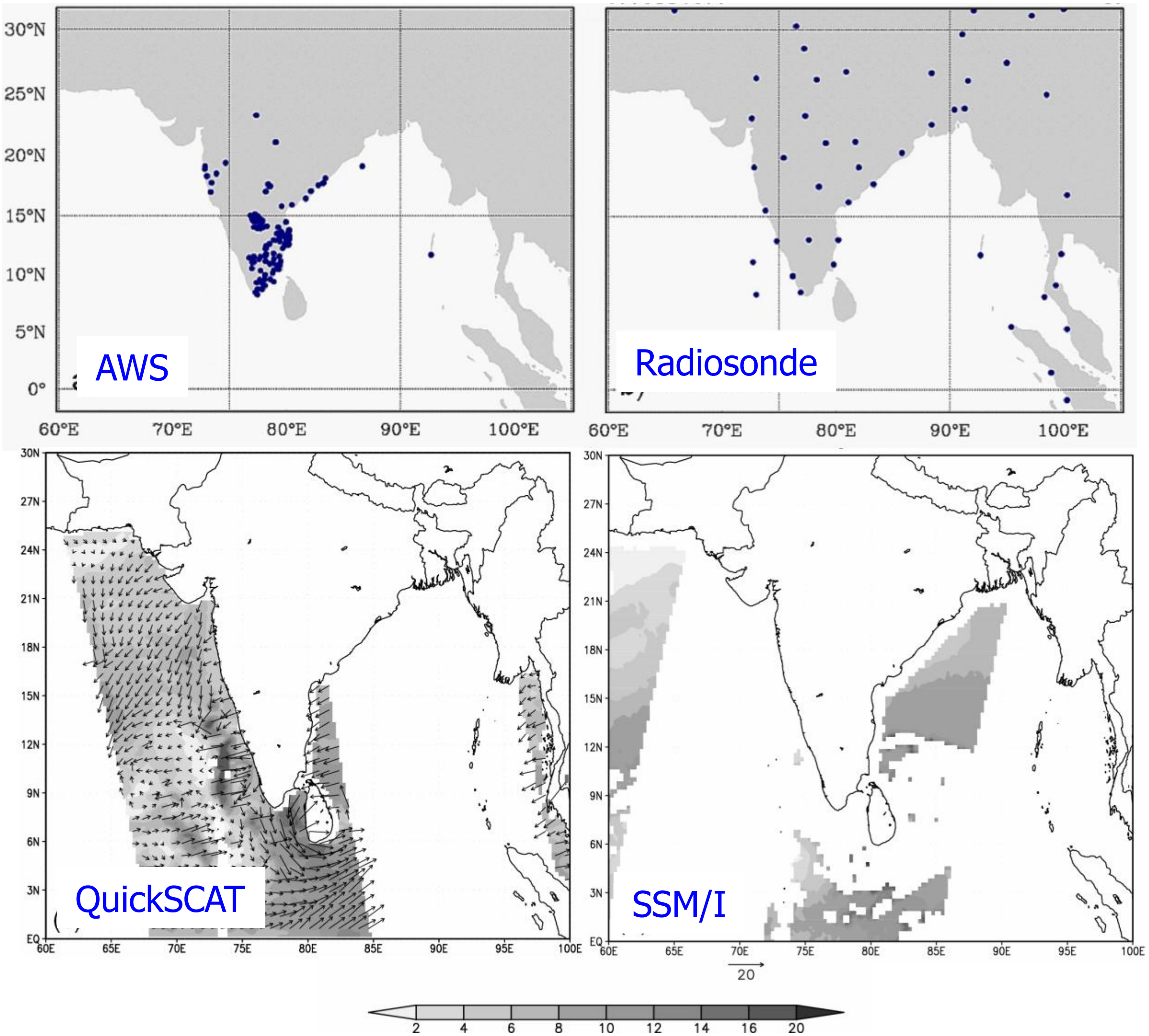
QSCAT Morning Pass



ASCAT Morning Pass

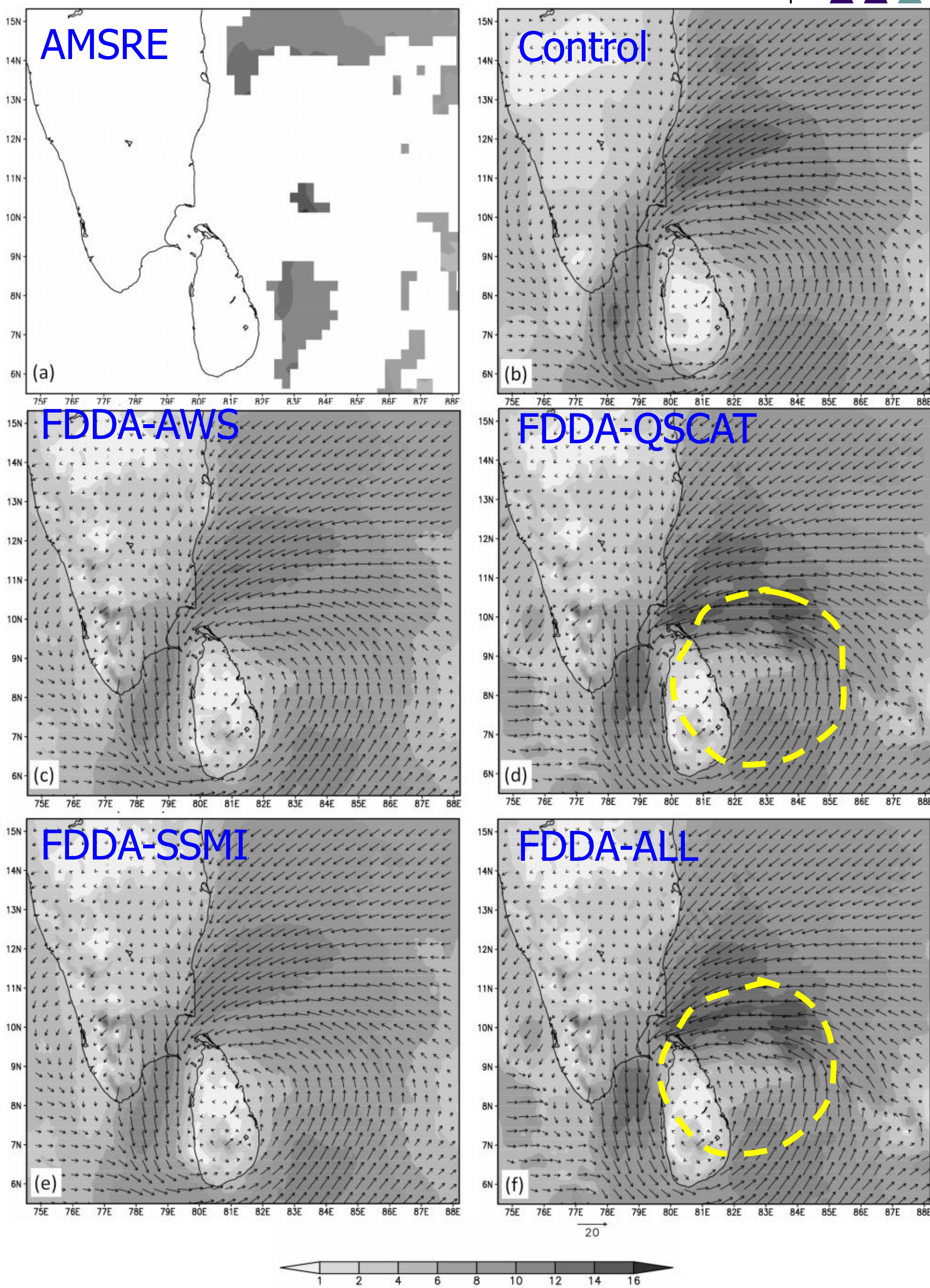


Experiments with assimilation of different observations

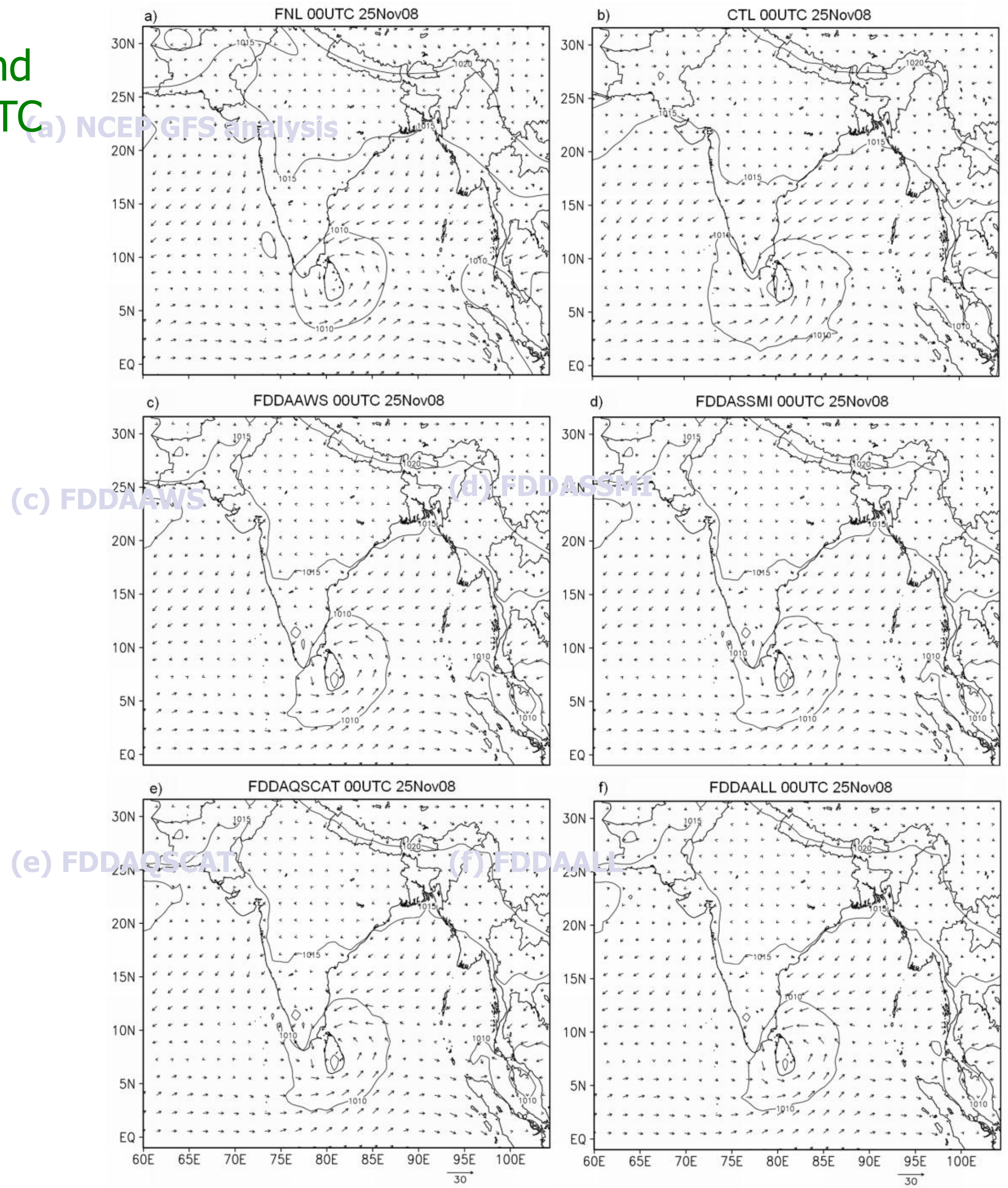


Cyclone - NISHA

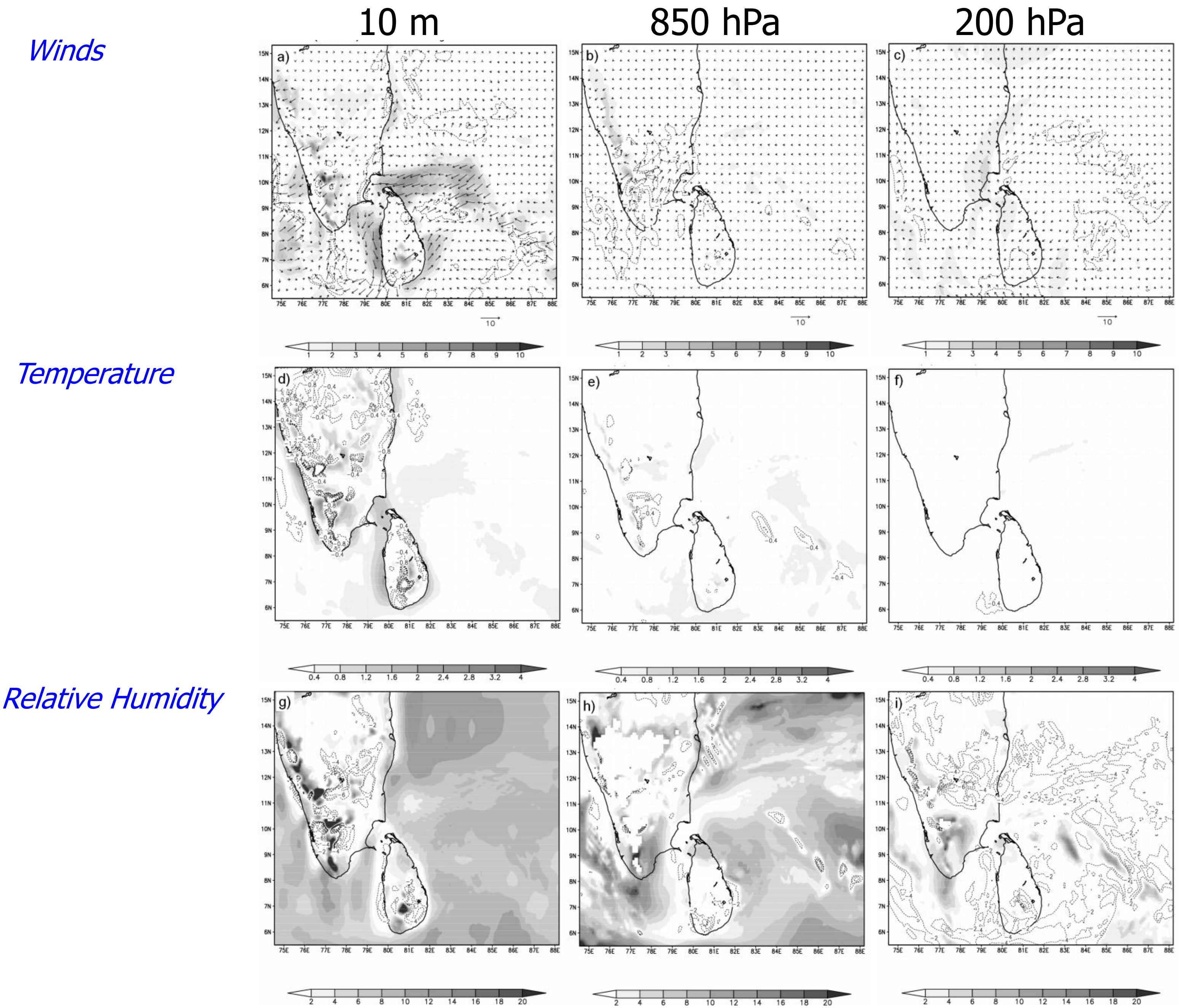
Comparison of 10 m winds from different analysis at 00 UTC 25 Nov



Seal level pressure and surface winds at 00UTC 25 Nov 2008



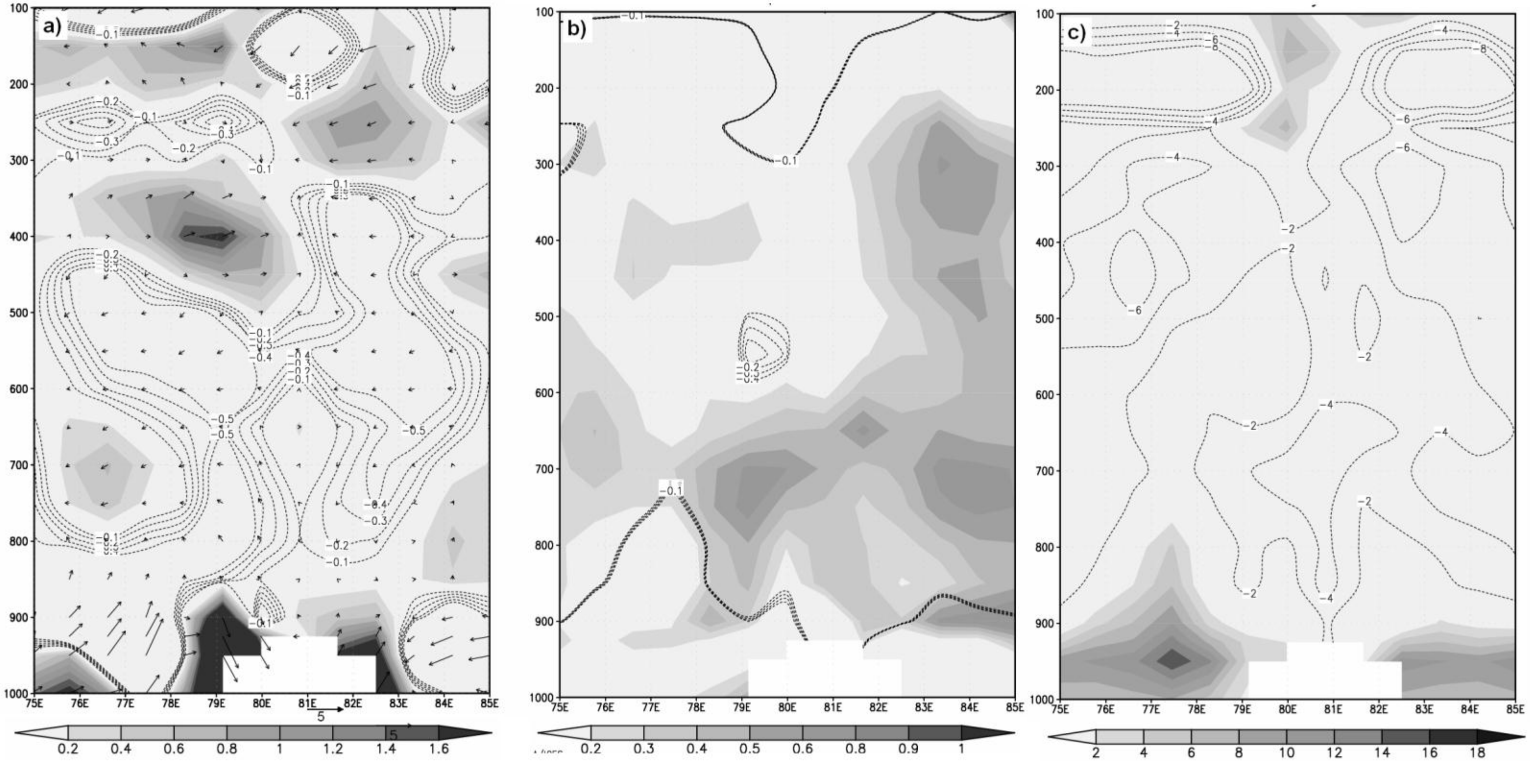
Difference in initial fields between FDDA and CONTROL 00 UTC 25 Nov 2008

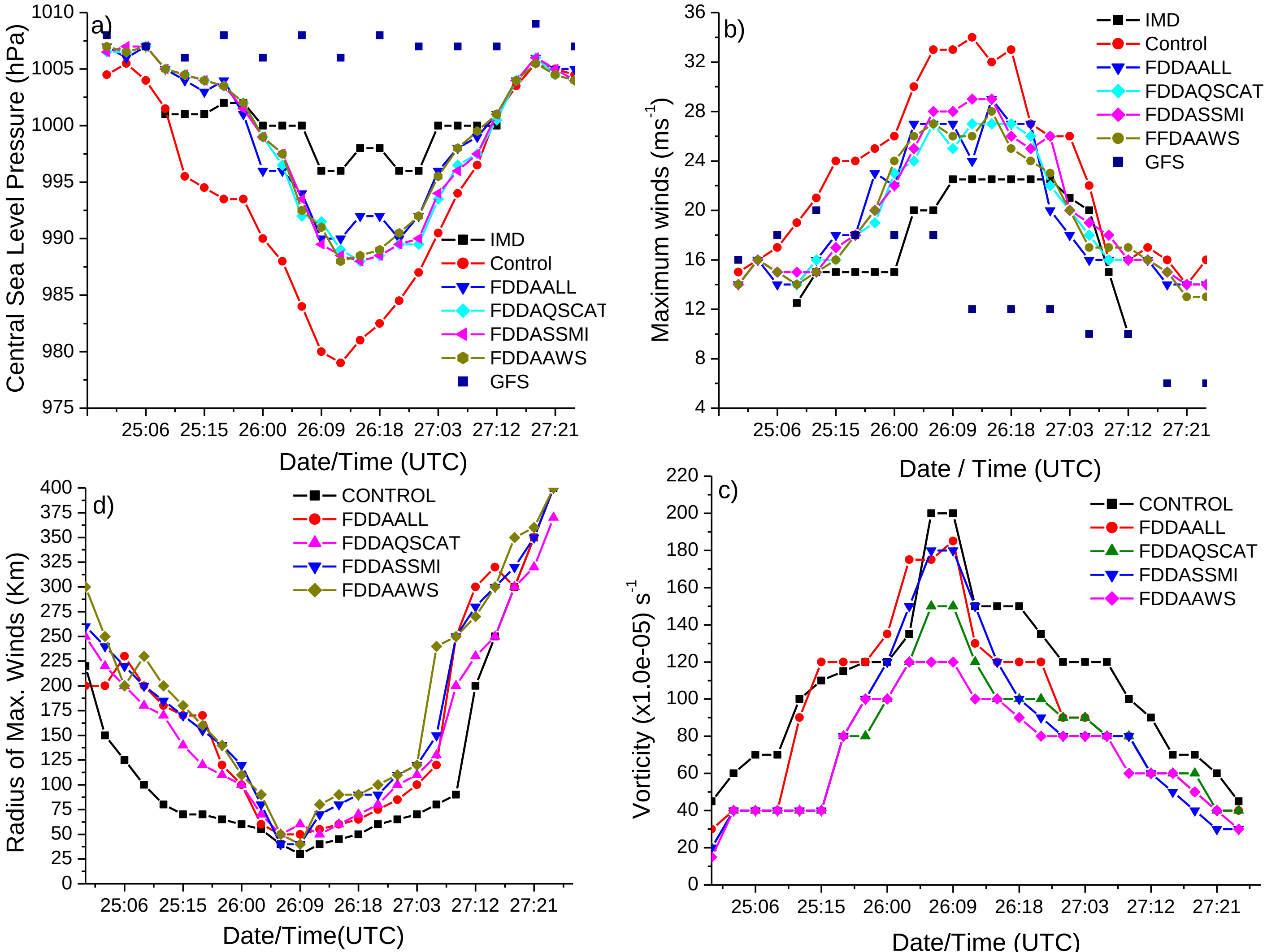


Vertical section of difference in initial fields FDDA and CONTROL runs for 25 Nov 2008, 00 UTC at 7 ° N

Analysis increments

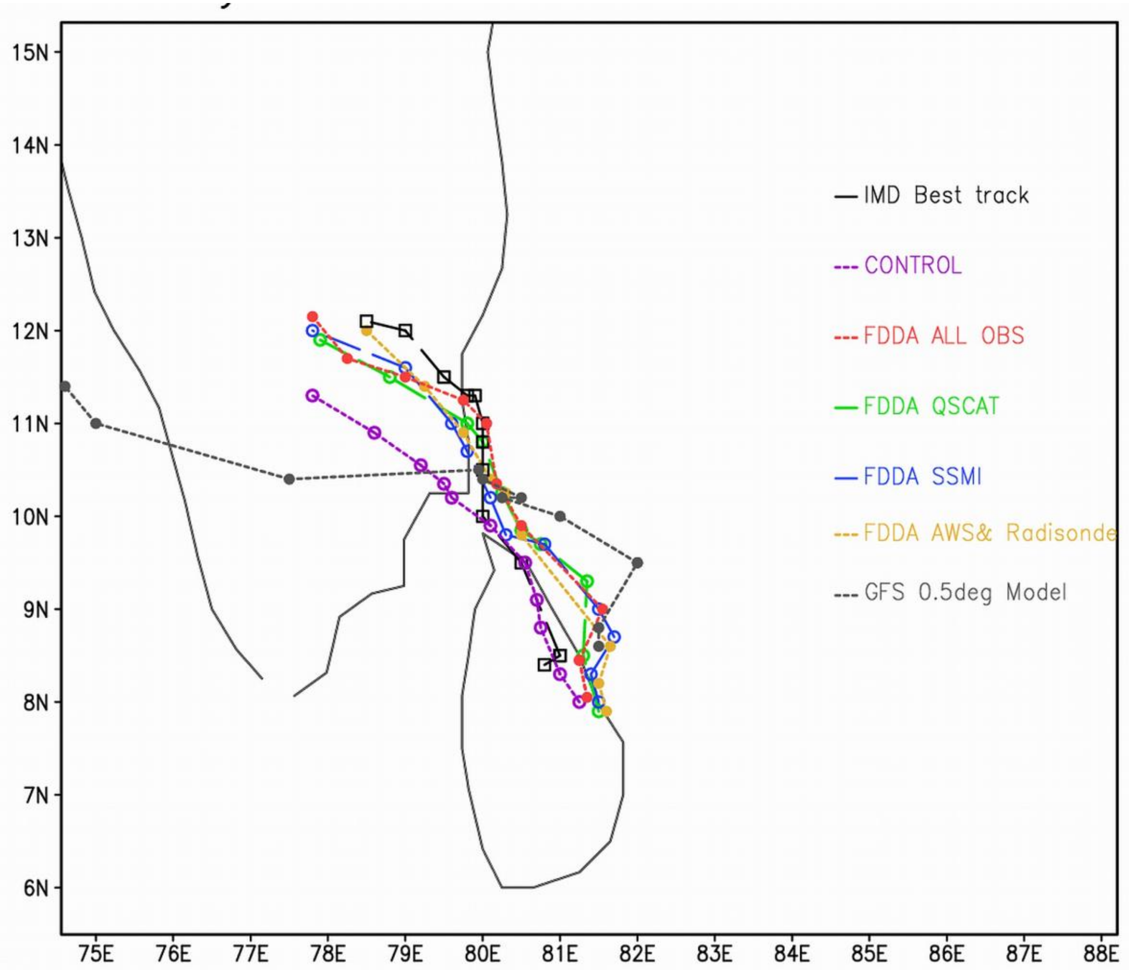
Horizontal winds | Potential temperature | Relative humidity





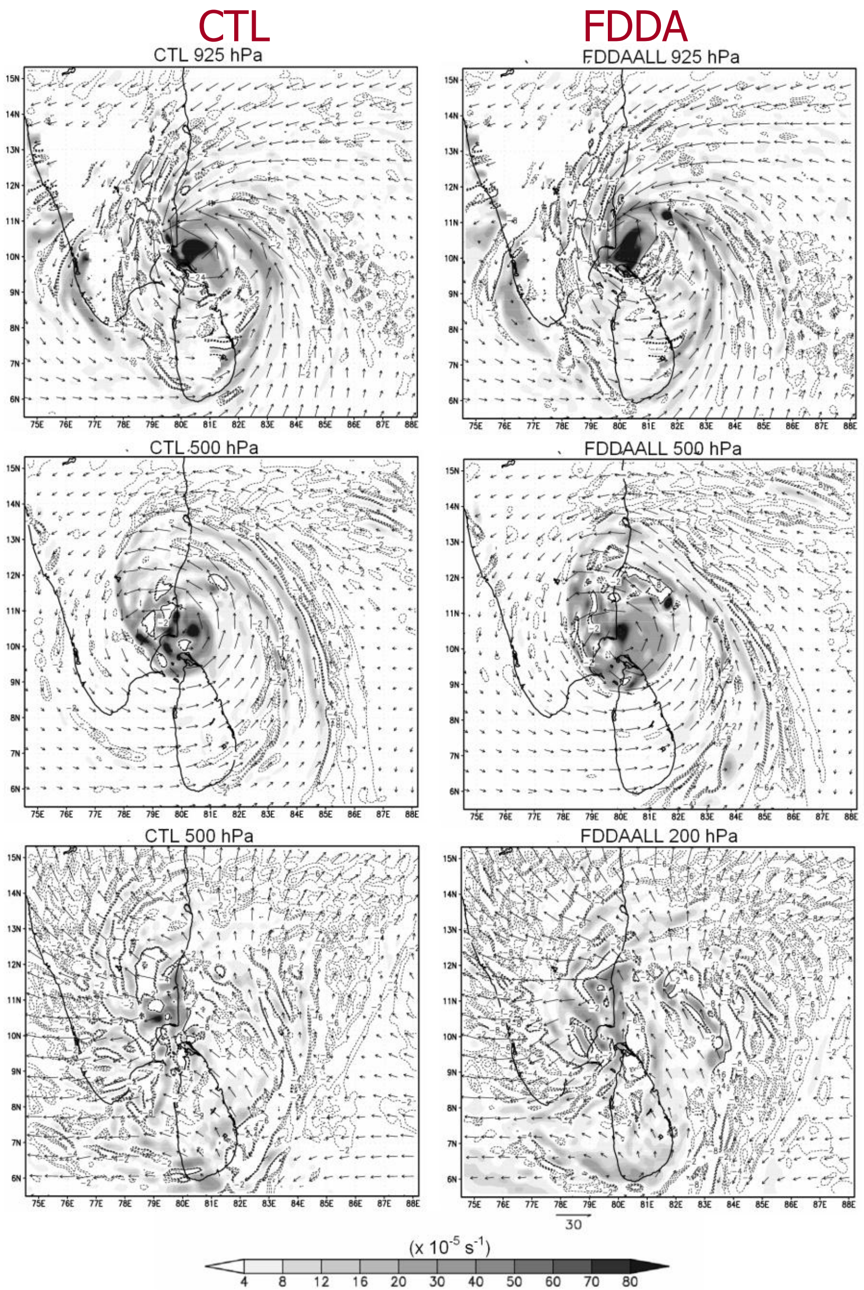
- FDDA reduces intensity of the storm and brings nearer to estimates
- FDDAQSCAT, FDDASSMI almost similarly perform except during peak development stages where QSCAT shows large impact with substantial reduction in the intensity
- FDDAQSCAT, FDDAALL gives the best simulations for CSLP, winds

Simulated track estimates



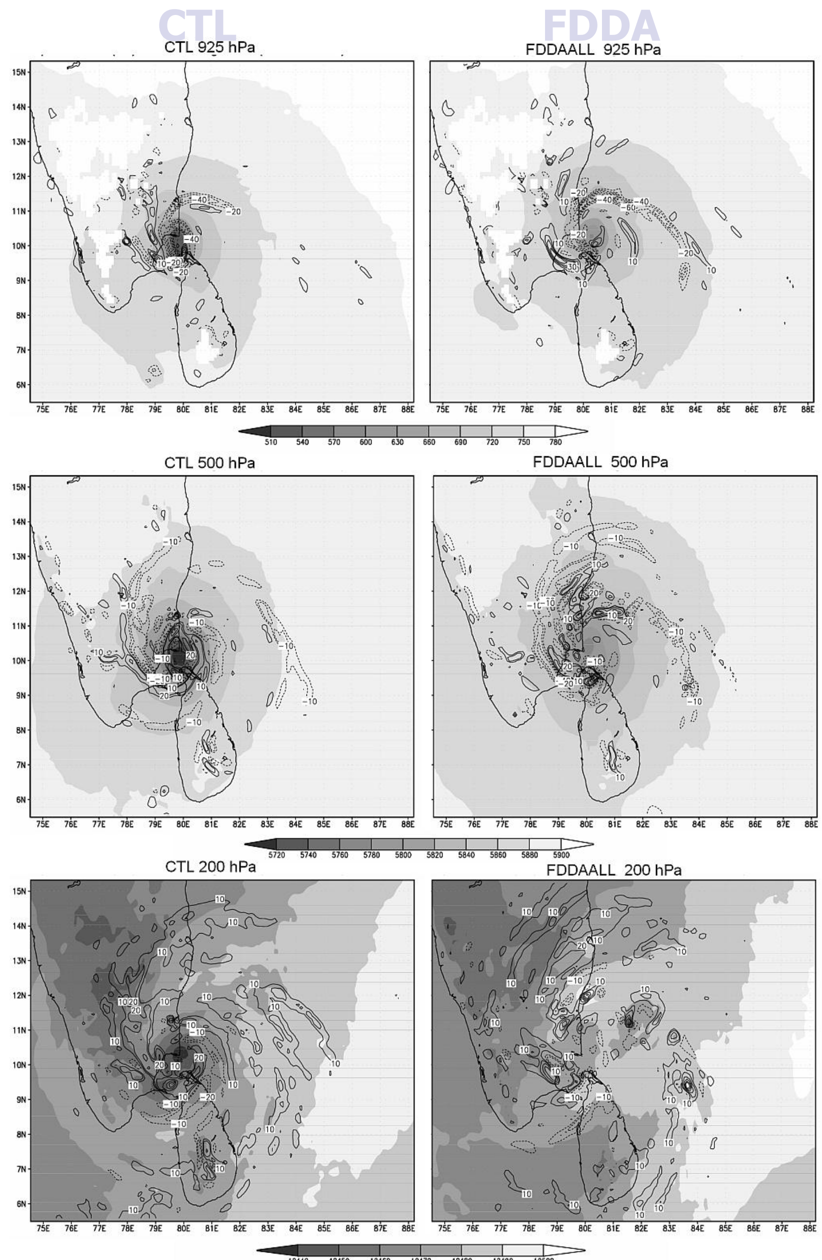
- FDDA QSCAT runs produce the minimum errors in the development phase
- FDDA AWS runs produce minimum errors during landfall phase
- FDDAALL (with all observations) produce the minimum track errors through out simulation

Wind field and Vorticity (x10-5 s-1) associated with the simulated storm for 09 UTC 26 Nov 09.

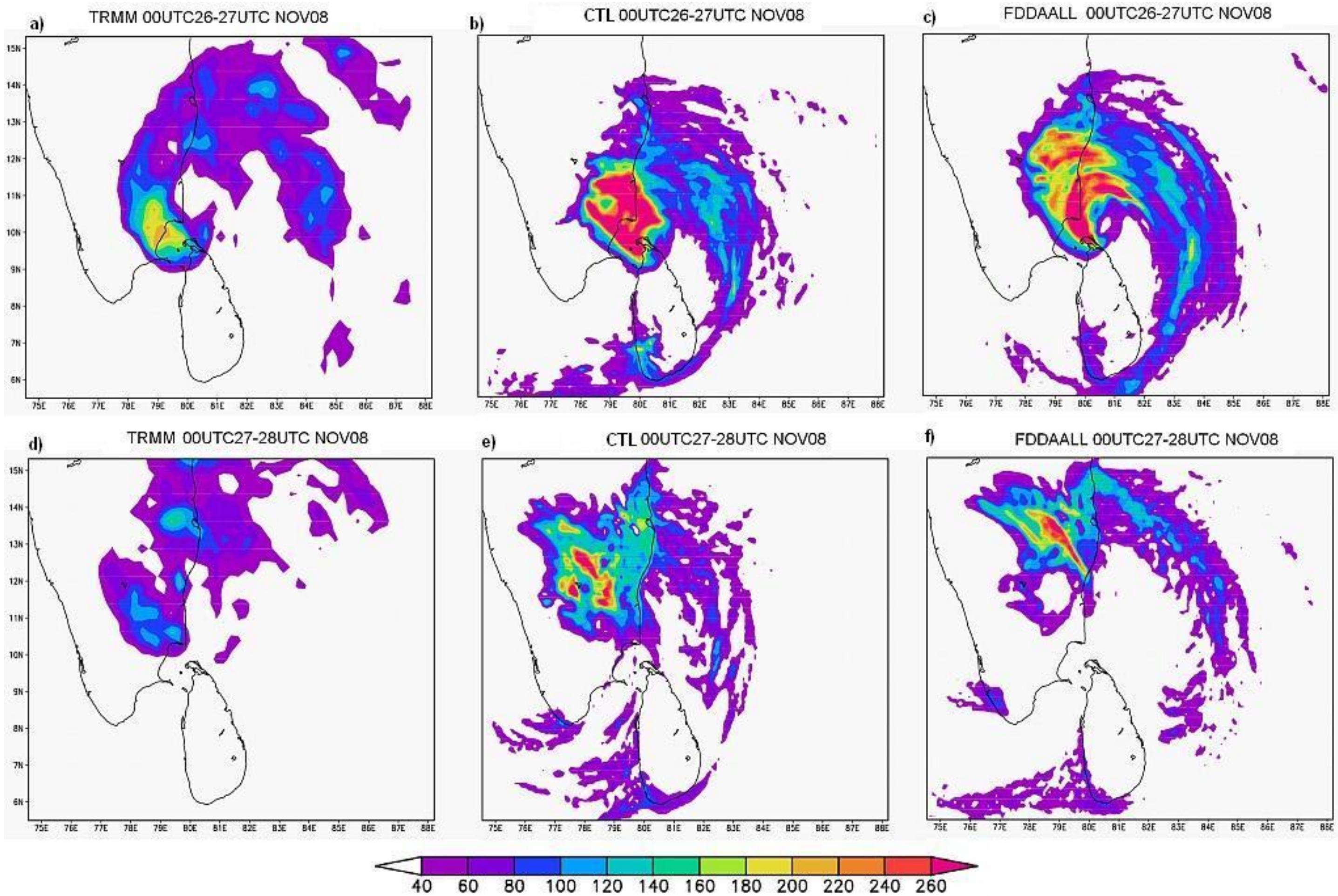


Assimilation of all observations shows improvement in simulations over control run with respect to wind field and vorticity and movement of the storm

Geopotential (m) and convergence/divergence (x10-5 s-1) associated with the simulated storm for 09 UTC 26 Nov 09.



Simulated Rainfall pattern in CTL, FDDA runs along with TRMM data

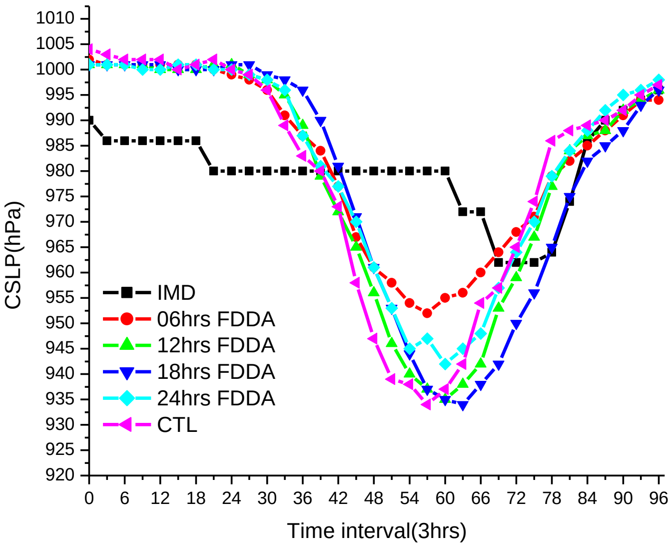


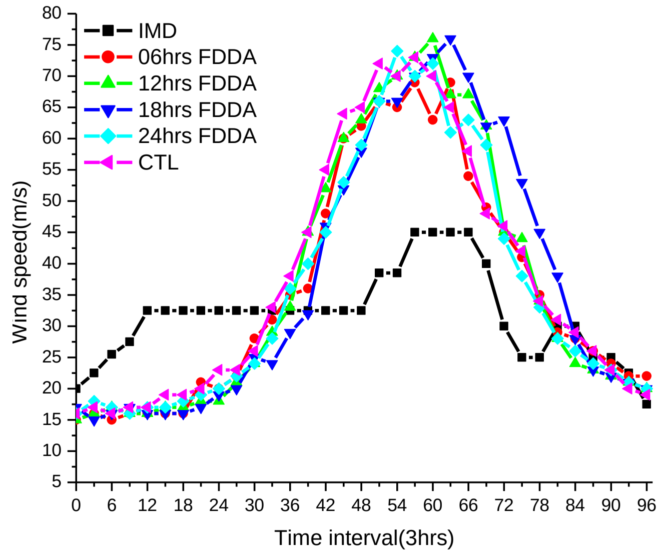
Control

FDDAALL

The distribution and pattern of rainfall is relatively better simulated with FDDAALL (with inclusion of all observations)

Experiments with different Nudging Periods



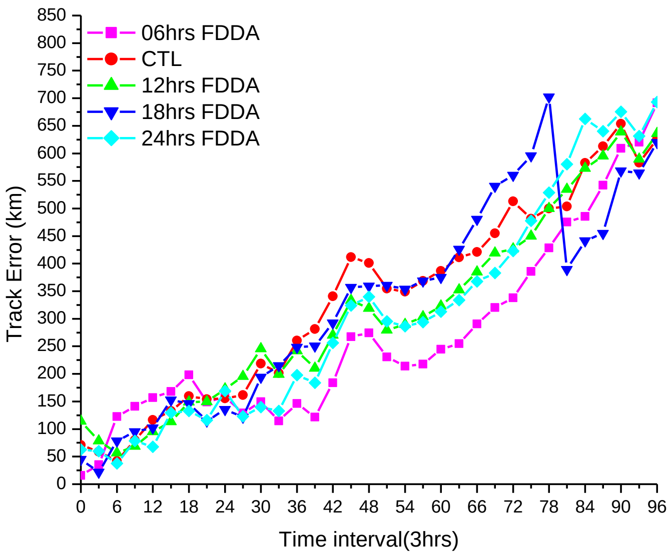


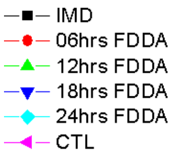
- FDDA reduced the intensity of the simulated storm and the maximum effect is found with 6h nudging

- Error in CSLP is minimum with 6hr/ 24 hr nudging and maximum with 12/18 h

- Error in winds is minimum with 6r nudging and increases with period of nudging further

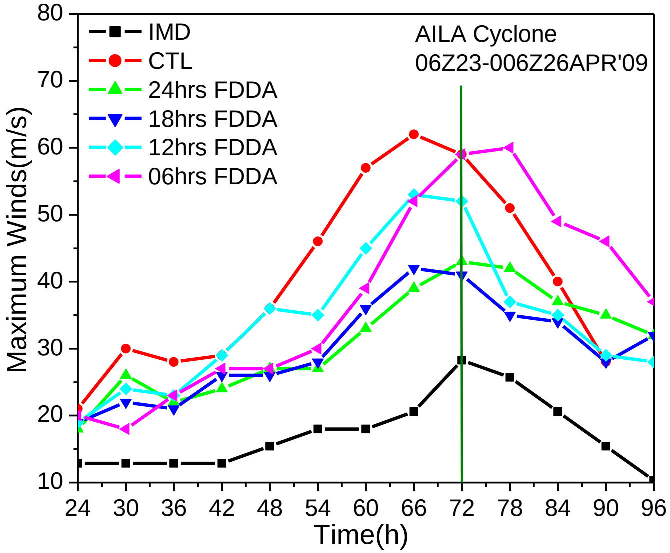
- Errors in track positions are improved after 24h simulation and minimum with 6h nudging

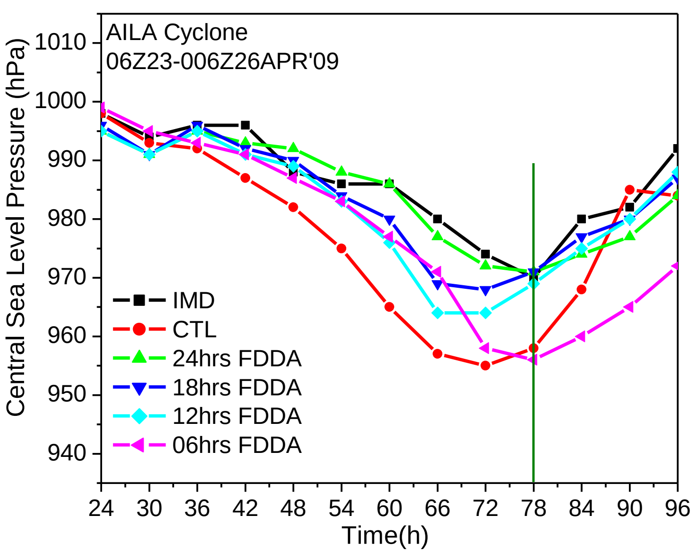


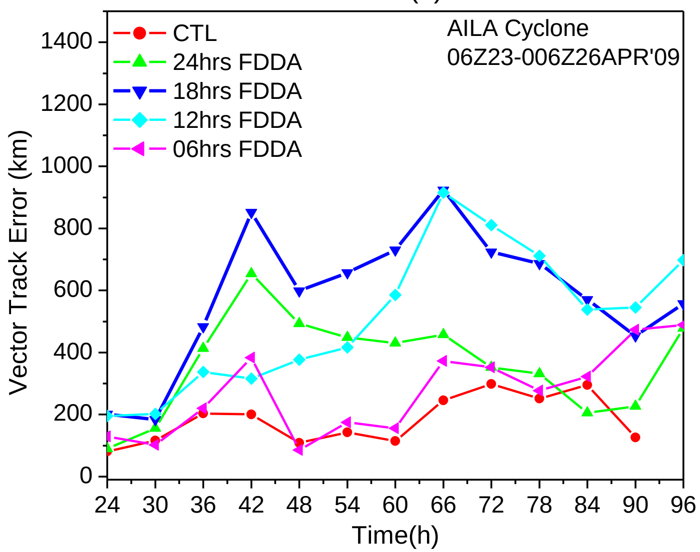


Experiments with different Nudging Periods

AILA Cyclone 06Z23 – 006 Z 6 Apr 2009
Conventional data alone used in Assimilation

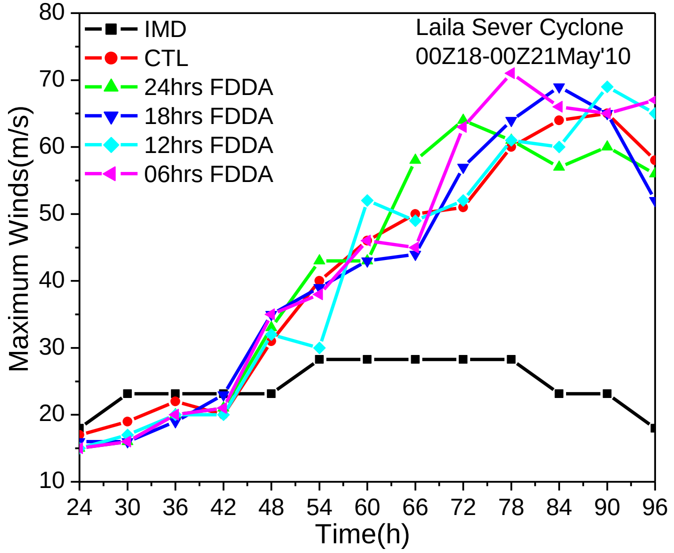


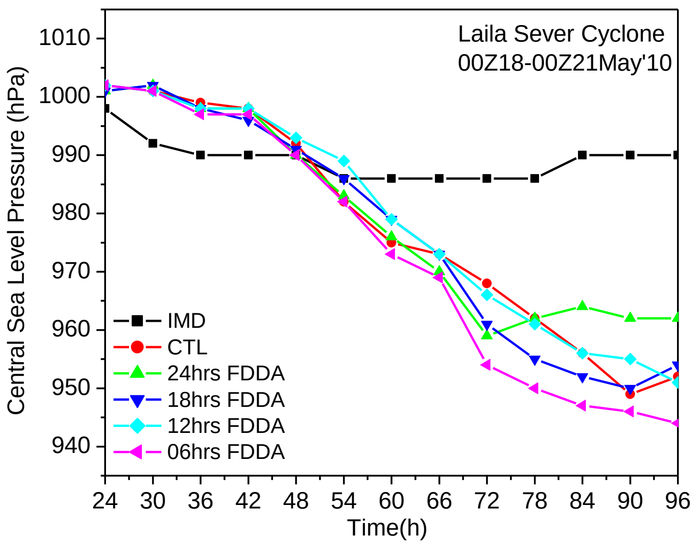


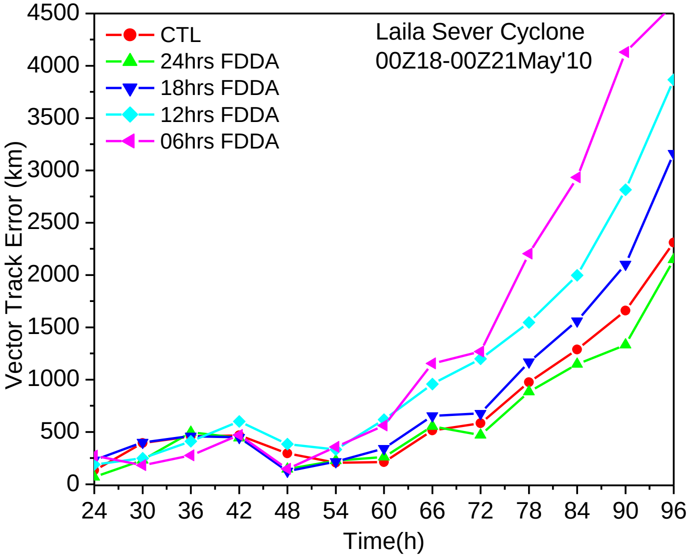


- FDDA reduced the intensity of the simulated storm and the maximum effect is found with 18/24 h nudging
- Error in CSLP is minimum with 18/ 24 h nudging
- Error in winds is minimum with 18/ 24 h nudging
- Errors in track positions are minimized with 6h /24h of nudging

LAILA Cyclone 00Z18 – 00Z21 May 2010



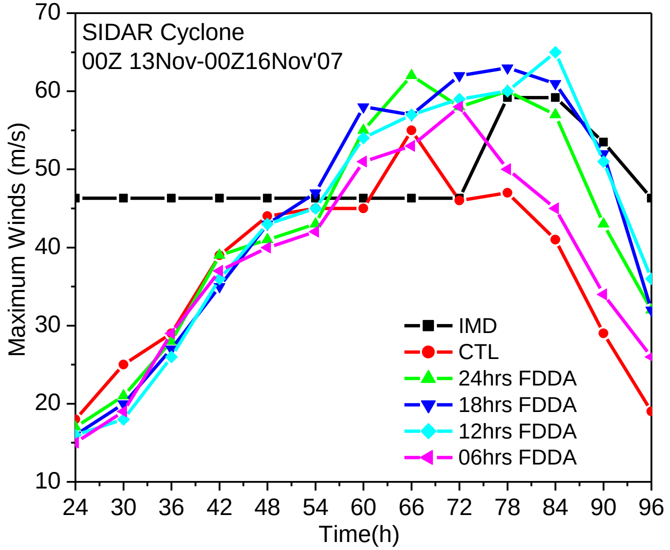


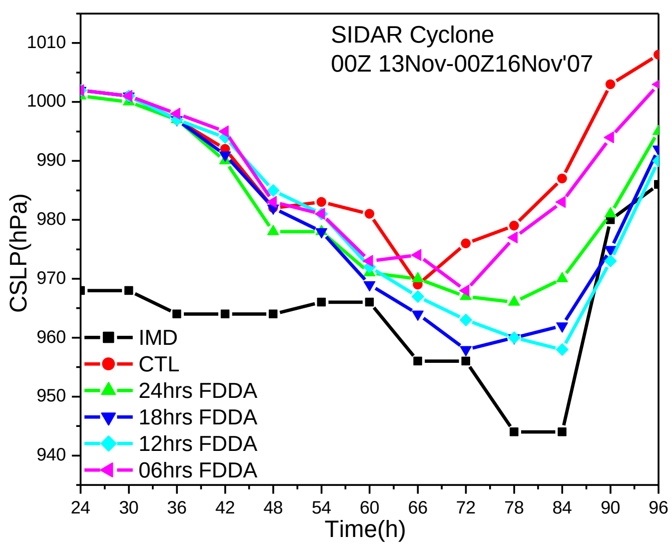


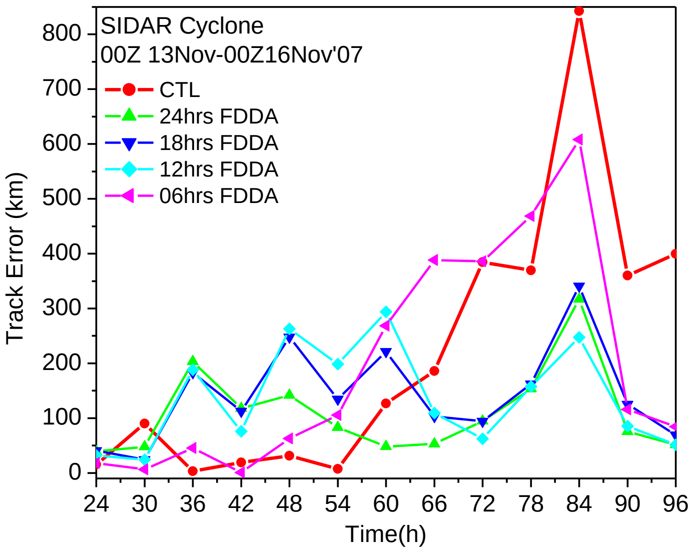
- FDDA marginally reduced the intensity of the simulated storm and the maximum effect is found with 24 h nudging

- Errors in track positions are minimized with 18/ 24h of nudging

SIDAR Cyclone 00Z13 – 00Z16 Nov 2007



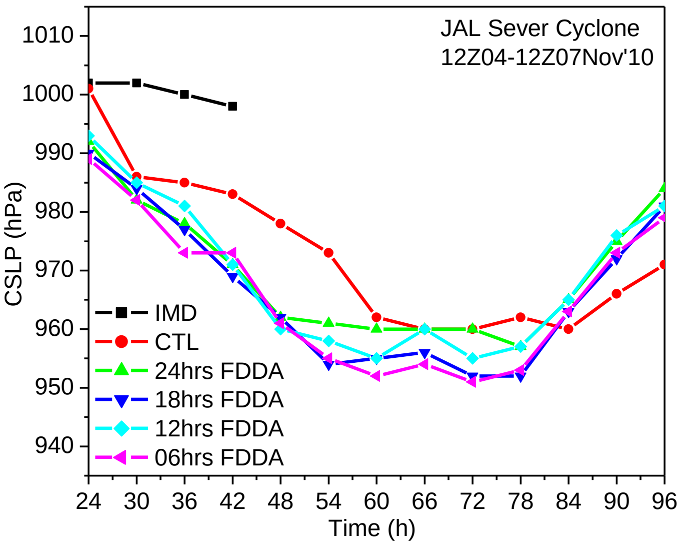


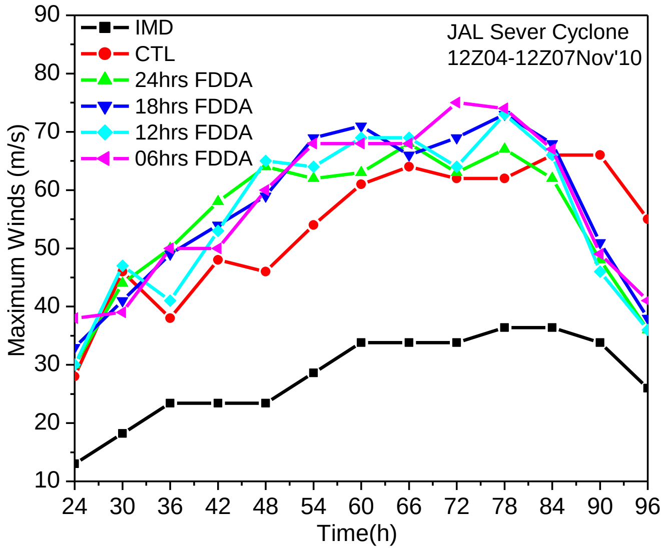


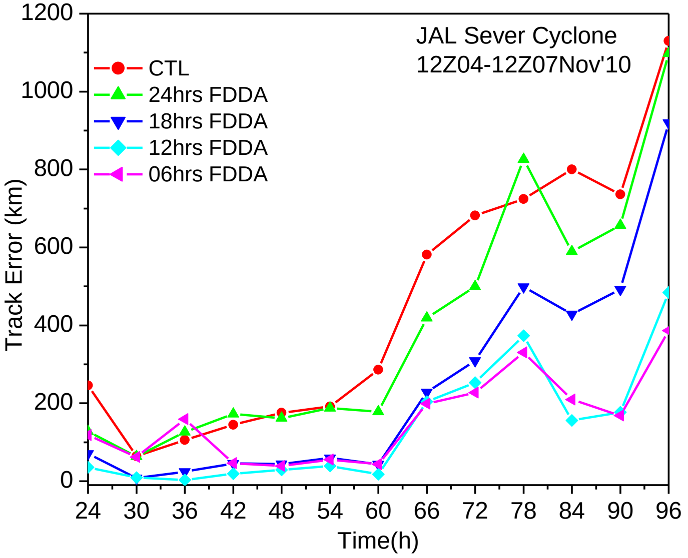
- Nearest simulated intensity of storm is give by FDDA 18/24 h nudging

- Errors in track positions are minimized with 18 /24h of nudging

JAL Cyclone 12Z04 –12Z07 Nov 2010



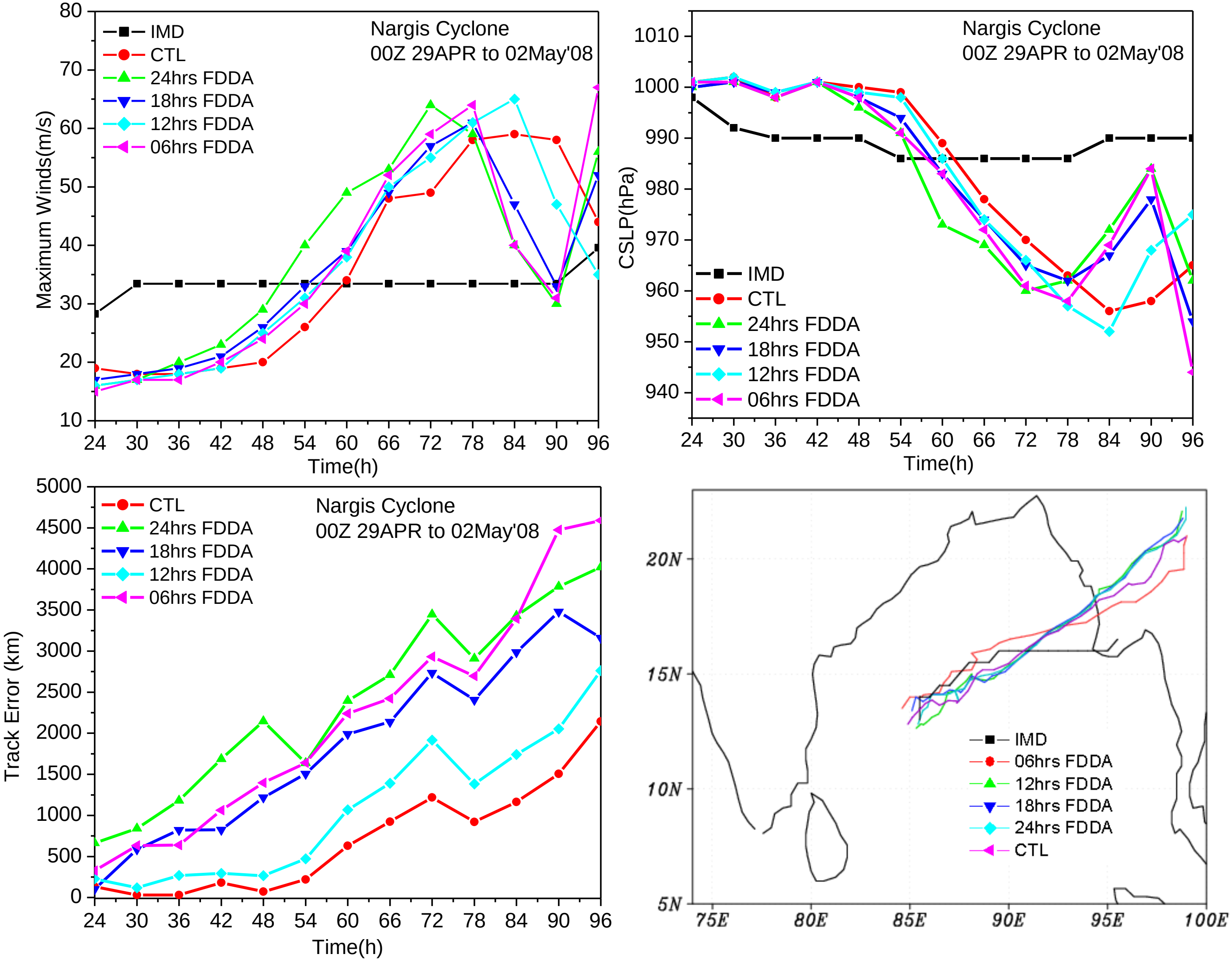




- No significant effect found on intensity of storm with FDDA nudging

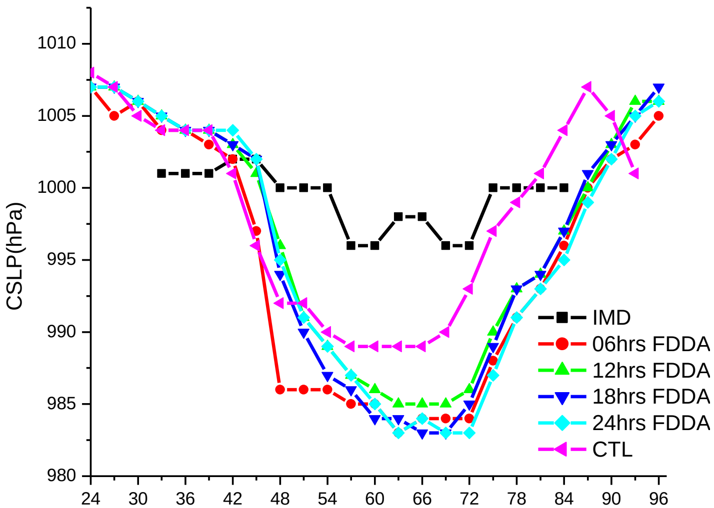
- Errors in track positions are minimized with 6h /12h of nudging

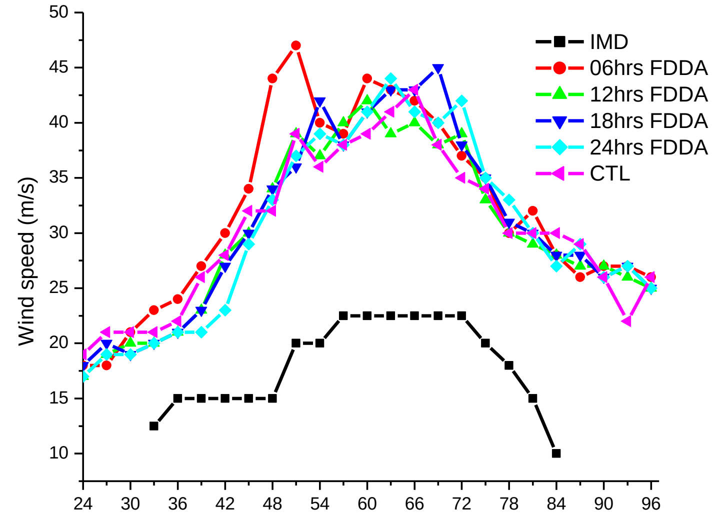
NARGIS Cyclone 00Z29 –00Z02 May 2008

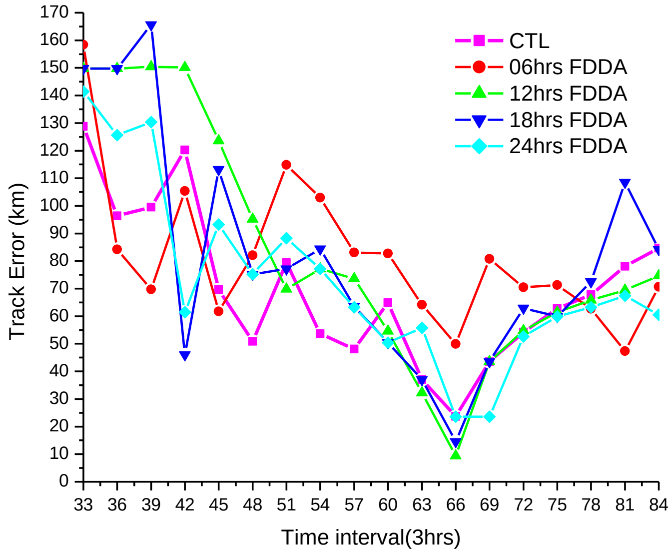


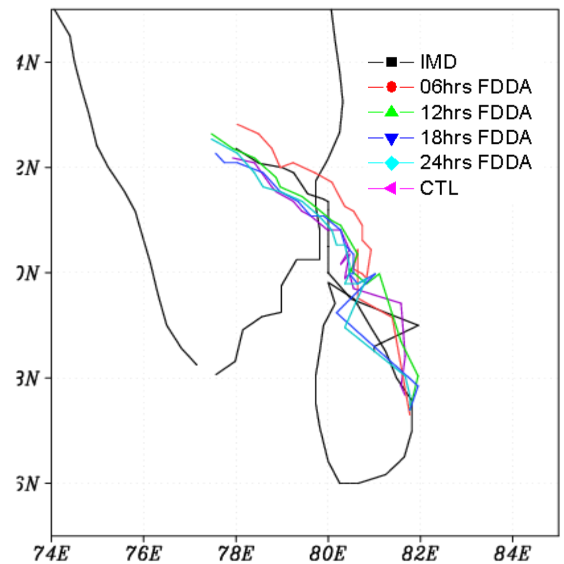
- No significant effect found on intensity of storm with FDDA nudging
- Errors in track positions are minimized with 6h /18h of nudging

Nisha (24-28 Nov 2008)



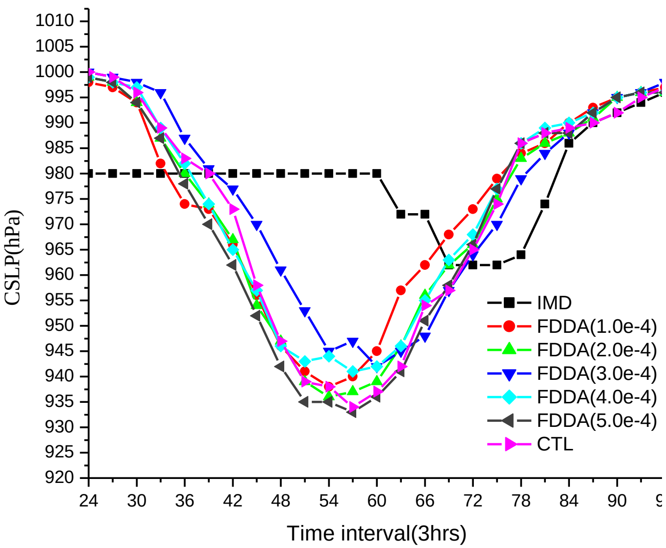


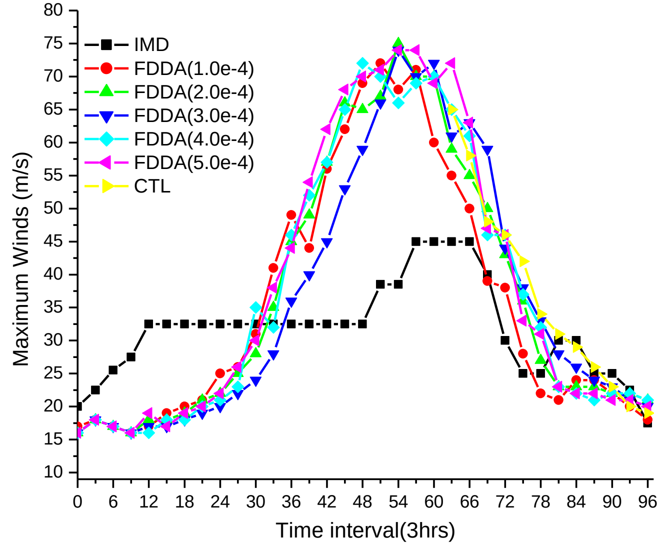


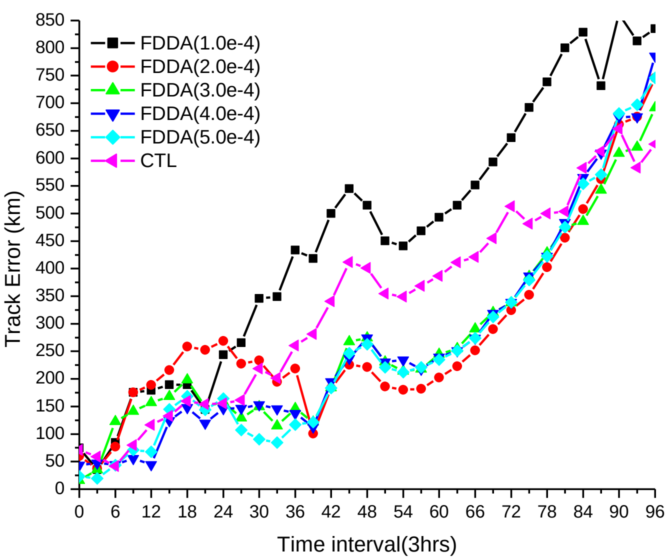


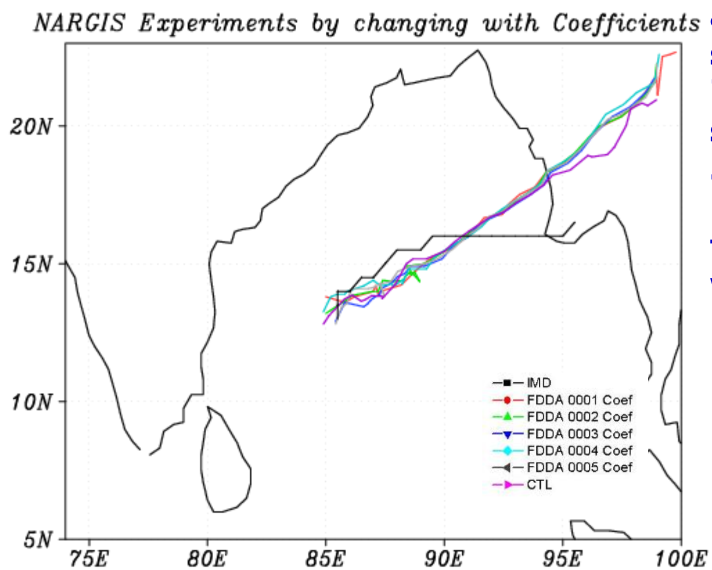
- The maximum effect is found with 12h/24 h nudging
- Error in CSLP is minimum with 12hr nudging and maximum with 18 h
- Error in winds is minimum with 12hr nudging and increases with period of nudging further
- Errors in track positions are minimum with 12h/24h nudging throughout simulation

Experiments considering different strengths of nudging



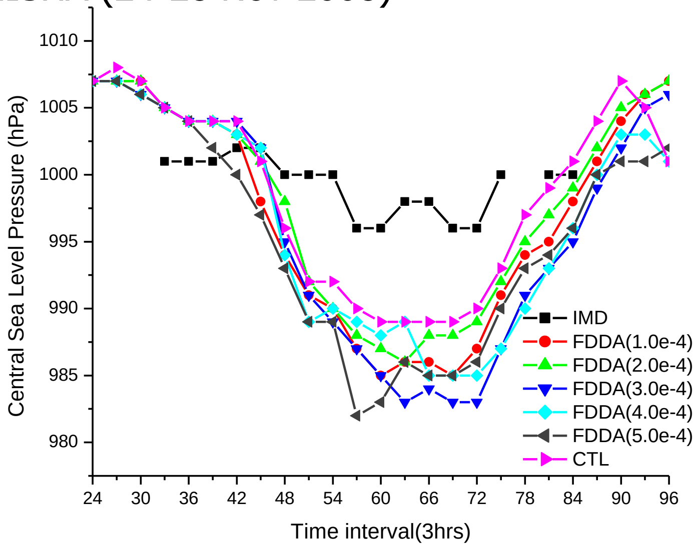


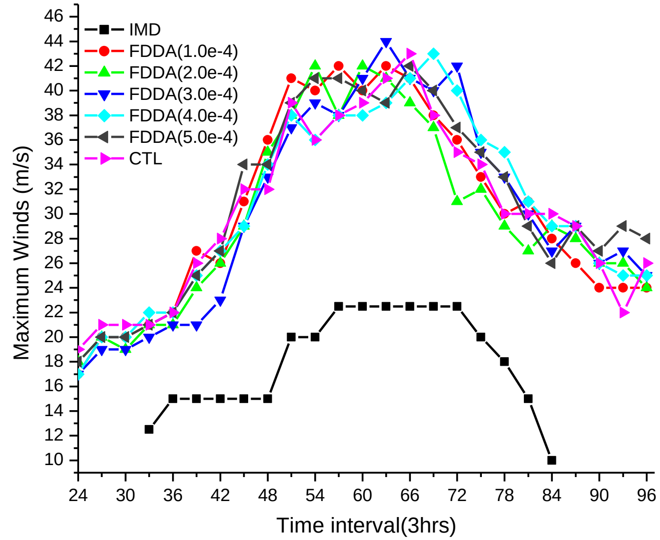


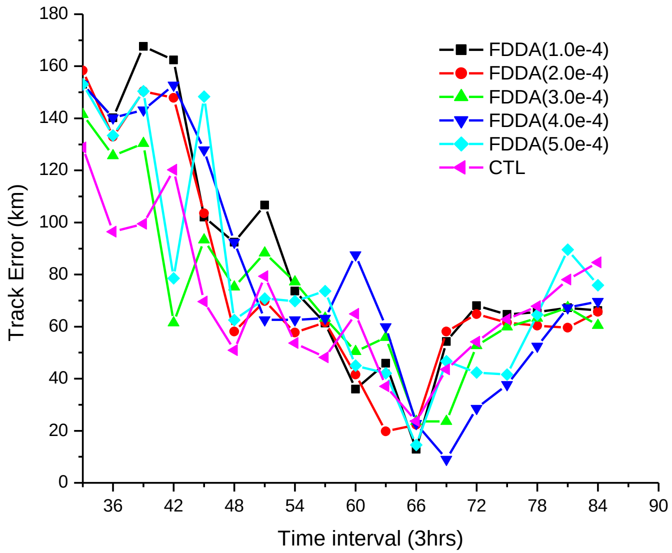


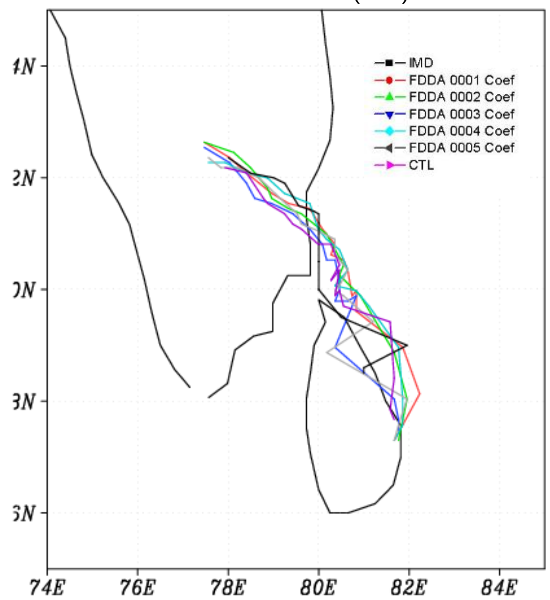
- **Error in CSLP are minimum with 3.0e-4/4.0e-4. The impact is much less with 1/2/5.0e-4**
- **Error in MW (winds) is minimum with 3.0e-4/4.0e-4. There is no impact with 1/2/5.0e-4**
- **Errors in track positions are minimum in the initial stages with 2.0e-4 but increase substantially with simulation time. Overall 3.0e-4/4.0e-4 give minimum errors up to land fall time. Errors increase with 1,2,5e-4**

NISHA (24-28 Nov 2008)









- Error in CSLP are minimum with 3.0e-4/4.0e-4. The impact is much less with 1/2/5.0e-4
- Error in MW (winds) is minimum with 4.0e-4. Impact is relatively less with 1/2/5.0e-4
- Errors in track positions are minimum with 4.0e-4 and increase with 1,2,3,5e-4

Main Results

❖The vlaue 3.oe-4/4.0e-4 is found to be optimum for nudging of wind observations

❖A pre-forecast period of 12-18 h nudging is sufficient for optimum forecasts

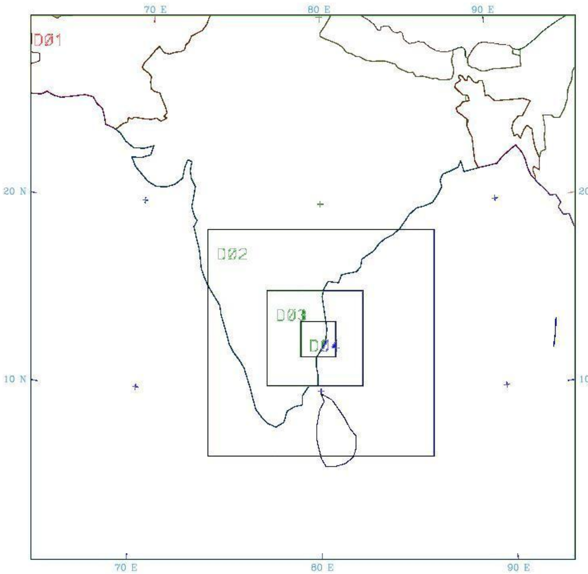
Application of Nudging to simulation of wind field and dispersion

A few cases of wind flow were studied with assimilation of QuickSCAT and conventional observations in NCAR/MM5 model

Observations 1. QSCAT
2. Surface AWS
3. Upper Air Radiosonde

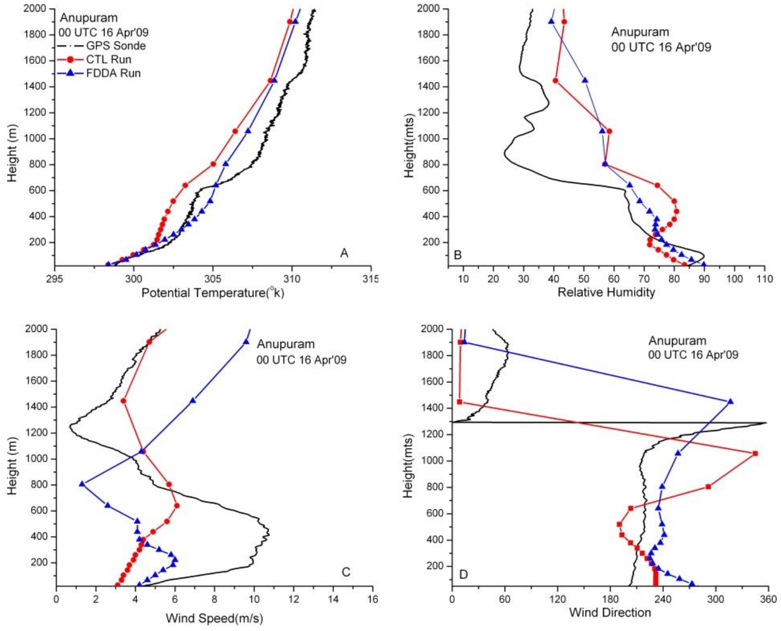
Dynamics	**Primitive equation, non-hydrostatic**			
Vertical resolution	**32 levels**			
Domains	**Domain1**	**Domain2**	**Domain3**	**Domain4**
Horizontal resolution	**36 km**	**12 km**	**4 km**	**1.33 km**
Grid points	**90 x 90**	**112 x 112**	**142 x 142**	**157 x 157**
Domains of integration	**62.61-95.37 E; 0.80-30.15 N**	**73.69-86.40 E; 6.49-18.60 N**	**77.04-82.31 E; 10.22-15.33 N**	**78.88-80.80 E; 11.81-13.69 N**
Radiation	**Dudhia scheme for shortwave and RRTM for longwave processes**			
Sea surface temperature	**NCEP FNL analysis data**			
Convection	**Grell scheme on the outer grids domain1, domain2**			
Explicit moisture	**Simple ice (SI) scheme**			
PBL turbulence	**Hong-Pan (MRF) PBL**			
Surface processes	**5 layer soil thermal diffusion scheme**			

New analysis prepared using Little_R objective analysis

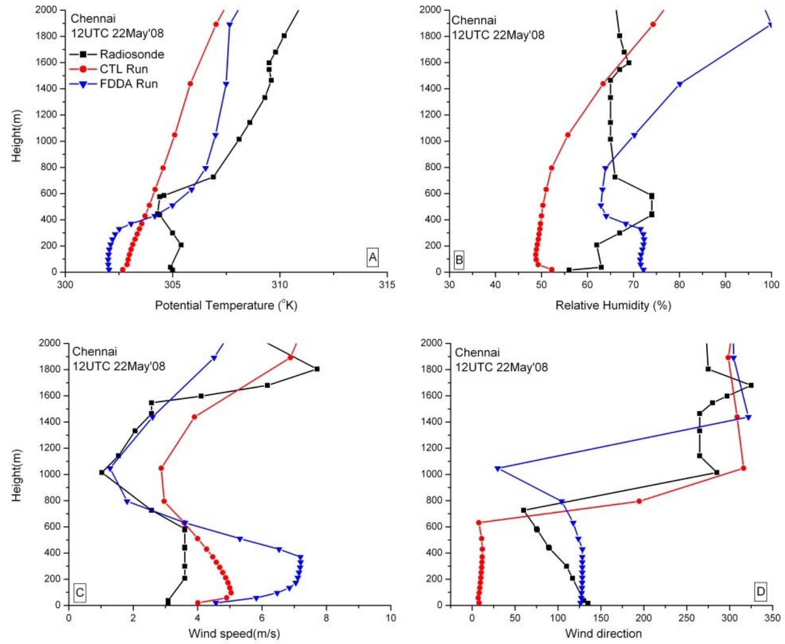


Comparison of model profiles with observations

GPS Sonde



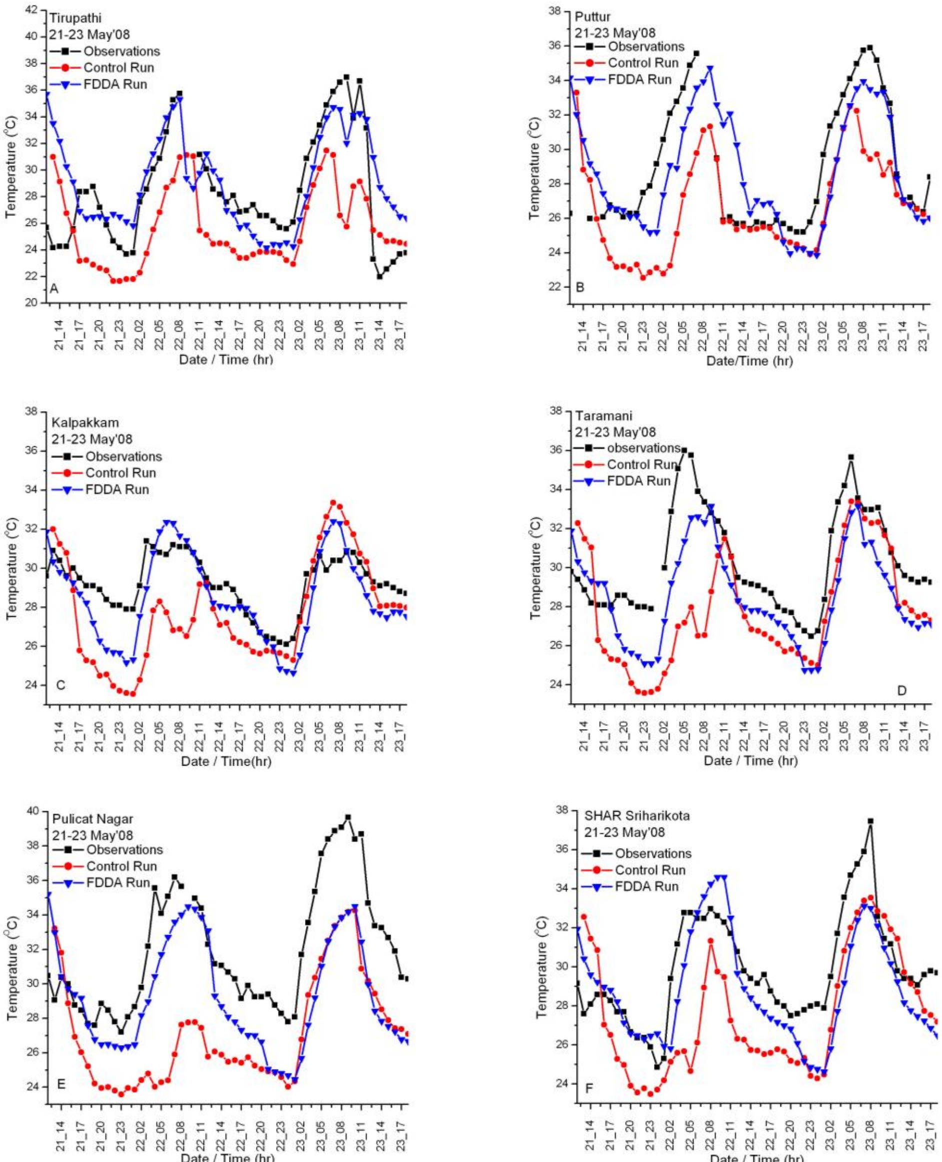
RS/RW Chennai



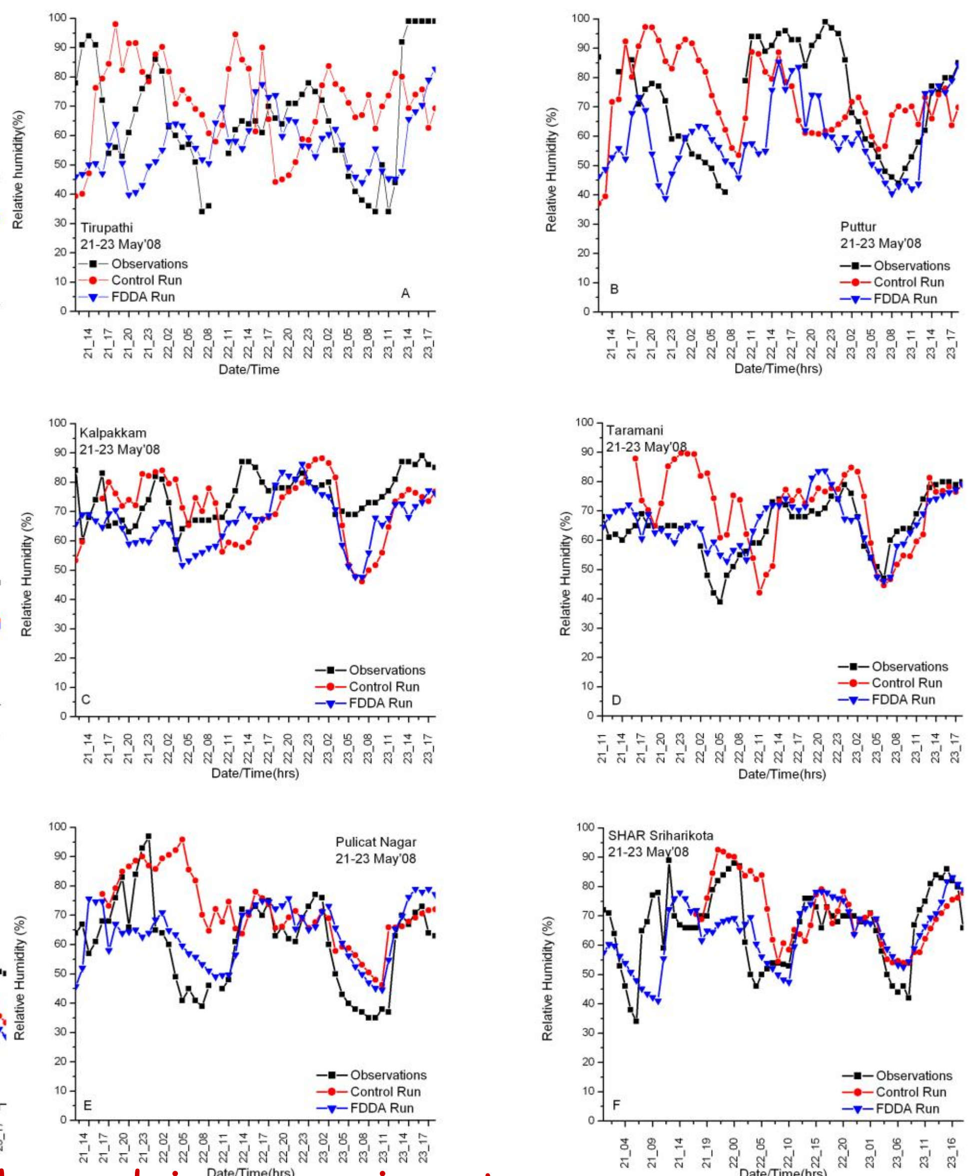
Model results for 25 stations analysed
Hourly observations for 72 days compared

No assimilation
Assimilation
Observation

Air Temperature

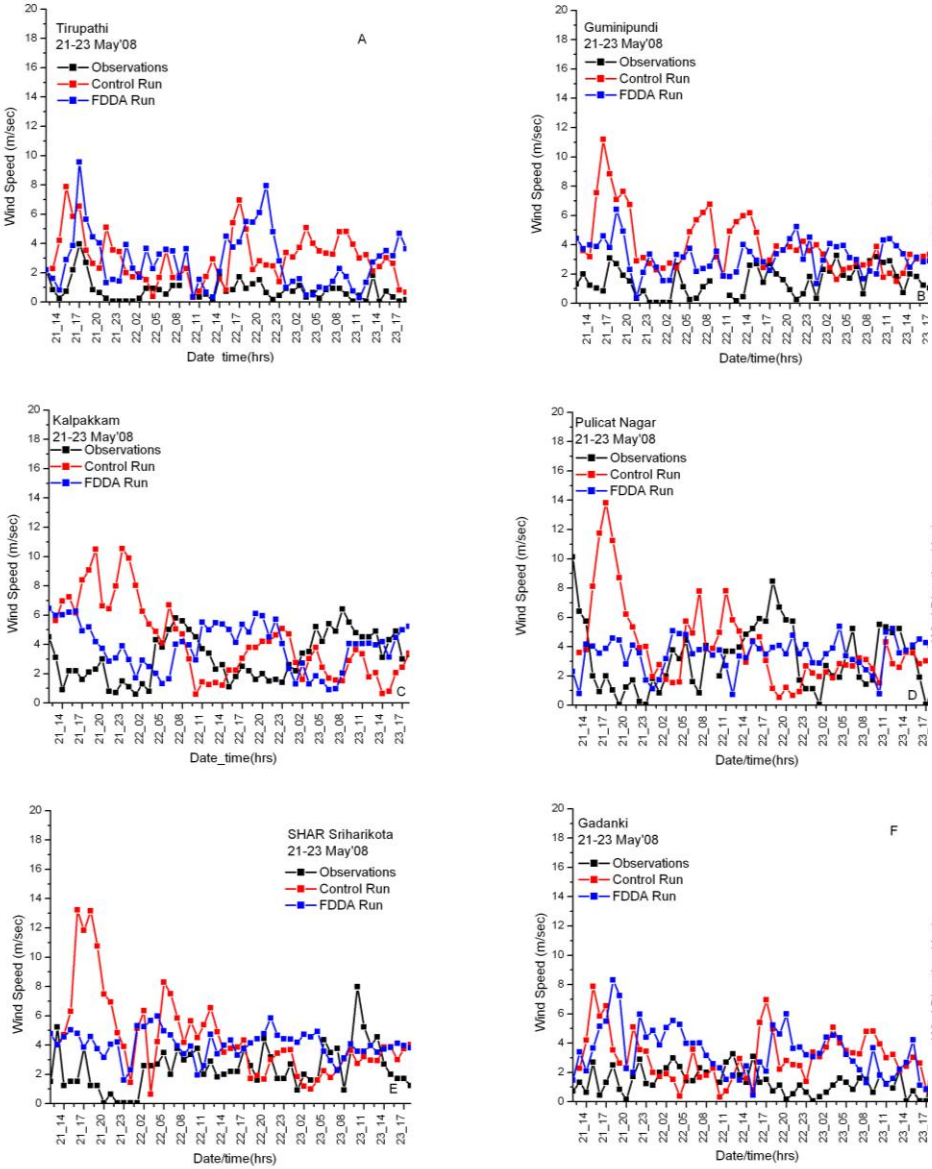


Relative Humidity

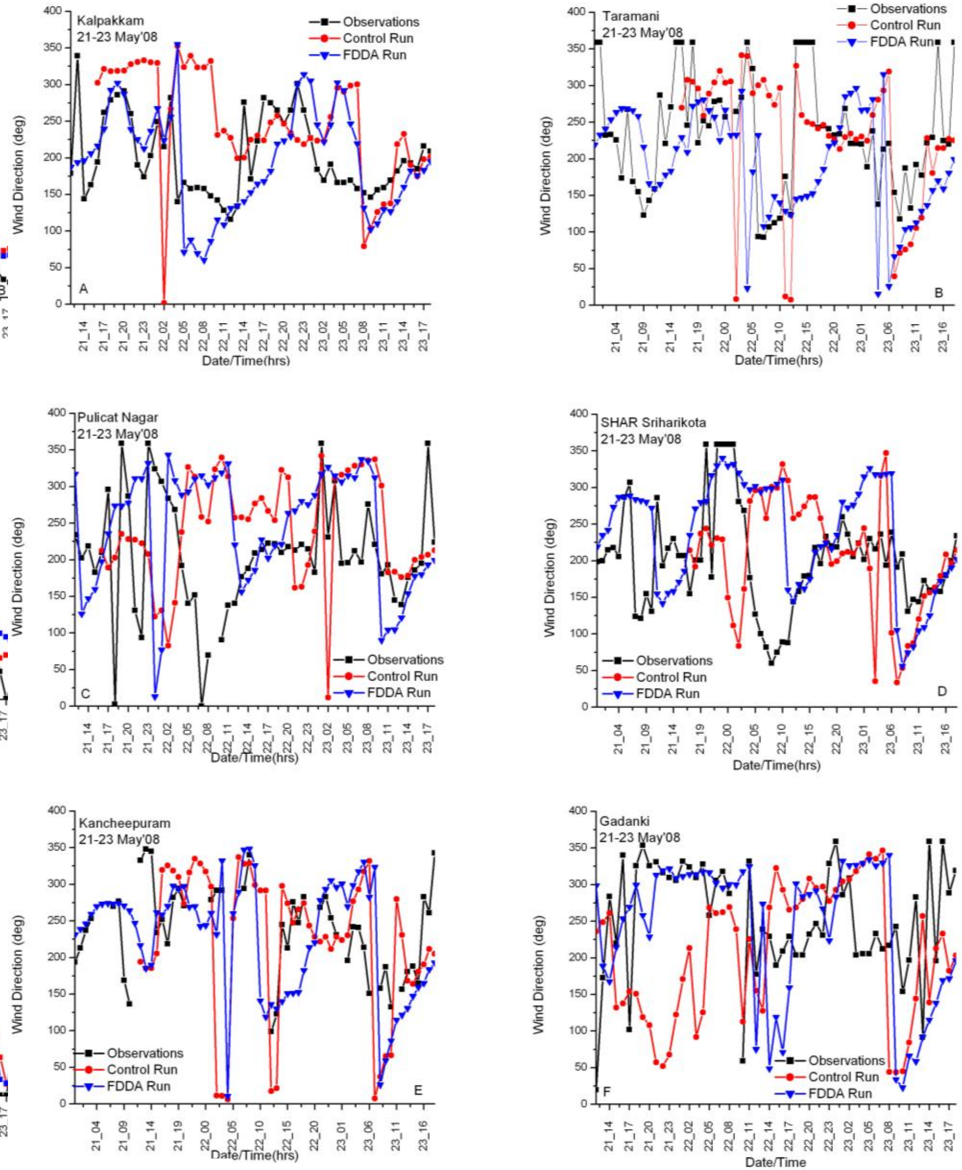


Diurnal trends are better simulated in the nudging experiment

Wind speed

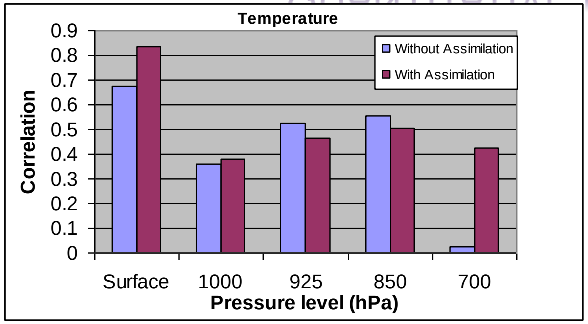


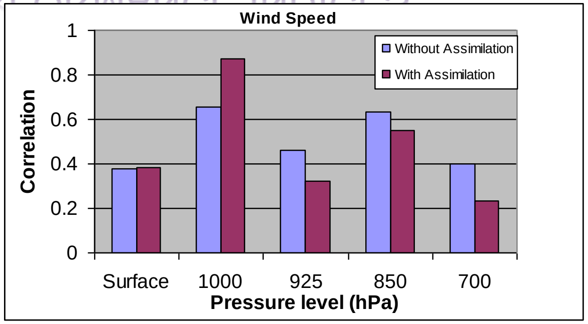
Wind direction

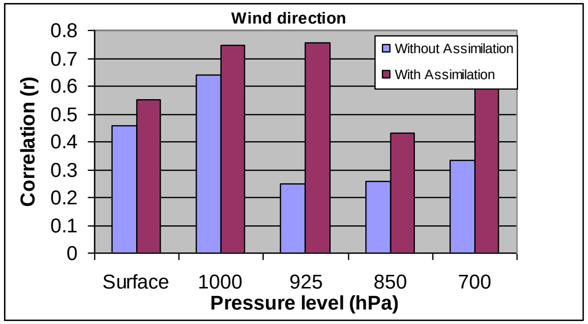


No assimilation
Assimilation
Observation

QUANTITATIVE PERFORMANCE INDICES





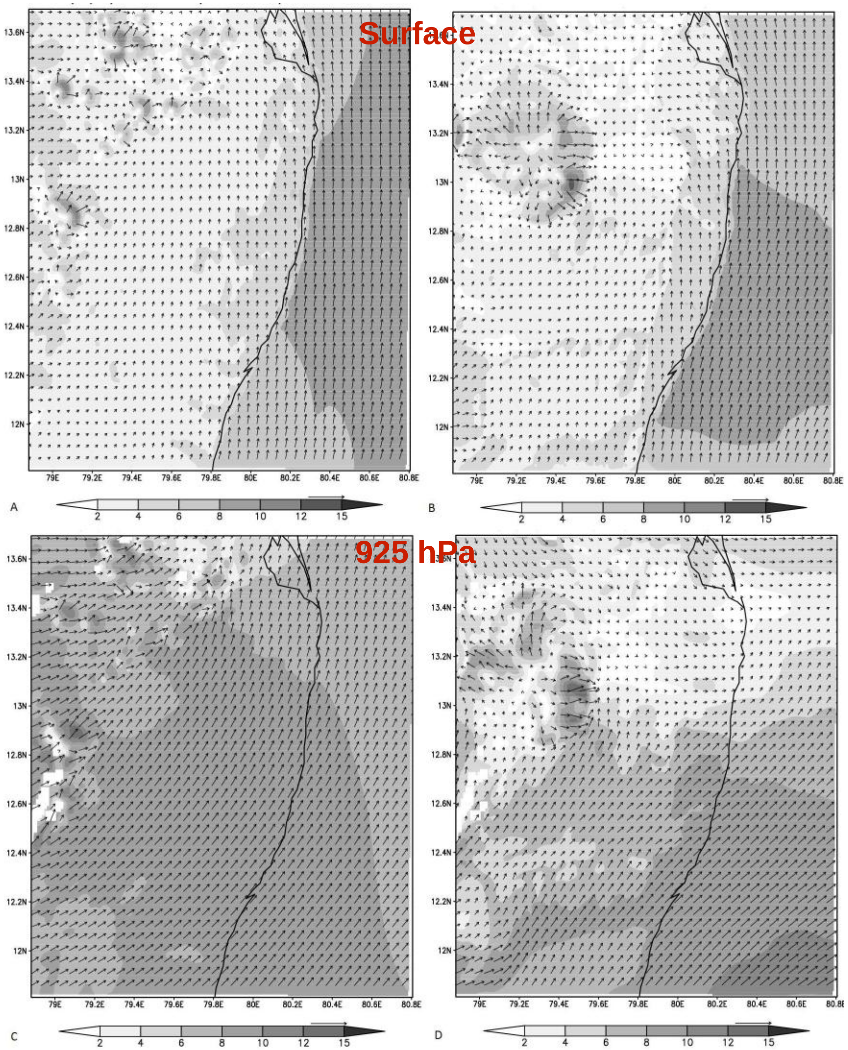


- There were differences in the flow field, temperature, humidity and mixing height in the two cases which differently simulated the plume dispersion.

- Assimilation of observations led to improved statistics (r,s,mb,me,rmse etc) for various parameters of interest.

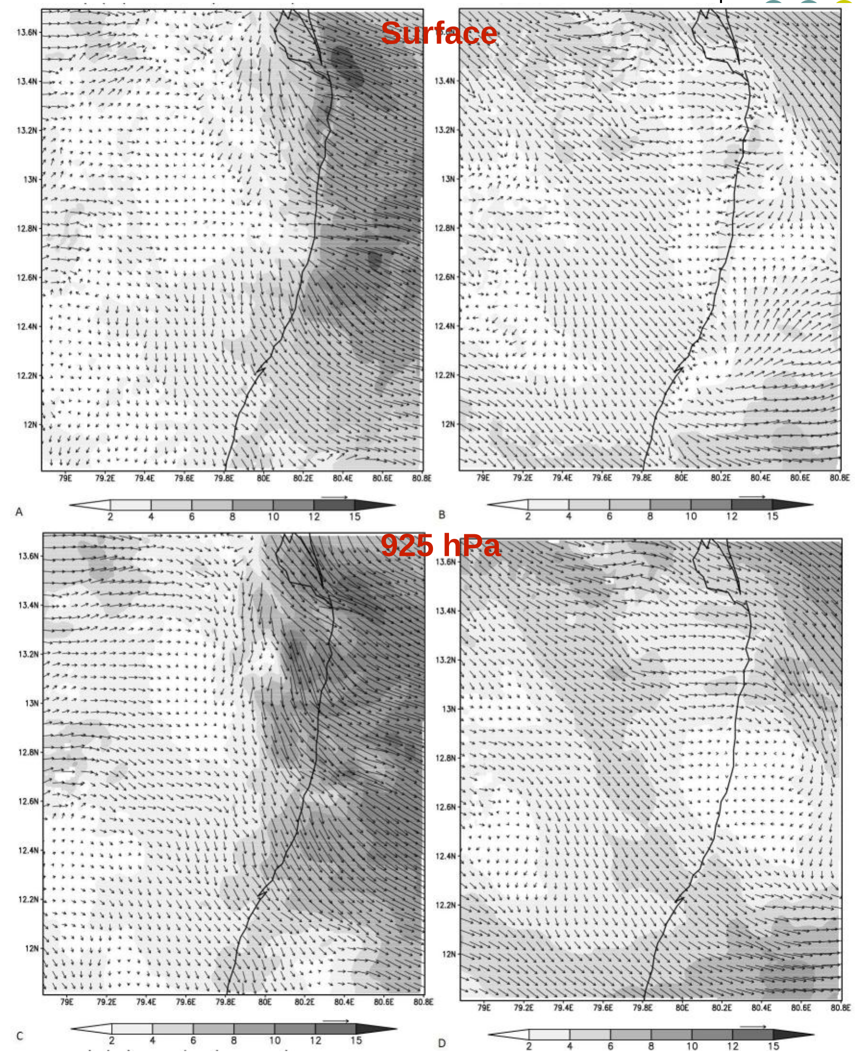
Initial wind field (12UTC 21 May’09)

Control Run | **FDDA Run**

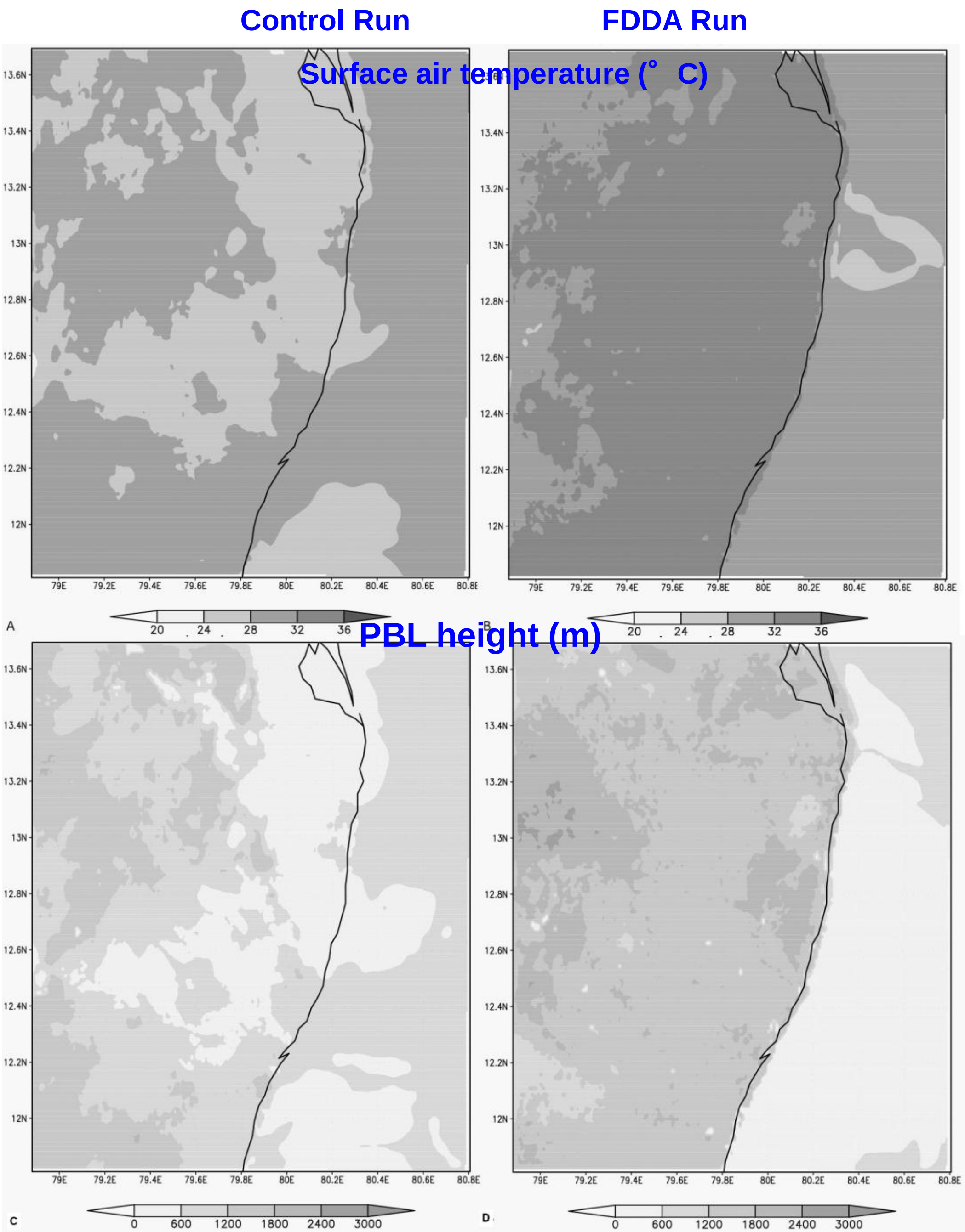


Simulated wind field (06UTC 22 May’09)

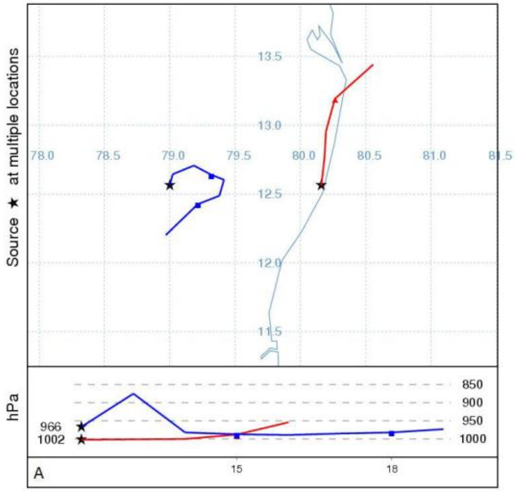
Control Run | **FDDA Run**



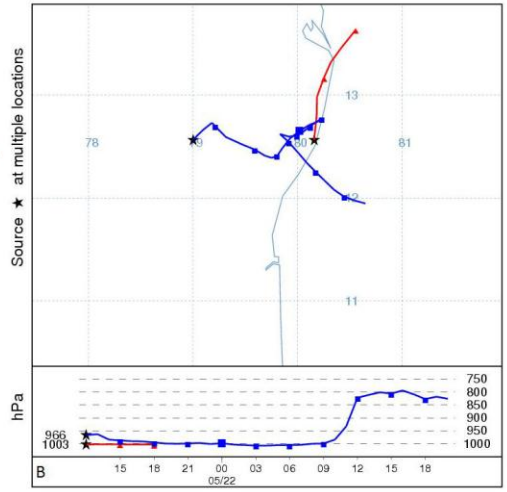
06UTC 22 May'09.



Control run

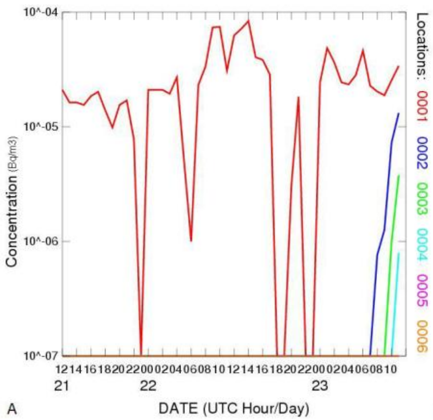


FDDA Run

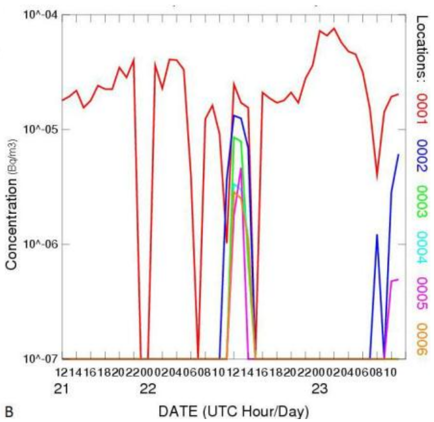


Time sereis of Receptor concentrations across coast

Control Run

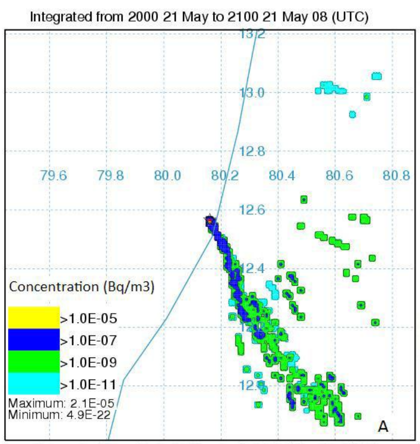


FDDA Run

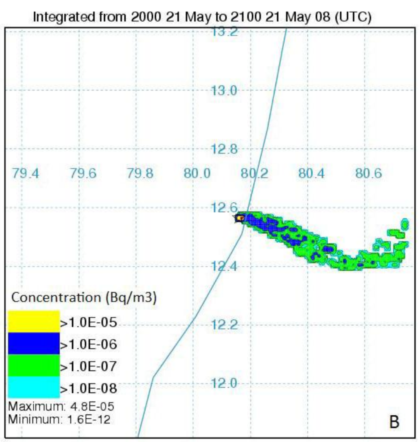


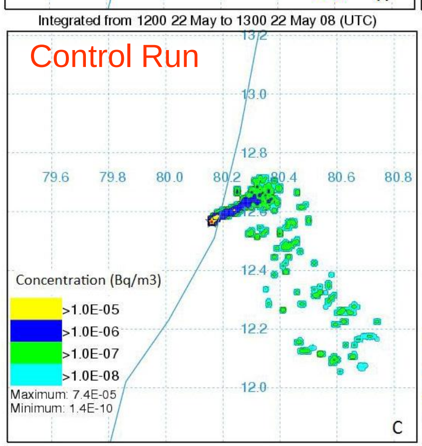
- *Winds from FDDA experiment direct the plume onshore while in control experiment the plume is offshore 14-17 h LT 22 May'08*

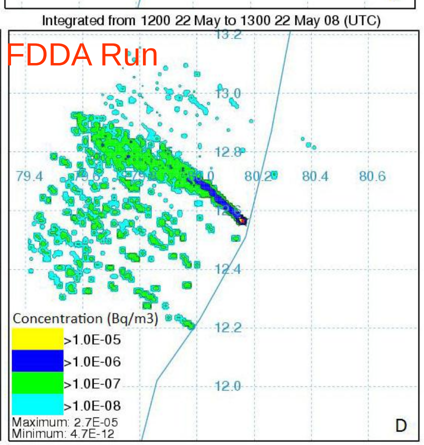
Control Run



FDDA Run







Assimilation of dense AWS observations with QsCAT winds in the FDDA case seems to produce large impact on the performance of the MM5 model for the parameters of diurnal wind field, temperature, mixing height in the domain of interest.

Comparisons with observations indicated better statistics with the FDDA fields than in the control run. The simulated plume, its concentration distribution varied in the two cases and shows realistic results from the MM5FDDA fields.

3D-VAR Method – A case study for a cyclone on southeast coast with WRF Model

3DVAR:Minimization of a cost function, which is sum of squares of deviation from observation

The cost function (J) is defined as

$$J(\mathbf{x}) = \underbrace{\frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b)}_{\text{Background term}} + \underbrace{\frac{1}{2}(H(\mathbf{x})-\mathbf{y}^o)^{\mathrm{T}}\mathbf{R}^{-1}(H(\mathbf{x})-\mathbf{y}^o)}_{\text{Observation term}}$$

B = background error covariance matrix

R = observation and representativeness error covariance matrix

H = nonlinear observation operator (model space → observation space)

- The minimization requires an estimation of the gradient of the cost function:

$$\nabla J(\mathbf{x}) = \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}(H(\mathbf{x})-\mathbf{y}^o)$$

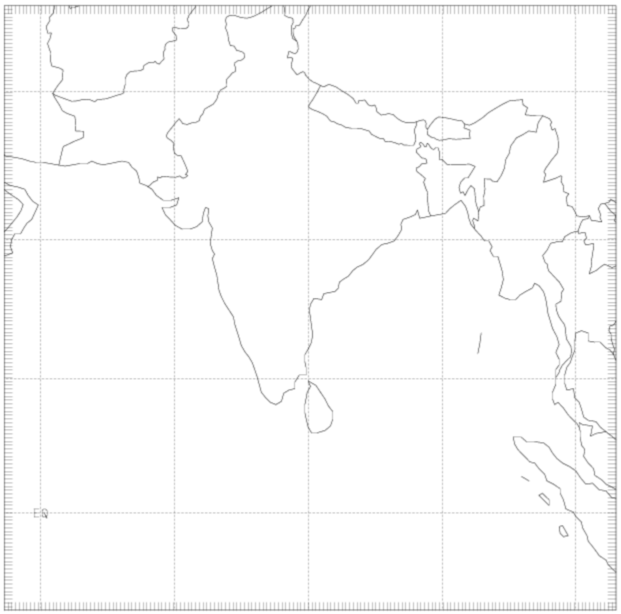
y^o = **Observation vector**

($X - X_b$) = Analysis increments

($H(X_b)$- y^o) = Innovation vector

Case study of Fanoos cyclone 4- 10 Dec 2006

Dynamics	Primitive equation, non-hydrostatic
Vertical resolution	28 vertical levels
Horizontal resolution	27 km
Domains of integration	74.50 E – 82.50 E (162X164) 9.00 N – 16.74 N
Radiation	Dudhia scheme for short wave radiation Rapid Radiation Transfer Model (RRTM) for long wave radiation
Explicit moisture	Lin microphysics (Lin et al., 1983)
Surface processes	5-layer soil thermal diffusion scheme
Planetary boundary layer	Yonsai University (YSU) PBL
Cumulus convection	Kain-Fritisch (KF-Eta)
Sea-surface temperature	Real SST



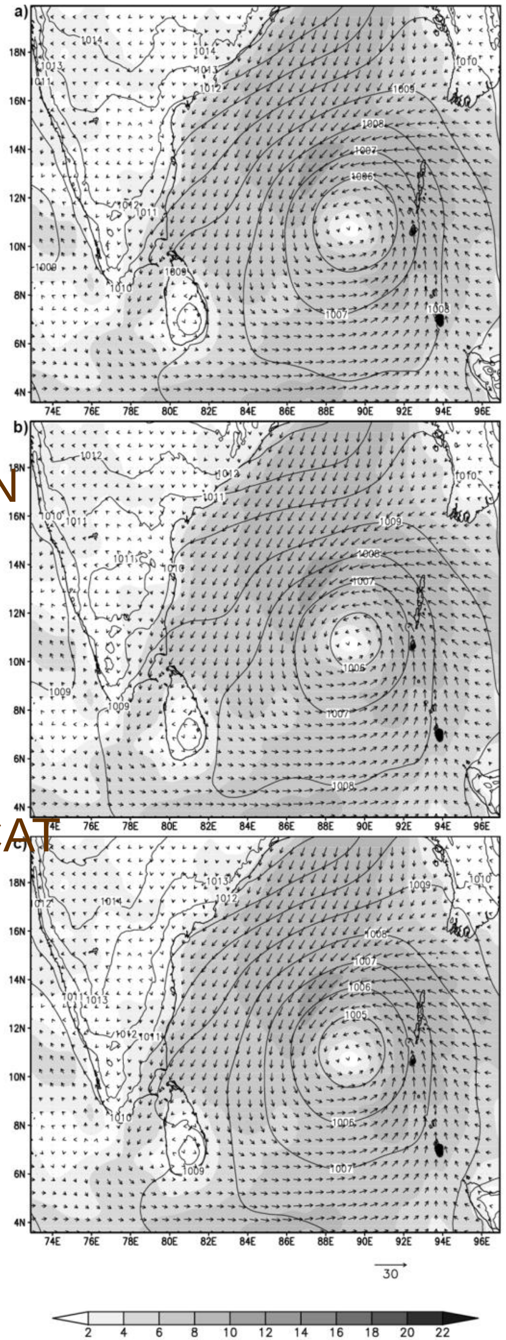
Background Error Covariance data Generated for this domain using simulations with FNL data for October 2009

Sea level pressure and surface winds at 10 m level for 00 UTC 06 Dec 2005

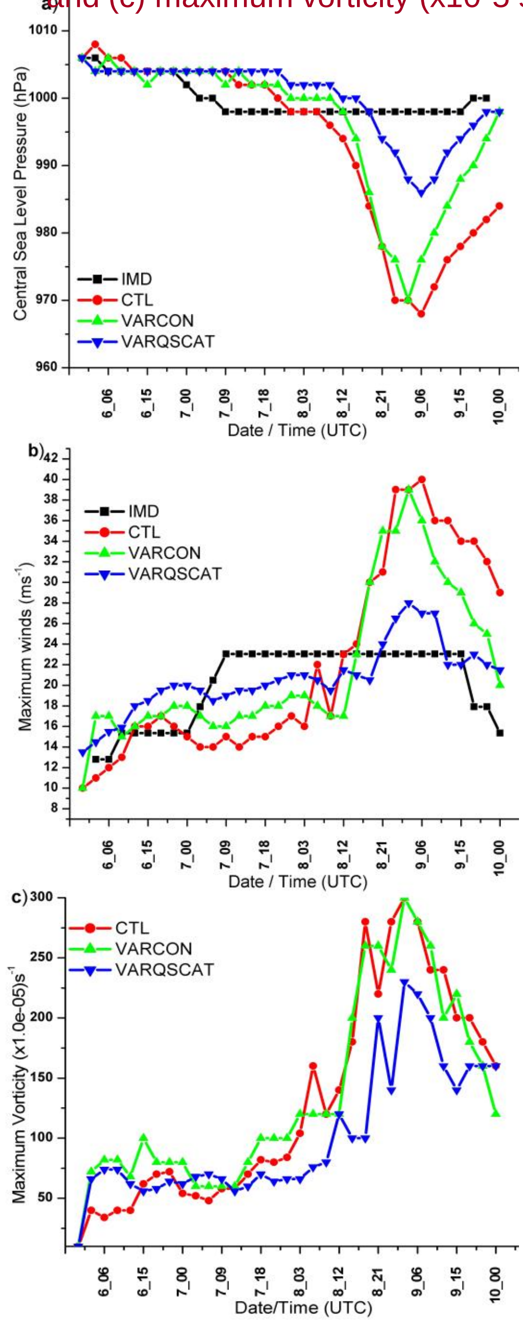
Control

VARCON

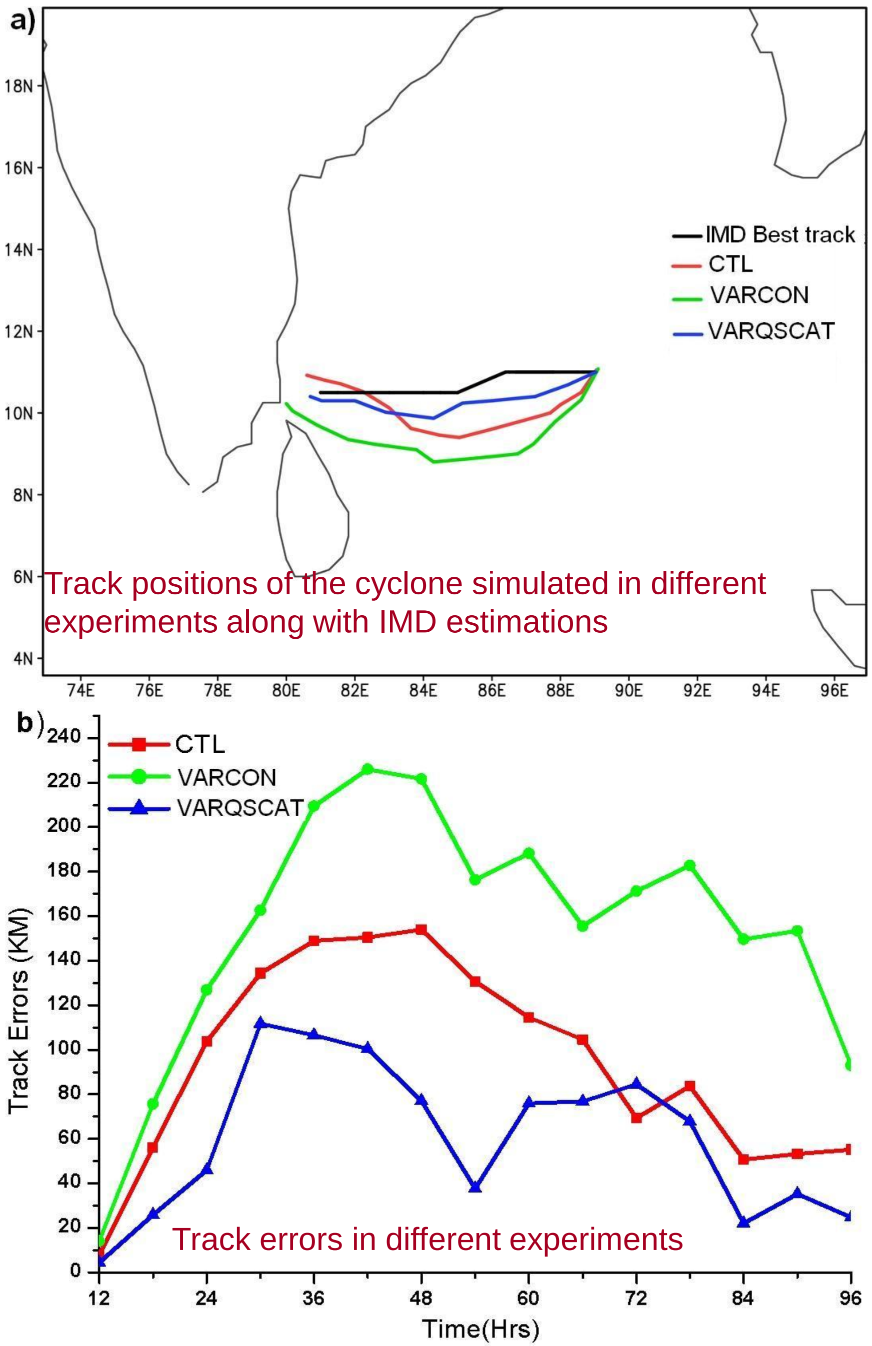
VARQSCAT



Time variation of model simulated (a) Central Sea level Pressure (hPa) (b) maximum wind (m/sec) at 925 hPa level and (c) maximum vorticity (x10-5 sec-1) at 925 hPa level.



- Assimilation of QSCAT winds produces more impact than conventional observations in terms of SLP, Winds and Vorticity fields

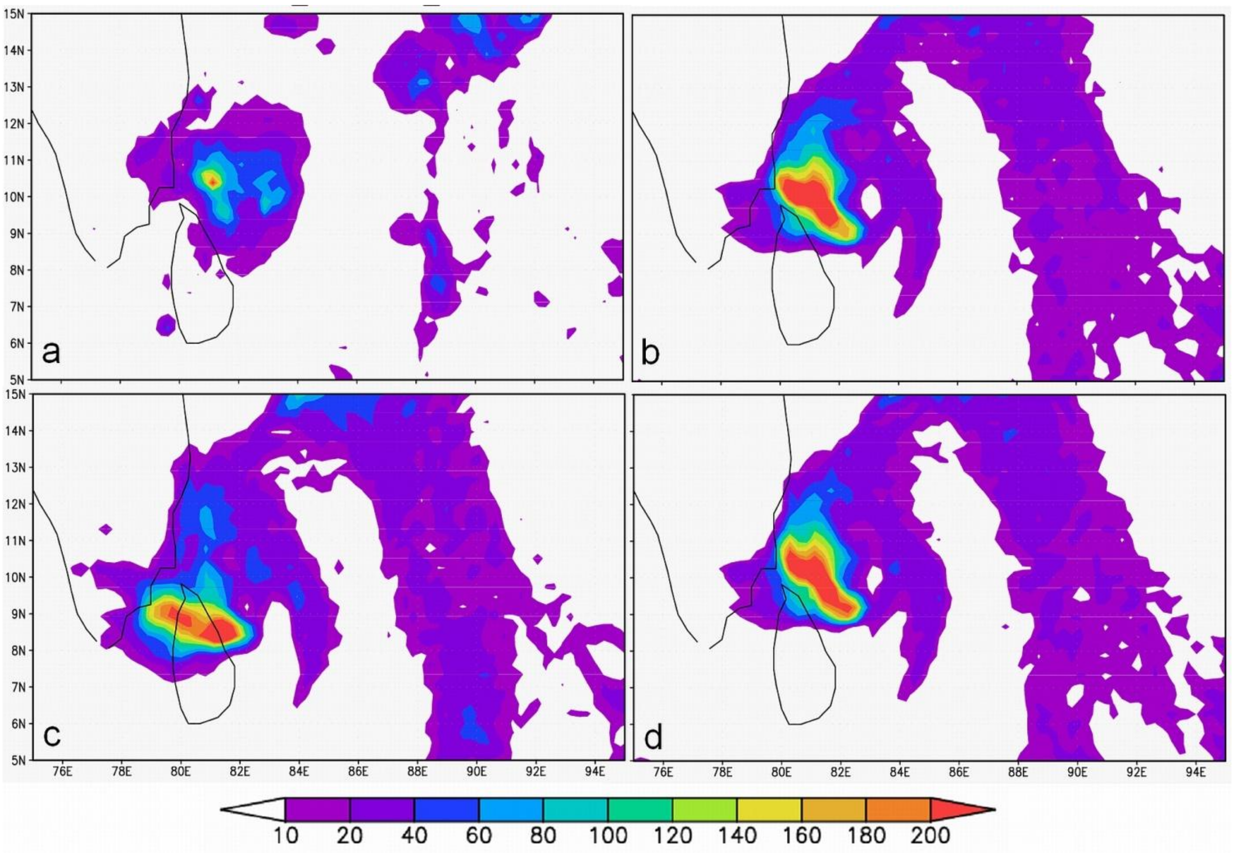


Track positions of the cyclone simulated in different experiments along with IMD estimations

Track errors in different experiments

- Assimilation of conventional data gives large errors with simulated cyclone moving to the south of observed storm

- Assimilation of QSCAT winds reduce the track errors considerably



Accumulated 24 h rainfall (mm/day) ending at 00 UTC 10 Dec 2005 from a) TRMM data b) CONTROL c) VARCON and d) VARQSCAT L experiments respectively

Conclusions

- FDDA nudging experiments using ARW with scatterometer wind observations indicates nudging reduced the overintensification of storm in the control run as well as reduced the track errors.
- A period of 12h/18 h nudging during the pre-forecast stage provides maximum impact on simulations.
- Nudging effect is maximum with coefficient of nudging for winds 3.0e-4 - 4.0e-4 which corresponds to a time scale of one hour.
- Simulations with assimilation of several individual data sets (AWS, Qscat winds, SSM/I winds, Alldata) clearly show that the movement of the storm while approaching the coast is substantially improved using all observations.
- Vector track errors are less in the FDDAQSCAT than in FDDASSMI and FDDAAWS cases upto the landfall time of the simulated storm
- The FDDAQSCAT has better produced the intensity of the cyclone (interms of maximum winds) than the FDDASSMI which may be because of better representation of wind field from QSCAT vector wind observations
- Satellite winds give higher impact using 3DVAR for cyclone simulation than the conventional observations

Thank You