Radar Data Assimilation and its Impact studies at NCMRWF

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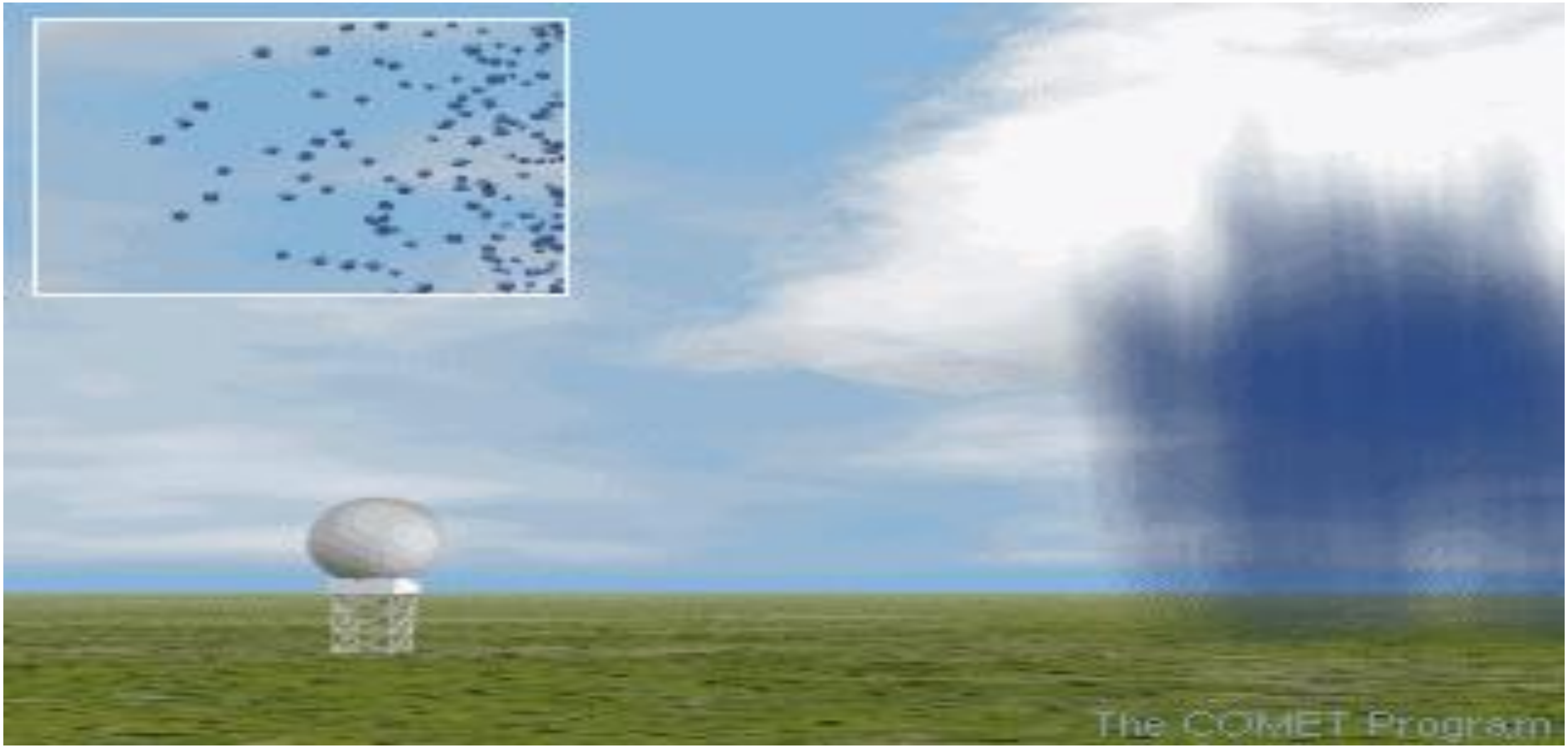
Basic of DWR

Radar

- **RAdio Detection And Ranging**
- **Developed during World War-II for detecting enemy aircraft.**
- ***Radar is Active* remote sensor**
  - **Transmits and receives pulses of electromagnetic radiation**
- **Numerous applications**
  - **Detection/analysis of meteorological phenomena**
  - **Defense**
  - **Aviation**
- **Scans horizontally 360˚, at various elevation angles**
- **Volume scan completed in about 5 min**

Radars emit pulses, listen for returns pulse



Only a small fraction of emitted energy is returned.

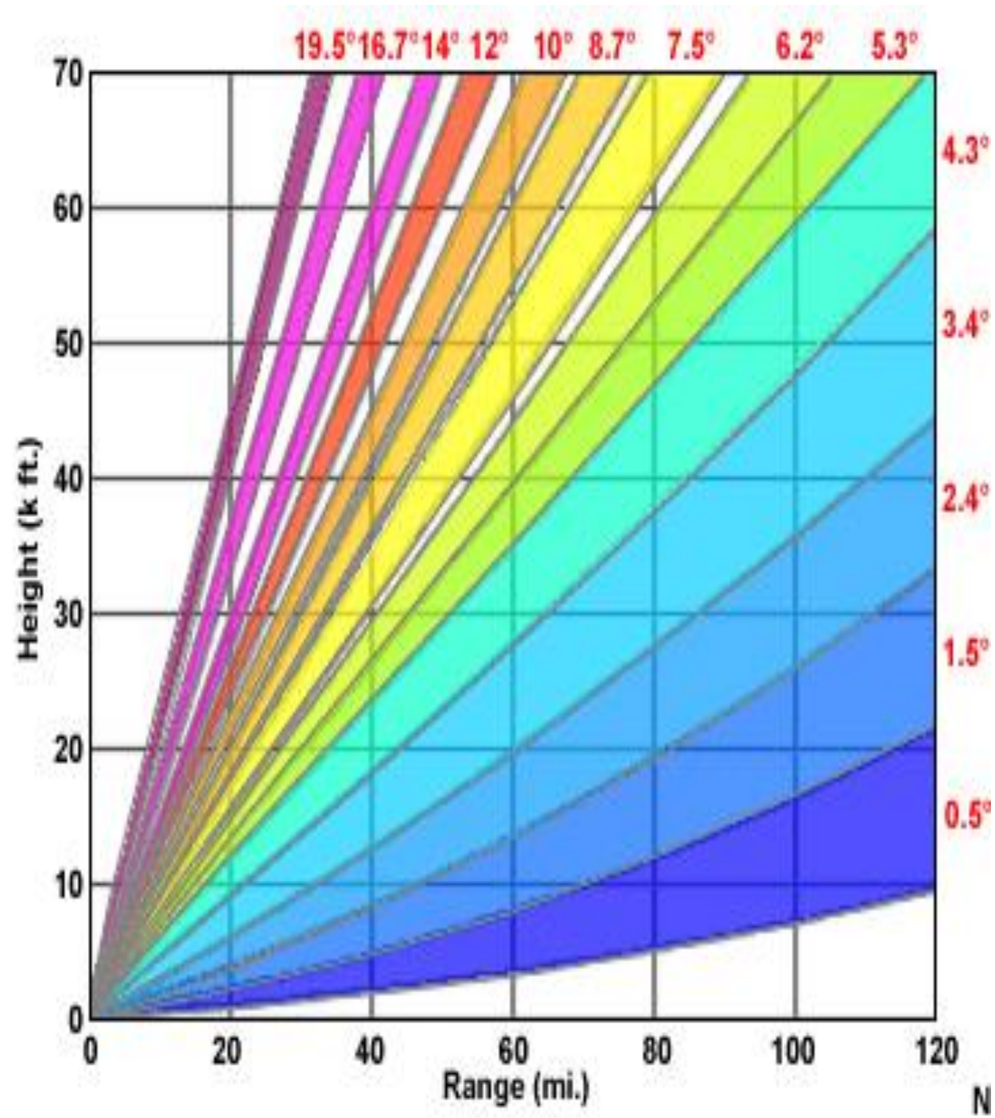
Returned energy = radar reflectivity.

Scanning modes of a Radar

Two types of scanning modes apply in a Radar:

1) Precipitation mode (illustrated at right) scans a wide variety of elevation angles.

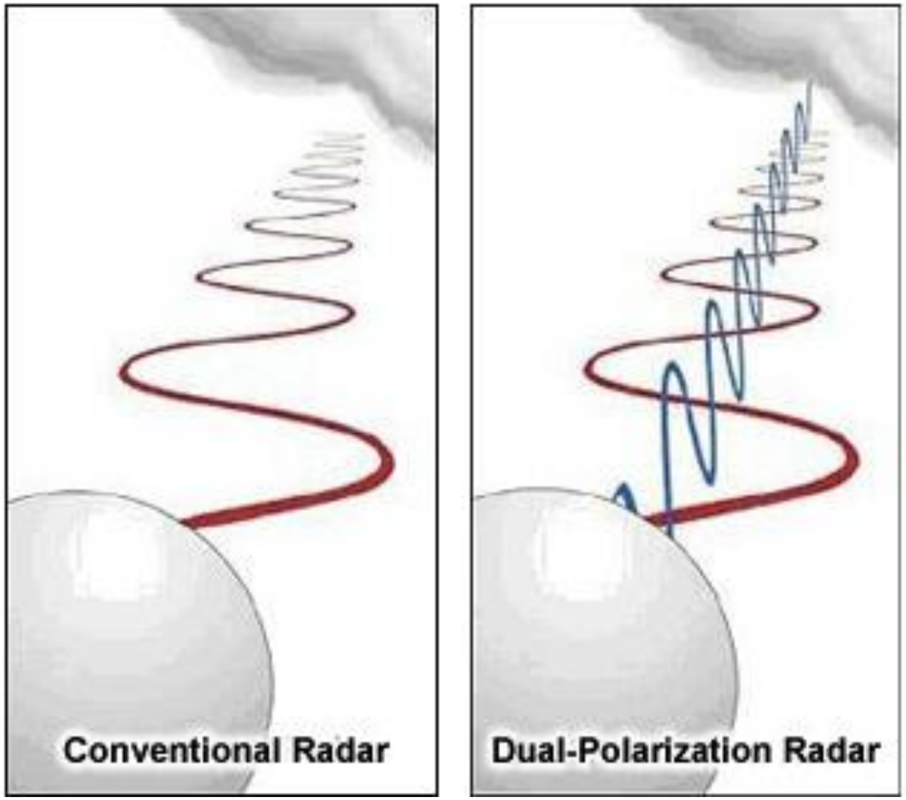
2) Clear air mode (not shown) more slowly scans only up to 4.3˚,inclusive



Radar types

- **Many different types of DWR radar but mainly we will dealt :**
- **Convectional Radar**
- **Dual polarization**

S-Band: λ=10cm, Frequencies=3GHz (Coastal area)
C-Band: λ= 5cm, Frequencies= 6GHz (Delhi; Jaipur)
X-Band: λ=3cm, Frequencies=10GHz (Hilly areas)



Dual-polarization radars improve:

- Identification of non-weather targets
- Determination of rain vs. snow vs. melting snow
- Hail detection
- Detection of areas of heavy rain
- Detection of debris from tornadoes

Reflectivity

- "Reflectivity" is the amount of transmitted power returned to the radar receiver after hitting precipitation or objects.

- Measured as "Z" based on diameter to the 6th power (mm^6) per cubic meter (m^3).

$$Z = \sum_{i=1}^{n} D_i^6$$

- Further converted to "dBZ", a dimensionless, log-scaled value ($dBZ = 10 \log_{10} z$).

- Reflectivities can range up to about 75 dBZ > 45dBZ: intense precipitation and > 60 dBZ generally indicates hail present.

- Ice is less reflective than liquid. Melting ice can be very bright on radar.

Radial Velocity

- Radars have been designed to measure the shift of object in frequency.
- The magnitude and direction of the shift give information about the motion of the target objects either toward (-ve) or away (+ve) from the radar. This measurement is called the "radial velocity.“
- It is important to note that the radar can only tell whether a target is moving toward or away from it, and how fast it is doing so.
- The actual speed and direction of the wind will only be observed at points where the radar beam aligns perfectly parallel to a target's direction of travel.
- In all other instances, only the component of the target's motion that is parallel to the radar beam is measured and plotted as the radial velocity value.

Assumptions in Radar Technology

- The calculations for radar reflectivity and other variables are based on five main assumptions about the radar beam, the targets, and the atmosphere:
  - The beam travels at the original inclination angle.
  - The targets absorb very little of the radar's electromagnetic energy.
  - Target particles are small, homogeneous precipitation spheres with diameters much smaller than the radar's wavelength (Rayleigh Scattering).
  - All targets are either liquid or frozen, but not a mixture.
  - Targets are uniformly distributed throughout the sample volume.

Detection of Precipitation

The degree of detection of precipitation targets is dependent on a variety of factors:

- **Atmospheric Condition between radar and target**
- **Target characteristics (Size, size distribution, Phase of water i.e liquid, ice, mixed).**
- **Distance from the radar to target.**
- **Radar characteristics (power return, wave length, antenna gain & beam width, pulse width, etc)**

- **Red points are unknown. Need some approximation.**
- **Blue points are know factors**

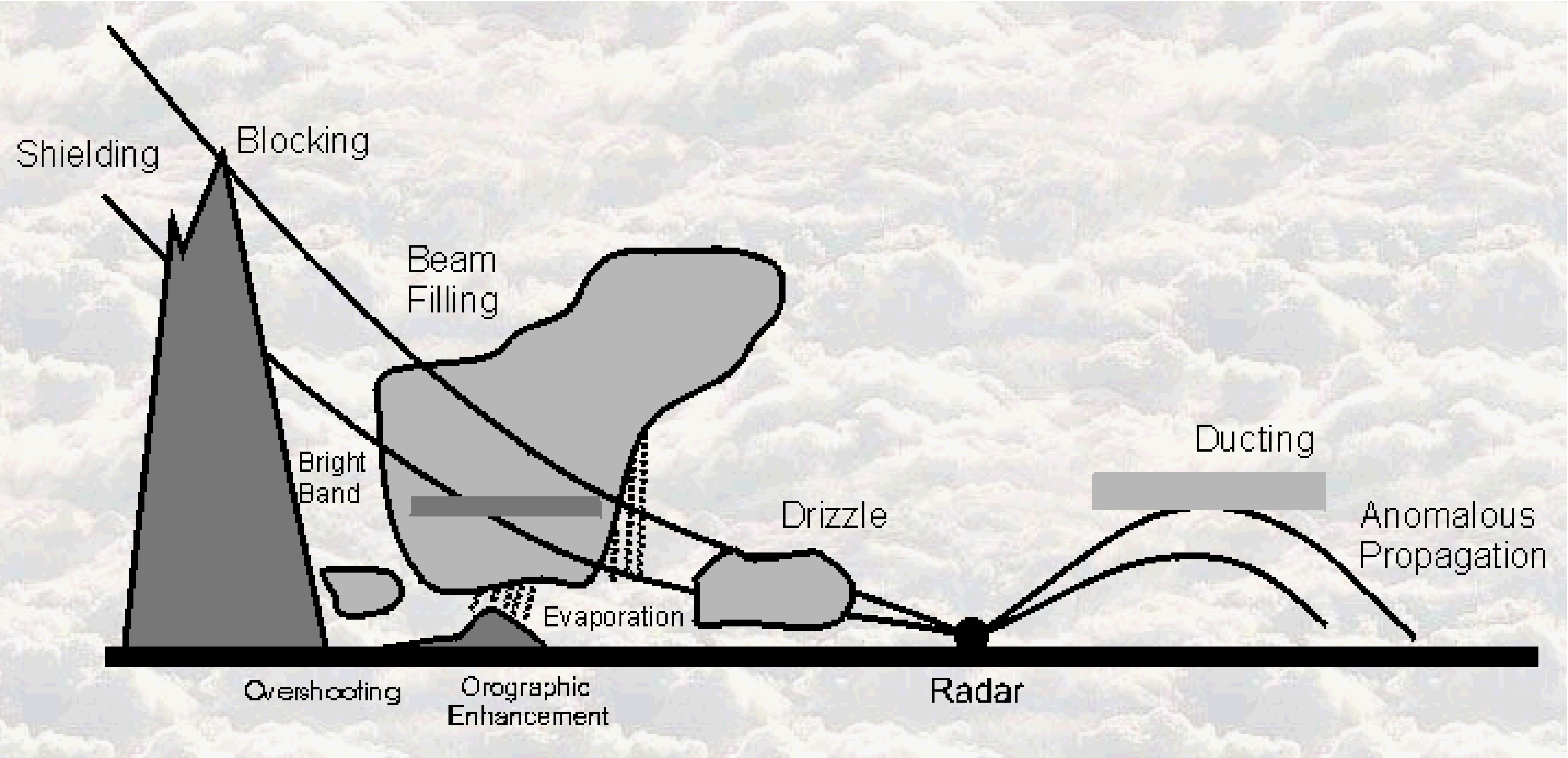
Quality Control

- Quality related issues are becoming the main research fields for the radar data users.
- Radar derived precipitation data are burdened with a number of errors from different sources (both meteorological and technical).
- Precise information about the data reliability is important for the end user.
- Radar based precipitation forecast and severe weather warning systems have become a fundamental part.

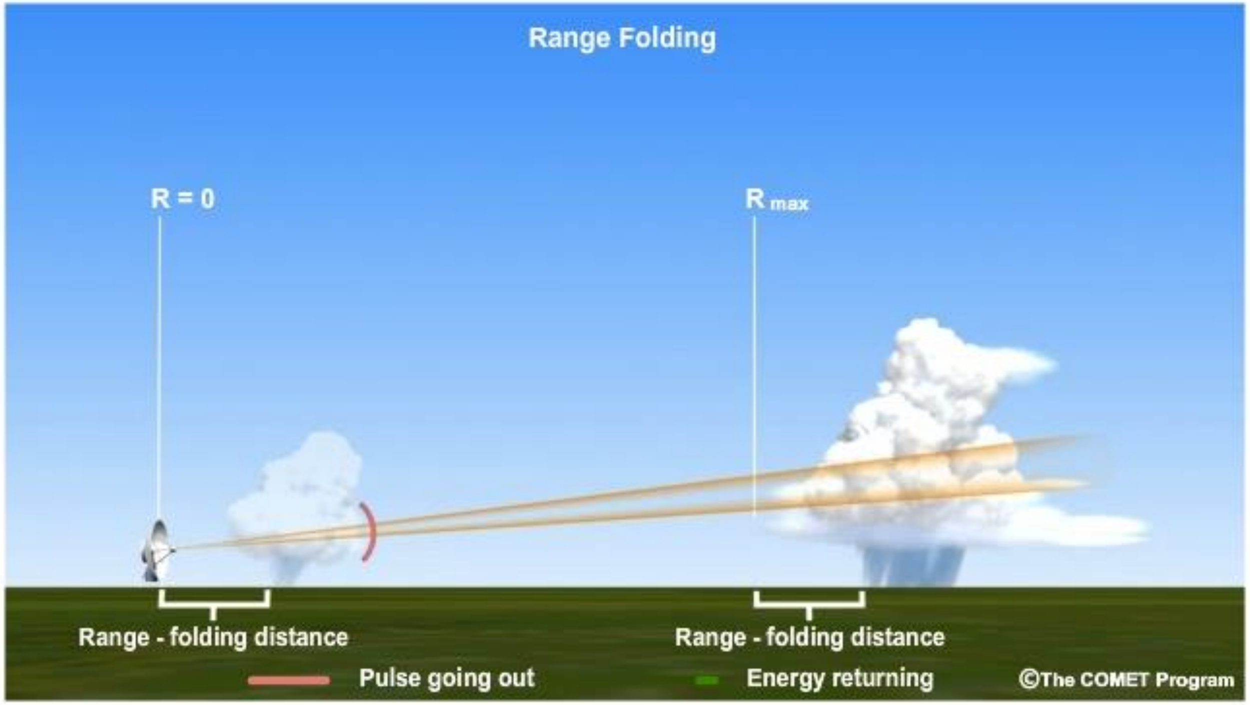
Sources of errors

- **Hardware sources**: Antenna accuracy, Signal processing accuracy, wave length, etc.
- **Non-Meteorological errors**:
  - Electromagnetic interference (sun/other microwave emitters)
  - Biological echoes (birds/insects)
  - Beam broadening
  - Range folding, Ground & Sea clutter,
- **Meteorological errors**:
  - Beam Attenuation (Water vapour, dense cloud & rain/snow on radome)
  - Anomalous Propagation (specific atmosphere gradient or moisture gradient)
  - Attenuation due to hydrometeors
  - Appropriate use of exact Z-R relation coefficients
  - Bright band effect, etc

Radar Sources of Error



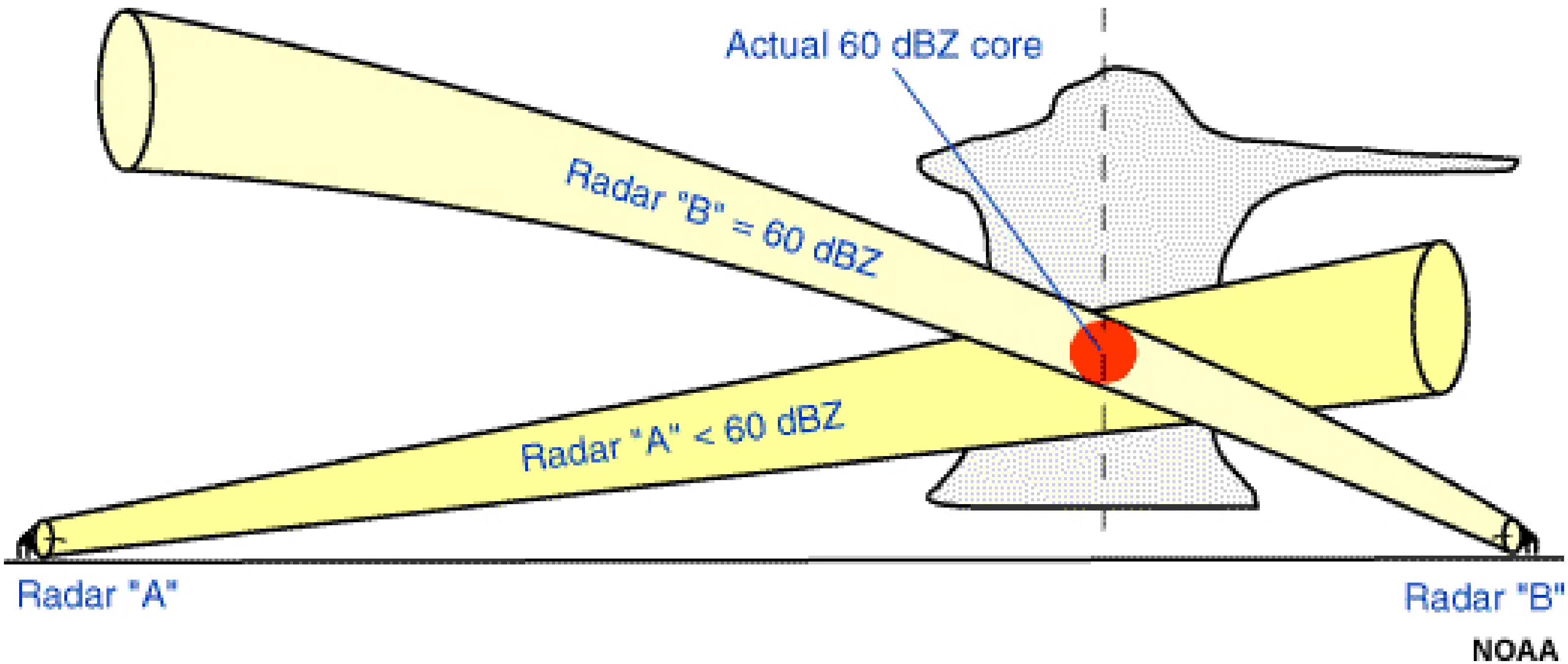
Range Folding



Range folding is commonly called second trip echo, i.e., the backscatter of the electromagnetic wave from the first pulse does not return to the radar before the second pulse is sent.

The range folding echoes usually appear as narrow and elongated shape echo and confined in the lowest few elevation angle scans.

Beam Broadening

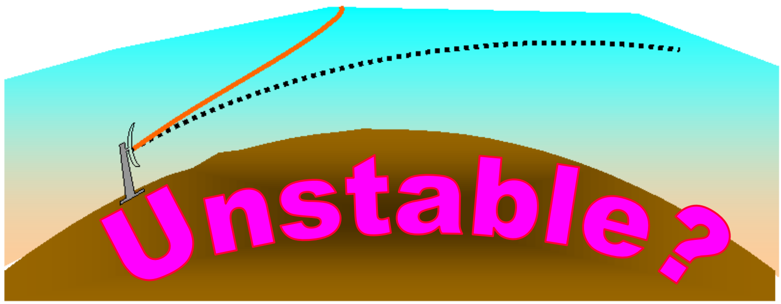


Radar "A" sees less than 60 dBZ at the same range as Radar "B" as the high reflectivity core does not fill the beam volume

- **For measurements taken at far distance, the radar beam expends in horizontal and vertical directions.**
- **The probability rises that the radar beam is inhomogeneously filled by meteorological echoes.**

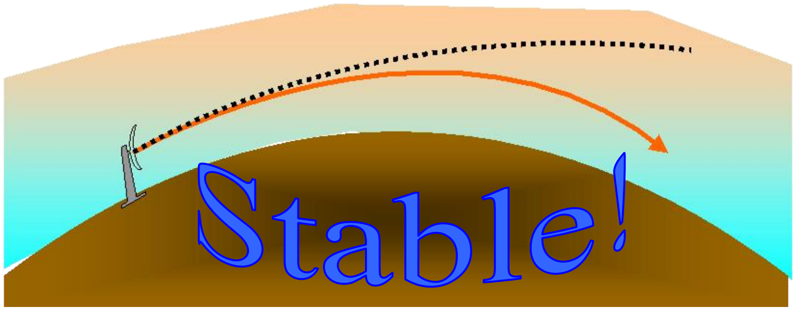
Abnormal Atmospheric Conditions

Subrefraction



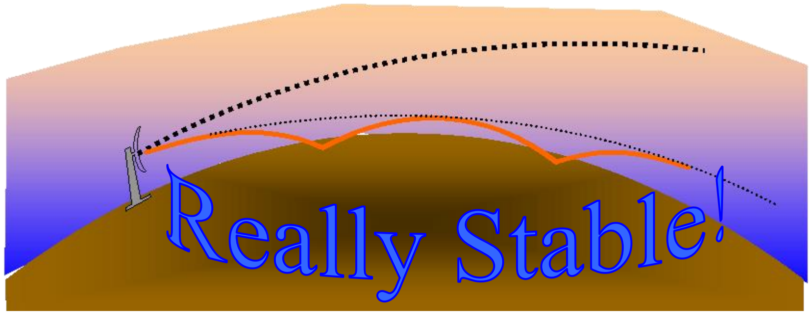
cool, moist air aloft
warm, dry air below

Superrefraction



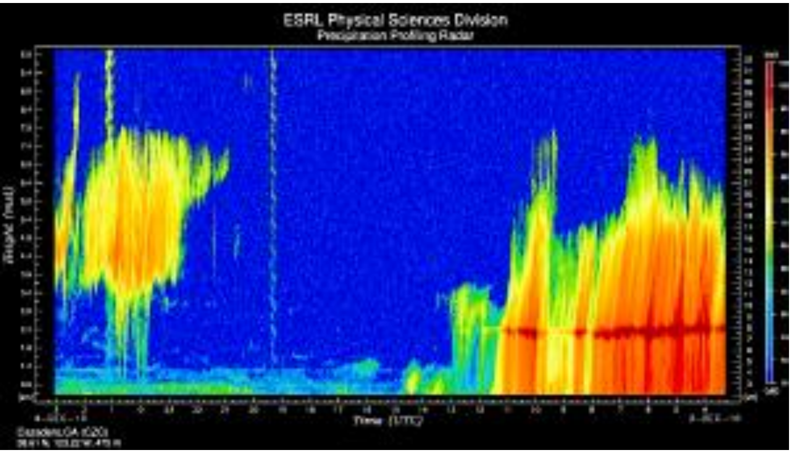
warm dry air aloft
cool, moist air below

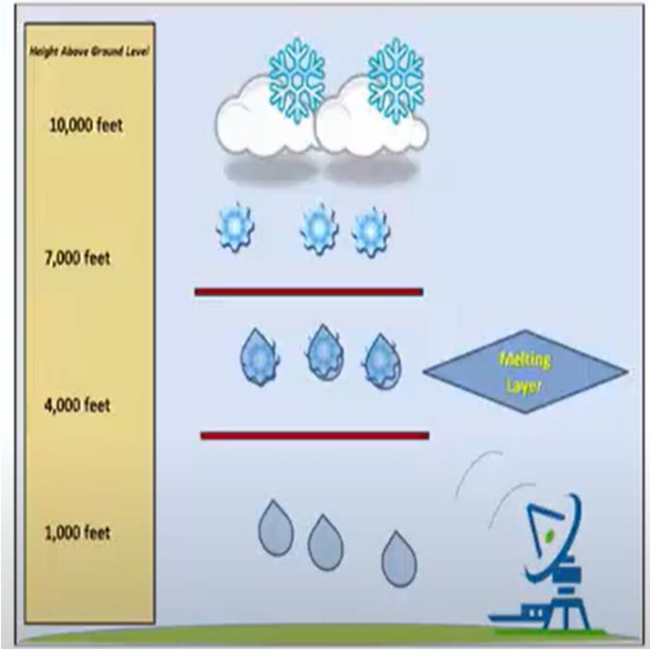
Ducting



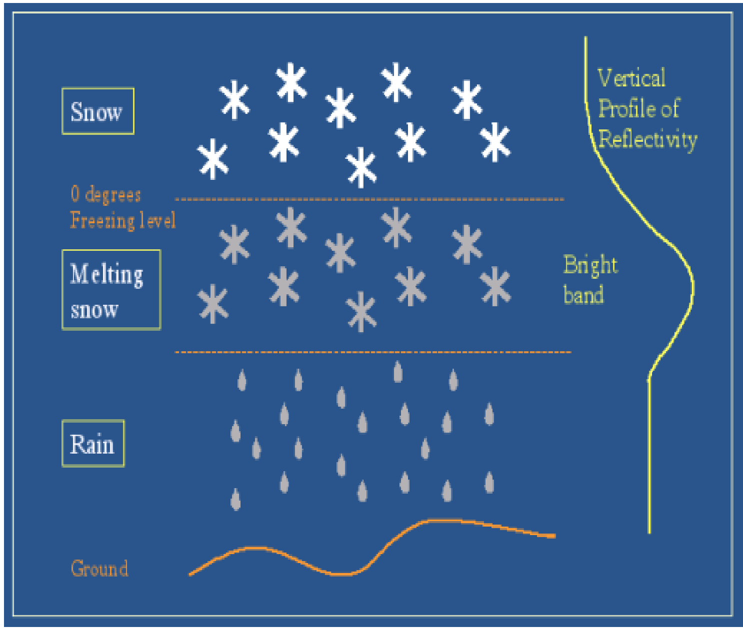
Atmospheric ducts are caused by rapid decrease in the refractive index of the lower atmosphere, and they significantly alter the near-surface wave propagation by trapping propagating signals

Bright Band Effect





- **Bright Banding** is a distinct feature observed by radar, that denotes the freezing level of the atmosphere and results in areas of enhanced reflectivity as snow melts to rain (returns more energy to the radar).
- **Bright Banding** can impact the radar's ability to produce accurate rainfall estimates, especially at greater distances, resulting in an overestimate of precipitation reaching the surface.



Biological echoes

Reflectivity

Radial Velocity

To summarize, here are a few things to keep in mind about diagnosing biological targets on radar:

- **Reflectivities are low, usually <15 dBZ, for small birds and bats.**
- **Often a small patch will move against winds and/or surrounding precipitation areas.**
- **An expanding ring may signal takeoff en masse.**
- **Take note of the time of day and season. Mass exit of roosting areas is typical at sunrise (birds) and sunset (bats, insects), and migration is most common in spring and fall. However, there are numerous exceptions.**
- **Birds typically cause wind speed errors of 19-29 kt (10-15 m s^{-1}); large insects might generate a bias as high as 12 kt (6 m s^{-1}).**

Assimilation of Indian DWR Data

Why Radar DA?

- There are wealth of Doppler radar observations from ground-based, airborne, and movable DWR radars.

- Assimilation of Doppler radar data should improve the small-scale structures in the initial conditions.
- It reduce the model spin-up time, and enhance the short-time NWP skills.

- **Increasing need for accurate forecast of precipitation timing & location.**

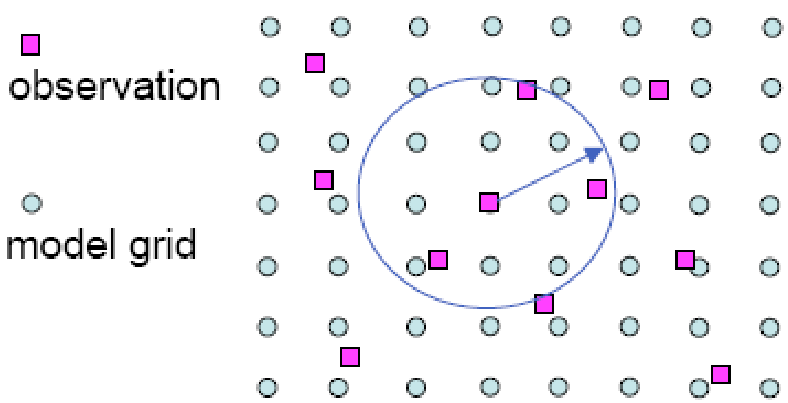
- **Huge amount of data in a storm mode, the estimate number of data is ~3 million/5minute from one radar.**

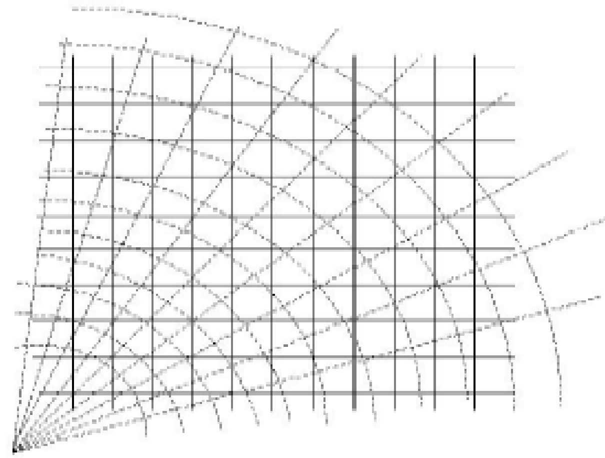
- **High spatial (250m-1km) and temporal resolution (1-10 min), but coverage is limited to regions with reflectors.**

- **Increasing computer power, advanced DA techniques and experience in cloud-scale modeling.**

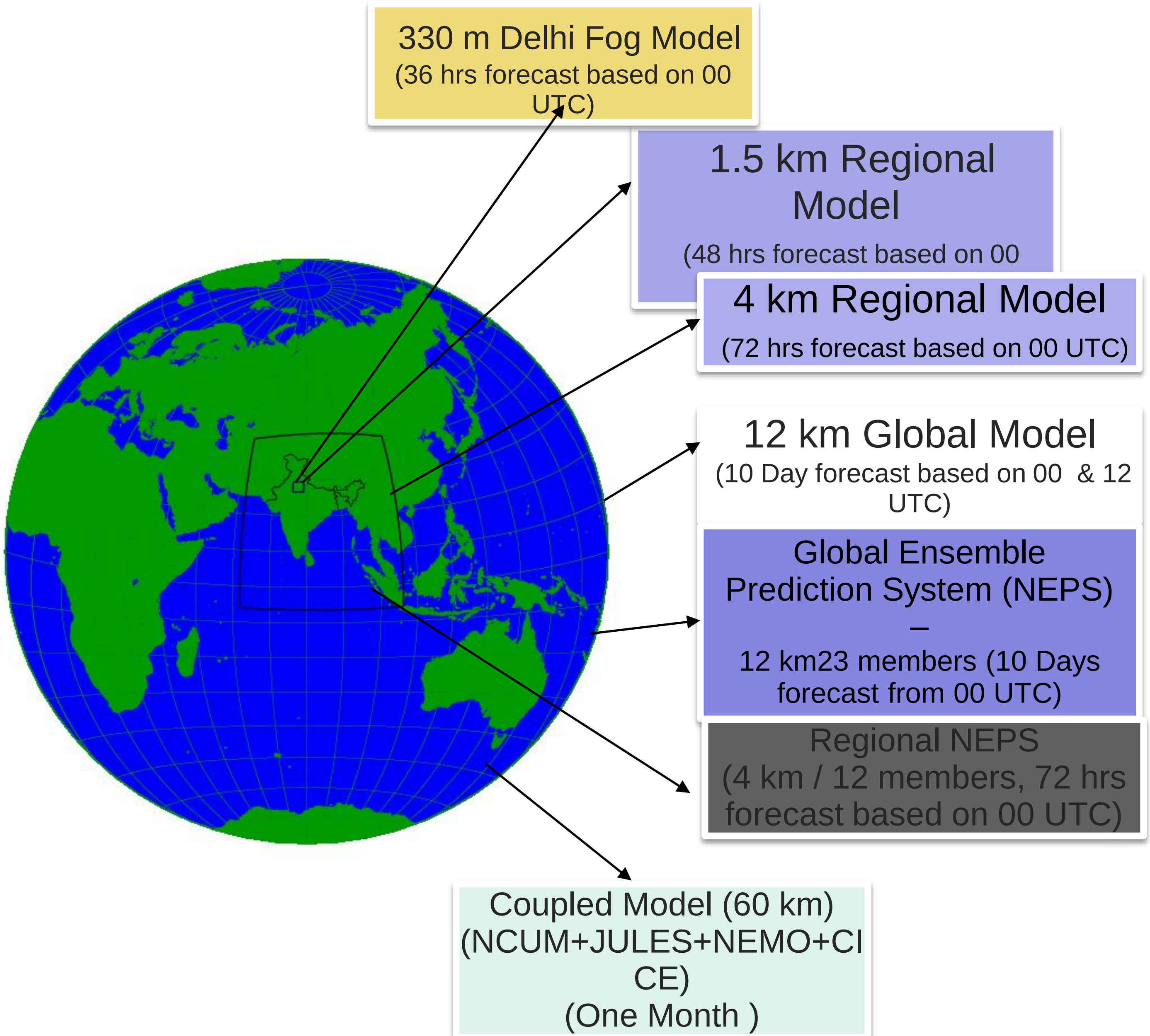
Comparing radar DA with conventional DA

Conventional DA	Radar DA
Obs. resolution ~ a few 100 km -- much poorer than model resolutions	Obs. resolution ~ a few km -- equivalent to model resolutions
Every variable (except for w) is observed	Only radial velocity and reflectivity are observed
Optimal Interpolation	Retrieval of the unobserved fields
Balance relations	Temporal terms essential





Unified Model at NCMRWF (NCUM)
Same Model for Global/Regional/Mesoscale – Seamless model



- **NCUM Global Model (12km) with Hybrid 4D-Var Data Assimilation (Atmosphere) and Extended Kalman Filter (EKF) based Land Data Assimilation**
- **NCUM Regional Model (4 km) with 4D-Var Data Assimilation**
- **Sri Amarnathji Yatra model (1.5 km) (Only during Yatra period) (downscaled initial condition)**
- **330 m Delhi fog model based on NCUM (Only during winter) (downscaled initial condition)**
- **NCMRWF Global Ensemble Prediction System (NEPS) (12 km / 22 +1 members) with Ensemble Transform Kalman Filter (ETKF) for Initial condition perturbations**
- **Regional NEPS (4 km /11+1 member) (only during specific events) (downscaled initial conditions from global NEPS)**
- **Coupled Model with Data Assimilation for Atmosphere (Hybrid 4D-Var), Ocean (3D-Var),Sea Ice (3D -Var) and Land (EKF)**

Impact of DWR Radial Wind from Multi Radar for Simulation of Convective Rainfall Events using NCUM-R Modeling System

Dutta; Routray et al. 2019 Pure Appl. Geophys. 176, 4575–4597

Rainfall Cases:

Three convective rainfall events occurred during the Summer Monsoon are considered in this study:

Case-1 (26-29th July 2016): During this period the south-west monsoon was active over large part of India. The heavy rainfall occurred over many parts of the India.

Case-2 (6-7th July 2016): Depression over northeast Madhya Pradesh and neighbourhood. Due to this heavy rainfall around 25-30 cm in 24hrs occurred over east and west MP region during the period.

Case 3 (10-12th July 2016): A low pressure system over Odisha and adjoining areas of Gangetic West Bengal and northwest Bay of Bengal moved westward and embedded in the monsoon trough increased the rainfall activity over central parts of India.

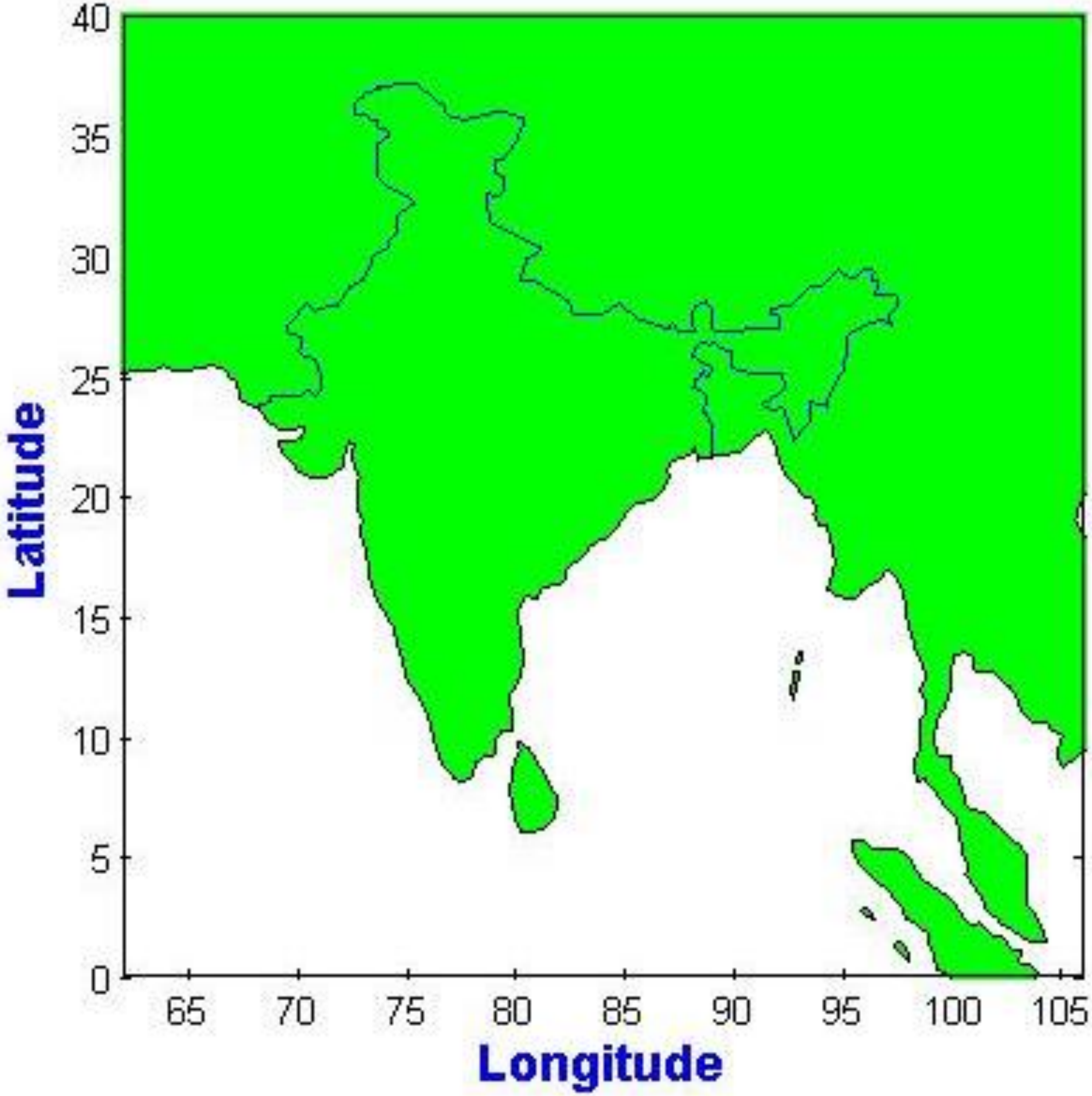
Numerical Experiments

Two numerical experiments are conducted using 3DVAR analysis system:

CNTL: Assimilating various conventional and satellite observations.

RAD: Assimilating the radial velocity from multiple Indian DWR stations along with all observations used in the CNTL experiment.

Model Domain

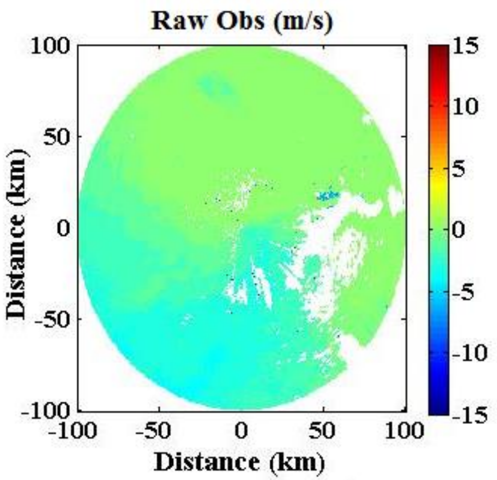


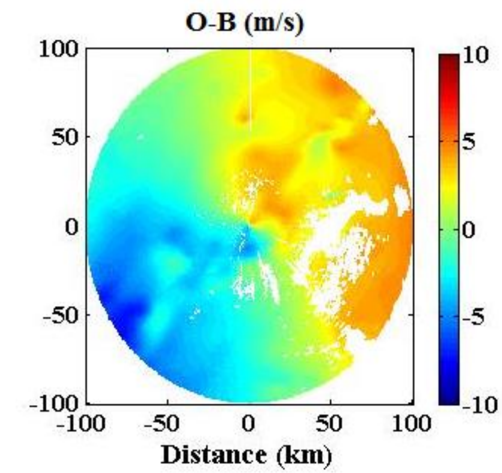
Grid : 1200 x 1200
Sigma Lev: 80
Model top : 38.5 km
Resolution : ~4.4 km
DA system: 4D-VAR
Forecast Length: 72 hrs

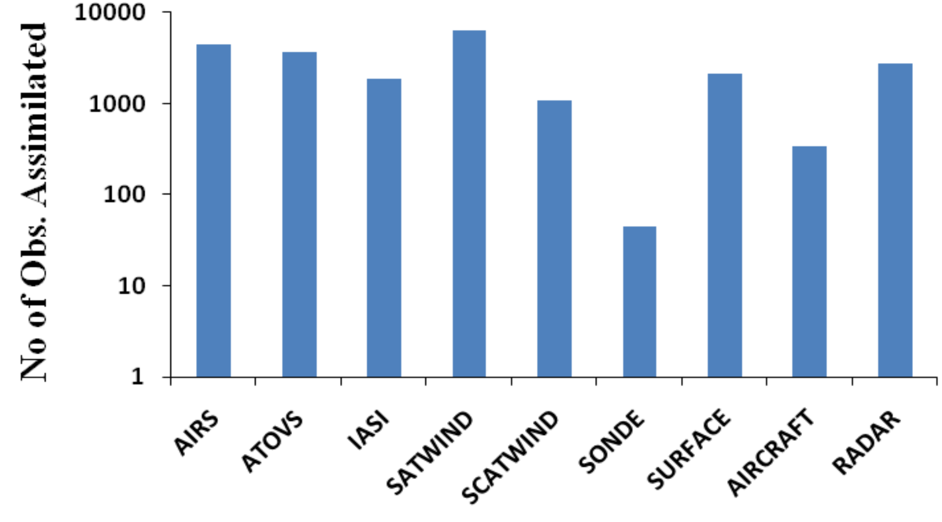
Observations Assimilated in NCUM Regional 4D-VAR DA System

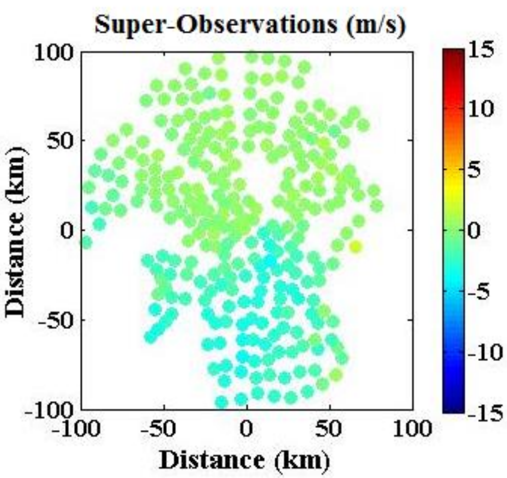
Observation Type	Observation Description	Assimilated Variables
Aircraft	Upper-air wind and temperature from aircraft	U,V,T
AIRS	Atmospheric Infrared Sounder of MODIS	T_b
ATOVS	AMSU-A, AMSU-B/MHS, HIRS from NOAA-18 &19, MetOp-A&B	T_b
ATMS	Advanced Technology Microwave Sounder in NPP satellite	T_b
CrIS	Cross-track Infrared Sensor observations in NPP satellite	T_b
GPSRO	Global Positioning System Radio Occultation observations from various satellites (including MT-ROSA)	Bending Angle
IASI	Infrared Atmospheric Sounding Interferometer from MetOp-A&B	T_b
MTSAPHIR	SAPHIR microwave radiances from Megha-Tropiques	T_b
Satwind	Atmospheric Motion Vectors	U,V
Scatwind	Advanced Scatterometer in MetOp-A & B, ScatSat-1, WindSat	U,V
SEVERIclear	Cloud clear observations from SEVIRI of METEOSAT 8	T_b
Sonde	Radiosonde observations, upper-air wind profile from pilot balloons,wind profiles, VAD wind observation from Indian DWR	U,V,T,q
Surface	Surface observations over Land and Ocean	U,V,T,q,Ps
Radwind	DWR radial wind	Radial Wind

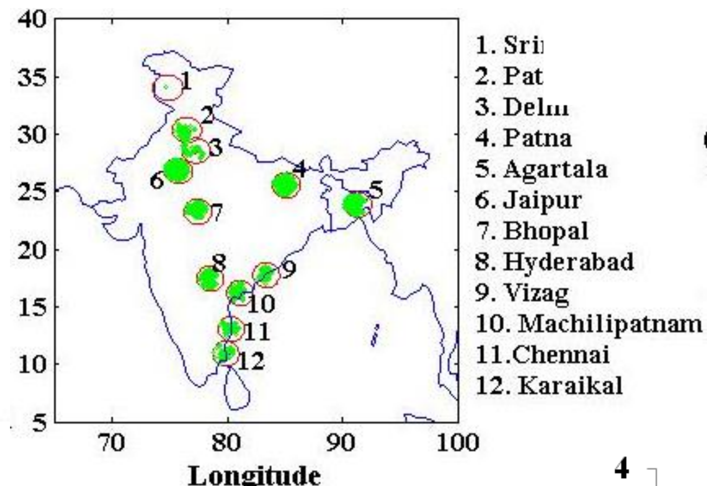
Latent Heat Nudging: Hourly rainrates from Indian DWR. Model produced profiles of Latent Heating is scaled by the ratio of model and observed precipitation rate





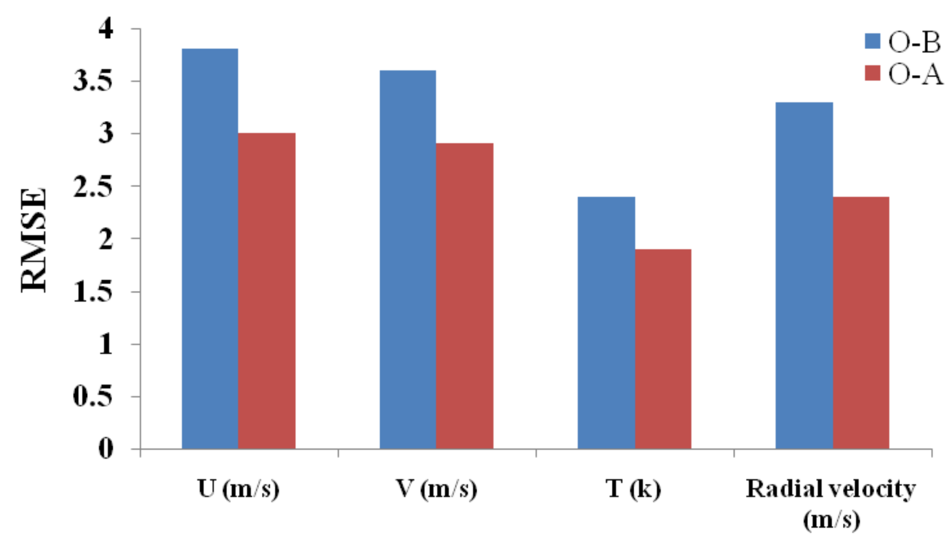




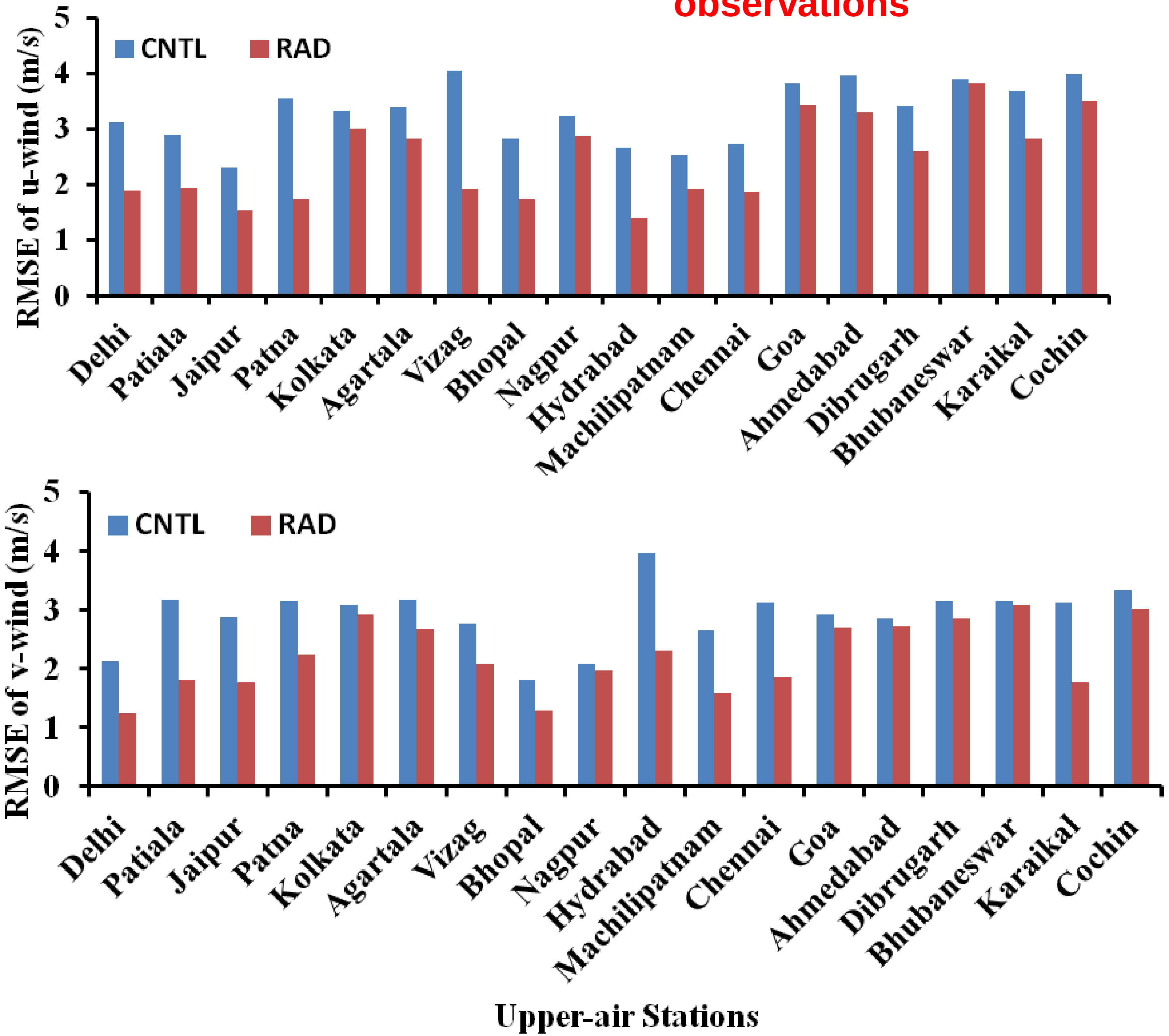


Specification for superobbing in NCUM:

Radar Minimum Range	3km
Radar Maximum Range	100km
Range step considered for superobbing	3km
No of azimuth considered for superobbing	3
Superobbs further Thinning	8 km

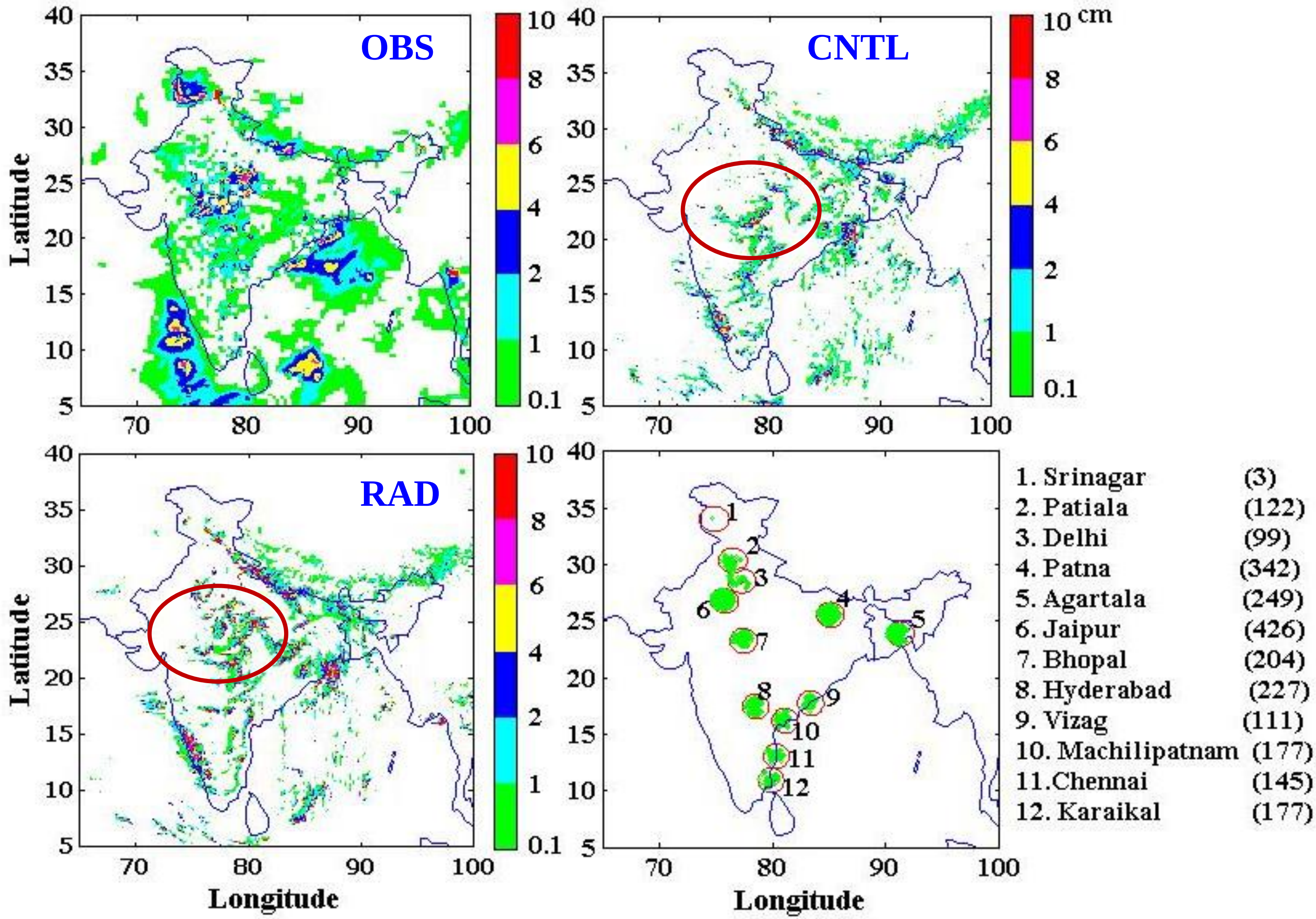


RMSE calculated against RS/RW observations



RMSE of u-wind and v-wind from both the analyses (CNTL and RAD) valid at model initial time (00 UTC of 26 July 2016) of Case-1.

Impact of Radial Wind Assimilation on Forecast



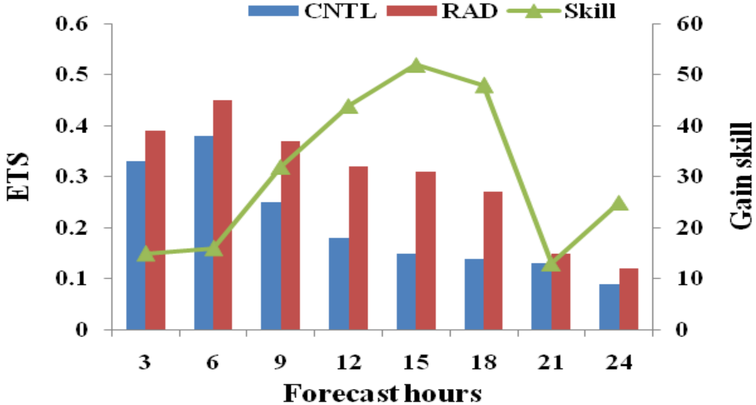
Observed and 24 hrs accumulated rainfall for Day-1 valid at 03 UTC 27 July 2016

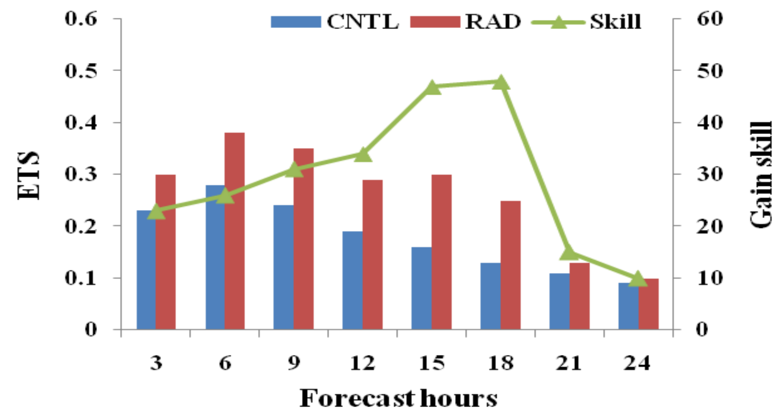
Day-1 fcst for all Cases at different threshold

Threshold: 05 mm

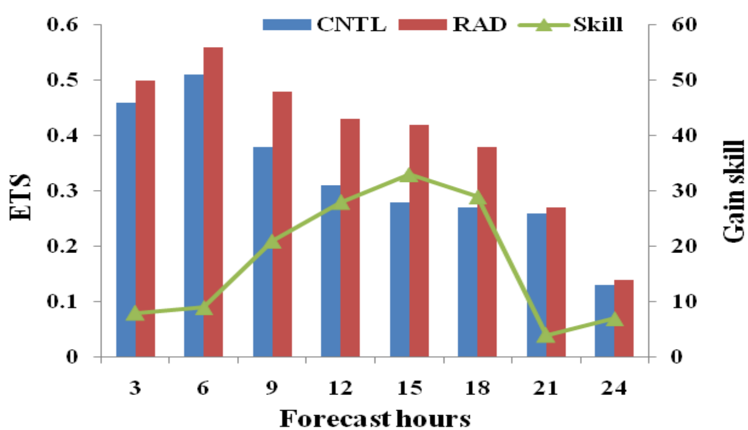
Threshold: 10 mm

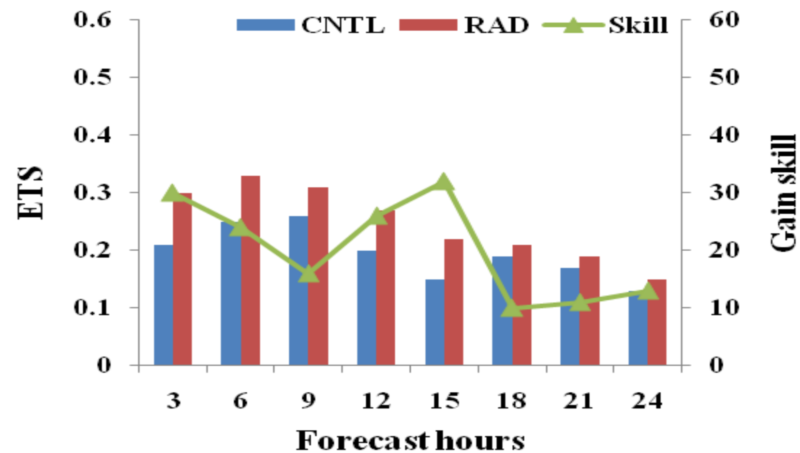
Case-1



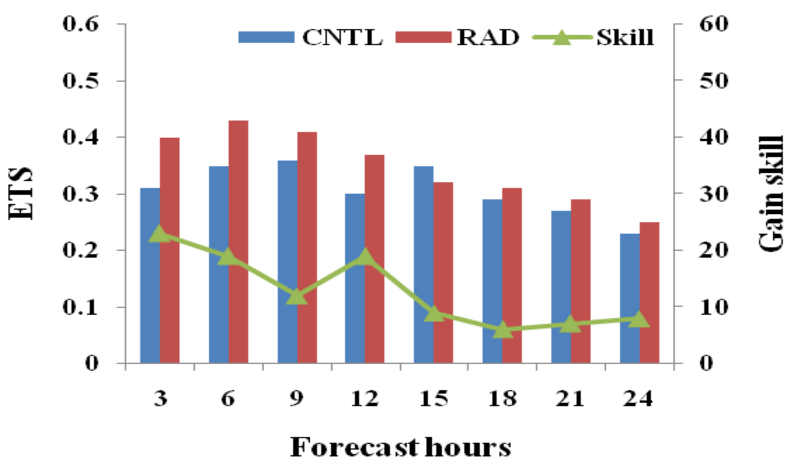


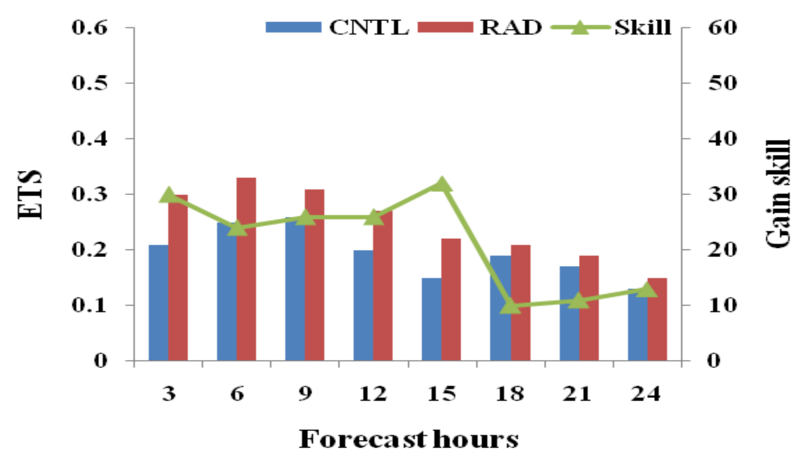
Case-2





Case-3





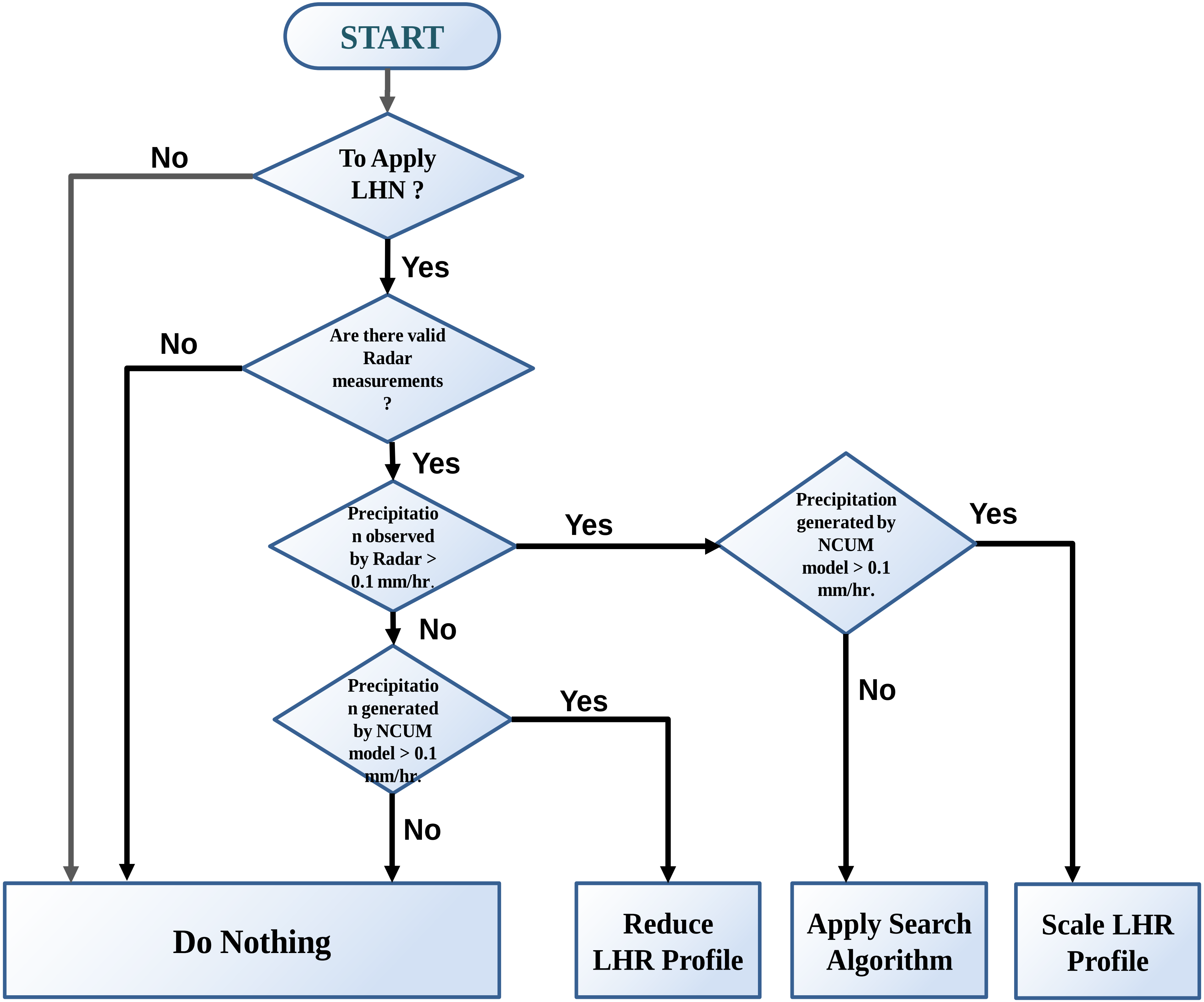
Impact of Assimilation of Rain Rate derived from DWR for Simulation of Heavy Rainfall Events

Routray et al. 2021, Journal of Hydrology 596, 126072

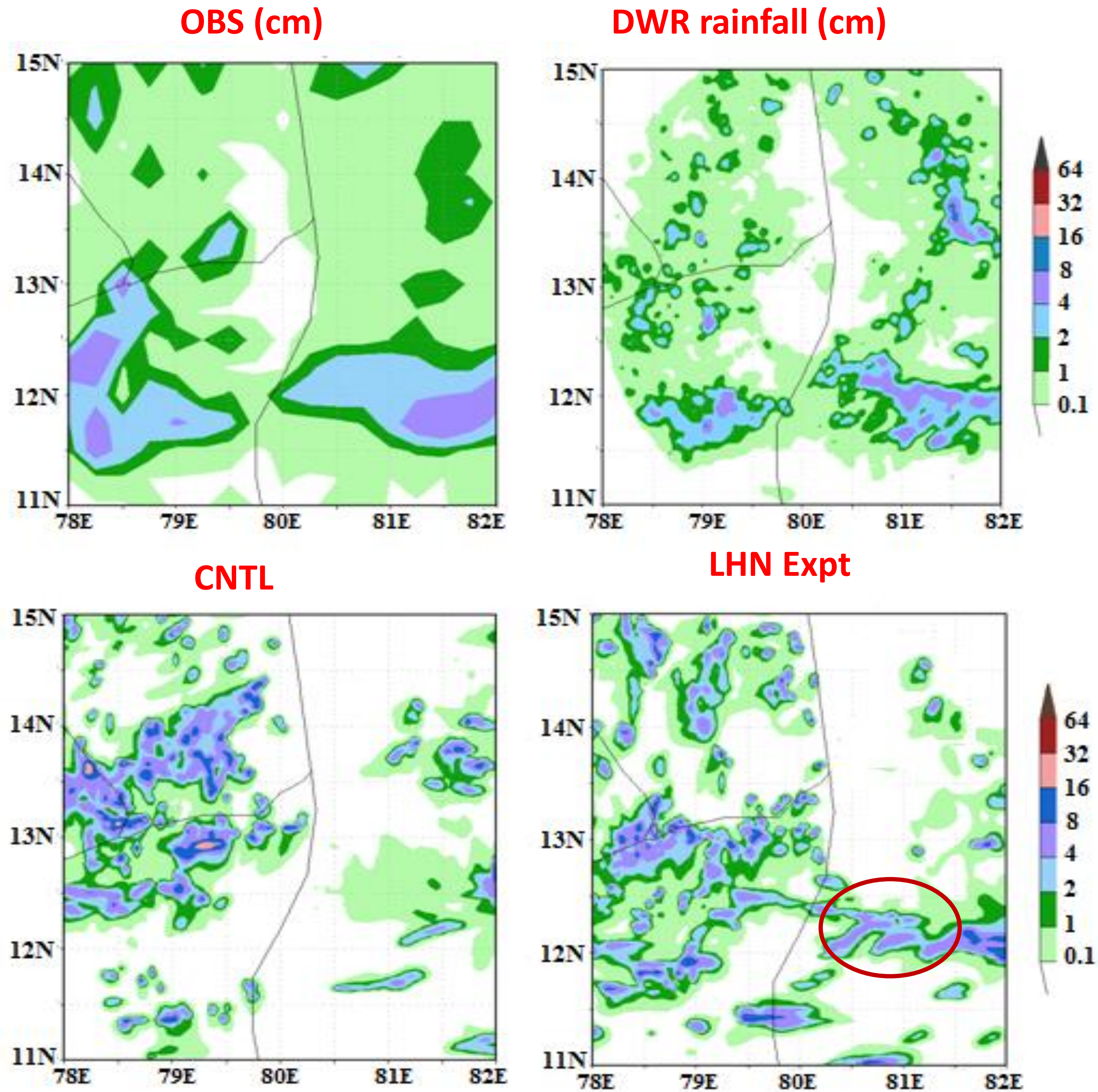
Latent Heat Nudging in Regional NCUM Model

- **Based on observation, relatively little moisture is stored in clouds. Therefore, the column integrated latent heating rate must be approximately proportional to the net precipitation rate.**
- **In Latent Heat Nudging (LHN), model produced profiles of latent heating is scaled by the ratio of model and observed precipitation rate (*Jones & Macpherson, 1997*).**
- **LHN increments to the temperature (often moisture) are added throughout a pre-forecasted period and also sometimes for a few hours into the forecasts.**
- **This alter the temp. & moisture in such a way that the diagnosed precipitation rate fits more closely with the observations.**
- **Previous studies suggested, LHN has beneficial impact on precipitation forecast skill in short-range scales.**

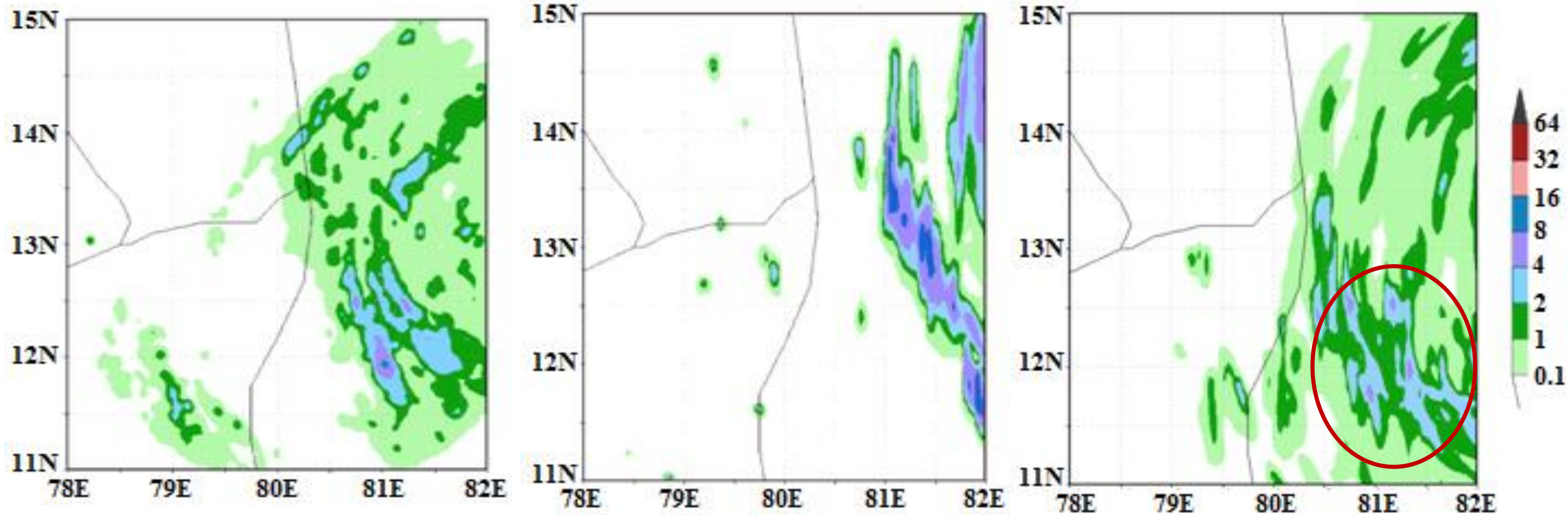
Schematic Diagram of Latent Heat Nudging (LHN) Algorithm.



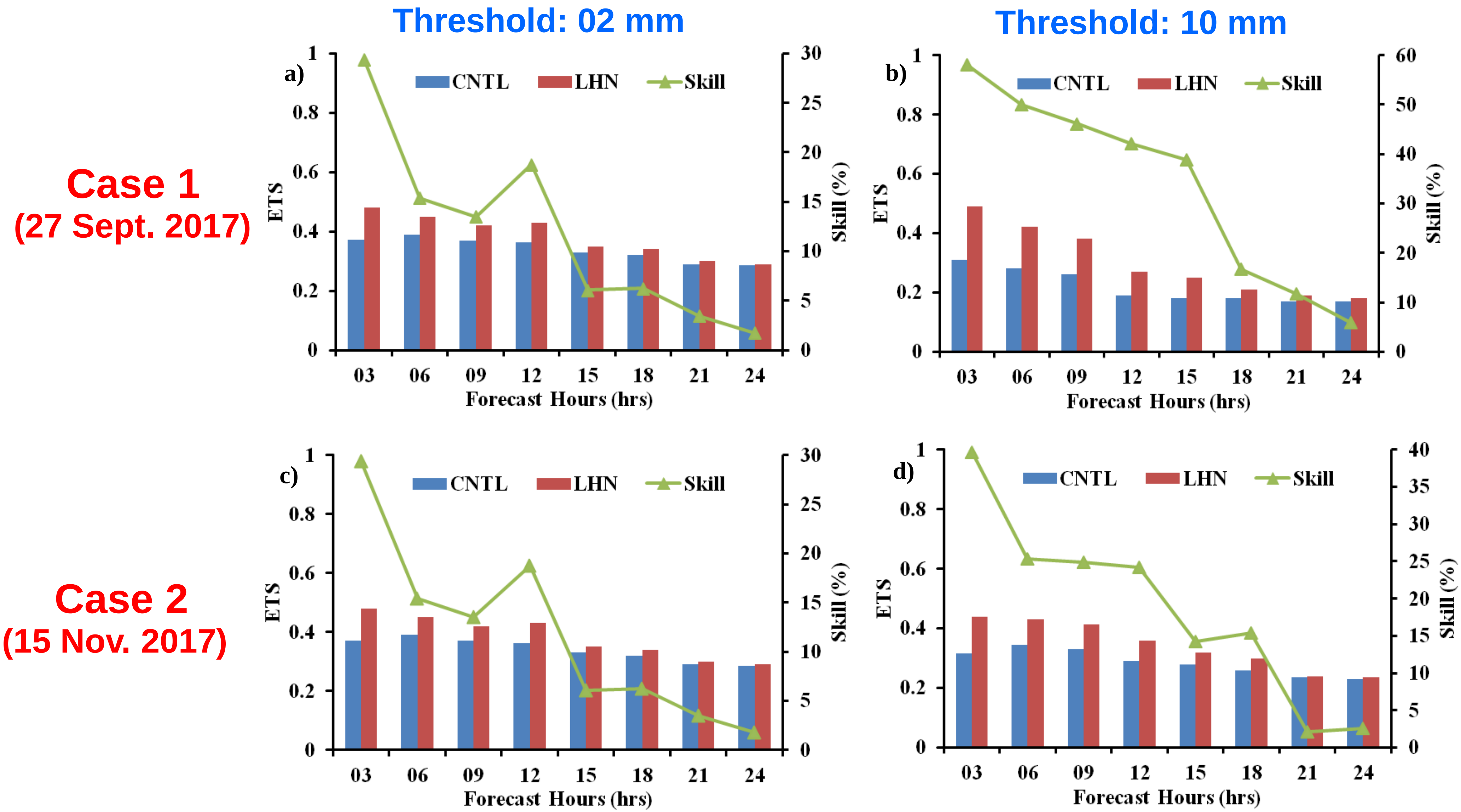
24 hr Forecast valid at 03 UTC 27 September 2017



Northeast Monsoon active in Tamil Nadu including Chennai. A well-marked low (WML) pressure area lying over coastal parts of Tamil Nadu. It further concentrated into a depression over westcentral BOB off Andhra Pradesh on 15th Nov. 2017. Moving nearly north-northeastwards, it weakened into a WML over northwest BOB off Odisha Coast on 17th Nov. 2017 . Heavy rains was occurred over various parts of Tamil Nadu state.



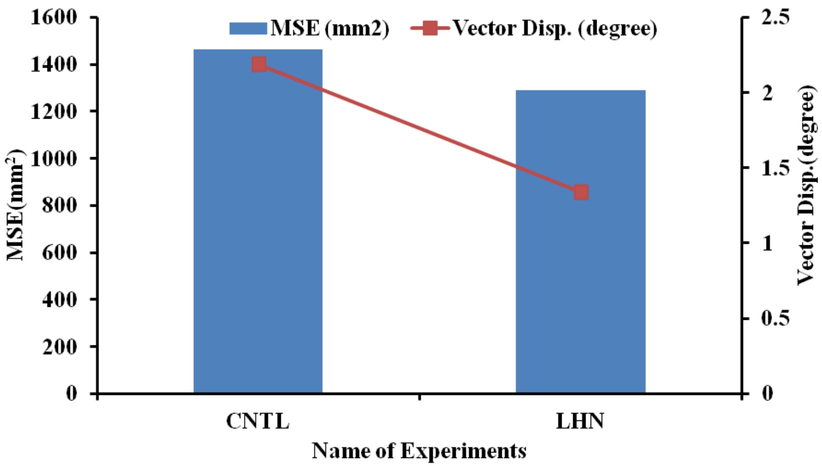
24 hr Forecast valid for 03 UTC 15th November 2017

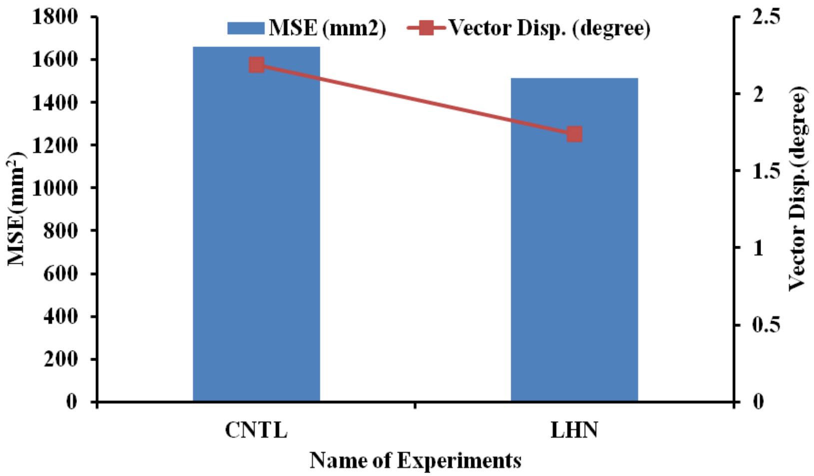


Threshold: 02 mm
Threshold: 10 mm
Case 1
(27 Sept. 2017)
Case 2
(15 Nov. 2017)
a)
b)
c)
d)
CNTL
LHN
Skill
ETS
Skill (%)
Forecast Hours (hrs)
03
06
09
12
15
18
21
24

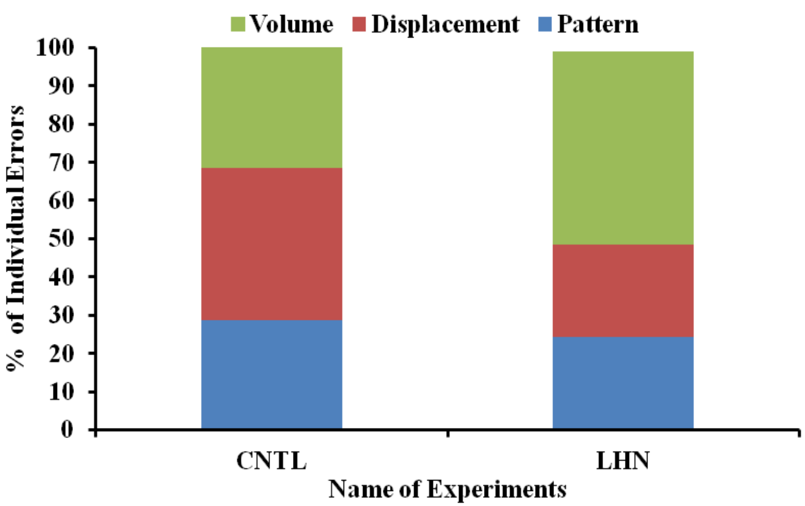
Contiguous Rain Area (CRA) verification of precipitation for threshold 10 mm

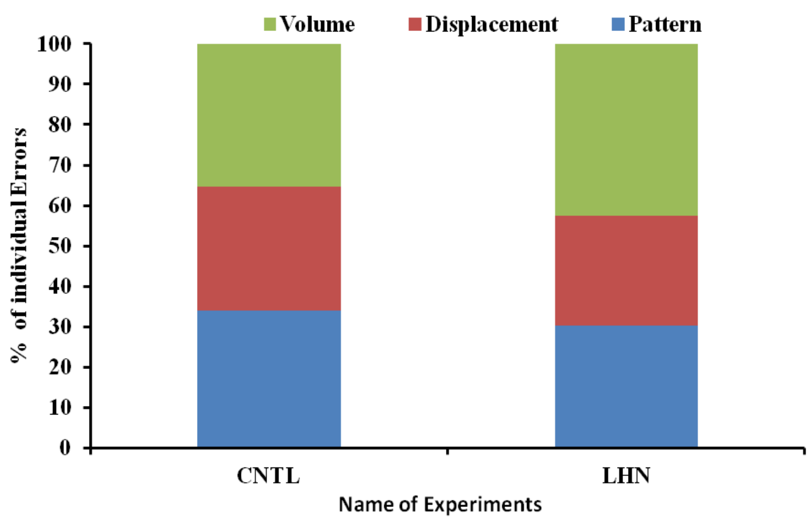
Case 1
(Day-1 valid at 27 Sept. 2017)





Case 2
(Day-1 valid at 15 Nov. 2017)





THANK YOU

Applications of radar data assimilation

- Improvement of cloud permitting simulation and forecast.
- Analysis and study of high impact weather.
- Now-casting.
- Wind energy prediction.
- Prediction of chemical dispersion.

Observation Operator

The observation operator for Doppler radial velocity is

$$V_r = u\frac{x-x_i}{r_i} + v\frac{y-y_i}{r_i} + (w-v_T)\frac{z-z_i}{r_i}$$

where (*u, v, w*) are the wind components; (*x, y, z*) are the radar location (*xi, yi, zi*) are the radar observation location; *ri* is the distance between radar and the observations

The terminal velocity (v_T ms^{-1}) is calculated by Sun and Crook (1998).

$$v_T = 5.40a \cdot q_r^{0.125}$$

q_r is the rainwater mixing ratio (g/kg)

The observation operator for reflectivity is derived analytically by assuming the Marshal-Palmer distribution of raindrop size. The *Z*-R relation between the rainwater and reflectivity (dBZ) is (Sun and Crook 1997)

$$Z = 43.1 + 17.5\log(\rho q_r)$$

Z is the reflectivity in the unit of dBZ
qr is the rainwater mixing ratio

Increment variables w' and qr'

-

  - Control variables (ψ', χ_u', T'_u, p'_{su}, r'_s) <=> model variables (u', v', T', p', q')

- **Doppler radar data assimilation**

- **Radial velocity data**
  - **3D-Var needs vertical velocity increments (w') to have a full assimilation of radial velocity data.**

- **Reflectivity data**
  - **3D-Var needs at least rainwater increments (qr').**
  - **It is better to have increments of all other hydrometeor variables as well in 3D-Var analysis.**

- **w' and qr' are obtained through diagnostic relations**

W Increments in WRF-Var

- Richardson's Equation ($\psi', \chi_u', T'_u, p'_{su} \rightarrow u', v', T', p' \rightarrow w'$)

$$\gamma \bar{p} \frac{\partial w'}{\partial z} = -\gamma p' \frac{\partial \bar{w}}{\partial z} - \gamma \bar{p} \nabla \cdot \vec{v}'_h - \gamma p' \nabla \cdot \vec{\bar{v}}_h - \vec{\bar{v}}_h \nabla p'$$

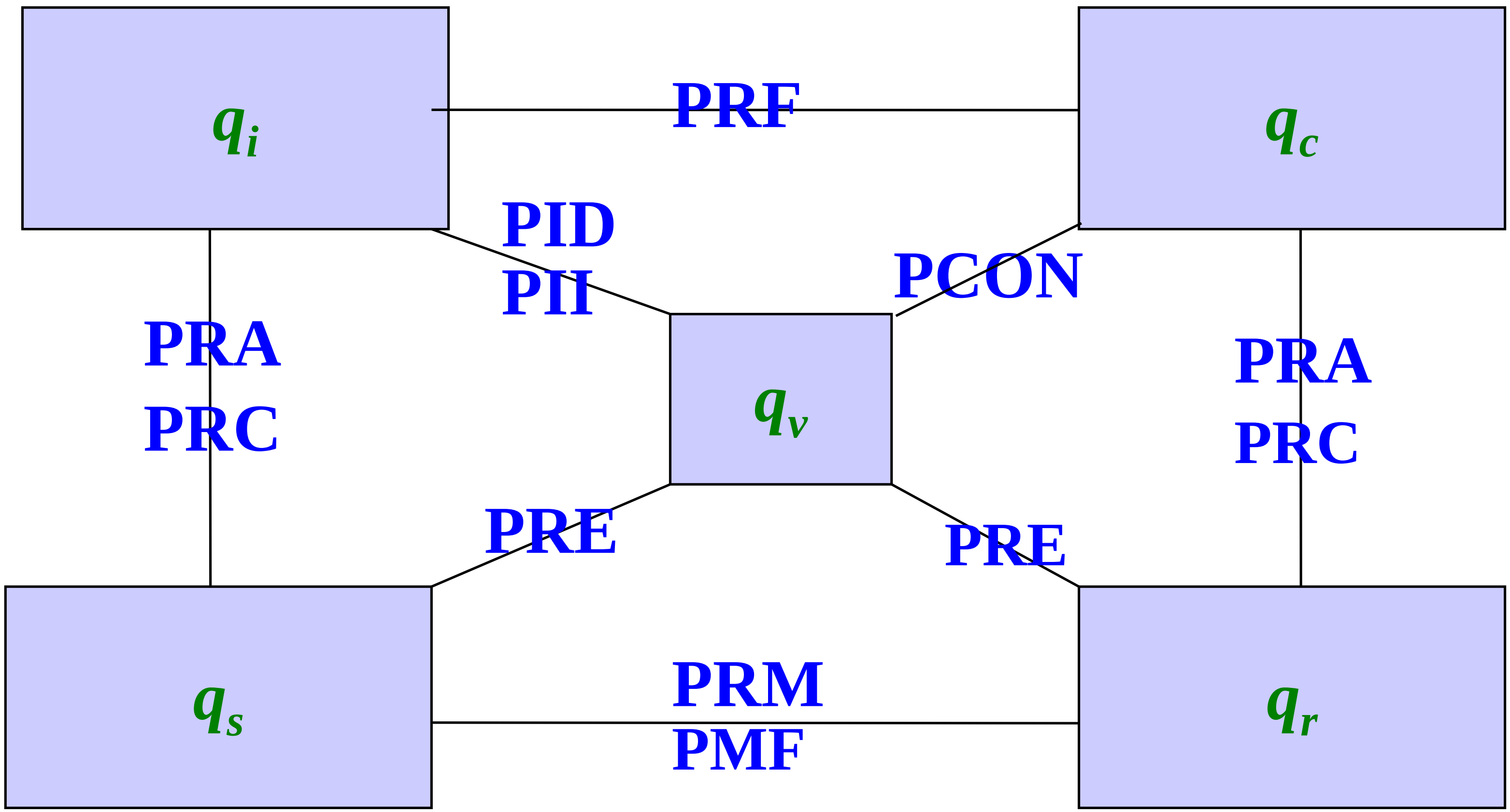
$$-\vec{v}' \nabla \bar{p} + g \int_z^\infty \nabla \cdot (\rho \vec{v}'_h) dz + g \int_z^\infty \nabla \cdot (\rho' \vec{\bar{v}}_h) dz$$

- **Richardson's equation is a higher-order approximation of the continuity equation than the incompressible continuity equation or anelastic continuity equation.**

- **It can build an efficient linkage between dynamic and thermodynamic fields because the thermodynamic equation is directly involved.**

- **Its computation is affordable, just a little more than the anelastic continuity equation.**

Partitioning of hydrometeor increments

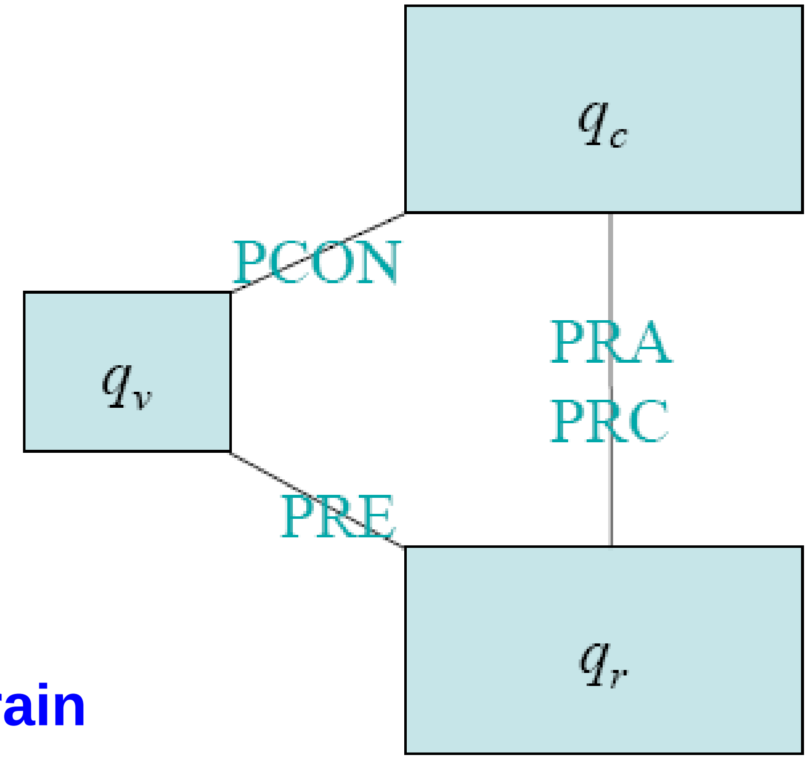


PCON: condensation/evaporation; PRA: accretion; PRC: conversion; PID: deposition onto ice; PRE: evaporation/deposition; PMF: melting/freezing; PII: initiation of ice; PRM: snow melting due to fall

Only the PCON, PRA, PRC and PRE processes are included in the partition

Hydrometeor increments in WRF 3D-Var

- **A warm rain process is currently built in WRF 3DVar to bridge water hydrometeors and other variables.**



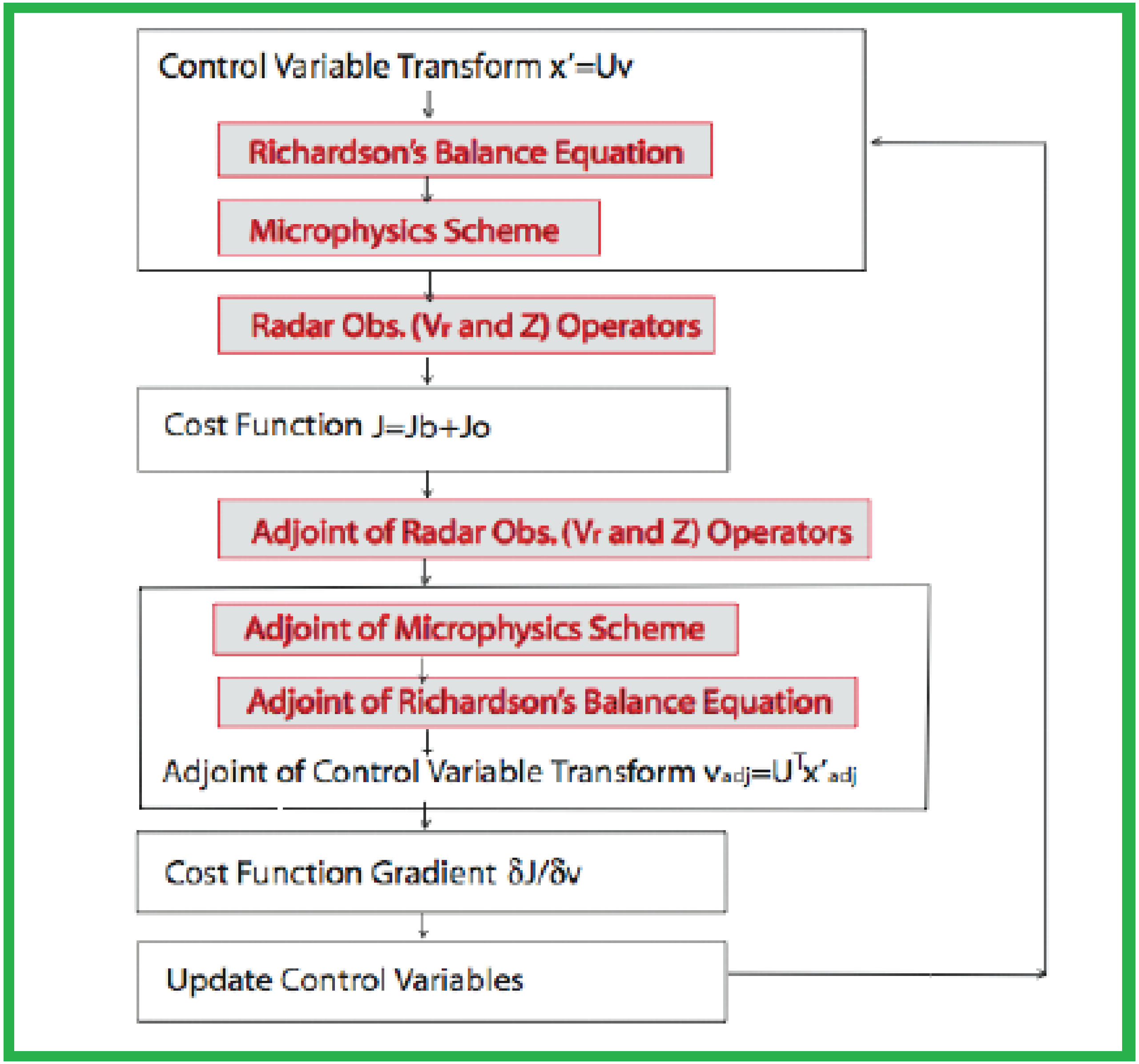
PCON: condensation/evaporation;

PRA: accretion

PRC: automatic conversion of cloud to rain

PRE: evaporation/deposition

Flow Chart of Radar Data Assimilation in WRF 3D-Var



Buid up radar data input (in Ascii format) as follows

- ==
- First line: Total number of radar observation
- Second line: Blank (It is read but not used)
- Third line: Blank (It is read but not used)
- Forth line: Radar station header

  Radar identification, lon, lat, elevation, date, No. of obs, levels
- Fifth line: Blank (It is read but not used)
- Sixth line: Blank (It is read but not used)
- Seventh line: Radar data header

  FM number, date, lat, lon, elevation, levels
- Eigth line: Actual radar data

  (height, radial velocity (value, qc index, error), reflectivity (value, qc index, error)

  -----and so on.

Data Format

TOTAL RADAR (14X, I3) – FMT = (A14,I3)

#--

Head record for specific Radar information (site, lat0, lon0, elv, date, # of data locations, max_levs)

– FMT = (A5,2X,A12,2(F8.3,2X),F8.1,2X,A19,2I6)

#---

Head record for the specific location (FM-128 RADAR, date, lat, lon, elv, levs)

-- FMT=(A12,3X,A19,2X,2(F12.3,2X),F8.1,2X,I6)

Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)

Data-level record (height<m>, Radial_V<m/s>, qc, err, Reflectivity<dbz>, qc, err)

…………………………………………………………………………………

– FMT=(3X,F12.1,2(F12.3,I4,F12.3,2X))

- For details refer wrfvar/da/da_obs/da_read_radar.inc
- Here is a sample radar data file with single data:

```
TOTAL RADAR =   1
#-----------------------------------------------------------------------------------#

RADAR KOLK  84.522  22.453  400.0  2002-06-13_00:00:48  3322    14
#-----------------------------------------------------------------------------------#

  FM-128 RADAR   2002-06-13_00:00:48  22.453      84.522     809.0      1
   2483.6      -1.150   0      1.270        5.220   0      1.320
   2583.7      -1.140   0      1.270        5.20    0      1.320

    =======================================================================
    ========
```