A Basis for Improving Numerical Weather Prediction by Assimilating Doppler Radar Radial Winds

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Outline

What is Data Assimilation (DA)?

What set of Initial Conditions (ICs) will seed the models to best predict the known observations? (Inverse problem).

- **The goal of DA is to construct the best possible ICs, known as the analysis, from which to integrate the NWP model forward in time.**
- **DA involves deriving the best current state of the atmosphere by combining a short model forecast (known as background[a]) with the latest observations, giving each a weighting which depends upon their error characteristics.**

[a] Background is the most recent information.

Why use Doppler Radar Data?

Doppler radar can be used in civilian proposes:

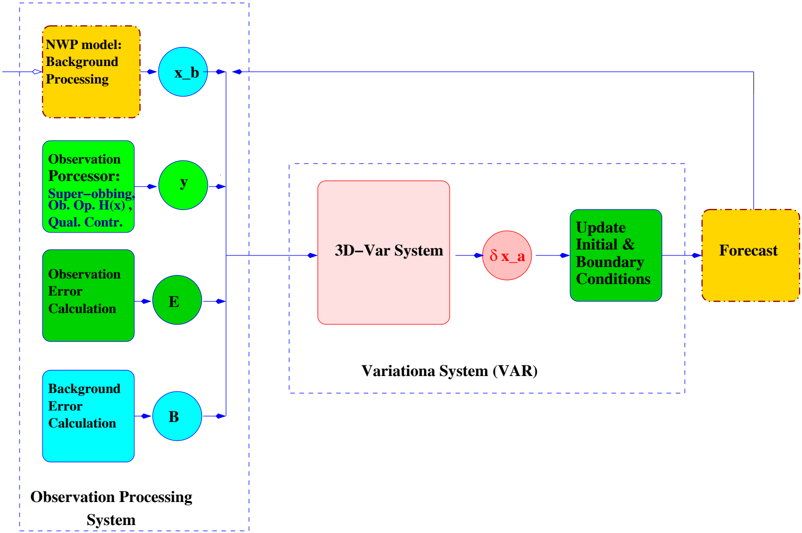
- **Limited Area Models require observations with high resolution to generate their initial conditions (ICs).**
- **Doppler radars**
  - **have the ability to scan large volumes of atmosphere,**
  - **provide measurements of radial velocity and reflectivity with high resolution.**
- **Doppler winds give extra information in forecasting quickly developing mesoscale systems.**
- **The resolution of radar data are however much higher than the resolution of the NWP models.**

Steps of NWP

NWP is an **IVP** $\frac{\partial \mathbf{x}}{\partial t} = F(\mathbf{x}, t), \quad \mathbf{x}(t_0) = \mathbf{x}_0$
for which we should provide the **initial conditions** (ICs).

1. Collect all possible atmospheric information (**background and observations**) for a given time;
2. This information is **analysed** (that represented in **data assimilation**) to **obtain** a **regular**, **coherent spatial** distribution of the atmosphere at that time;
3. This **analysis** becomes the **initial conditions** for the time integration of the **NWP** model;
4. Finally, given the estimate of the **present state** of the atmosphere, the model **forecasts** its evolution.

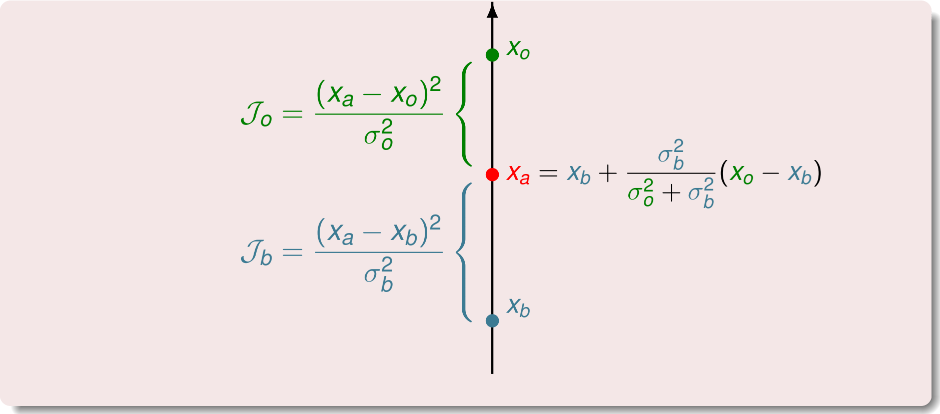
Continued: NWP Process



Cost Function

$$\textbf{Total Cost} = \textbf{Departure from backg.} + \textbf{Departure from obs.}$$

$$\mathcal{J}[x_a] = \mathcal{J}_b[x_a] + \mathcal{J}_o[x_a]$$



Continued: Cost Function

$$\mathcal{J}[\mathbf{x}] = \frac{1}{2}(\mathbf{x}_b - \mathbf{x})^T \mathbf{B}^{-1}(\mathbf{x}_b - \mathbf{x}) + \frac{1}{2}(\mathbf{y} - \mathcal{H}[\mathbf{x}])^T \mathbf{E}^{-1}(\mathbf{y} - \mathcal{H}[\mathbf{x}]).$$

$\mathbf{x}$ denotes the analysis, $\mathbf{x}_b$ background, $\mathbf{y}$ observation vector. $\mathbf{B}$ and $\mathbf{E}$ are back. and obs. error covariance matrices.

$\mathcal{H}$ is the observation operator that relates the model variables to the observation variable and a transformation between the different grid meshes.

$\mathcal{H}$ can be linearized as $\mathcal{H}[\mathbf{x} + \delta\mathbf{x}] = \mathcal{H}[\mathbf{x}] + \mathbf{H}\delta\mathbf{x}$. Then

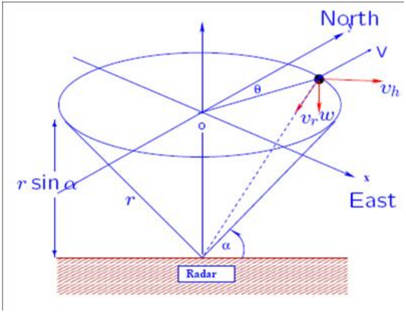
$$\mathcal{J}[\delta\mathbf{x}] = \frac{1}{2}\delta\mathbf{x}^T \mathbf{B}^{-1}\delta\mathbf{x} + \frac{1}{2}[\mathbf{H}\delta\mathbf{x} - \mathbf{y} + \mathcal{H}\mathbf{x}_b]^T \mathbf{E}^{-1}[\mathbf{H}\delta\mathbf{x} - \mathbf{y} + \mathcal{H}\mathbf{x}_b],$$

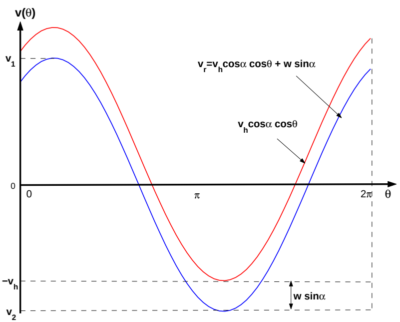
where $\mathbf{H}$ is linear operator $\equiv \partial\mathcal{H}/\partial\mathbf{x}$.

Objectives and Challenges

1. **The aim is to develop an incremental assimilation of Doppler radar winds using 3D-Var/4D-Var, leading to an improved representation of the Initial Conditions (ICs) for storm-scale forecasting of winds, sand or dust in UAE!!.**
2. **Main Challenges:**
   - **Data assimilation at high resolution; loss of vertical resolution of the radar data.**
   - **The observed quantities are not model variables.**
3. **Organization:**
   - **Obtain data for radial winds for which the model output is available,**
   - **The very high resolution raw data is re-mapped to model resolution, and make it suitable for input to the Var system,**
   - **Formulate an observation operator,**
   - **Assimilate the processed data, and investigate the impacts on the analysis and model forecasts.**

Pre-processing the Doppler radar data



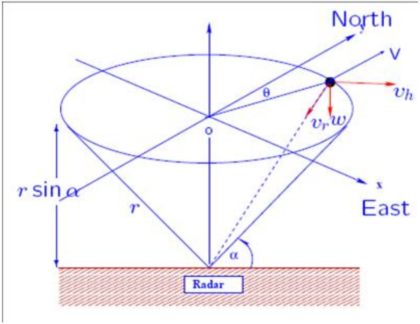


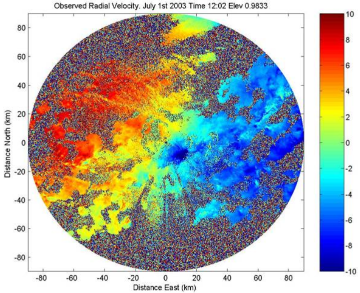
- Bilinear interpolation of u, v&w to the obs locations.
- Projection of the horizontal model wind towards the radar beam $v_h = u \sin\theta + v \cos\theta$, where θ is the azimuth angle.
- The radial wind v_r is v_h + the vertical velocity term, in direction of the radar beam,

$$v_r = u \cos\alpha \sin\theta + v \cos\alpha \cos\theta + w \sin\alpha.$$

α is the elevation.

Getting the Doppler radar data





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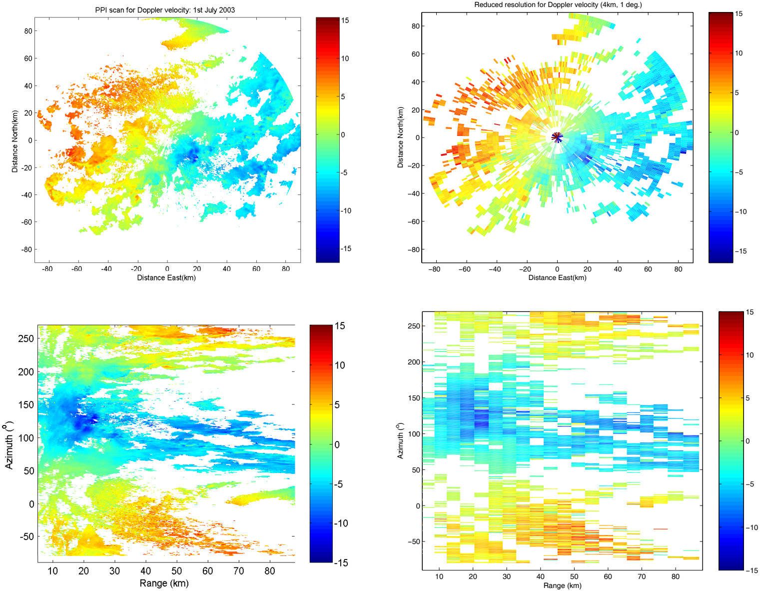
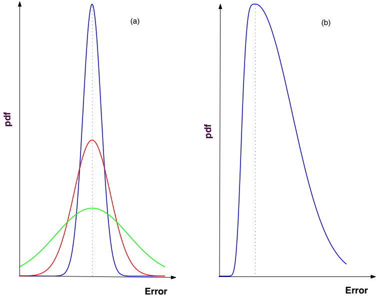
Pre-processing data - Super-obing



Types of Errors in Doppler Radial winds

- Errors in the original measurements with each pulse volume that depends on the velocity gradients within the pules volume (vary with range);
- Errors due to super-obbing procedure (vary with range);
- Errors due to hardware degradation (random);
- Errors in the assimilation process and observation operator.



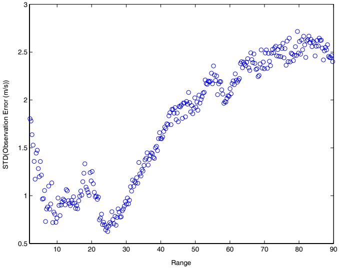
Distribution of wind speed error due to (a) instrumental noise, (b) strong velocity gradient across the pulse volume.

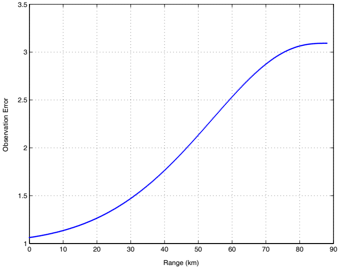
Continued: Types of Errors in Doppler Radial winds

- The obs errors are uncorrelated in space and time.
- The error in radial winds due to the velocity gradient along the pulse volume, varies with the range R, is

$$\breve{\sigma}^2(\varepsilon_v) = \left(1 - e^{-|\Delta v_r / v_r|}\right) \sigma^2(v_r).$$

- The instrumental error $\hat{\sigma}^2(\varepsilon_i)$ does not vary temporally.
- The total error variance of the radial winds is $\sigma^2(\varepsilon) = \breve{\sigma}^2(\varepsilon_v) + \hat{\sigma}^2(\varepsilon_i)$.





Local Observation errors (m/sec) of the radial velocity as a function of the range (left), proposed s-function (right).

3D-Var System

- The Met Office 3D-Var system uses the incremental cost function,

$$\mathcal{J}[\delta\mathbf{x}] = \frac{1}{2}\delta\mathbf{x}^T\mathbf{B}^{-1}\delta\mathbf{x} + \frac{1}{2}[\mathbf{H}\delta\mathbf{x} - \mathbf{y} + \mathcal{H}\mathbf{x}_b]^T\mathbf{E}^{-1}[\mathbf{H}\delta\mathbf{x} - \mathbf{y} + \mathcal{H}\mathbf{x}_b],$$

  H is linear operator $\equiv \partial\mathcal{H}/\partial\mathbf{x}$.

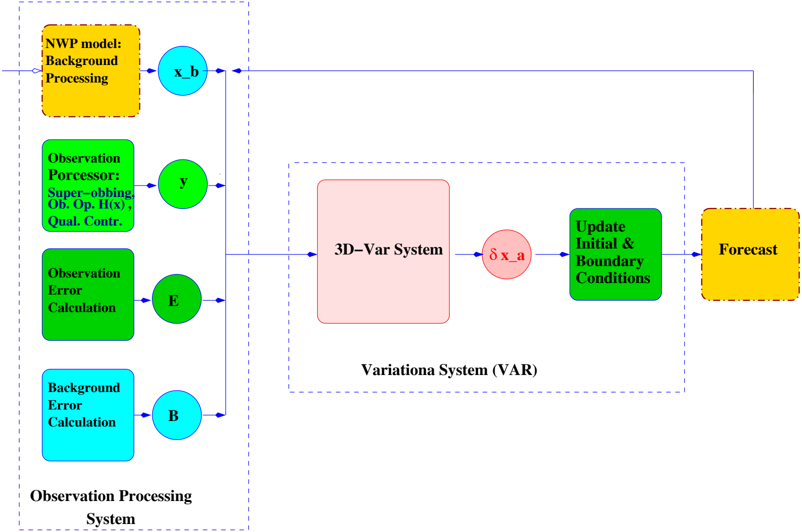
- To avoid inversion of **B**, we use ($\mathcal{X} = \mathbf{U}\delta\mathbf{x}$)

$$\mathcal{J}[\mathcal{X}] = \frac{1}{2}\mathcal{X}^T\mathcal{X} + \frac{1}{2}[\mathbf{H}\mathbf{U}^{-1}\mathcal{X} - \mathbf{y} + \mathcal{H}\mathbf{x}_b]^T\mathbf{E}^{-1}[\mathbf{H}\mathbf{U}^{-1}\mathcal{X} - \mathbf{y} + \mathcal{H}\mathbf{x}_b].$$

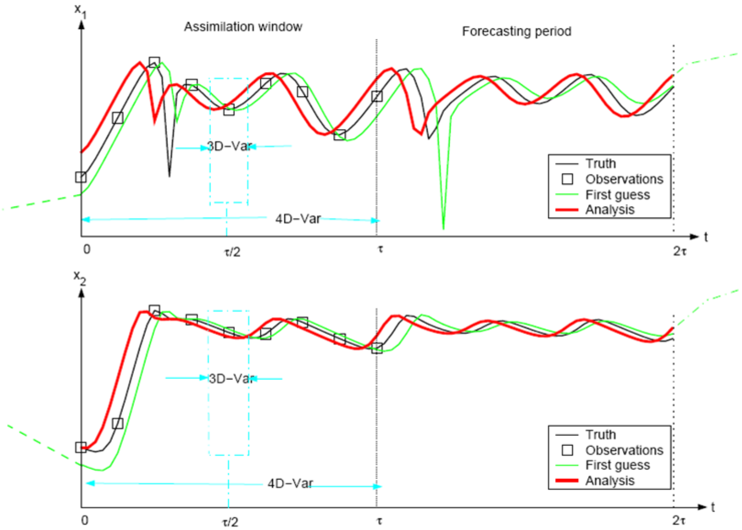
  U transforms the forecast error in the physical model space into a space where the covariance is identity matrix.

- **E** is a diagonal matrix, includes: observation errors + error from super-obbing + errors from the observation operator.

Continued: 3D-Var system

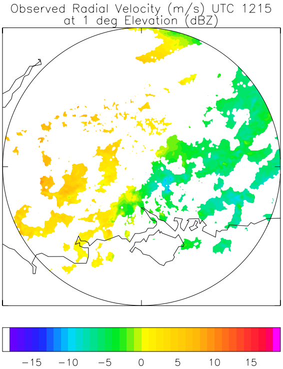


Continued: 3D-Var system



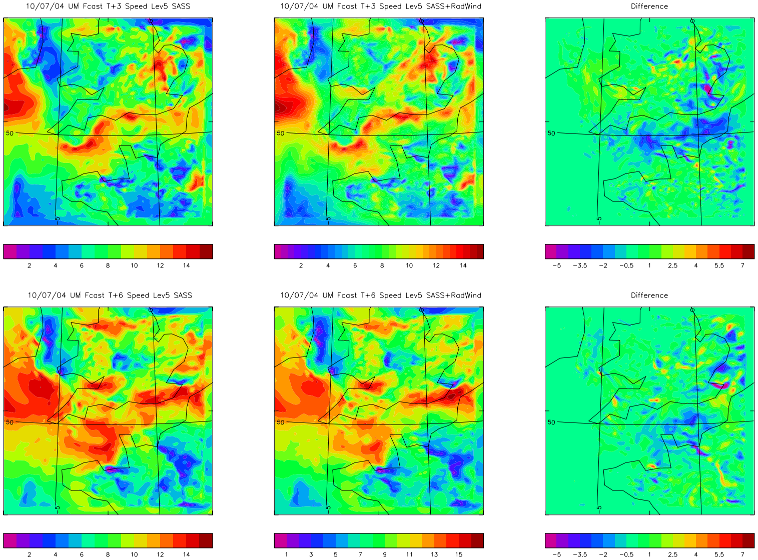
Case Study: Assimilating Doppler Radial Velocity

Observed radial winds for the case study in UK have been assimilated using 3D-Var system in the Met Office. We insert total errors varying with range from 2m/s to 6m/s.



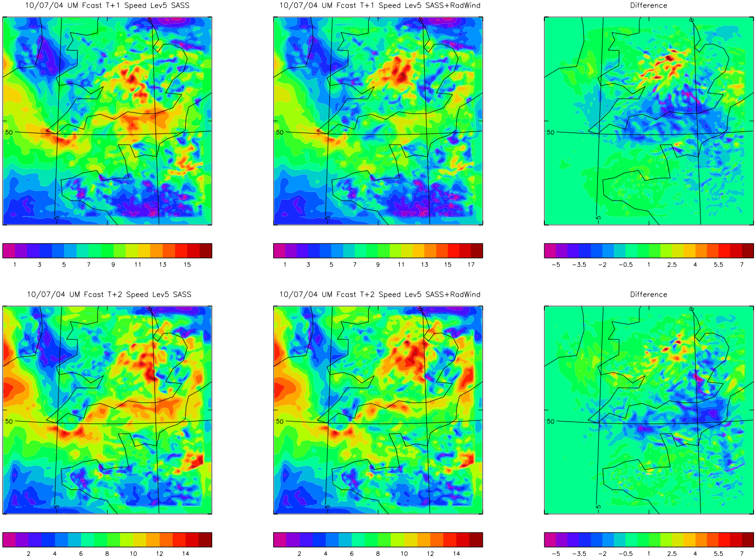
Observed radial velocity compared with assimilated radial velocity, when running 3D-Var system at 4km resolution.

UM Forecasts 10^{th} July 2004 Case



Wind speeds at $T+3$ (top) & $T+6$ (bottom), level 5 from $12UTC$. From left to right: radial wind, and the difference.

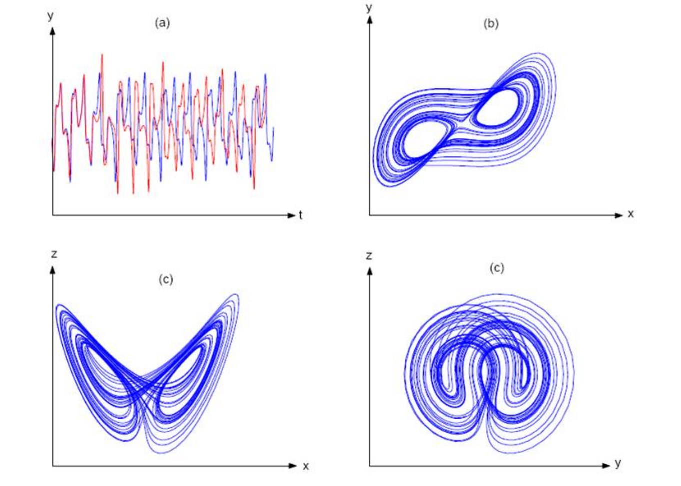
Continued: UM Forecasts



Why Are Weather Forecasts Sometimes Wrong?

There are two main reasons: (i) Sensitivity & (ii) Nonlinearity.

(i) Sensitivity to the ICs



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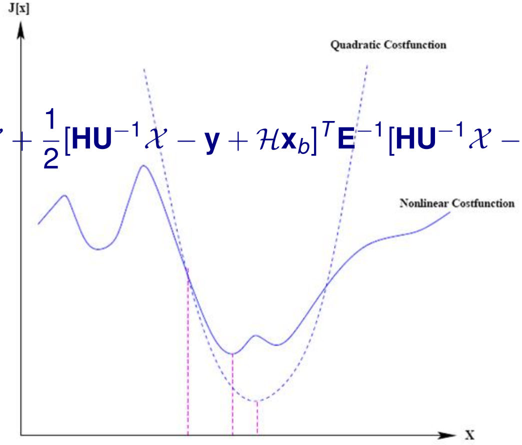
(ii) Biases due to nonlinearity



$$\mathcal{J}[\mathcal{X}] = \frac{1}{2}\mathcal{X}^T\mathcal{X} + \frac{1}{2}[\mathbf{HU}^{-1}\mathcal{X} - \mathbf{y} + \mathcal{H}\mathbf{x}_b]^T\mathbf{E}^{-1}[\mathbf{HU}^{-1}\mathcal{X} - \mathbf{y} + \mathcal{H}\mathbf{x}_b].$$

Fig. 4. Iterative solution for quadratic and nonlinear cost function.

Summary & Future Directions

Steps & Requirements:

- **Observation processing and data collections;**
- **Variation systems and analysis;**
- **Forecast.**

Future Directions:

- **Assimilate radial velocity, using 4D-Var technique to produce ICs for 1-4km resolution forecasts.**
- **Applications to sand and dust storm in Abu Dhabi Area.**

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