Sensitivity of the WRF-4DVar Assimilation System to the Control Variables: A Case Study on Uttarakhand Heavy Rainfall Event

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Abstract
The impact of different formulations of background error covariances (BECs) are examined for the simulation of Uttarakhand heavy rainfall episode with a regional 4-dimensional variational (4DVar) data assimilation (DA) system. Three BEC formulations are analyzed, in which two of them employ stream function and velocity potential (ψ and χ) as momentum variables and the third one uses zonal and meridional velocity components (u and v) as momentum variables. Results from the study show that the $\psi\chi$ based experiments have better skill in reproducing the observed rainfall distribution, particularly when the moisture variable is also analyzed the multivariate balance relations.

Introduction

A major challenge in employing the variational data assimilation system is the formulation of a realistic error statistics of the forward model. This is usually achieved through the modeling of background error covariance (BEC) matrix. Different sets of control variables are being used in the formulation of BEC.[1] The present study focuses on the impact of different control variables used in the BEC formulation on the simulation of Uttarakhand heavy rainfall event that occurred in 2013.

Uttarakhand heavy rainfall event: An overview

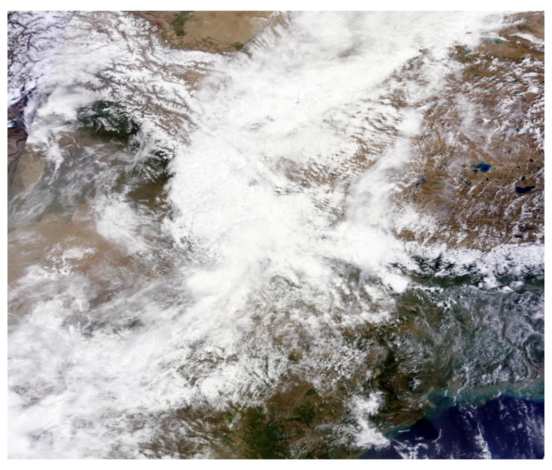

Figure 1: NOAA satellite image of the cloud cover over Uttarakhand, valid at 00Z 17 June 2013

- **Exceptionally heavy rainfall occurred over Uttarakhand during 14-17 June 2013.**
- **More than 350 mm rainfall was recorded for 17 June 2013.**
- **The heavy rainfall events are attributed to the manifestation of dynamical interaction between the tropical, monsoonal circulation and the mid-latitude western disturbances.**

WRF-4DVar DA System

The four dimensional variational (4DVar) scheme within the Weather Research and Forecast (WRF) model has been utilised in this study. The 4DVar method is based on the minimization of the cost-function $J(x)$, which is defined as:

$$J(x(t_0) = \frac{1}{2}[(x(t_0) - x^b(t_0))^T B^{-1}(x(t_0) - x^b(t_0))] + \sum_{i=i}^{N}[(H(x_i) - y_0^i)^T R^{-1}(H(x_i) - y_0^i)] \quad (1)$$

Here, x is the state vector, x^b is background field, B is the background error covariance matrix, H is the observation operator, which maps the model variable to the observation space, y^o is the observation and R is the observation error covariance matrix.

BEC Modeling

- **BEC is considered to be a critical component of variational DA systems.**
- **It can propagate the assimilated information to adjoining areas and to other variables.**
- **Dynamical balances among the variables are represented using regression relations.**

Model configuration

The WRF ARW model version 3.8.1 has been used in this study.

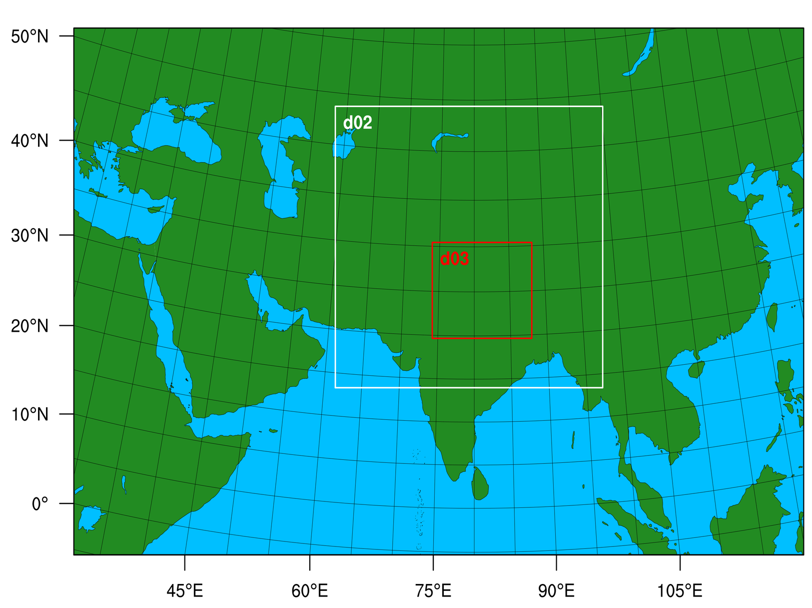

Figure 2: Model domain

- **3 domains with 27, 9, and 3 km horizontal resolution.**
- **36 vertical levels.**
- **Kain-Frisch scheme for convection (except for domain 3).**
- **Eta-Ferrier scheme for microphysics parameterization.**
- **YSU scheme for boundary layer processes.**
- **Noah scheme for land surface processes.**
- **RRTM model and Dudhia scheme for longwave and shortwave parameterization.**

Numerical experiments

- **A spin-up run for 6h**
- **5 cyclic assimilations - 00Z 15 to 00Z 16 June 2013**
- **24h free forecast - 00Z 16 to 00Z 17 June 2013**

Table 1. List of experiments and corresponding control variables.

Experiment	Control variables used
$\psi\chi$-BE	$\psi, \chi_u, T_u, Ps_u, rh$
$\psi\chi$-MBE	$\psi, \chi_u, T_u, Ps_u, rh_u$
UV-BE	u, v, T, Ps, rh

Initial and boundary conditions are derived from NCEP-GFS forecast fields. Surface and upper-air conventional observations and satellite derived winds are utilized for assimilation.

Single observation experiments

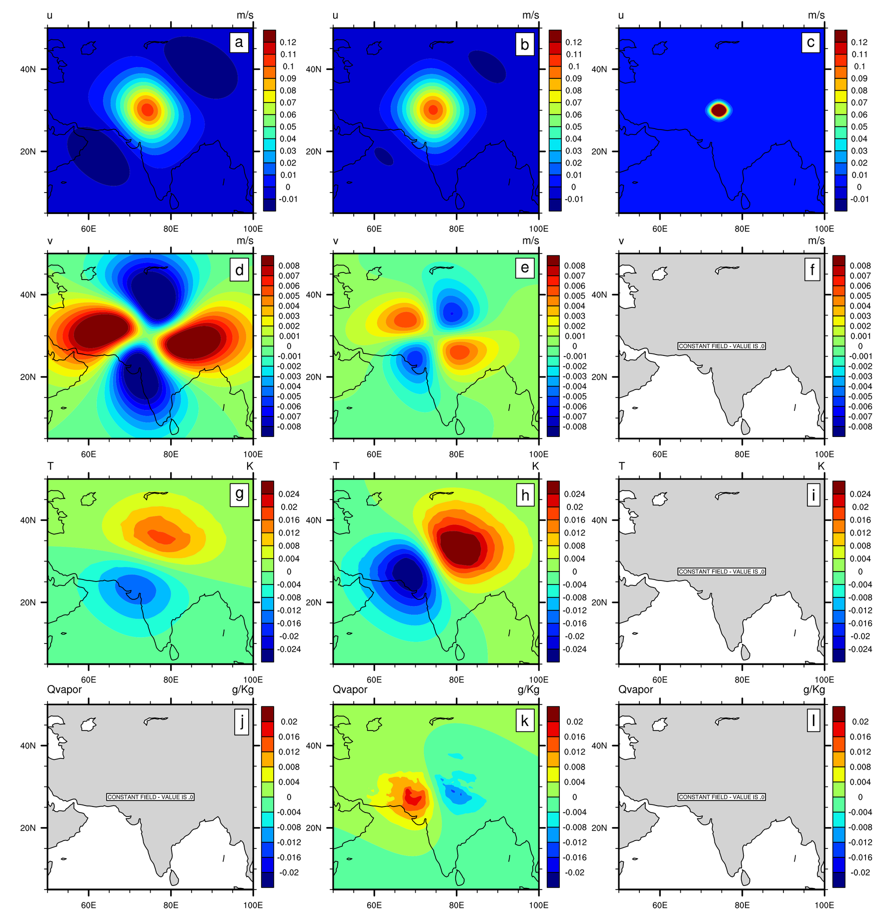

Figure 3: Analysis increment in 'u', 'v', 'T', and 'Q' for assimilation of single 'u' observation when $\psi\chi$-BE, $\psi\chi$-MBE, and uv-BE are employed.

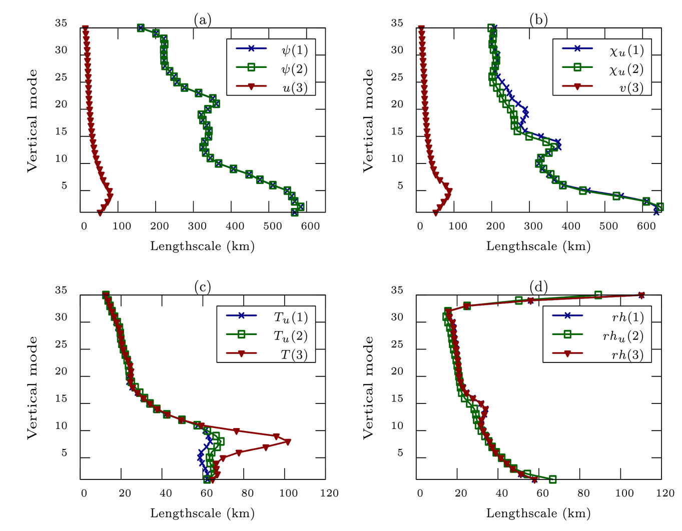

Figure 4: Vertical variation of horizontal length scale for all the control variables. In legend, '1', '2', and '3' indicate $\psi\chi$-BE, $\psi\chi$-MBE, and uv-BE respectively.

Assimilation of single 'u' observation utilizing all the three BECs reveals the univariate nature of the uv-BE (Fig. 3). The multivariate nature of humidity variable in $\psi\chi$-MBE enables that wind information to influence the moisture field also. The additional regression coefficients introduced in $\psi\chi$-MBE also show notable impact on v and T fields.
The most striking feature is the difference in information spread with the uv-BE.

Improvement in the analysis fields

Analysis fields show that the uv-BE fields are more closer to the radiosonde observations (Fig. 5). The distribution of observation minus analysis (O-A) fields (with respect to surface synoptic observations) also shows lower standard deviation for the uv-BE analysis (Fig. 6).

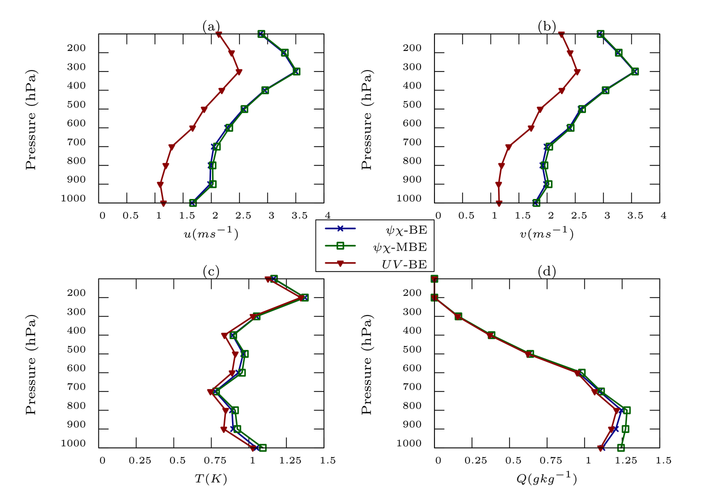

Figure 5: RMS fit to radiosonde observations

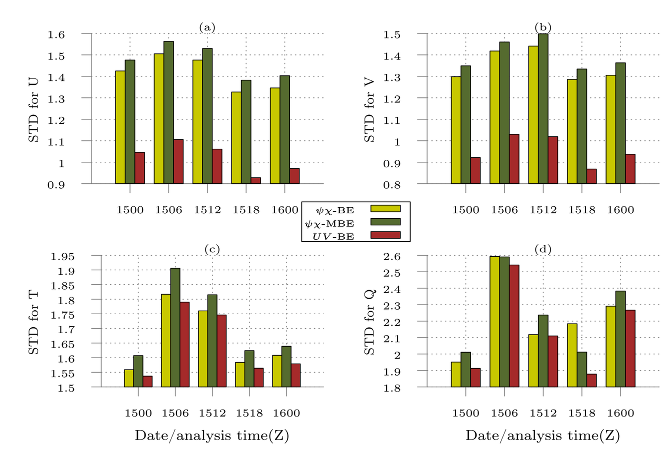

Figure 6: Standard deviation of O-A fields with respect to synoptic obserations

Rainfall forecast verfication

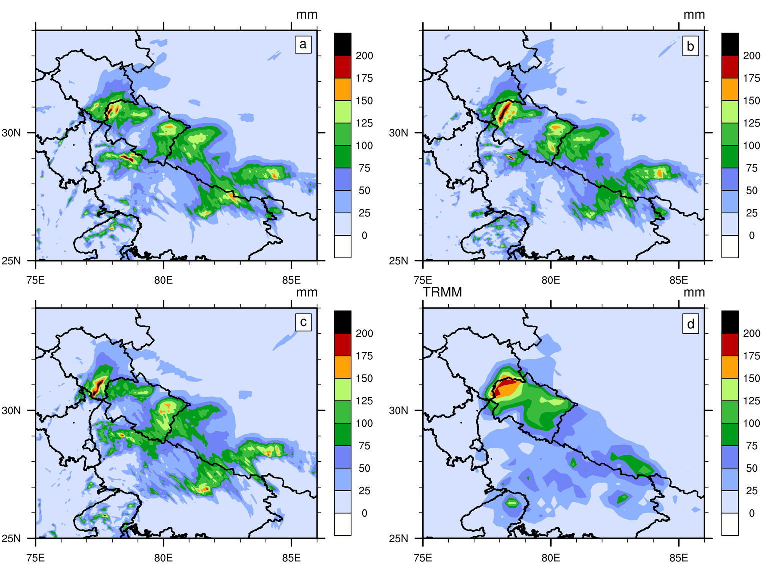

Figure 7: 24h accumulated rainfall for $\psi\chi$-BE, $\psi\chi$-MBE, uv-BE, and TRMM observation

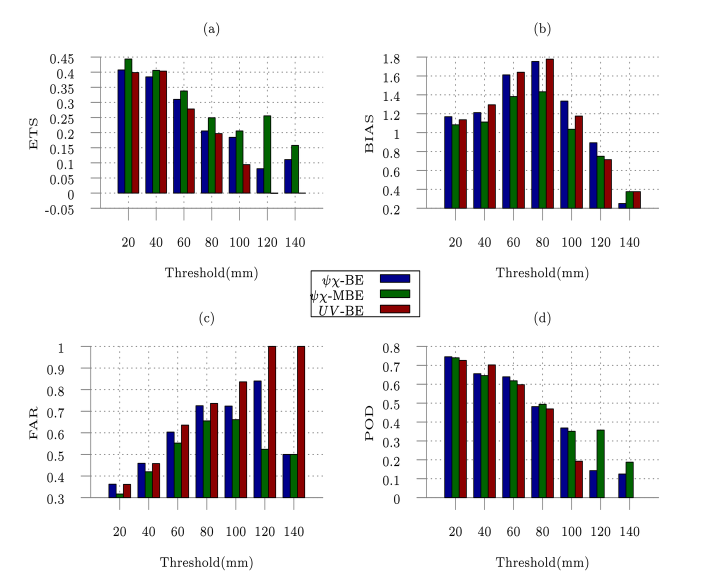

Figure 8: Skill scores for 24h accumulated rainfall for $\psi\chi$-BE, $\psi\chi$-MBE, uv-BE

Even though the analysis fields found to be better for the uv-BE experiment, the same did not yield the best rainfall forecast (Fig. 7). Quantitative skill scores indicate that the $\psi\chi$-MBE forecast have better rainfall forecast skill, especially for the higher rainfall thresholds (Fig. 8).

Conclusions

- **There is a significant difference in the spread of assimilated observations among the uv-based BEC and $\psi\chi$-base BECs**
- **The uv-BE analysis fields show more closeness to the radiosonde observations.**
- **The $\psi\chi$-MBE experiment shows appreciable improvement in rainfall 24h forecast.**

[1] Yuanfu Xie, Chungu Lu, and Gerald L Browning. Impact of formulation of cost function and constraints on three-dimensional variational data assimilation. Monthly weather review, 130(10):24332447, 2002.