Testing of Newtonian Nudging Technique in Data Assimilation on the Meso-Beta-Scale

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Introduction

The Newtonian nudging technique originally developed by Anthes (1974) and Hoke and Anthes (1976) is a practical and flexible method for synoptic scale and meso-α-scale data assimilation (Kuo and Guo 1989; Stauffer and Seaman 1990). The application of the nudging technique for meso-ß-scale data assimilation has been rare (Stauffer and Seaman 1994). As part of the development of an Integrated Data Assimilation and Sounding System in support of the ARM measurement program, we have been experimenting with the Newtonian nudging technique for meso-ß-scale data assimilation. The formulation of the nudging technique used here for a variable α is as follows:

$$\frac{\partial \alpha}{\partial t} = F + G \bullet \frac{\sum_{n=1}^{N} w_n^2 \cdot \Delta\alpha}{\sum_{n=1}^{N} w_n}$$

where *F* represents all the normal model forcing terms.

$\Delta\alpha = (\alpha_{obs}^n - \alpha)$, and α_{obs}^n is the *n*th observation of variable α. *G* is the nudging coefficient, *N* is the total number of the observations, and $W_n = W_t^n \bullet W_{xy}^n$, where *T* is the half period of a predetermined time window over which an observation will influence the model simulation,

$$W_t^n = \begin{cases} 1.0 & \left|t_{obs}^n - t\right| \le \frac{T}{2} \\ \frac{2\left(T - \left|t_{obs}^n - t\right|\right)}{T} & \frac{T}{2} < \left|t_{obs}^n - t\right| < T \\ 0.0 & \left|t_{obs}^n - t\right| \ge T \end{cases}$$

t is the model time and t_{obs}^n is the time when the *n*th observation is taken.

$$W_{xy}^n = \begin{cases} \frac{R^2 - \left(r_{xy}^n\right)^2}{R^2 + \left(r_{xy}^n\right)^2} & r_{xy}^n < R \\ 0.0 & r_{xy}^n \ge R \end{cases}$$

where *R* is the radius of influence, and r_{xy}^n is the distance between the grid point and observation *n*. The use of the Newtonian nudging technique requires the specification of several parameters, such as the nudging coefficient (*G*), the radius of influence of the observation (*R*), and the time window (*T*), etc. The specification of these parameters is somewhat arbitrary, and there is no general theory to guide the selection of these parameters.

During the 1991 Winter Icing and Storms Program/ Atmospheric Radiation Measurement (WISP/ARM-91) field exercise over the front range of Colorado, a set of measurements was taken on a meso-ß-scale network (Figure 1). The fifth-generation Penn State/NCAR mesoscale model (MM5) with data assimilation capability can be integrated with a horizontal grid size of few kilometers. In this study, we used this dataset and the MM5 to test the nudging coefficient and radius of influence in Newtonian nudging technique on the meso-ß-scale.

The WISP/ARM-91 Intensive Operating Period 4

Many types of measurements were available during the WISP/ARM-91 intensive operating period (IOP) 4, including

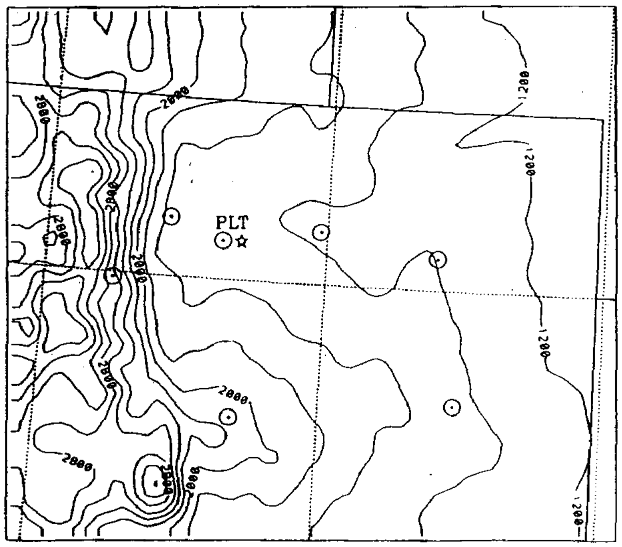

Figure 1. The 7 CLASS stations (⦿) and wind profiler (*) at Platteville during WISP/ARM-91 IOP 4. The contours with interval of 200 m are the terrain height field used in the mesoscale model.

from the cross-chain loran atmospheric sounding system (CLASS), portable automated mesonet (PAM), wind profiler, radio-acoustic sounding system (RASS), ground-based microwave radiometer, and Doppler SODAR, etc.

In this study, the 3 hourly observations from the network of 7 CLASS stations (Figure 1) from 0000 to 1200 UTC 6 March 1991 were assimilated into the MM5. These observations and the hourly data from a wind profiler at Platteville were used as the verification of the data assimilation. The average station separation of the CLASS stations is 90 km.

We would like to emphasize that the observations from the wind profiler is a 2-dimensional (z,t) dataset; however, the CLASS measurements give a 4-dimensional (x,y,z,t) dataset since the balloon is drifted from the release point while it is ascending. In the assimilation process and in calculating the *rms* errors with CLASS data, we have taken the balloon drift, which was derived from the wind and the elapse time, into account.

Experiment Design

The model domain covers northeastern Colorado and has a horizontal mesh of 65 x 73 with a grid distance of 5 km. There are 23 layers in the vertical. The explicit moisture scheme with ice is used as the precipitation physics; the planetary boundary layer (PBL) formulation, originally developed by Blackadar (1979), includes surface fluxes of sensible heat, latent heat, and momentum. The initial condition at 0000 UTC 6 March 1991 and the hourly lateral boundary conditions are provided by a 20-km hydrostatic model (MM4).

The nudging formulation has three arbitrary parameters: *G*, *T*, and *R*. The time window *T* usually depends on the temporal resolution of the observations. The resolution of the CLASS sounding data to be assimilated here is 3 hours. We set the *T* = 2 hours. The nudging coefficient *G* and the radius of influence *R* therefore are tested in the following three categories of 13 experiments.

- Control experiment: standard 12-h forecast, without data assimilation starting from 0000 UTC 6 March (Exp. MM)
- Nudging coefficients (*G*) experiments: assimilation of wind, temperature and specific humidity from all 7 CLASS stations during, the 12 h-period, from 0000 UTC to 1200 UTC 6 March, with *R* = 100 km and the nudging coefficients of 3×10^{-4} (Exp. NC1), 6×10^{-4} (Exp. NC2), 1×10^{-3} (Exp. NC3), 1.5×10^{-3} (Exp. NC4), 2×10^{-3} (Exp. NC5), and $3 \times 10^{-3}\ s^{-1}$ (Exp. NC6)
- Radius of influence (*R*) experiments: same as the nudging coefficient experiments, but with the nudging coefficient $G = 1 \times 10^{-3}\ s^{-1}$, and the radius of influence of 10 (Exp. NR1), 25 (Exp. NR2), 50 (Exp. NR3), 100 (Exp. NR4), 200 (Exp. NR5), and 300 km (Exp. NR6).

Results

We used the noise parameter, *NL*, the first order derivative of pressure at the lowest model level (σ_K = 0.995), to measure the degree of balance of the model solution.

$$NL \quad (\ddagger) \left(\frac{1}{S} \sum_{S} \left| \frac{\partial p}{\partial t} \right| \right)_{0.995}$$

We also calculated the time average ($\overline{NL}$) of *NL*, and its standard deviation *SD* between the integration time of 3 h to 12 h for all the experiments.

$$SD = \left\{ \int_{3h}^{12h} \left(NL(t) - \overline{NL} \right)^2 dt \right\}^{1/2}$$

$$\overline{NL} = \int_{3h}^{12h} NL(t)\, dt$$

The vertically integrated *rms* error, ER_α for the variable is used to measure the accuracy of the data assimilation.

$$ER_\alpha = \frac{1}{M} \sum_{t=1}^{M} \sum_{k=1}^{K} \sqrt{\frac{1}{S} \sum_{S} (\Delta\alpha)^2 \Delta\sigma_k}$$

where $\Delta\alpha = (\alpha - \alpha_{obs})$, and α_{obs} is the observed value of α. *S* is the number of grid points of the model domain, but in the calculation of ER_α, $S = 7$ for the 7 CLASS stations, and $S = 1$ for the Platteville wind profile and CLASS. *M* is the total number of time periods used in calculating ER_α, $M = 5$ for the CLASS data, and $M = 13$ for the wind profiler data. $K = 23$, the total number of σ layers.

Nudging Coefficient

From Figure 2, the values of *NL* during the first hour of all the experiments are very high, which implies significant imbalance and inconsistency in the initial condition. After-hour 3, however, the *NL* stays low with small oscillations for Exps. *MM* and *NC3*; for Exp. NC6, *NL* still has a high value with large oscillations. Figure 3 gives the mean value of *NL* and its standard deviation, $\overline{NL}$ and *SD*, as a function of nudging coefficient *G*. Both $\overline{NL}$ and *SD* increase very slowly for $G \leq 1 \times 10^{-3}\ s^{-1}$ and increase very quickly for $G \geq 1.5 \times 10^{-3}\ s^{-1}$.

Figure 4 shows the wind *rms* errors for different types of verifications. The errors against the CLASS data, which were assimilated into the model, are expected to decrease as the *G* increases; however, the decrease of errors is much faster for $G \leq 1 \times 10^{-3}\ s^{-1}$. The independent verification

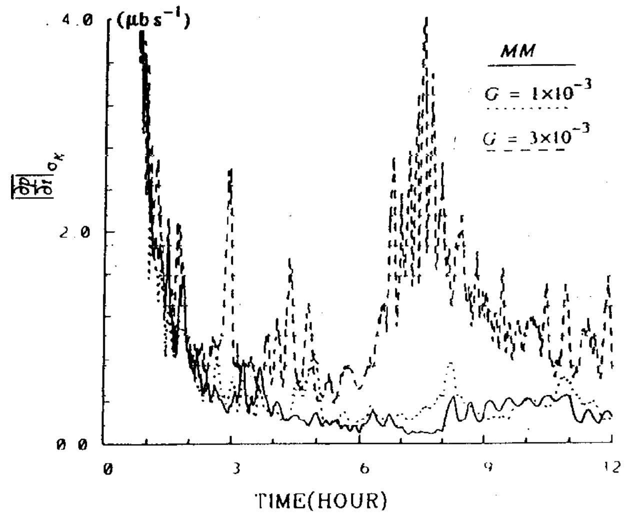

Figure 2. Noise level *NL*(*t*) for Exps. MM, NC3, and NC6.

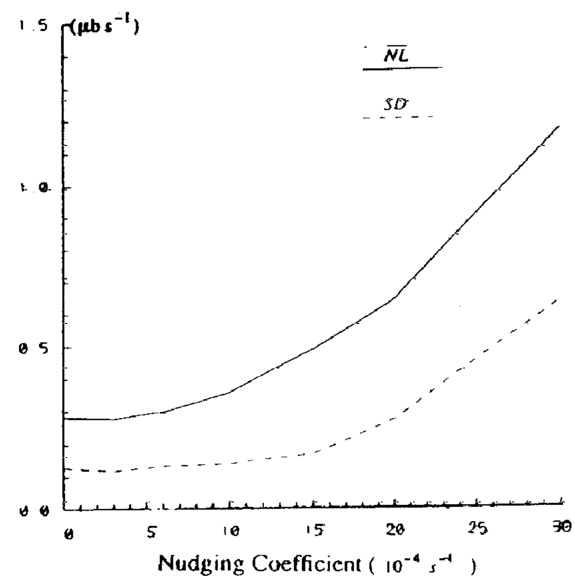

Figure 3. The mean noise level $\overline{NL}$ (solid line) and its standard deviation *SD* (dashed line) as a function of nudging coefficient *G*.

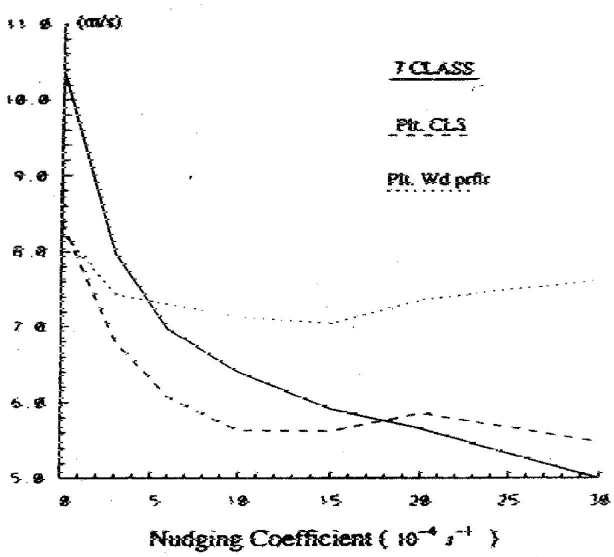

Figure 4. The wind *rms* error as a function of nudging coefficient *G*. The errors are computed based on the wind observations from 7 CLASS stations (solid line), CLASS at Platteville only (long dashed line), and wind profiler at Platteville (short dashed line).

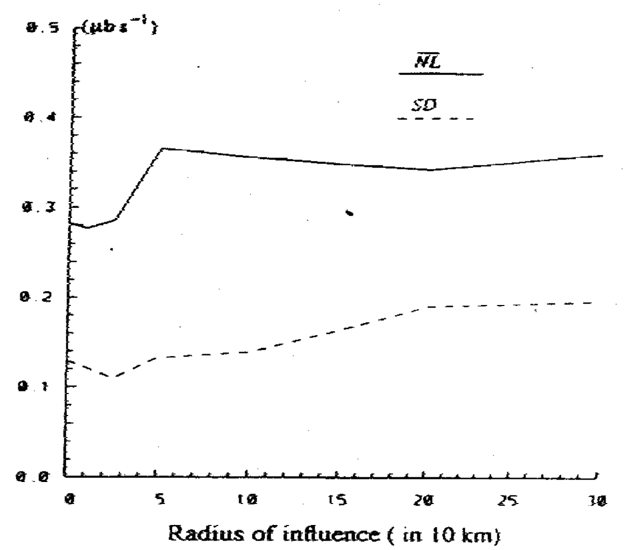

Figure 5. The mean noise level $\overline{NL}$ (solid line) and its standard deviation *SD* (dashed line) as a function of radius of influence *R*.

with the wind profiler data at Platteville (short dashed line in Figure 4) indicates that $G = 1.5 \times 10^{-3}\ s^{-1}$ gives the smallest error of wind. To keep the model solution as balanced and as accurate as possible, the value between 1×10^{-3} and 1.5×10^{-3} is the best choice of nudging coefficient *G*.

Radius of Influence

Figure 5 shows the mean noise level $\overline{NL}$ and its standard deviation *SD* as a function of radius of influence *R*. The increase of *R* did not cause a significant change in $\overline{NL}$ and *SD*, compared with the variations in *G*. The wind *rms* errors as a function of radius of influence *R* are given in Figure 6. All three curves show that the errors decrease rapidly with an increase in *R* for $R \leq 50$ km. In the current version of MM5, when $R = 50$ km, the radius of influence is 50 km at surface, increasing linearly to 100 km up to 500 mb. Above 500 mb, the radius of influence stays constant at 100 km.

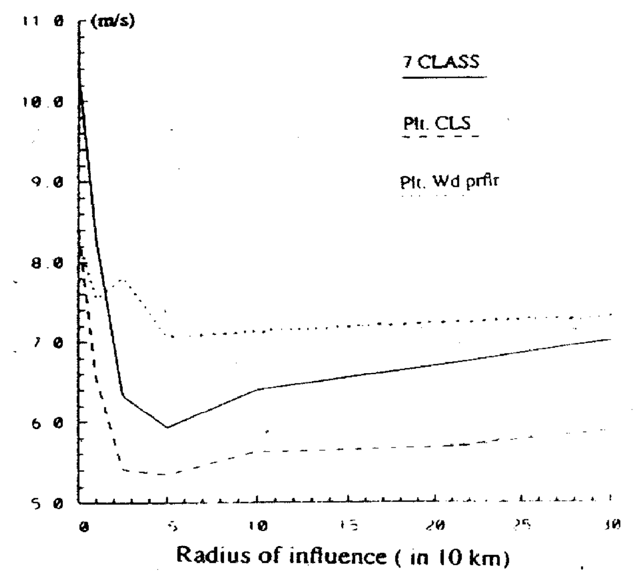

Figure 6. Same as Figure 4, but the wind *rms* errors as a function of radius of influence *R*.

In this study, the station separation is approximately 90 km. For a good part of the troposphere, the *R* is close to the station separation. Based on the experiments presented here, the noise level seems to be relatively independent of *R*. Choosing *R* to be comparable to the station separation appears to give the better results.

Conclusions

With the meso-ß-scale dataset (station separation is 90 km) available in WISP/ARM-91, the optimal nudging coefficient *G* is around 1 X 10^{-3} s^{-1} for a high-resolution (5 km) mesoscale model.

A good choice of radius of influence *R* is a value close to the station separation. In this study, *R* = 50 km gives smaller errors, and neither the noise parameter nor the wind *rms* errors are sensitive to the radius of influence for $R \geq 50$ km.

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