Initialization of 3DVAR using Incremental Analysis Updates (IAU)

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1. Introduction

Without a proper control of spurious gravity waves, an intermittent cycling data assimilation system can generate noise and imbalance, resulting in poor performance. Even though variational system has practical advantages such as the ability to assimilate observations directly, imposing balance constraints through preconditioning, and finding optimal solution via minimization of cost function, there are still issues associated with spin-up and initialization. These issues become more severe with rapid update cycle to incorporate more frequent observations. Because the analysis increments as a result of variational assimilation are poorly balanced even with the imposition of balance constraint, a procedure should be introduced to remove spurious high-frequency gravity-wave noises. These noises can have detrimental effect on the first few hours of the forecast, and on the results of the data assimilation cycle as a whole.

A number of approaches have been developed to address the initialization problem, including static initialization (Phillips, 1960), dynamic initialization (Miyakoda and Moyer, 1968), nonlinear normal-mode initialization (Daley, 1979), bounded derivative initialization (Semazzi and Navon, 1986), damped time-differencing scheme (Baker *et al.*, 1987), diabatic initialization (Puri, 1985), linear balance constraints (Parrish and Derber, 1992), nudging technique (Grell *et al.*, 1995), digital filter technique (Lynch and Huang, 1992, Benjamin, 2003), and incremental analysis updates (IAU, Bloom *et. al.*, 1996).

Main purpose of this paper is to investigate the impacts of IAU process on reducing gravity waves through coupling with high-resolution 3DVAR (3D VARiational assimilation). We will also study the improvement on precipitation forecast skill due to moisture spin-up as a side benefit of IAU process.

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2. Model and 3DVAR

This study uses MM5 version V3.6 with Reisner 2 microphysics, Kain-Fritsh convection scheme, and nonlocal boundary-layer parameterization (Hong and Pan, 1996). The model grid resolution is 10km with a mesh of 178 X 160 in the horizontal and 33 levels in the vertical.

Main characteristics of the MM5 3DVAR are described in Barker *et al* . (2003 and 2004). In the application of IAU, we treat analysis increments from 3DVAR as an additional forcing of the model. Total increments are evenly distributed during assimilation window centered at analysis time for MM5 forecast variables (u, v, T, q, w, and p').

In this experiments, we use 3hr assimilation window (-1:30 to +1:30 centered at analysis time) for a 3hr cycling 3DVAR system. Boundary conditions of 10km model come from operational model (30km) at Korea Meteorological Administration (KMA).

3. Initializations by nudging and IAU

We compare the initialization performance of IAU with those of nudging technique known as FDDA (Four Dimensional Data Assimilation) in the MM5 community. Nudging technique has been used for KMA operation model (30km) since 1999.

Figure 1 shows the power spectral density of temperature per wave period (Press ., 1992) at a land point with vertical layers. Model initial time was set at 00 UTC 9 Dec 2003, and 12hr relaxations (from 12UTC 8 to 00UTC 9, ie, night time) are applied for both nudging and IAU techniques before analysis time for a clean comparison. In this case, we use 30km analyses and increments from KMA 3DOI (3D optimal interpolation method) for analysis nudging and IAU application. Initial condition at 12 UTC 8, boundary condition, and model configurations are identical as for both experiments. To investigate the filtering properties during and after assimilation window, we divide the temperature time series before and after analysis time (00UTC 9). Time series during 2nd 12 hours (i.e. day time, after completing the 12-h initialization period) indicates the strong semi-diurnal spectra near the surface as a result of the short wave radiation during the day time for both nudging and IAU (not shown here). However, temperature time series at night time (i.e., the time when nudging or IAU is applied) are totally different. Nudging filtered out significant amount of low frequency oscillations such as semi-diurnal waves (spectra at 720 minutes) as well as high frequency waves (Fig. 1a). However, temperature time series of IAU retain the energy of semi-diurnal waves near the surface, as well as long wave spectra at upper troposphere and lower stratosphere at night time (Fig. 1b). According to Bloom *et al* (1996), filtering of low frequency waves by nudging can be severe with longer nudging period such as 12hr.

To gradually relax the model state toward the analysis, analysis nudging uses the forcing term of differences between model state and the analysis. Thus, this nudging forcing is applied to every model grid point independent of the presence observations. This causes nudging to remove low frequency wave generated by the model with forcing term including the model state. On the other hand, IAU forcing term is expressed as difference between analysis and background (namely increments). Thus, if analysis increment is zero at a specific location without observations, IAU forcing will be zero. IAU is applied to only increments not the total field like nudging.

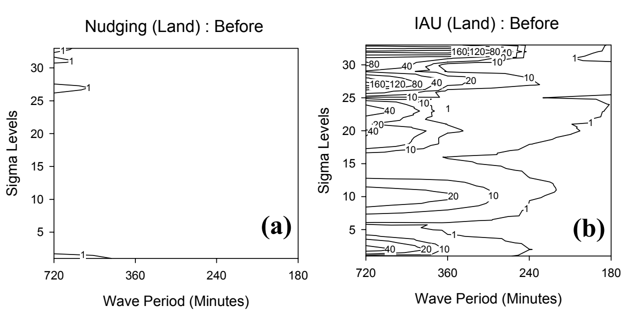

Fig. 1 Power spectra density (Press *et al*., 1992) for T selected at a land point which is displayed in wave period and vertical sigma levels. (a) and (b) show power spectra density during 12 hours assimilation period, respectively.

Figure 2 shows the initialization performance in terms of absolute tendency of surface pressure from 10km 3DVAR cycling system. In these experiments, 3hr window is used for both nudging and IAU. However, window starts 3hr prior to analysis time for nudging and 1.5 hr for IAU because center of assimilation window should be at the analysis time to prevent drifting in cycling system with IAU. First finding is that the surface pressure tendency by nudging and IAU comes nearly at the same level after 4 hours from the analysis time (12 UTC). Bloom *et al* (1996) also pointed out that assimilation window less than 3hr gives similar filtering properties for nudging and IAU. The other feature is a jump of pressure tendency in nudging at 12 UTC. We suspect that this small jump results from the uninitialized LBCs from 3DVAR analysis and sudden switch off of nudging term at 12 UTC. An important consideration is the computational cost in operational implementation of IAU. Because the half window of IAU covers 1.5 hours forecast before the initial time, IAU is less expensive than nudging.

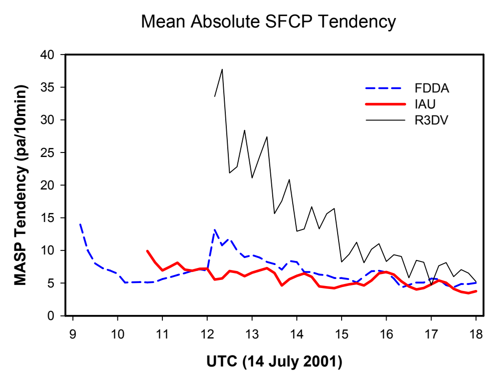

Fig. 2 Absolute tendency of surface pressure averaged over the model by 3DVAR system without IAU as a control (R3DV in thin line) and with IAU (thick line), and by 3hr nudging (dashed line).

Interesting question is why 3DVAR analysis produces large amplitude gravity waves in Fig. 2. Even though balanced constraints in 3DVAR was imposed, most of gravity wave in the atmosphere is caused mainly by sounding data in this study (not shown here). There are several possible imbalance sources between wind and mass fields (pressure and temperature) in the current 3DVAR system. Control variables in 3DVAR are stream function, velocity potential, unbalanced pressure, and specific humidity, not temperature which is the analysis increment. First possible source is the process for calculation of balanced pressure by balance equation. This finally leads to the unbalanced pressure as the control variable. After getting unbalanced pressure by minimizations, hydrostatic density is derived from total pressure (unbalanced + balanced pressure). Finally, hydrostatic temperature as the analysis increment is calculated using hydrostatic density and hydrostatic equation. Thus, imbalance between winds and mass field using hydrostatic and balance equation in 3DVAR system may be generated in 3DVAR system, especially largely at time with more sounding data.

4. IAU application on rapid update cycles

Rapid update cycle (RUC) procedure falls within a class of schemes that include all sequential data assimilation methods. It can be interpreted in the general framework of Kalman Filtering (Daley, 1991). In order to meet the requirement of frequent analysis and forecast, most of operational center has an interest in rapid update cycle. Because current KMA 3DVAR operational system uses 3hr update cycle, we perform experiments with 1 and 2hr update cycle using IAU. The impacts of IAU on the precipitation forecast are attributed to the improvement in the spin-up of water cycle due to the fast production of cloud water during the initial forecast time.

Figure 3 shows the cloud and rain water integrated over the 3D model domain generated from 2hr RUC with (IAU2) and without IAU (RUC2). The results indicate that RUC2 has repeated moisture adjustments through spin-up and spin-down processes during the assimilation period until 12 UTC. On the other hand, IAU2 has a smooth increase of cloud water. Based on these results, 1hr and 2hr cycling with IAU give better precipitation forecast skill than cycling without IAU (not shown here). One interesting result of standard 3DVAR (RUC2) is the repeated spin-up and spin-down of moisture variables like cloud and rain. This happens at every cycling system regardless of chosen period of update cycle: 1, 2, or 3hr. Current 3DVAR system uses specific humidity as the control variable which belongs to the univariate analysis and is independent of temperature increment. Thus this may cause the imbalance between moisture and dynamic variables like temperature. IAU gradually incorporating analysis increments helps reduce this imbalance. Furthermore, IAU with half window before analysis time also contributes to solve the spin-up and spin-down in frequent cycling system.

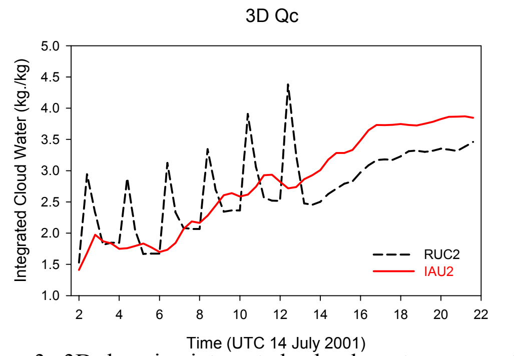

Fig. 3 3D-domain integrated cloud water amount (kg/kg) by 2hr update cycle without IAU (RUC2) and with IAU (IAU2). 2hr updates cycle was performed by 12 UTC.

5. Skill of precipitation forecasts

We apply IAU and 3DVAR system to a heavy rainfall case in Seoul (Capital in South Korea) that occurred on 14 July 2001. Observed rainfall amount was 370.40 mm from 12 UTC 14 to 00 UTC 15 July. One day forecast from 12 UTC 14 July is generated after 3hr cycling system during a 12hr pre-forecast period. Major differences of forecast from standard 3DVAR and IAU are in the orientation of the rain-band near Seoul, precipitation in north-eastern part of the Korean peninsula and the maximum rainfall amounts (not shown here). Figure 4 shows the threat score (otherwise Critical Successive Index; CSI) with different threshold values (0.1, 1, 5, 10, 30, and 60 mm) for 6-h precipitation ending at 21 UTC. from the results show that IAU gives better precipitation skill scores, particularly on heavier precipitation amounts.

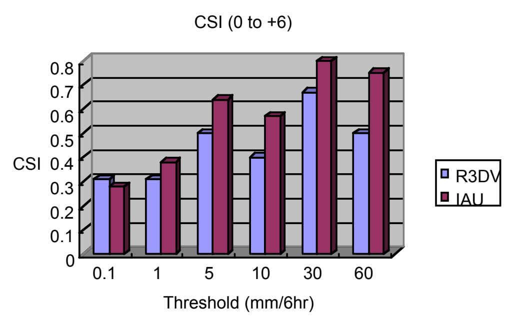

Fig. 4 Critical Success Index (CSI) for first 6hr accumulated rain in different threshold rainfall amount.

6. Conclusions

Incremental Analysis Updates (IAU) technique is implemented for 3hr update cycles with MM5 3DVAR system at 10km resolution to remove spurious gravity waves. IAU with 3hr updates to 3DVAR system represents a significant improvement over the 3DVAR system without any initialization scheme in terms of the removal of gravity waves and moisture spin-up. IAU filtering properties, which focus on analysis increments, are more desirable than those of nudging method, especially for longer assimilation window (Bloom *et al.* 1996).

IAU scheme avoids the physically unsound backward time integration which is needed for digital filter initialization (Adam, 2003). The outstanding characteristics of IAU are low computational cost, no need for backward integration regardless of the use of adiabatic and diabatic model, and easy implementation without the use of an optimal digital filter. The IAU reduces initial noise level and improves moisture spin-up. The humidity fields are initialized consistent with the other prognostic variables. The advantage of IAU is most significant in improving precipitation spin-up. As a result, a clear improvement of precipitation forecast is obtained with the IAU approach.

The possibility of application of IAU to RUC (Rapid Update Cycle) is supported by results of 1 and 2 hr update cycles, which show fast minimization and less fictitious spin-up and spin-down of moisture.

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