Implementation of the Incremental Analysis Update Initialization Scheme in the Tropical Regional Atmospheric Modeling System under the Replay Configuration

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ABSTRACT

In traditional simulations of heavy rainfall events, the regional model is often initialized by using a global reanalysis dataset and a cold start method. An alternative to using global analysis data is to gradually introduce the analysis field via an incremental analysis update (IAU) method under the replay configuration. We found substantial differences in the forecast of a heavy rainfall event in southern China between a precipitation forecast using the traditional method and a forecast using the IAU method in the Tropical Regional Atmospheric Modeling System (TRAMS), based on the ECMWF global analysis. The IAU method is efficient in removing spurious high-frequency gravity wave noise, especially when the relaxation time is more than 90 min. The regional model needs to be pre-integrated for about 12 h to warm up the convective system in the background field. The improvement by the IAU method is supported by verification of simulations over 1 month (1–30 April 2019). In general, the IAU technique improves the initialization and spin-up process in the simulation of the heavy rainfall event.

Key words: incremental analysis update, initialization, replay

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1. Introduction

The incremental analysis update (IAU) technique is an effective method for keeping the mass and momentum fields in dynamic balance during model initialization through removing spurious gravity waves (Bloom et al., 1996). By gradually incorporating analysis increments during a short forecast centered on the analysis time, the IAU technique has the properties of a low-pass time filter, which is equivalent to digital filtering initialization (Lynch and Huang, 1992; Liu and Xue, 2019) in a linear context (Clayton, 2003; Polavarapu et al., 2004). It has been successfully adopted in several centers and in multiple applications (e.g., Schubert et al., 1993; Lorenc et al., 2000; Lee et al., 2006; Ourmières et al., 2006; Balmaseda et al., 2008; Carton and Giese, 2008; Zhang et al., 2015; Ham et al., 2016). The IAU technique was extended to four dimensions by Lorenc et al. (2015) and used by Buehner et al. (2015) and Lei and Whitaker (2016).

The horizontal resolution of many operational global numerical weather prediction centers has been increased to < 30 km in recent years—for example, the resolution of the ECMWF Integrated Forecasting System is about 9 km. Global models can assimilate many more satellite observations than regional models and are not affected by biases in lateral boundaries. This means that it is feasible to drive a regional model directly with global analysis fields in operational forecasts—for example, the Tropical Regional Atmospheric Modeling System (TRAMS) of Guangdong Meteorological Administration has been directly initialized by the analysis field of ECMWF Integrated Forecasting System in operational forecasting. The analysis field used to calculate the analysis incre-
ment in the traditional IAU method is replaced with the pre-existing global analysis dataset. This method of running the IAU with pre-existing analysis was first referred to as “replay” by NASA’s Global Modeling and Assimilation Office (Rienecker et al., 2008).

The replay method can be considered as a variation of the IAU technique. The advantage of the replay method is that it does not need to run expensive analysis software, only the model. The replay framework using a pre-existing analysis to calculate the IAU increments produces an assimilation that is a blend of the analysis and background from the particular version of the model used in the simulation. The word “replay” means that the IAU technique is implemented “after the fact” by using the pre-existing global analysis dataset to correct the bias in the regional background field. Lim et al. (2016) used the replay capability of the IAU technique with the Modern-Era Retrospective Analysis for Research and Applications (MERRA) reanalysis dataset (Rienecker et al., 2011) to include large-scale controls on simulations of tropical cyclone activity in the Atlantic Ocean. Orbe et al. (2017) used the GEOS (Goddard Earth Observing System)-replay approach to simulate large-scale atmospheric transport in a study of atmospheric composition.

In the replay mode, the forecasts are run from a poorly balanced analysis as a result of the clear inconsistency between the model used for the simulation and the pre-existing analysis field generated by a different model. This leads to two issues associated with spin-up and initialization, which are more severe in short-term forecasts. Takacs et al. (2018) identified a stability problem in the application of the IAU technique under a replay strategy. The replay technique has been applied to studies of model errors (e.g., Bengtsson et al., 2019; Chang et al., 2019; Schubert et al., 2019) and a typhoon initialization scheme (Xu et al., 2019).

We assessed the performance of the IAU method under the replay configuration in the short-term simulation of a heavy rainfall event in southern China with a focus on initialization and spin-up problems. The numerical simulations were implemented by using the TRAMS and the ECMWF global analysis field. Section 2 describes the TRAMS and Section 3 introduces the initialization scheme in the replay experiments. Section 4 discusses the effects of the IAU technique on precipitation process simulation in the replay experiment, and our conclusions are presented in Section 5.

3. Overview of IAU and replay

The imbalance between global analysis and regional models requires some type of initialization to be implemented to minimize the effects of spurious waves (e.g., Kalnay, 2002, their Section 5.7). The IAU of Bloom et al. (1996) is an alternative to nudging and is better than nudging itself (Lee et al., 2006).

Figure 1 is a schematic illustration of the implementation of the IAU technique under a replay configuration. For an analysis time $t_0$, the IAU time window begins at $t_0 - \frac{\tau}{2}$ ($\tau$ is the relaxation time). A free-running regional model is integrated for $\Delta t$ (from $t_0 - \Delta t$ to $t_0$; blue arrow in Fig. 1), generating “background” fields at $t_0$ ($F_{\text{back}}$). The analysis increment ($F_{\text{back}} - F_{\text{ana}}$) is then calculated according to the difference between a given analysis ($F_{\text{ana}}$) and the background ($F_{\text{back}}$) valid at time $t_0$. The model is then rewound to $t_0 - \Delta t$ and run a second time for another $\Delta t$ (black arrow in Fig. 1), starting from the same initial and boundary conditions used for the first time, but now forced with a constant tendency term $\frac{F_{\text{back}} - F_{\text{ana}}}{\tau}$. Note that the effects of the global analysis dataset appear as an extra diabatic forcing during a continuous integration of the regional model and the replay integration is thus a blend of the given analysis and model.
results. This form of replay can be conveniently applied to cases in which the model is different from the original model used in the assimilation cycle. In the replay test used here, the analysis increments are added onto the corresponding wind fields, temperature, specific humidity, and pressure perturbation.

To avoid the instability problem discussed by Takacs et al. (2018), the background field $F_{\text{back}}$ is produced by integrating the regional model with global analysis as initial and boundary conditions at time $t_0$, so the amplification factor of high frequencies will not be accumulated in the replay cycle through the background field.

4. Numerical experiment

4.1 Description of case study

We applied the IAU technique under the replay configuration to simulate a heavy rainfall event that occurred during 13–14 April 2019 in southwestern Guangdong Province of South China. The operational forecast with the TRAMS at GITMM failed to predict this event. We therefore focused on improving the forecast by the application of the IAU technique.

Figure 2 shows the synoptic environments of this case. Strong southerly air flows converged over South China at 850 hPa and the upper level trough (located within 24°–28°N, 100°–104°E) intensified at 500 hPa during 12–13 April 2019, which favored the occurrence of heavy rainfall in the warm sector (Chen et al., 2018; Zhang and Meng, 2019). The hourly precipitation record for western Guangdong Province (Fig. 3) shows that the heavy rainfall was mainly concentrated from 0600 to 0900 UTC 13 April 2019. The maximum 24-h accumulated precipitation from 0000 to 2400 UTC 13 April 2019 was 226 mm and occurred in western Guangdong (Yangjiang station; red rectangle in Fig. 4). Evolution of the hourly combined radar reflectivity from 0500 to 0800 UTC 13 April indicates that the convective systems around Yangjiang moved southeastward and had a peak intensity between 0600 and 0700 UTC (Fig. 4).

4.2 Configuration of numerical experiments

We set 0000 UTC 13 April 2019 as the analysis time $t_0$ for the five numerical experiments outlined in Table 1. In test-ctrl, the ECMWF analysis field at $t_0$ is used to

![Fig. 1. Schematic representation of the IAU technique under the replay configuration. The regional model was first integrated freely forward (blue arrow) for $\Delta t$ (warm-up time) to generate the background field $F_{\text{back}}$. The replay corrector segment $\delta X$ was then calculated according to the increment ($F_{\text{ana}} - F_{\text{back}}$) and the relaxation time $\tau$. The model was back-tracked to $t_0 - \Delta t$ (the black arrow) to run a second time with IAU, and the corrector segment was added to the forecast at every time step during the IAU time window.](#)

![Fig. 2. Synoptic environments (500-hPa geopotential height contours in gpm and 850-hPa horizontal vector winds in m s$^{-1}$) of the heavy rainfall event in South China at (a) 1200 UTC 12 April and (b) 0000 UTC 13 April 2019, based on the ECMWF global analysis data. Color shading denotes wind speed in m s$^{-1}$.](#)
provide the initial condition $F_{\text{ana}}$ for the cold start of the TRAMS. The background field $F_{\text{back}}$ in the IAU experiments is integrated from the global analysis field at $t_0 - \Delta t$, where $\Delta t$ is the warm-up time. If the warm-up time is too short, the convective-scale information in the background field is insufficient to solve the issues associated with spin-up and spin-down.

| Experiment          | Description                                                                 |
|---------------------|-----------------------------------------------------------------------------|
| test-ctrl           | Without IAU, cold start with ECMWF analysis field as initial condition       |
| test-IAU-6h-90min   | With IAU, $\Delta t = 6$ h, $\tau = 90$ min                               |
| test-IAU-12h-90min  | With IAU, $\Delta t = 12$ h, $\tau = 90$ min                              |
| test-IAU-12h-60min  | With IAU, $\Delta t = 12$ h, $\tau = 60$ min                              |
| test-IAU-12h-30min  | With IAU, $\Delta t = 12$ h, $\tau = 30$ min                              |

**Table 1.** Configuration of numerical experiments

**Fig. 3.** Hourly area-averaged precipitation in western Guangdong Province from 0000 UTC 13 to 0000 UTC 14 April 2019.

**Fig. 4.** Combined radar reflectivity (dBZ) in western Guangdong Province at (a) 0500, (b) 0600, (c) 0700, and (d) 0800 UTC 13 April 2019. The red rectangle shows the area in which heavy rainfall occurred in the warm sector.
To study the influence of the warm-up time, the value of $\Delta t$ in the IAU experiments was either specified as 6 h (test-IAU-6h-90min) or 12 h (test-IAU-12h-90min). The schematic diagram of the IAU technique (Fig. 1) shows that the relaxation time $\tau$ determines the filtering properties of the analysis increments and that more longwave atmospheric information will be damped with a longer $\tau$. The sensitivity of the IAU technique to the frequency of the analysis increment was thus examined with additional experiments: test-IAU-12h-30min ($\tau = 30$ min), test-IAU-12h-60min ($\tau = 60$ min), and test-IAU-12h-90min ($\tau = 90$ min).

4.3 Results and discussion

4.3.1 Sensitivity of initialization to relaxation time

We investigated the sensitivity of the IAU relaxation time in this heavy rainfall event under the replay mode. The average tendency of the surface pressure is an indicator of the level of noise in the external gravity wave component. Excessive noise presented in the test-ctrl uninitialized experiment (black line; Fig. 5a), indicating the presence of gravity waves. However, the high-frequency noise was effectively removed by the IAU scheme (colored lines; Fig. 5a) and the relaxation time had a significant effect on filtering the gravity wave noise. The surface pressure tendency was about 2.0 hPa (10 min)$^{-1}$ in test-ctrl and about 1.0 hPa (10 min)$^{-1}$ in test-IAU-12h-30min. The reduction in gravity wave activity with the use of the IAU technique was greater with the larger values of $\tau$ in test-IAU-12h-60min and test-IAU-12h-90min, which implies that extending the relaxation will help initialization in replay simulations.

We focused on the influence of IAU initialization on precipitation forecasts. Figures 5b, c show the variation with time of the average cloud water content ($Q_c$) between 850 and 500 hPa and the precipitation rate in western Guangdong Province (red rectangle; Fig. 4) every 10 minutes. The variable $Q_c$ generated during the warm-up period ($\Delta t = 12$ h) in the IAU experiments helped to reduce the spin-up and spin-down times compared with the test-ctrl experiment, in which there were no cloud hydrometeors at the initial time. The precipitation rate was also strengthened in the IAU experiments in the following 24-h forecast, which was mostly attributed to the increase of $Q_c$. However, there was only a slight difference between $Q_c$ and the precipitation rate in the IAU experiments with various relaxation times (30, 60, and 90 minutes).

In general, the initialization process is sensitive to the relaxation time in the IAU experiments, but its influence on cloud and precipitation forecasts is less clear. We therefore set the relaxation time to 90 minutes (blue dotted rectangle; Fig. 5) to remove the high-frequency noise. According to Eq. (6) in Bloom et al. (1996), longwave radiation will be more greatly damped when the IAU window is extended to 3 and 6 h. We wanted to retain as much useful large-scale information as possible in the global analysis field, so it was not necessary to choose a longer IAU window once the high-frequency noise had been removed.

4.3.2 Sensitivity of precipitation forecast to warm-up time

We investigated the sensitivity of the short-term precipitation forecast skill to the warm-up time ($\Delta t$). Figure 6a shows the temporal variation of the surface pressure tendency in the control and the IAU experiments with warm-up times of 6 and 12 h. The large gravity wave fluctuation at the initial time gradually disappeared after about 3-h integration. This indicates that the TRAMS needs at least 3 h to achieve a balanced state when initiated with the ECMWF analysis field. The warm-up time must therefore be longer than 3 h to ensure that the background field is not influenced by the initialization process. Figure 6b shows a clear difference of $Q_c$ between test-IAU-6h-90min (red line) and test-IAU-12h-90min (blue line). In test-IAU-12h-90min, the cloud water experienced the complete spin-up and spin-down process during the warm-up period, so the background field in the IAU technique was influenced by the problem of a cold start. The increase in the cloud water content before the IAU process in test-IAU-6h-90min indicated that a period of 6 h is too short to accomplish the spin-up process. As a result, the strength of the convective updraft was much weaker than that in test-IAU-12h-90min. The same results were obtained for the precipitation rate (Figure 6c).

More cloud hydrometeors were generated in test-IAU-12h-90min than those in test-IAU-6h-90min and test-ctrl after 0600 UTC 13 April and the amount of cloud increased during the period when heavy rainfall occurred in western Guangdong Province (0600–0900 UTC 13 April), which agrees well with the evolution of the observed radar reflectivity (Fig. 4). The precipitation was also significantly enhanced when the warm-up time of the background was extended from 6 to 12 h (Fig. 6c).

Figure 7a shows the observed 3-h accumulated rainfall from 0600 to 0900 UTC 13 April. Test-ctrl almost completely failed to predict the heavy rainfall in western Guangdong Province, which exceeded 70 mm (Fig. 7b). The maximum amount of rainfall was successfully simu-
lated by test-IAU-6h-90min, although the area of heavy rainfall was too small (Fig. 7c). The underestimation was significantly reduced by extending the warm-up time to 12 h (Fig. 7d).

Figure 8 compares the simulated radar reflectivity and wind field between test-IAU-6h-90min and test-IAU-12h-90min. The radar reflectivity is strengthened in western Guangdong Province in test-IAU-12h-90min and the direction of the wind field changes from southwest to southeast, causing convergence of the air mass at the low levels. The vertical cross-section in Figs. 8c, d shows that the increase in the warm-up time contributed to the development of the convective system in the background field. The altitude of the strong radar reflectivity (> 90 dBZ) lifted from 2 to 4 km when the warm-up time was extended from 6 to 12 h. The updraft was also clearly increased in test-IAU-12h-90min to the south of the convective system (figure omitted).
4.3.3 A one-month test

A one-month test was conducted from 1 to 30 April 2019 to verify the influence of introducing global analysis data through the IAU method under the replay configuration. In the control group (test-ctrl), the simulation was initialized at 0000 UTC and integrated forward for 24 h each day with ECMWF analysis data as initial and boundary conditions. The configuration in the IAU group (test-IAU) was the same as in test-IAU-12h-90min of the above case study, i.e., the model was initialized with analysis data at 1200 UTC on the previous day and then the ECMWF analysis data at 0000 UTC was introduced according to the IAU method with a time window of 90 minutes. Figure 9 shows the monthly averaged verification of hourly precipitation forecast from 0000 to 2400 UTC. The improvement of the threat score in the IAU group was mainly concentrated in the 0–9-h forecast. According to the bias score in Fig. 9b, underestimation of precipitation in the 0–9-h forecast and overestimation in the 9–24-h forecast were both reduced in test-IAU.

Fig. 6. As in Fig. 5, but for sensitivity of forecast results to different warm-up lengths of time (Δt).
5. Summary and discussion

We applied the IAU technique to improve the initialization and short-term precipitation forecasts with the TRAMS. In contrast with its traditional use in the rapid update cycle system (Lee et al., 2006), the pre-existing global analysis field was used to build the IAU tendencies under the replay configuration.

Numerical simulation of a heavy rainfall event in South China was implemented with the ECMWF global analysis field and the TRAMS regional model. The IAU experiments significantly improved the forecast by removing the gravity wave and reducing the spin-up time. The IAU filtering properties were sensitive to the relaxation time; an appropriate increase in the relaxation window achieved a more consistent blending of the global analysis and regional background data. Because the background field is generated by a cold start forecast initialized with the analysis field from the global model, the regional model needs to be pre-integrated to warm up the convective system. The warm-up time had a clear effect on the forecast of the intensity of precipitation when it was extended from 6 to 12 h. In general, the spin-up phenomenon related to the cold start of the background was effectively avoided by using a longer warm-up time. A one-month replay experiment based on the IAU technique showed a clear improvement in the short-term forecast of precipitation.

The replay simulations are similar to “nudged” simulations in which an online model is relaxed in response to an external analysis dataset—for example, the Whole Atmosphere Community Climate Model simulations described by Kunz et al. (2011) and Lamarque et al. (2012). The replay only affects the high-frequency features caused by increments in the analysis, whereas the nudging technique filters out some meaningful information in the background field (Lee et al., 2006). The replay method can be seen as a blend of large-scale information from the global analysis data and small-scale information from the background field. The meaningful physical signal in the background field will not be smoothed out by the IAU technique.

The area with strong precipitation was still missed in test-IAU-12h-90min, which implies that improvements

Fig. 7. The 3-h accumulated precipitation (mm) between 0600 and 0900 UTC 13 April. (a) Observed rainfall, (b) test-ctrl, (c) test-IAU-6h-90min, and (d) test-IAU-12h-90min. The observed rainfall was obtained from the hourly surface meteorological station observations of China, available at http://data.cma.cn/data/detail/dataCode/A.0012.0001.html.
are still required in the IAU technique under the replay configuration. The first issue is that the low-resolution global analysis used in the IAU technique cannot provide enough small-scale information to correct the localization of the convective system (e.g., the warm sector heavy rainfall event considered here), so high-resolution observations (e.g., Doppler radar data) should be considered to further improve the forecast of local heavy
rainfall. The second issue is that our case study occurred with a uniform southwesterly wind without any obvious large-scale force to trigger convection (Fig. 2). Although the large-scale bias was corrected by the IAU technique, this method does not improve the distribution of heavy rainfall in space because the triggers of warm sector rainfall have little direct relationship with the large-scale field. We found that the space distribution was clearly improved in the IAU test for other events controlled by large-scale convergence (figure omitted) and a full study of this issue will be reported in a follow-up paper.

Future work will consider the sensitivities of the IAU forcing variables (e.g., skin temperature forcing) and different treatment of the lateral boundaries under the replay mode. The impact of the IAU technique on other forecast variables (e.g., wind and temperature) also needs to be studied.

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