On the instability of IAU and its interplay with ensemble recentering

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Outline

Note: Originally we were planning to show results on

Preliminary experiments extending the assimilation window of the GMAO Hybrid 4DEnVar

but, with apologies to the audience, results on it are postponed to another time.

With all sophistication of current assimilation systems it is the case today, as it was in the early days of NWP and DA, that the way to initialize the underlying model remains a key component behind the quality of results.

Most systems use some type of initialization technique:

- Normal mode initialization (NMI), and its variants (e.g., nonlinear NMI)
- Digital filter (DF), and its variants (i.e., incremental DF)
- Incremental analysis update (IAU)

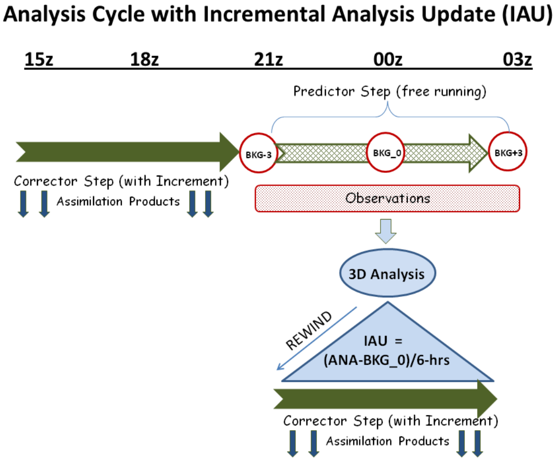
GMAO (DAO) introduced IAU in the mid-90's and has used it (almost) ever since.

Use of Incremental Analysis Update in Two Contexts

- Context I: Cycling of Assimilation Systems
  - Traditional (original) 3D-Var application of (3D-) IAU (Bloom et al. 1996).
  - Modified 4D-IAU extension to 4D assimilation applications (Lorenc et al. 2015).

- Context II: Initializing General Model Integration Exercises
  - Downscaling applications.
  - Quickly assessing the impact of model changes without need to run full DA.

Context I: Schematic of original (3D) IAU
A Predictor-Corrector Scheme



Brief Recap of Bloom et al. (1996)

The IAU procedure is modeled as a damped harmonic oscillator with complex frequency $\tilde{\omega} = \omega + i\kappa$, driven by a piece-wise constant forcing over the analysis time interval

$$\frac{dU}{dt} = i\tilde{\omega}U + \frac{\Delta U}{\tau}, \qquad t_n < t < t_n + \Delta t_c,$$

where ΔU is the analysis increment; κ a damping parameter; Δt_c is the length of the Corrector step; and τ is a scaling parameter. The solution at the end of the analysis interval is simply

$$U_{iau}(t_n + \Delta t_c) = U(t_n)e^{i\tilde{\omega}\Delta t_c} + \Delta U\, e^{i(\tilde{\omega}\Delta t_c/2)} \left(\frac{2\sin(\tilde{\omega}\Delta t_c/2)}{\tau\tilde{\omega}} \right).$$

This is compared in Bloom et al. with the solution of the intermittent problem, when the analysis increment is used directly as a correction to the state at time $t_n + \Delta t_c/2$:

$$U_{int}(t_n + \Delta t_c) \quad = \quad U(t_n)e^{i\tilde{\omega}\Delta t_c} + \Delta U e^{i(\tilde{\omega}\Delta t_c/2)}.$$

Comparison of the two results shows how the highlighted factor in the IAU solution operates as a low-pass filter and effectively reduces the effect of high-frequency oscillations from contaminating the prediction.

The benefits of IAU when compared the intermittent approach are evidenced in measures of balance and consistent time-behavior of precipitation, fluxes, etc.

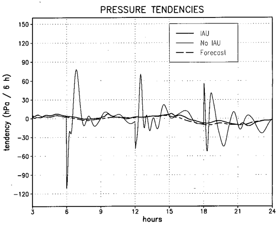


FIG. 7. Surface pressure tendency traces at a grid point over North America, results displayed from every time step over the course of a 1-day assimilation: IAU (heavy solid); no IAU (light solid); model forecast, no data assimilation (heavy dashed).

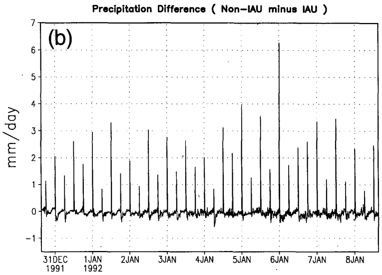


FIG. 6. Globally averaged precipitation, plotted in 10-min intervals: (a) non-IAU precipitation for a 1-week period; (b) precipitation difference between IAU and non-IAU runs for same period as (a); (c) 24-h precipitation, overlaying IAU and non-IAU results; (d) difference of the precipitation traces in (c).

Above: Time evolution of surface pressure tendency at a grid-point evolves as smoothly with IAU as in a Free-running model integration, as opposed to intermittently assimilating data (spikes).

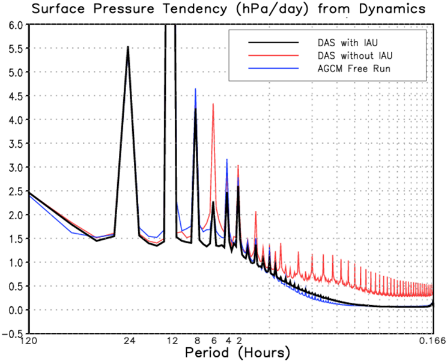
Above: Time evolution of globally-averaged precipitation difference between IAU and non-IAU cases.

Figures above from Bloom et al. (1996)

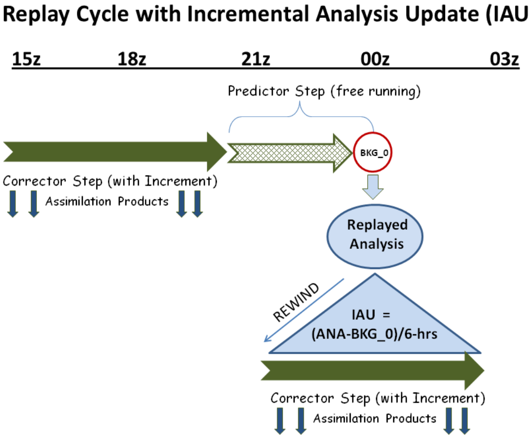
Harmonic analysis of 30S-30N PS tendency due to dynamics in three contexts:

1. Assimilation with IAU
2. Assimilation without IAU
3. Free-running model

Clearly the motivation for IAU.



Context II: IAU-based Replay Strategy used in, say, dynamical downscaling



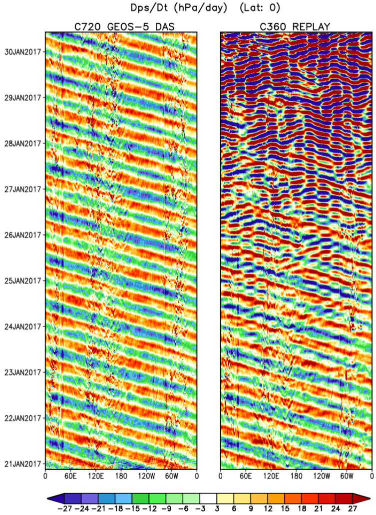
Note: By construction, in a Replay Strategy the cycle never changes the analysis it replays to.

Applications of IAU in GEOS Atmospheric Model: Replay

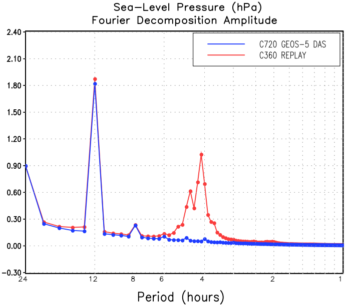
- Re-forecasts to testing impact of model changes on forecast scores
- Use of external analyses to forecast with GEOS AGCM:
  - geos-NCEP
  - geos-ECMWF
- Sub-seasonal-to-Season Coupled Model and ODAS:
  - Assimilate ocean
  - Replay atmosphere
- Chemical Constituent Assimilation:
  - Assimilate chemistry
  - Replay atmosphere
- Downscaling exercises

Emergence of Instability in Replay Applications:

1. Some GMAO researchers testing changes to the chemistry component of GEOS AGCM have reported not being able to Replay much beyond 6 months before their, typical 1^o, simulations run into trouble after developing an instability.
2. More recently, a Downscaling project Replaying the 50 km MERRA-2 analyses to 12.8 km could not be run beyond a few days, after developing an instability; a quick remedy was implemented by filtering the increment at T60.



Below: Harmonic analysis of 30S-30N sea-level pressure (SLP) from last 5 days of DAS and REPLAYED integrations on the right.



Left: Hovmöller of PS tendency at 0^o latitude of DAS (left) and REPLAYED (right) model.

The Bloom et al. analysis says nothing about the stability of IAU. To look into that, and to accommodate both the usual DAS and the Replay scenarios, consider the analysis at time $t_n + \Delta t_p$ written in the following form:

$$U_a(t_n + \Delta t_p) = K\,U_T(t_n + \Delta t_p) + (1 - K)U_b(t_n + \Delta t_p)$$

where Δt_p is the time interval of the IAU Predictor step, U_b is the background state, K represents the analysis gain, and U_T is a target state which can be either the observation vector in the case of the DAS, or a prescribed state when considering the Replay scenario.

Writing the analysis increment at time $t_n + \Delta t_p$ as

$$\Delta U = U_a(t_n + \Delta t_p) - U_b(t_n + \Delta t_p),$$

it follows that

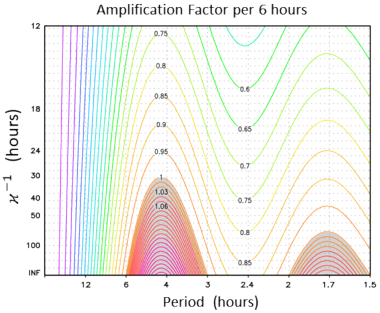
$$\Delta U = K\left[U_T(t_n + \Delta t_p) - U_b(t_n + \Delta t_p)\right].$$

Plugging the above in the IAU solution at the end of the Corrector step leads to

$$U(t_n + \Delta t_c) = U(t_n)e^{i\tilde{\omega}\Delta t_c} + \frac{\Delta t_c}{\tau}K\left[U_T(t_n) - U(t_n)\right]e^{i\tilde{\omega}(\Delta t_P + \Delta t_c/2)}\mathrm{sinc}\left(\frac{\tilde{\omega}\Delta t_c}{2}\right),$$

where $\mathrm{sinc}(x) = \sin(x)/x$.

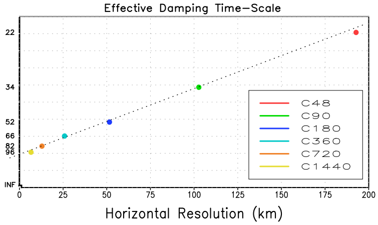
Below: Amplification factor for given idealized Replay case ($K = 1$) as a function of period and damping time scales.



For $\delta U = U - U_T$, with $\Delta t_p = \Delta t_c/2$

$$\frac{|\delta U(t_n + \Delta t_c)|}{|\delta U(t_n)|} = e^{-\kappa \Delta t_c} \left| 1 - \operatorname{sinc}\left(\frac{\tilde{\omega}\Delta t_c}{2}\right) \right|$$

for the Replay case, $K = 1$.

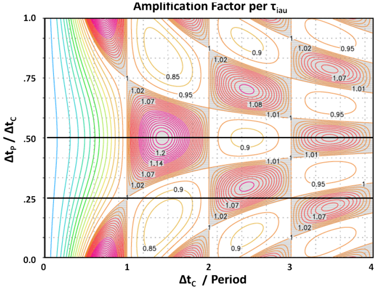


Above: Estimate of effective damping time scales for different GEOS model resolutions from roughly 200 km (C48) to roughly 6 km (C1440).

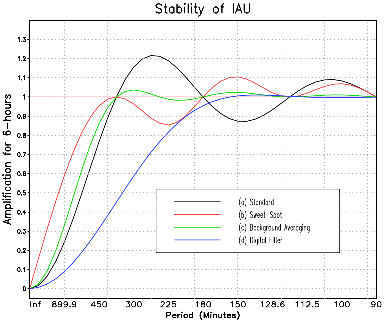
Implications: For most GEOS model resolutions, use of traditional IAU to Replay to existing analyses leads to eventual development of instabilities.

The theoretical study points to the following strategies to avoid the IAU instability:

1. Sweet spot (in the stability diagram)
2. Background averaging
3. Modulation by Digital Filter (DF; Polavarapu et al., 2004)



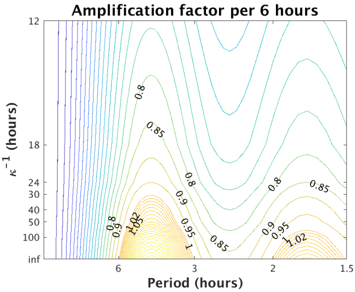
Above: Amplification factor for an inviscid model ($\kappa = 0$) Replay ($K = 1$) of length τ_{iau} as a function of normalized frequency and ratio of Predictor-to-Corrector duration.



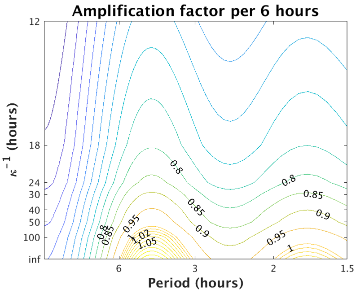
Above: Amplification factor for 6-hour IAU Corrector with difference strategies to avoid instability; traditional 3-hour Predictor shown as Standard (black curve).

Why cycling Data Assimilation Systems do not typically show the instability?

Replay case: K=1



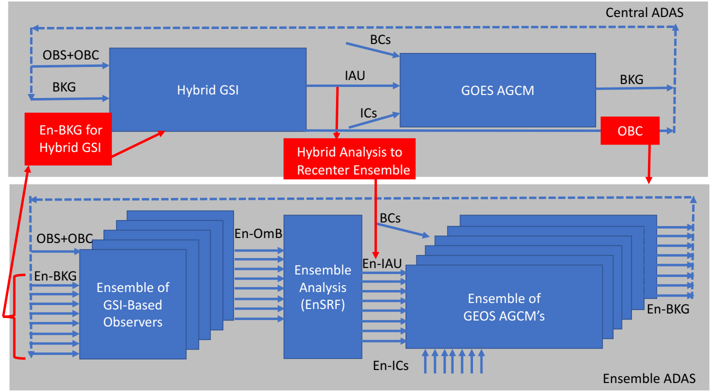
DAS case: K=0.5



The stability diagram shows DA applications to be considerably more dispersive than the Replay case, thus explaining why instability is more easily kept in check under DA.

However, with increasing resolution of models in DA, it is likely the IAU instability will manifest itself at some point, unless, for example, a Digital Filter is used to modulate the IAU tendencies.

Schematic of the GEOS Hybrid Atmospheric Data Assimilation System



GMAO applies a dual resolution approach with the EnADAS running at coarser resolution than the Deterministic ADAS.

Configuration of GMAO Hybrid Systems:

- Deterministic ADAS component:
  - Uses (3D) IAU when employing Hybrid 3D-Var.
  - Uses a Nudged-4D-IAU approach when employing Hybrid 4D-EnVar.
- The Ensemble ADAS component uses traditional (3D) IAU.

Brief history of relevant configuration changes to GMAO Hybrid DA:

- The first hybrid system was a Hybrid 3D-Var implemented for a 25 km (C360) deterministic model using a 32-member ensemble at roughly 100 km (C90).
- The upgrade to Hybrid 4D-EnVar came with a combined deterministic model resolution upgrade to 12.8 km (C720) and a corresponding ensemble resolution upgrade to 50 km (C180).

This upgrade stumbled on an instability that seemed to go away when ensemble recentering was removed.

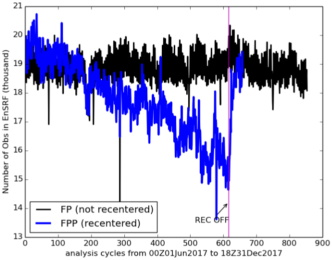
At the time no understand of the cause of the instability was at hand, therefore:

The first 12.8 km Hybrid 4D-EnVar went operational with recentering turned off.

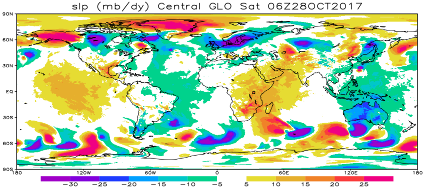
Manifestation of the instability in a high-resolution Hybrid 4D-EnVar System

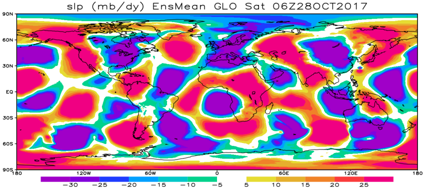
A future upgrade of the 12.8 km system tried to reinstate recentering ⋯

Below: PS Obs count in EnSRF for over six months of assimilation in the GMAO Forward Processing (FP) (non-recentered) System and its replacement candidate FPP (recentered).



Note: As soon as recentering is turned off in FPP the obs count jumps up.





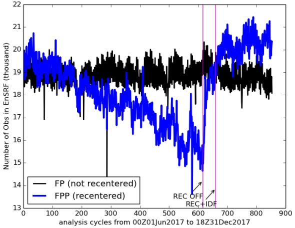
Above: SLP tendency in DAS at give time: Central (top) and Ensemble Mean (bottom).

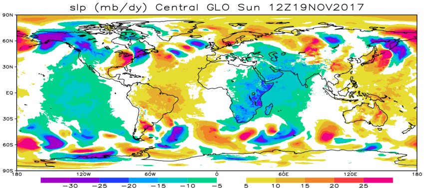
Digital Filter modulation of IAU in En-ADAS

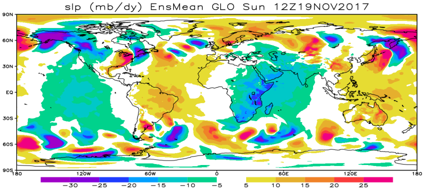
Recentering viewed as a form of Replay:

$$\tilde{U}_T^m = \alpha U_a + \beta(U_a^m - \bar{U})$$

Below: With a DF modulation of IAU applied to the members of ensemble, recentering can be turned back on in FPP with no risk of an instability developing.





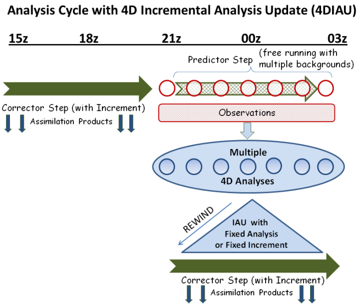


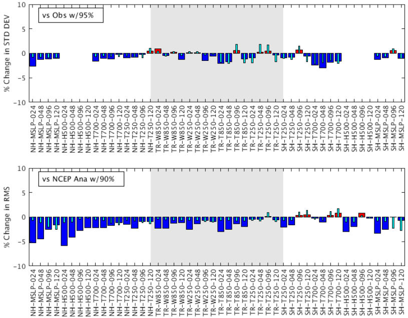
Remark: With this, we get an increase in the number of accepted observation by the Ensemble.

Above: with the Digital Filter modulation of IAU, recentering can be turned back up and the system remains stable.

Digital Filter + 4D-IAU in Hybrid 4D-EnVar

Question: Is there an advantage in using DF to modulate 4D-IAU?





Left: Score cards comparing GMAO's present Nudged-4D-IAU settings with the DF-modulated 4D-IAU. Blue colors indicate improvement by new over current settings.

Answer: The answer is yes, at least over Nudged-4D-IAU.

Remark: There are, however, multiple ways to modulate flavors of 4DIAU with DF; a comprehensive study is being carried out to provide an accurate assessment.

Closing Remarks

IAU Instability

This study of IAU:

1. Reveals a thus-far unnoticed instability associated with the procedure.
2. Explains why the instability has remained in check in most applications.
3. Presents three approaches to avoid the instability from arising: (i) sweet spot; (ii) background averaging; and (iii) modulation of IAU increments with a Digital Filter (DF).

Recentered Hybrid DA and IAU

This study also shows that:

1. The instability can arise in the ensemble of Hybrid DA systems when doing ensemble recentering.
2. In such context, modulation of IAU with a DF weights provides the simplest approach to avoid the instability.
3. A combined IAU-DF framework opens the door for a variety of viable model initialization configurations in a 4D-scenario, being presented explored and to be reported elsewhere.