The impact of the temporal spacing of observations on analysis errors

John Eyre and Peter Weston

1) Introduction

This poster presents a theoretical study of the impact of the temporal spacing of observations on average analysis errors in a simple system analogous to a numerical weather prediction data assimilation system. The results are relevant to questions concerning the optimal distribution of polar-orbiting satellites, and particularly to the question of how available satellite assets might be deployed in the three orbital planes recommended by the World Meteorological Organisation (WMO) in its "Vision for the Global Observing System (GOS) in 2025".

In initial experiments, it is assumed that observations from satellites deployed in different orbits have equal information content. In subsequent experiments, information content is simulated for a range of systems corresponding to present and future satellite observing systems. In addition to satellites operational in the period 2010-2011, the potential has been assessed of data from the satellites Suomi-NPP, Metop-B and FY-3C. In each case, the impact of these observations on mean analysis error variance is assessed.

2) WMO Vision for the GOS in 2025

The WMO has agreed a "Vision for the GOS in 2025", which recommends a system of operational polar-orbiting sun-synchronous satellites in three orbital planes roughly 60 degrees apart, as shown in Figure 1. Such a system will provide observational coverage approximately every 4 hours at mid and low latitudes. Currently Europe, via EUMETSAT, plans to ensure coverage in the "mid-morning" orbit, and the USA in the "afternoon" orbit. China also plans to launch satellites into both of these orbits. However, there is the possibility that China might move one of its future satellites into the otherwise empty "early morning" orbit. This study aims to calculate whether equally spaced observations in time lead to smaller analysis errors and subsequently smaller forecast errors in order to help to justify this potential move.

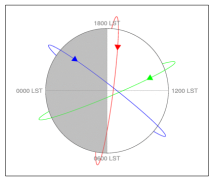

Figure 1: Vision for the GOS: The three equally spaced orbits are: "early morning" LECT = 0530 descending (red); "mid-morning" LECT = 0930 descending (blue); "afternoon" LECT = 1330 ascending (green). Viewed from above the North Pole in a sun-synchronous frame of reference with the sun on the right. LST stands for local solar time

3) Toy Model

We have simulated the error characteristics of a very simple data assimilation system: a Kalman filter for a system with a single variable, $x(t)$, i.e. zero-dimensional in space, when assimilating observations of the same variable distributed over time in various ways. Equations (1), (2) and (3) define the system.

$$A_i^{-1} = B_i^{-1} + R_i^{-1} \quad (1)$$

$$B_i = \beta A_{i-1} + Q \quad (2)$$

$$A_i^{-1} = \beta^{-1} A_{i-1}^{-1} + R_i^{-1} \quad (3)$$

Where A_i^{-1}, B_i^{-1} and R_i^{-1} are the analysis, background and observation accuracies at time i respectively, A_i and B_i are the analysis and background errors at time i, β is the forecast error growth term and Q is the model error term. We assume that Q=0 for most of our study.

$$\frac{1}{N}\sum_{i=j+1}^{j+N} A_i^{-1} = (1-\beta^{-1})^{-1}\frac{1}{N}\sum_{i=j+1}^{j+N} R_i^{-1} \quad (4)$$

$$\frac{dF}{dt} = \alpha F + \gamma \quad (5)$$

$$\beta = \exp(\alpha\delta t) = \exp\left(\frac{\ln(2)\delta t}{\Delta t}\right) \quad (6)$$

If we then consider a repeating set of observations over a 12 hour period (as in the case of polar-orbiting sun-synchronous satellites) and solve the resulting recurrence relation we find the mean analysis accuracy over that period given by equation (4). This is a slightly surprising result, which indicates that the mean analysis accuracy is independent of the spacing of observations in the 12 hour period. However there is no such result for the mean analysis error. We consider the two parameter forecast error model in the early stage of a forecast far from saturation defined by equation (5), where F is forecast error, α is another forecast error growth term and γ is a model error term. From this we can derive a realistic value for β given in equation (6), where δt is the time step and Δt is the forecast error variance doubling time. In modern NWP systems the forecast error variance doubling time is approximately 12 hours and we consider values of 12, 6 and 3 hours in our subsequent experiments. The lower values are more representative of the modelling of high-impact weather events such as storms in the mid-latitudes. Figure 2 shows how the 12 hour running mean of forecast error variance converges as the model is iterated forwards in time.

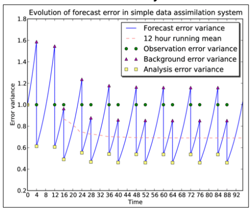

Figure 2: Example Evolution of forecast error variance as the model is iterated forwards in time. This example has an error doubling time of 6 hours and observations of accuracy 1 added at 0 and 4 hours of each 12 hour period

4) Idealised experiments

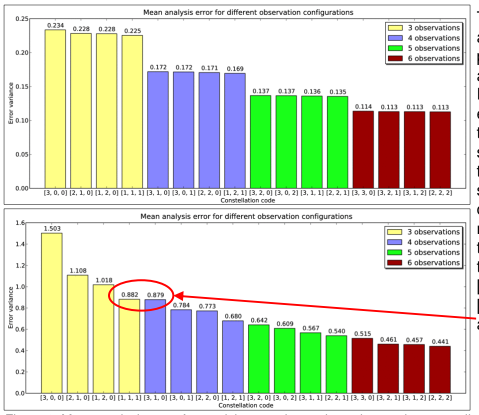

Figure 3: Mean analysis error for model runs using various observation constellations with forecast error doubling times of 12 (top) and 3 (bottom) hours. These constellations are defined by codes of the form [x,y,z] where x, y and z represent the observation accuracies from polar-orbiting satellites in three orbital planes

The first set of idealised experiments run are based upon different constellations of polar-orbiting satellite observations being assimilated in a 12 hour repeating period. Figure 3 shows that the mean analysis error is reduced in configurations where the observations are more uniformly spaced across the period even when the total number of observations used is the same. The effect of the temporal spacing of observations on the analysis errors is much more important in the case where the forecast errors grow more quickly to the point where the analysis errors for a [1,1,1] configuration of 3 satellites and a [3,1,0] configuration of 4 satellites are almost identical.

Figure 4 shows that, in the case of having 3 observations available every 12 hours, the mean analysis error is 70.5% larger in the model run with the least uniformly spaced observations ([3,0,0]) compared to the most uniformly spaced observations ([1,1,1]) with an error doubling time of 3 hours. For longer error doubling times the differences in mean analysis error are less striking but still significant with a corresponding 3.6% increase in analysis error between these same two configurations when the forecast error doubling time is 12 hours.

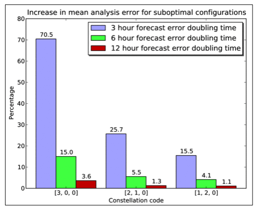

Figure 4: Differences in mean analysis error for model runs using various constellations of 3 observations. The differences shown are with reference to the constellation resulting in the lowest mean analysis errors ([1,1,1])

5) Realistic experiments

Using Forecast sensitivity to observations (FSO) results we can simulate the current observing system within our model. This involves totalling the observation accuracies of satellites in each of the three orbits and also including contributions to observation accuracies every hour from distributed observations such as GPSRO and surface observations. Figure 5 shows that the effect of denying MetOp-A observations in our model is a ~33% increase in mean analysis error. Whereas similar results in OSEs suggest a 9-13% increase in forecast errors. This discrepancy highlights some of the limitations of our approach.

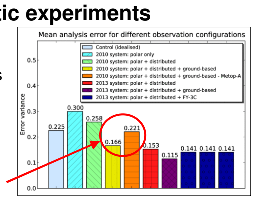

Figure 5: Mean analysis error for model runs using various observation constellations based on the 2010 and 2013 Met Office data assimilation systems. The difference is the addition of data from the recently launched MetOp-B and Suomi NPP satellites using representative values of observation accuracies from similar existing instruments

Figure 6 shows that simulating putting an FY-3C-like satellite into the early morning orbit leads to lower mean analysis errors than putting it into either of the other two orbits. Again the differences are most striking in the case where the forecast error doubling time is 3 hours but differences of 0.2 to 0.3% for the 12 hour error doubling time, although small, are similar to most operational changes which often take many months to research and implement.

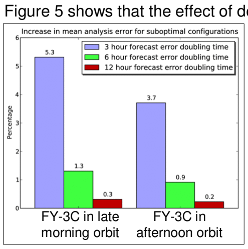

Figure 6: Differences in mean analysis error for model runs simulating including an FY-3C-like satellite into the three orbital planes

We have also performed model runs which account for non-zero model error. These result in the sensitivity of the mean analysis error to the temporal spacing of observations being increased, the effect of denying MetOp-A being decreased and the result from equation (4), that the mean analysis accuracy is independent of the observation spacing, breaking down.

References

Eyre J, Weston P. 2013. 'The impact of the temporal spacing of observations on analysis errors'. Met Office, UK; Weather Science Technical Report No. 573. (Also to appear in *Q. J. R. Meteorol. Soc.*)

Simmons AJ, Hollingsworth A. 2002. Some aspects of the improvement in the skill of numerical weather prediction. *Q. J. R. Meteorol. Soc.*, 128: 647-677.

WMO. 2009. 'The Vision for the GOS in 2025'. http://www.wmo.int/pages/prog/www/OSY/gos-vision.html

6) Conclusions

The results of this study show that the sensitivity of analysis error to observation spacing depends on the metric used. The mean analysis error variance is sensitive to observation spacing, but the mean analysis "accuracy" (defined here as the inverse of error variance) is not sensitive in the limit of zero model error. Moreover, although the sensitivity of mean analysis error variance is small when forecast error variances double at their average rate (~12 hours), it is much greater when doubling times are shorter (6 or 3 hours), as might be expected in some high-impact weather events. The results support the case for deploying satellites in orbits that are approximately equally spaced where possible. When exploring a more realistic representation of the global observing system we found that each observation type had an over-estimated impact on the analysis accuracy. We also found that the placement of an FY-3C-like satellite into the early morning orbit would be more beneficial than putting it in either of the other orbits.

7) Future Work

We expect these simple experiments to over-estimate the impact on analysis error variance relative to equivalent real-world systems, because the system used here contains only a single, well-observed variable. In the real world, some variables and scales are observed poorly or not at all. To study this problem further, we intend to extend this study to consider a two-variable problem in which one variable is observed but the other is not, and the errors in the two are coupled through a more flexible forecast error growth process.

Met Office FitzRoy Road, Exeter, Devon, EX1 3PB United Kingdom
Tel: 01392 884049 Fax: 01392 885681
Email: peter.weston@metoffice.gov.uk