

Ensemble Data Assimilation for Reanalysis

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INTRODUCTION

Compared to those used for modern operational numerical weather prediction (NWP), the observing networks used for historical reanalysis are often quite sparse. For example, prior to the advent of radiosondes in the 1940's, there were only a few hundred to a few thousand surface meteorological observing stations around the world. Currently, most operational centers assimilate hundreds of thousands to millions of individual observations, with remotely sensed data from space composing the vast majority. Consequently, for historical reanalysis it is crucial to 'spread out' the information in the observations into observation voids and into unobserved model state variables. In operational NWP, there is less need to 'spread out' the observational information, since there are fewer regions and variables that are not observed, at least indirectly.

Observing networks for historical reanalysis are also quite inhomogenous in time, varying from a few hundred surface observations in the early 20th century, to hundreds of thousands of surface, upper-air and remotely-sensed observations in the late 20th century. Therefore, analysis errors can change dramatically with time, and methods for assessing the impact of changing observation networks on analysis error are needed for climate studies that utilize long reanalysis datasets.

In this paper, we illustrate how ensemble data assimilation techniques can address both of these problems. This is done by performing an observing system experiment, decimating the observations used for operational NWP in January and February 2005 so that the network resembles what is currently available for the 1930's. The reduced set of observations are assimilated into a three-dimensional variational (3D-Var), a four-dimensional variational (4D-Var) and an ensemble data assimilation (EnsDA) system. The accuracy of the resulting analyses are assessed by comparing to the operational NWP analyses (which used all available observations). It is found that 4D-Var and EnsDA systems produce analyses of comparable quality, and both are much more accurate than the analyses produced by the 3D-Var system. However, the EnsDA system also produces useful estimates of analysis error, which are not directly available from the 4D-Var system.

DATA ASSIMILATION SYSTEMS

The 3D-Var and 4D-Var assimilation experiments were run at ECMWF with the global data assimilation system and forecast model that were operational in May 2005 (cycle 29R1). The resolution of the forecast model was T159 with 60 vertical levels. The 3D-Var system uses FGAT (first-guess at analysis time) to make better use of asynoptic observations (Andersson et al., 1998). The 4D-Var system (Klinker et al., 2000) uses a 12-h window, and is similar to the system used in the ERA-Interim reanalysis. The EnsDA system is an implementation of the serial ensemble-square root filter, similar to that described in Whitaker et al., (2004) and Compo et al. (2006). In EnsDA, an ensemble of short-term forecasts from the previous analysis time is used to

estimate the background-error covariances (Hamill 2006). The forecast model used to run the ensemble is the National Centers for Environmental Prediction (NCEP) global forecast model operational in June 2007, run at T62 resolution with 28 levels. The ensemble consists of 64 members.

THE OBSERVING NETWORK

Only surface pressure observations are assimilated, since prior to radiosondes they are the most widespread and reliable observations available. The operational network of surface pressure observations in January 2005 is shown in Figure 1a. Figure 1b shows the thinned network of surface pressure stations that was used in the experiments. The thinned network consists of approximately 3800 observations poleward of 20°N, and is similar to the network of digital observations that has been recovered for the 1930's.

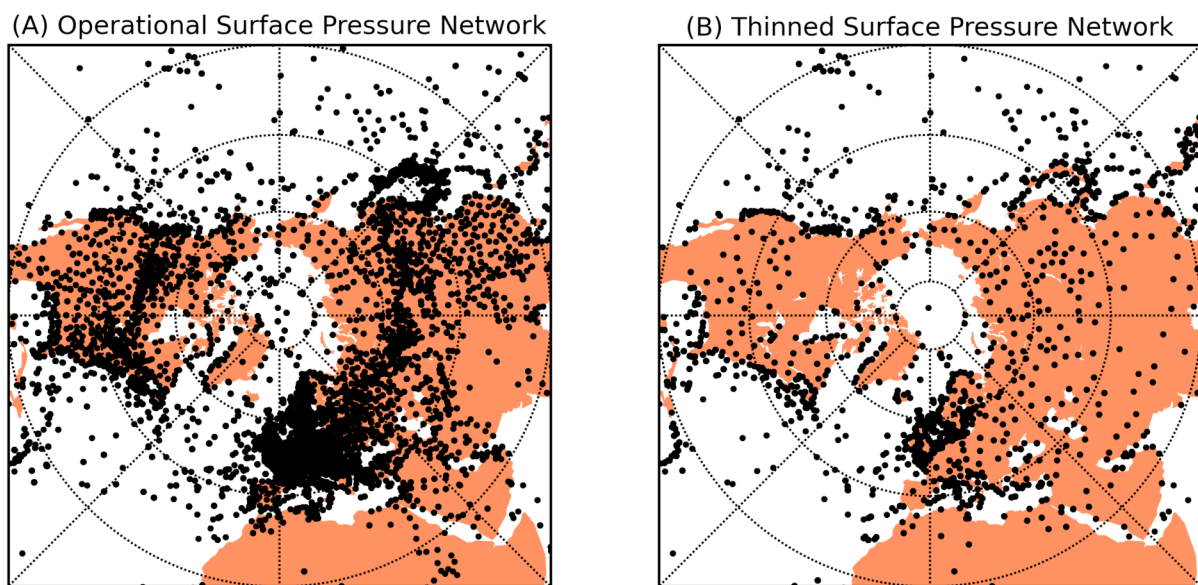


Figure 1: Operational and thinned surface pressure networks for 00 UTC 1 January 2005.

EXPERIMENTS

All three data assimilation systems were run from December 15, 2004 through February, 27 2005. Verification statistics were computed for January and February 2005 by comparing the resulting analyses to the operational NCEP analyses (which were computed with 3D-Var at T254 resolution, using all available observations). The background-error variances for the ECMWF 3D-Var and 4D-Var systems were multiplied by factors of 7.29 and 4.0, respectively, to account for the fact that the first-guess forecasts are much less accurate when only surface pressure observations are assimilated. These factors were computed using the fact that, if the assumptions inherent in the Kalman filter are satisfied, and the background and observation error covariances are optimal, the expected value of the observation minus first-guess variance should equal the background-error variance at the observation locations plus the observation error variance. However, this does not imply that the 3D-Var and 4D-Var results shown here are necessarily optimal, since the background-error structure functions were more not modified for the reduced network.

RESULTS

Figure 2 shows a time-series of Northern Hemisphere 500 hPa root-mean-square geopotential height error for the three experiments. Both 4D-Var and the EnsDA produce analyses with less than half the error of 3D-Var. Figure 3 shows an example set of analyses for 12 UTC February 20, 2005. Both 4D-Var and the EnsDA capture accurately represent all of the synoptic scale features in the NCEP operational analysis, including the block over the North Atlantic. The 3D-Var analysis completely misses some large amplitude features, such as the cutoff low in the central North Pacific. The errors of the 4D-Var and EnsDA analyses are roughly comparable to 72 hour forecast errors in modern NWP systems, consistent with the results of Compo et al. (2006). The 3D-Var analyses are not significantly better than one could obtain with a purely statistical analysis system that does not use a NWP forecast model, but instead uses the climatological mean as a first-guess and climatological anomaly covariances for the background-error covariance (Whitaker et al., 2004).

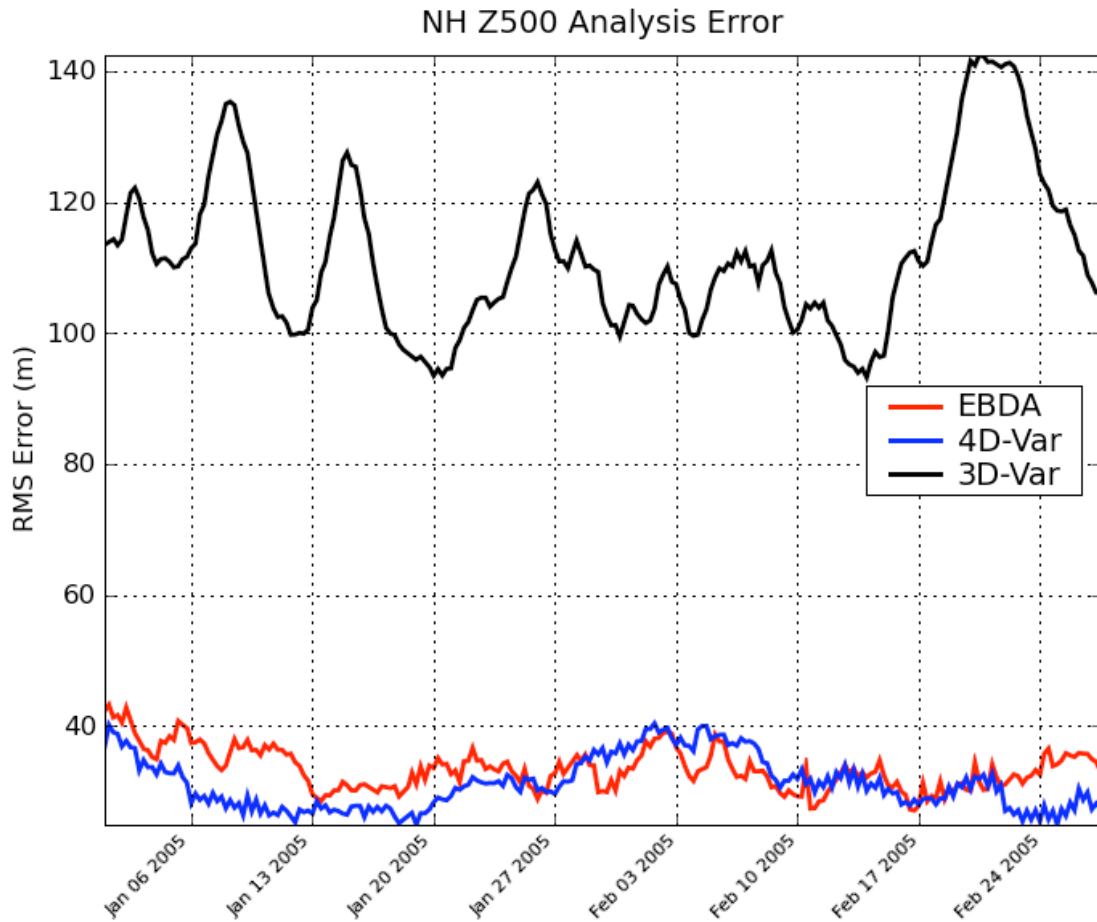


Figure 2: Time series of Northern Hemisphere (poleward of 20° N) 500 hPa geopotential height root-mean-square analysis error (measured relative to NCEP operational analysis) for 3D-Var (black), 4D-Var (blue) and the EnsDA (red).

The superior performance of the 4D-Var and EnsDA systems can be traced to their ability to utilize *flow-dependent* background-error covariance estimates. In 4D-Var, the background-error covariance is evolved with the tangent-linear dynamics over the 12-hour assimilation window. In the EnsDA system, the

background-error covariance is derived from a sample estimate using the 64-member forecast ensemble. Each ensemble member has its own analysis cycle, so that the background-error covariance information is continuously evolved as the ensemble is propagated through the analysis-forecast system. All other things being equal, in the absence of model error, one would expect EnsDA with a large enough ensemble to perform better than 4D-Var with a 12-hour window, since the covariance information can evolve continuously in time (instead of being reset to a fixed value every 12 hours). However, in practice, it appears that the presence of model error, which is only accounted for with simple covariance inflation (Anderson and Anderson, 1999), limits the ability of the EnsDA to accurately propagate background-error information in time for more than about 12 hours. It is important to keep in mind, however, that the 4D-Var system was run with a higher-resolution model than the EnsDA, so the effect of model errors in the EnsDA system should be proportionately larger.

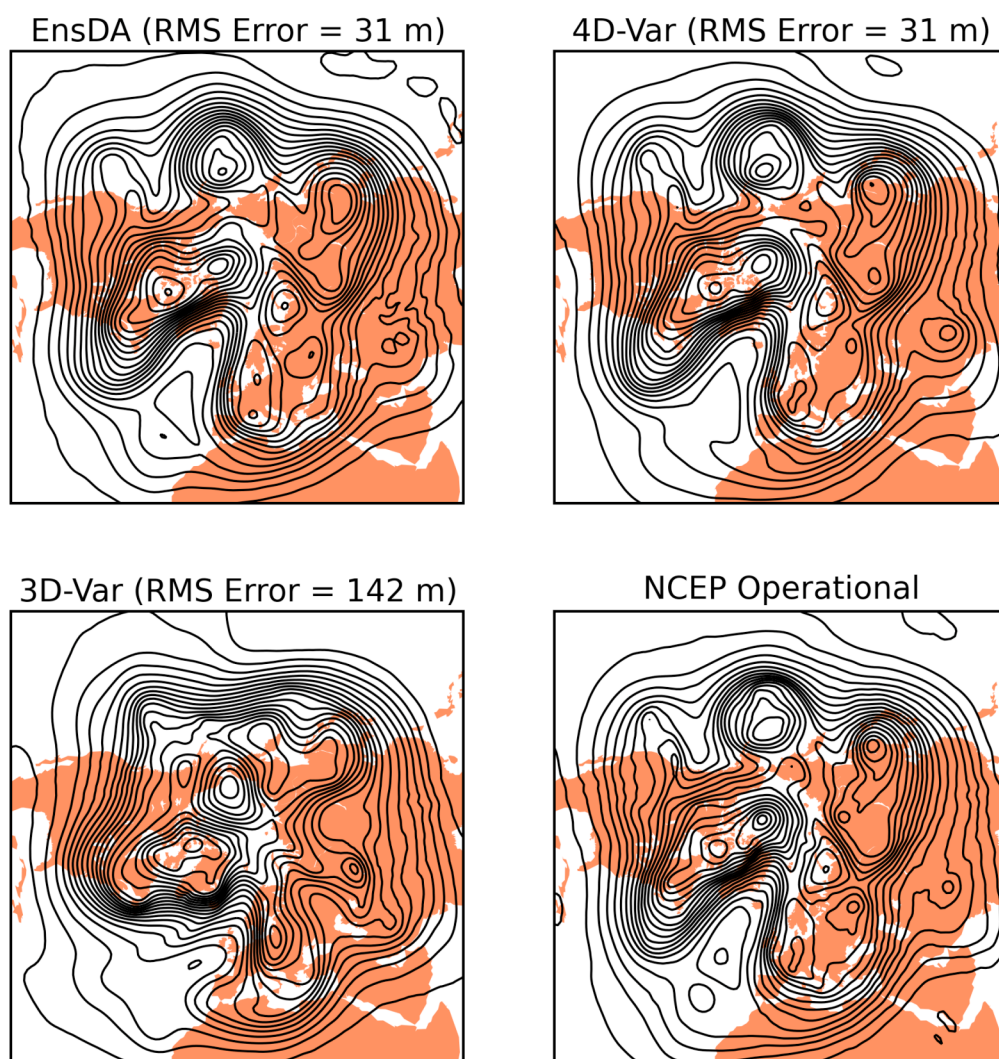


Figure 3: Example 500 hPa geopotential height analyses for 12 UTC February 20, 2005. Contour interval 50 m. The lower right panel shows the NCEP operational analyses, which used all available observations, and is used as a reference to estimate analysis error. The root-mean square analysis error in the Northern Hemisphere poleward of 20°N is noted on each panel.

Analysis spread provides a direct estimate of ensemble-mean analysis error in the EnsDA system. Such an estimate is not directly available from 4D-Var. This is particularly important for reanalysis over very long periods, over which the observing network (and hence the analysis error) changes substantially. Figure 4 shows both the ensemble mean and spread for 500 hPa height analyses for January 1, 1920 and 1950, obtained from the EnsDA system as part of the surface-pressure based NOAA-CIRES 20th Century Reanalysis Project. The solid contours in this figure show the ensemble mean, the shaded field is the analysis error estimate derived from the ensemble spread, and the dots show the location of the assimilated surface pressure observations. In 1920, the relatively sparse observing network is associated with a significantly larger expected analysis error, particularly over the Arctic and North Pacific.

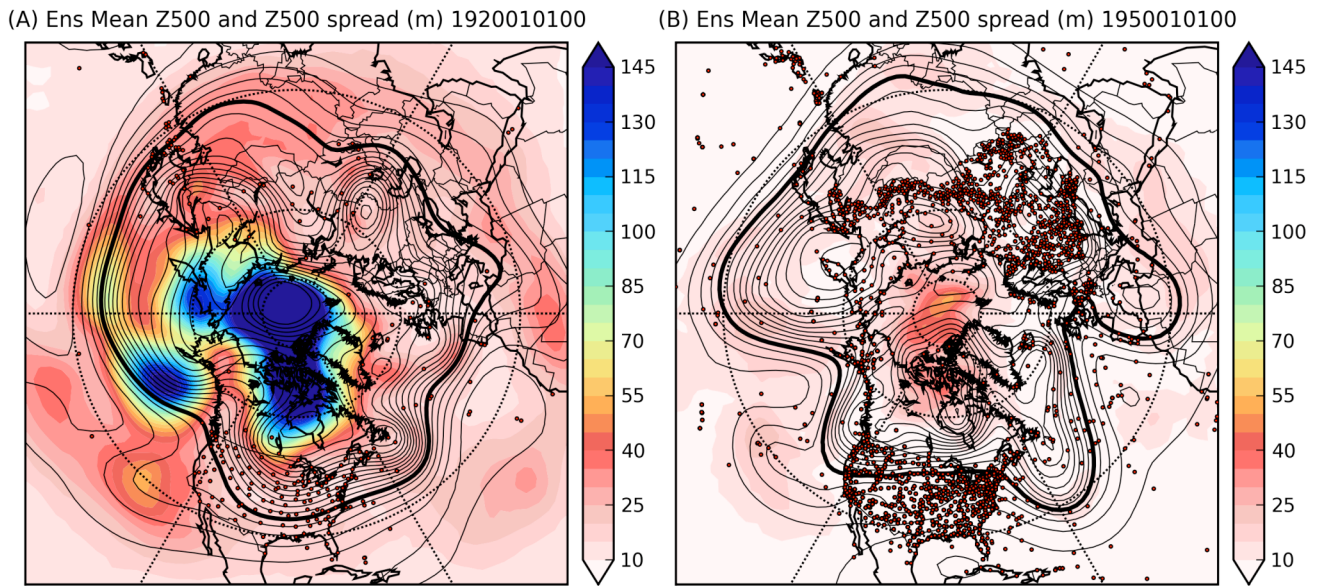


Figure 4: Ensemble mean analysis (solid contours) and analysis spread (color shading) for 500 hPa geopotential height analyses on 00 UTC January 1, 1920 and 1950. The contour interval is 50 m for the ensemble mean, with the 5600 m contour thickened. The color-scale for the analysis spread is shown on the right of each panel. The black dots denote the position of all the surface pressure observations assimilated at each analysis time.

CONCLUSIONS

Flow-dependent background error information provided by advanced four-dimensional assimilation schemes, such as 4D-Var and EnsDA, appear to be crucial in producing useful analyses when observations are very sparse, as is the case for meteorological observations prior to the widespread use of radiosondes in the 1940's. Both 4D-Var and EnsDA perform comparably when given a network of sparse surface pressure observations similar to what is available for the 1930's. However, the EnsDA system does not require manual re-tuning of the background-error covariance model as the observing network changes. Furthermore, the EnsDA system yields an estimate of analysis error, which may be crucial for users of reanalysis datasets to assess the significance of long-term changes in analyzed quantities over periods in which the observing network changes substantially.

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