Assimilating only surface pressure observations in 3D and 4DVAR

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1. Introduction

Observing System Experiments (OSEs) have been performed to assess the performance of modern assimilation systems (3DVAR and 4DVAR) in a scenario where the atmospheric Observing System is substantially degraded, i. e. reduced to surface pressure observations from a limited number of ground based stations.

Beyond documenting the importance of surface pressure observations for NWP and the relative merits of 3DVAR and 4DVAR in presence of few observations, these impact studies support and document the feasibility of possible future reanalyses extended over long periods of time (1930 or even beyond).

2. Experimental set-up

The data assimilation framework used for the OSEs presented in this paper corresponds to a state-of-the-art system (cycle 29R1, operational until June 2005). However, assimilations have been run at low resolution to limit the computer time and resources. The main characteristics are therefore listed below:

- T159 L60 forecast model resolution
- 4DVAR assimilation (12 hour window) of 3DVAR FGAT
- T95/T159 L60 analysis inner loop resolution
- T159 L60 analysis outer loop resolution
- Conventional observations assimilated in the CONTROL experiments (3D and 4DVAR) include:
  - Radiosondes, Pilots and wind profilers
  - Synops, Ships, METARS and buoys (moored and drifters)
  - Aircrafts (AMDARS, AIREPS, ACARS) including ascent/descent reports
- Satellite observations assimilated in the CONTROL experiments include:
  - Atmospheric Motion Vectors from GEO (Met-5/7, Goes-9/10/12 and LEO (MODIS Terra and Aqua) platforms
  - Clear-sky water vapour radiances from GEO (Met-5/8, Goes-9/10/12)
  - Level 1c IR radiances from NOAA-17 (HIRS) and AQUA (AIRS)
  - Level 1c μw radiances from NOAA-15 (AMSU-A), NOAA-16 (AMSU-A and AMSU-B), NOAA-17 (AMSU-B), AQUA (AMSU-A) and DMSP 13/14/15 (SSM/I)
  - Sea surface winds from scatterometers QuikScat and ERS-2
  - Ozone products from NOAA-16 (SBUV) and ENVISAT (SCIAMACHY)

Six different assimilations have been run for a period of more than two months (20041204 until 20050225), the first 12 days being merely used for warm-up and therefore excluded from the statistics:

- 4DVAR CONTROL
- 3DVAR CONTROL
- 3DVAR “surface pressure only”
- 4DVAR “surface pressure only”
- 3DVAR “surface pressure only” retuned (see explanation below)
- 4DVAR “surface pressure only” retuned (see explanation below).

In order to simulate a reduced ground surface observing system, the “surface pressure only” experiments consisted in assimilating surface pressure observations from the GCOS Ground System Network (GSN, see Figure 1) over land and Ships over sea (no buoys were assimilated). This resulted in roughly 950 observations assimilated in 3DVAR and 1300 observations assimilated in 4DVAR (where asynoptic data are fully exploited).

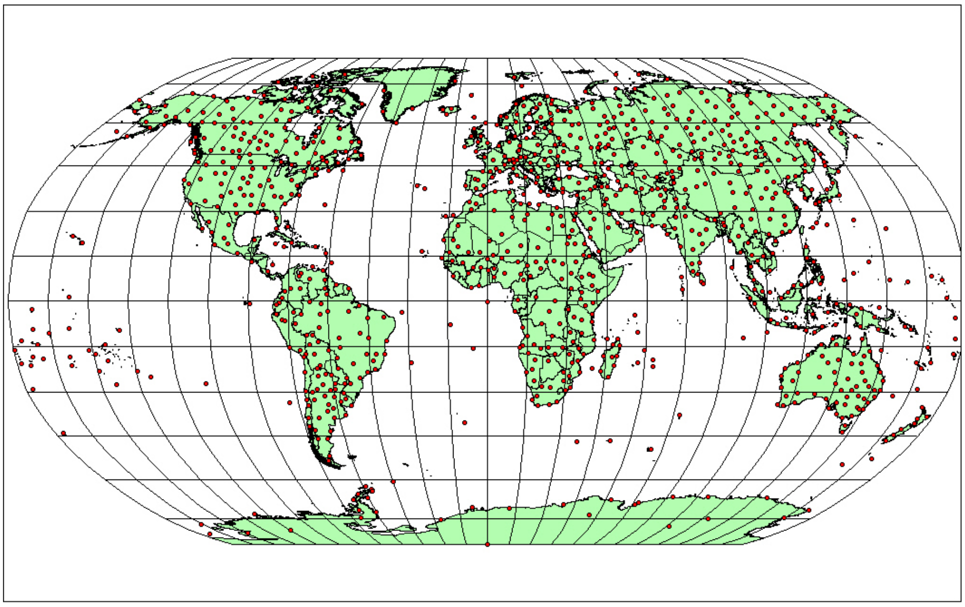

Figure 1: GCOS GSN surface network

3. Assimilation results

The 3DVAR and 4DVAR CONTROL experiments (using all available observations) turned out to be fairly similar in terms of analysis performance (the forecast skill being largely in favour of the 4DVAR CONTROL). For the sake of simplicity, the “surface pressure only” experiments have therefore been compared to the 4DVAR CONTROL (used here as the reference) thereafter.

3.1. Tuning of the 3DVAR and 4DVAR systems

To account for the simulated degradation of the Observing System, the background error covariances used in the assimilation have to reflect the poorer accuracy of analysis and short range forecast due to the sole use of a limited number of surface pressure observations. This tuning has been done objectively for the 3D and 4DVAR “surface pressure only” experiments in the following way:

- Surface pressure innovation statistics from the 3DVAR and 4DVAR "surface pressure only" experiments have been accumulated throughout the the assimilation period.
- The effective surface pressure background error variance has been accordingly computed (knowing the variance of the innovations and the observational error variance)
- A correction coefficient (tuning factor) has been applied so that the newly specified background error variance matches the effective one.

In principle, this procedure can be applied several times until convergence of the tuning factor. However, this was applied only once and considered as a good proxy for an optimal tuning of the "surface pressure only" assimilation experiments. A factor of $(2.7)^2$ (resp. $(2.0)^2$) had to be applied to the originally specified background error variance in the 3DVAR (resp. 4DVAR) experiments. Figure 2 represents the time series of the Northern Hemisphere Z500 hPa 24 hour RMS forecast error (verified against the operational ECMWF analysis) for the 4DVAR CONTROL, 4DVAR "surface pressure only", and 4DVAR "surface pressure only" retuned assimilation experiments. Whilst the CONTROL error is about 10m, retuning the covariances of the "surface pressure only" assimilation system reduces the error from 60-65 m to 40 m. Only the retuned experiments will be discussed thereafter.

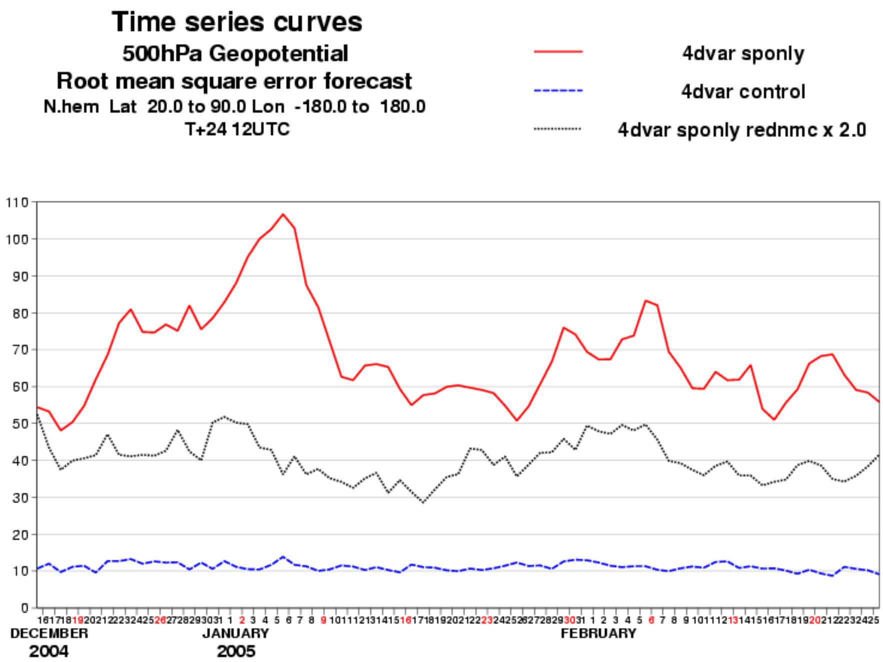

Figure 2: Time series of the Northern Hemisphere Z500 hPa 24 hour RMS forecast error (verified against the operational ECMWF analysis) for the 4DVAR CONTROL (blue dash), 4DVAR "surface pressure only" (red full) , and 4DVAR "surface pressure only" retuned (black dotted) assimilation experiments

3.2. Respective performances of 3DVAR and 4DVAR "surface pressure only" assimilation experiments.

The quality of the analyses and forecasts have been systematically compared between the 3DVAR and 4DVAR "surface pressure only" assimilation experiments. One of the main findings of this comparison is the outstanding superiority of 4DVAR over 3DVAR. Figure 3 represents the Z1000 hPa analysis field on 2005021500UTC for the CONTROL (top), 3DVAR (middle) and 4DVAR (bottom) "surface pressure only" experiments (the 4DVAR surface pressure observations assimilated in this particular cycle are represented as black dots). Over the pacific, the 3DVAR analysis underestimates the low located at the date line and misses a low west of the USA. The Mediterranean low is also largely underestimated by the 3DVAR analysis. Conversely, 4DVAR captures all the weather patterns present in the CONTROL, even in data void areas (e.g. pacific ocean).

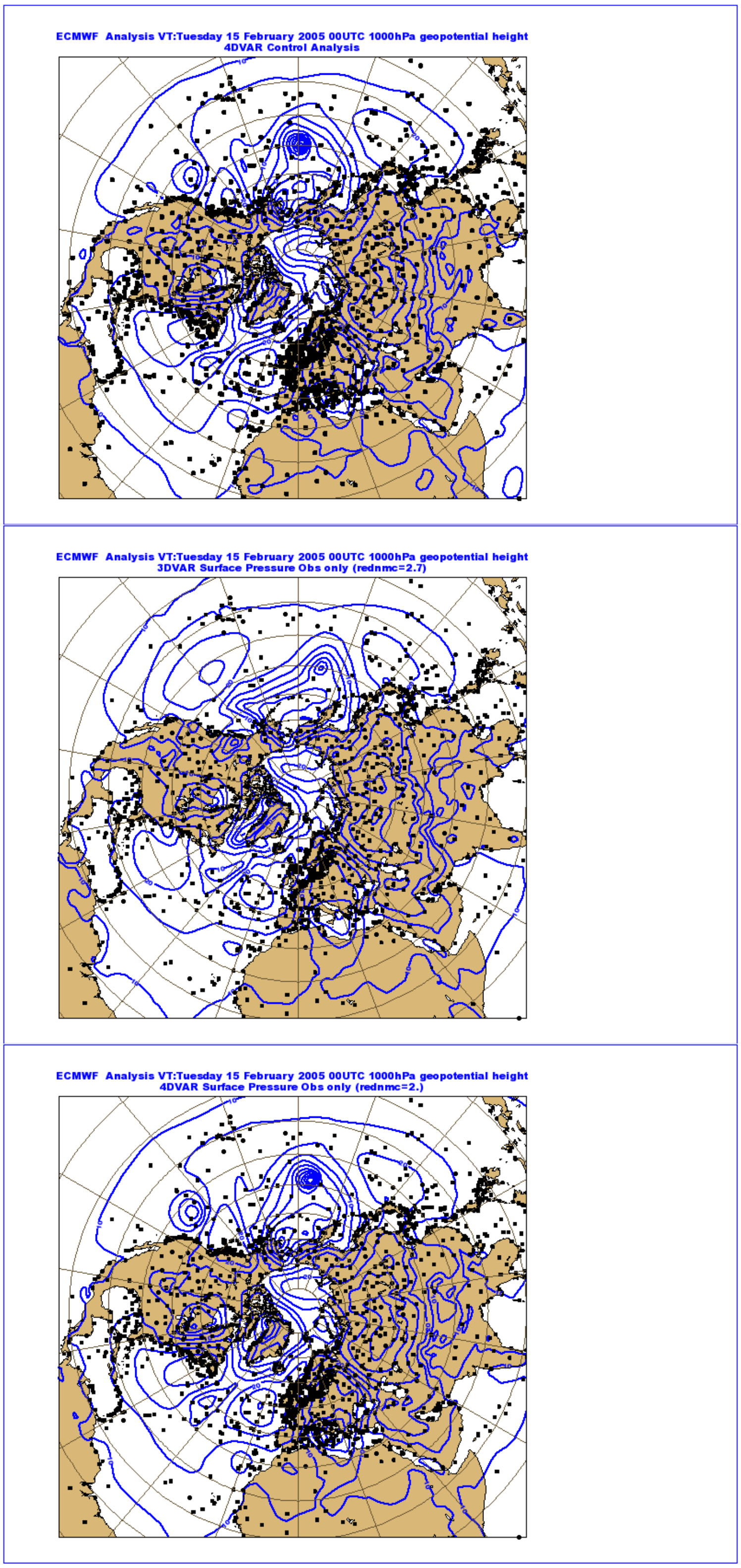

Figure 3: Z1000 hPa analysis field on 2005021500UTC from 4DVAR CONTROL (top), 3DVAR (middle) and 4DVAR (bottom) "surface pressure only" experiments

The difference of behaviour between 3DVAR and 4DVAR is even more spectacular at 500 hPa (see figure 4) and 200 hPa (not shown). The realism of the 4DVAR analysis as compared with the CONTROL analysis is quite remarkable, demonstrating the ability of 4DVAR to propagate information upwards in dynamically consistent way. In fact, by exploiting the time dimension of the surface pressure observations, 4DVAR actually extracts surface pressure tendency information and feeds this information back to the model dynamics.

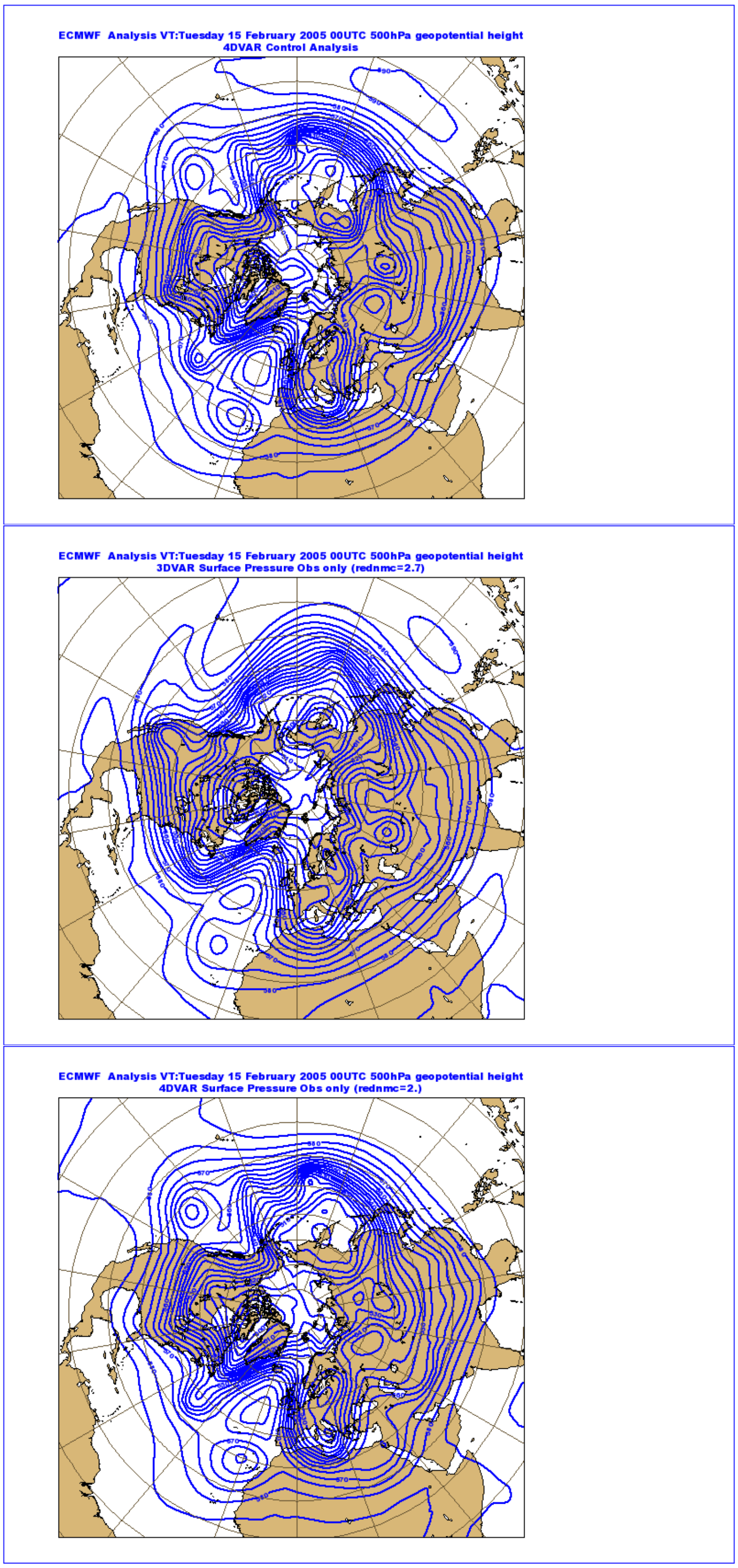

Figure 4: same as figure 3 but at 500hPa

The quality of the analyses at various levels, as expressed by the mean RMS analysis error (verified against 4DVAR CONTROL and expressed in meters), averaged over 72 days, is summarised in the table below, showing a reduction by a factor of 3 of the RMS analysis error in favour of 4DVAR:

	4DVAR "surface pressure only" retuned	**3DVAR "surface pressure only" retuned**
Z1000 hPa	10.4	38.3
Z500 hPa	30.4	104.3
Z200 hPa	51.7	151.1

In terms of forecast skill, it is worth noting that the quality of the 4DVAR "surface pressure only" 3 and 5 day forecast at 500 hPa is almost equivalent to the quality of the operational ECMWF forecast (at day 3 and 5 respectively)…back in 1981!

4. Conclusions

The main findings of the impact studies carried out and described in this paper can be summarised as follows:

- It is essential that the covariance statistics of an assimilation system represent correctly its quality. In the context of a substantially degraded Observing System, it turned out vital to inflate the background error variances accordingly. A similar tuning should be applied to long reanalysis experiments covering periods over which the Observing System is significantly modified. Ideally, an adaptive covariance model should be designed.
- In the presence of a reduced surface observing system (roughly $1/4^{th}$ of the current one), 3DVAR does not seem to provide sensible upper air analyses in the Northern Hemisphere. This finding is in agreement with Bengtsson et al., 2004). However, a more advanced assimilation scheme such as 4DVAR, when properly tuned, is able to extract and transfer information from data full to data void areas in a dynamically consistent way, providing reasonable mid to upper tropospheric analyses and short range forecasts. The quality of the 4DVAR analyses using a reduced ground station network is equivalent to the quality of a one day forecast in the low troposphere and three day forecast in the UTLS obtained with the current ECMWF NWP system.
- The results obtained in these OSEs confirm Compo et al. (2006)'s findings in that there is probably scope to reanalyse past periods when only surface observations were available (e.g. early 1900s), provided the assimilation system is "dynamical" enough (4DVAR or Ensemble Kalman Filter) and adequately tuned towards past observational coverage and quality. However, to be fully convincing, the experiments presented above should be more directly tailored towards an Observing System representative of the first half of the 20^{th} Century (Compo et al 2006), in particular to evaluate the breaking point beyond which a sensible meteorological analysis becomes impossible.

5. References

Bengtsson, L., S. Hagemann and K. I. Hodges, 2004: Sensitivity of the ERA40 reanalysis to the observing system: determination of the global atmospheric circulation from reduced observations. *Tellus*, **56A**, 456-471.

Compo, G., J. S. Whitaker, and P. D. Sardeshmukh, 2006: Feasibility of a 100-Year Reanalysis Using Only Surface Pressure Data.. *Bull.Americ.Meteor.Soc.*, **87**, 175-190.