

Data Assimilation for Atmospheric Reanalysis

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Abstract

This paper is a summary of a lecture given at the ECMWF Annual Seminar 2011 on Data Assimilation for Atmosphere and Ocean. It is not a comprehensive review of atmospheric reanalysis, and does not cover regional or specialized topic reanalyses (such as a reanalysis of atmospheric constituents and chemistry). The major element of difference between this lecture and others presented during the course of the Seminar is the constant, particular attention that reanalysis needs to give to the treatment of the time dimension. Reanalyses strive to produce datasets that are time-consistent, while at the same time trying to improve our understanding of discrepancies between observations and Numerical Weather Prediction (NWP) models by incorporating as many observations as possible. This makes it difficult to achieve both goals but allows for successive improvements. At the same time, the growing use of reanalysis for climate studies seems to indicate that the first objective remains feasible, even if it is not yet attained for all geophysical variables.

After a brief review of reanalysis products and applications, we present selected results from the data assimilation in ERA-Interim, insisting on the importance of biases. Plans for reanalysis activities at ECMWF are summarized. We present ongoing investigations for the preparation of the data assimilation system to be employed in a 20th century reanalysis assimilating only surface pressure observations, in the same fashion as done by Compo et al. (2011) with the 20th Century Reanalysis. We review the experiments conducted so far to study the impact of using such a “degraded” observing system and present results of various 24-hour four-dimensional variational (4DVAR) assimilation experiments, compared with 12-hour 4DVAR as used by ERA-Interim. Finally, our conclusions point to missing ingredients to bridge the gap between “NWP reanalysis” and “climate reanalysis”.

1. Introduction: Time, the fundamental concern in reanalysis

From the early days of operational Numerical Weather Prediction (NWP), meteorologists and atmospheric physicists alike have attempted to use the analyses produced by NWP systems over long time periods to better understand the atmosphere, its variability and its predictability. However, because of NWP upgrades every few months (resolution, parameterization, etc...), the output of such systems over several years may be, at best, marginally discontinuous in time, or, at worst, not available for study; for example some variables only started being analyzed at some point in time (such as ozone; others are still being added such as cloud condensates). These changes have also been suggested to present some interest for weather modellers in order to better understand how the changes they make to the NWP systems improve the NWP results.

Consequently, it is no surprise that the concept of reanalysis was invented nearly at the same time as NWP took off. The First GARP (Global Atmospheric Research Program) Global Experiment (FGGE), in 1979, collected observations that were reanalyzed a posteriori for several years, to

initialize models, compare performance and track progress in NWP modeling and data assimilation. Reanalyses were then proposed to study:

1. how changes in any component of NWP (observation usage, resolution...) affects the quality of NWP forecasts
2. the atmospheric variability and its predictability, by providing datasets in which the geophysical variables, even if not completely observed, are constrained by a model to be balanced and to follow known physical relationships.

Obviously these two goals are somewhat contradictory in nature, and this still triggers debate today as to the intrinsic capabilities of reanalyses. Today global reanalyses of the atmosphere are conducted at various centers in the world, usually relying on infrastructure that is spun off NWP. In spite of this apparent similarity with NWP practice, the major difference is that, once a reanalysis system is built, it is held invariant for several years – for the goal of producing a dataset that is as much as possible consistent in time, and presents value for studies covering several years or decades. In all of this, time is the crucial element that sets reanalysis different from NWP.

Depending on context, the word “reanalysis” is typically employed to refer to reanalysis products, or reanalysis process. The reanalysis process very much resembles the NWP process (differences are in parentheses): integration of a modern (and invariant) version of a data assimilation system and numerical weather prediction model, (over a long time period,) assimilating a selection of observations. The outline of the paper is as follows. Section 2 presents reanalysis products and applications. Section 3 expands on the reanalysis process with an emphasis on data assimilation results from ERA-Interim (Dee et al., 2011). Section 4 presents plans for reanalyses at ECMWF. Section 5 includes a selection of recent developments, with a focus on the preparation of a 20th century reanalysis that would assimilate only surface pressure observations in the same fashion as the 20th Century Reanalysis project (Compo et al., 2011). Section 6 presents conclusions.

2. Reanalysis products and applications

Although we do not draw here a comprehensive list of all reanalysis products, the following short history of reanalysis may serve as a quick look-up reference. In the 1990s, the first-generation comprehensive global reanalysis products (generated by optimal interpolation assimilation schemes) were: the NASA/DAO reanalysis (1980 - 1993), the NCEP/NCAR reanalysis (1948 - present), also called NCEP-1 reanalysis, and the ECMWF ReAnalysis (ERA) ERA-15 reanalysis (1979 - 1993), with significant funding from USA. In the mid 2000s, second-generation reanalysis products (based on three-dimensional variational (3DVAR) assimilation schemes) were: the JRA-25 reanalysis (1979 - 2004) from Japan, the NCEP/DOE reanalysis (1979 - present), also called NCEP-2 reanalysis, and the ERA-40 reanalysis (1958 - 2001), with significant funding from EU FP5.

Today, third-generation of comprehensive global reanalyses products (generated by data assimilation schemes improved as compared to 3DVAR) are: the NASA/GMAO MERRA reanalysis (1979 - present, using Incremental Analysis Update), the NCEP CFSRR reanalysis (1979 - 2008, with land, ocean, and ice coupling), the JRA-55 reanalysis (1958 – 2012, using a 4DVAR assimilation), the 20-CR reanalysis (1871 – present, using an Ensemble Kalman Filter, assimilating only surface pressure observations), and the ERA-Interim reanalysis (1979 – present, using a 4DVAR assimilation).

The currently ongoing reanalysis at ECMWF, ERA-Interim (Dee et al., 2011), was originally intended to cover the years from 1989 to 2008. Since 2009, it has been updated monthly into the present, thus attracting users interested in a dataset covering climate time-scales and that is extended in near-real-time. In 2011, ERA-Interim was also extended back to 1979.

The products of a reanalysis typically include:

- gridded fields of model variables (control, or derived): for example, vorticity, temperature, humidity, but also precipitation, radiation,...
- fit of these fields to observations (so-called observation feedback), before and after assimilation and bias-correction (when applicable).

Because the first type of products present regular shapes (gridded data, without gap in either of the four spatio-temporal dimensions), they are the most popular with users. For example the number of users of the ECMWF ReAnalysis (ERA) data server exceeds 12000, and the gridded fields of ERA-40 and ERA-Interim have been copied to several national websites.

Reanalysis users operate in many diverse fields, such as disaster damage evaluation (insurance) and prevention, health management, water and energy resources management, biodiversity and ecosystems research and management, and food resources management and agriculture. The convenience of gridded fields allows non-experts outside the meteorological community (government, academia, industry) to use these data for their particular applications, whenever those present weather or climate exposure.

Beyond the typical applications listed above, reanalyses are increasingly used in weather studies, but also climate studies. For example, the Annual State of the Climate (published by the American Meteorological Society and the US National Oceanic and Atmospheric Administration, NOAA) now includes reanalysis datasets to show global anomalies.

3. Reanalysis process: focus on data assimilation, with examples from ERA-Interim

At the core of the reanalysis process is the determination of the analysis on any given day and time, given:

- a previous estimate provided by a short-term forecast (background),
- observations (with quality control rules),
- error assumptions about both of the above.

The optimal combination of this information is realized inside a data assimilation system. ERA-Interim uses a four-dimension variational (4DVAR) assimilation, with variational bias correction of satellite radiance brightness temperature observations. The quality control rules vary over time to include for example the so-called blacklisting of satellite instruments when they have degraded beyond acceptable standards.

The determination of this “best analysis estimate” employs the same technique as described in several lectures of the Seminar (for example, see lecture by J. Derber). It is not repeated here. Instead, we insist on the aspects that are different in reanalysis as compared to NWP.

First, because a reanalysis tries to cover several decades in a reasonable amount of time, it cannot employ the best/latest model resolution available. Instead, global reanalyses tend to use (approximately) ten- to fifteen year-old resolution configurations. For example, ERA-Interim, started in 2006, uses a horizontal resolution of 80 km (truncation T255), which is close to that used by operational NWP at ECMWF in the early 1990s.

Second, the data assimilation system (and model) is held invariant for the duration of the reanalysis. This implies that before starting a reanalysis one must include all that is needed observation-wise such as a blacklist that covering the entire reanalysis period, observation operators for all satellites whose data are to be assimilated, thinning rules, and observation error specifications for all observation types to be assimilated. An illustration of the complexity that this entails is given in Figure 1a, where all the satellite radiometers assimilated in ERA-Interim are listed. Monitoring all these observing systems requires to develop innovative solutions (integrated data supply chain) that allow users to visualize quickly, as a reanalysis runs, the amount (and characteristics) of the various types of data being assimilated.

Figure 1b shows a time-series of observation minus background departures for radiosonde temperatures assimilated in ERA-40. In the Northern Hemisphere (NH, between latitudes 20oN and 90oN), the statistics appear to be stable (though with seasonal variations) between July 1977 and January 1982. However, in the Southern Hemisphere (SH, between latitudes 20oS and 90oS), a great improvement is visible around the beginning of the year 1979, related to the assimilation of observations collected by the first operational infrared and microwave vertical sounder suite (TOVS) onboard a satellite (TIROS-N). This jump illustrates that the quality of short-term forecasts (backgrounds) improves over time in reanalysis with changes in the observing system. The data assimilation scheme should ideally account for such improvement, by using background error covariances that are spatially and temporally varying.

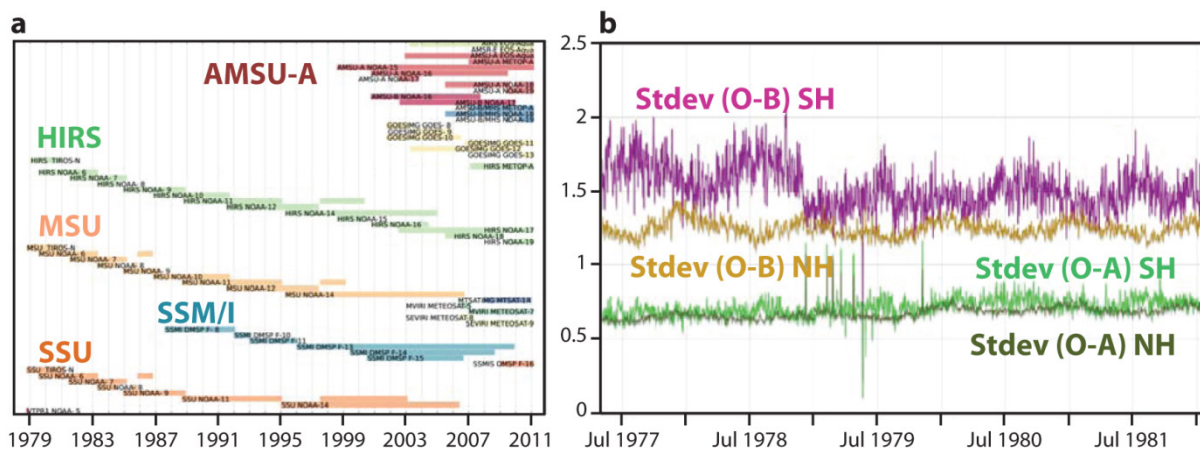


Figure 1: (a) time-lines of satellite instruments providing radiances that were assimilated in ERA-Interim (1979-2011); (b) time-series of ERA-40 standard deviation (Stdev) of observation (O) minus background (B) and analysis (A) departures (in K), for radiosonde temperature observations at 500 hPa (July 1977-January 1982)

Third, particular attention should be given to handle biases in observations and in the model. The reason is that varying amounts of observations (even if they have a constant bias) will result in analyses featuring varying biases. The same problem characterizes varying amounts of observations (even unbiased) assimilated in a biased model. In both cases the analysis will retain some of these biases and the mean characteristics of the resulting reanalysis products will change over time. This can affect the climate signal represented in reanalysis products. In fact, if left unchecked, this “pollution” of the climate signal can go to the extent that the reanalysis may not be trusted at all to characterize long-term trends for some geophysical variables.

Algorithms for observation bias correction should have, as much as possible, sound underlying physical foundations. ERA-Interim uses for example an instrument type-dependent radiation correction as well as homogenization correction for radiosondes (Haimberger and Andrae, 2011), and a variational bias correction for satellite radiances where the predictors resemble those used as input to the radiative transfer model (Dee and Uppala, 2009).

Last, keeping a data assimilation system to a frozen version for several years is no easy feat, but represents merely a technical challenge. In doing, so one difficulty is to retain a backward-compatibility so as to be able to re-run any past date if needed. Furthermore, continuing a reanalysis into the present time (as in ERA-Interim) implies to back-phase new developments in order to be able to use new satellites and to remain capable of using current computer infrastructure.

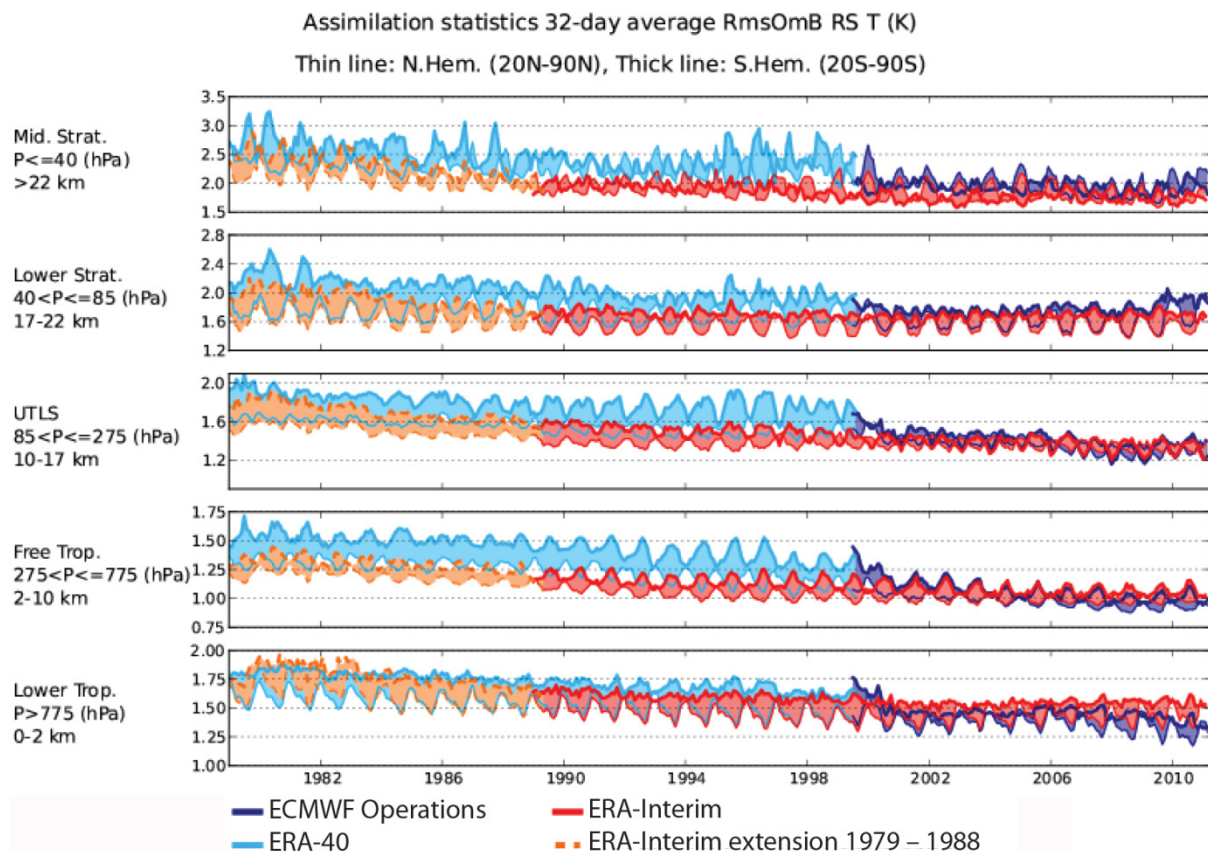


Figure 2: Time-series of observation minus background departures from ERA-40, ECMWF operations, and ERA-Interim (1989-onward stream, and extension 1979-1988, with some overlap in the first months of 1989 to show overall good agreement), for radiosonde temperatures that were assimilated

One way to monitor the spatio-temporal consistency of reanalysis products is to inspect time-series of observation minus background departure statistics. Figure 2 shows the root mean square (RMS) of radiosonde temperature departure statistics, grouped in five broad vertical layers, for the NH and SH regions.

The separation in Figure 2 between the original ERA-Interim production (1989-onwards) and its extension (1979-1988) enables to check the agreement in the match in year 1989 for the levels up to the lower stratosphere. The agreement appears virtually excellent between the surface and the tropopause layers.

However, looking closely, one can see some differences of the order of 0.2 K in the lower stratosphere and above. This small mismatch on 1 January 1989 in the stratosphere is studied in Figure 3 by looking at the bias corrections estimated adaptively by ERA-Interim for a satellite sounding channel peaking in the lower stratosphere (namely, Microwave Sounding Unit -MSU- channel 4). For this exercise the extension run was in fact prolonged by a year to verify the convergence with the earlier production. After a few months, the differences drop to 0.05K and within a year they have completely disappeared. This suggests that the stratosphere takes a long time to reach equilibrium in the ERA-Interim configuration. For future reanalyses, it would seem that a production in multiple streams would be more continuous in the stratosphere with a spin-up of at least 3 months between the various production runs.

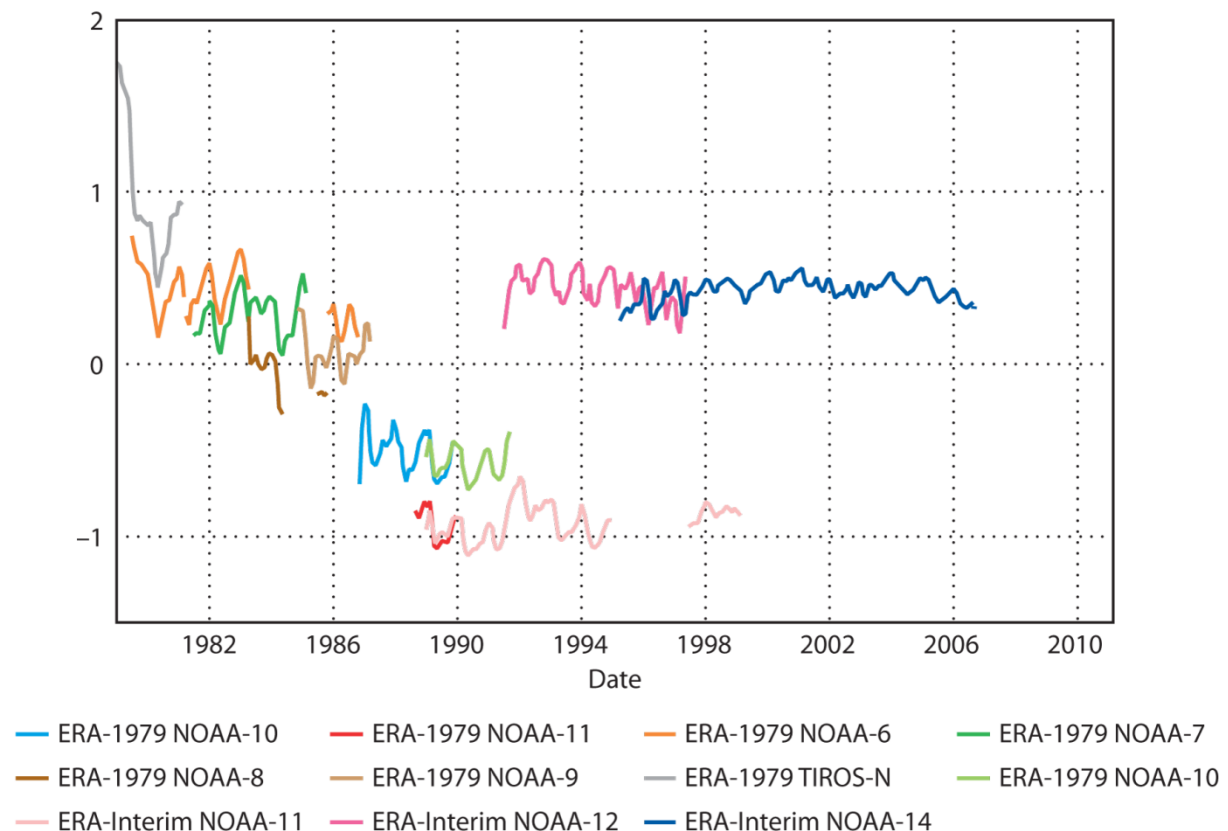


Figure 3: Time-series of mean bias corrections (in K) for MSU channel 4 (peaking in the lower stratosphere) as estimated by ERA-Interim. In the legend, 'ERA-1979' refers to the extension stream (started on 1/10/1978), while 'ERA-Interim' refers to the original production stream (started on 1/12/1988).

A diagnosis of time inconsistency in reanalysis is provided by time-series of analysis increments in model space. If all the hypotheses of data assimilation were true (unbiased model errors, and observation biases removed) the mean increments would be, on average, zero. Figure 4 shows that these hypotheses must not be true, for the mean increments in temperature in the Tropics (region defined by latitudes ranging between 20 degrees South and 20 degrees North) are far from zero-mean, and also vary by altitude and time, in amplitude and sometimes in sign. The largest feature in the stratosphere (Figure 4a) is the switch in 1998 from consistently negative increments (magnitude of about -1.5 K) to near-zero mean increments. This results in a change in the mean analyzed temperatures shown in Figure 4c at the same time; such discontinuity is typically one that users of the gridded reanalysis products would notice and be bothered by. The reason for this abrupt change in behavior is the switch from using uncorrected brightness temperatures from the Stratospheric Sounding Unit (SSU) channel 3 to use as references at the top of the model to using the Advanced Microwave Sounding Unit-A (AMSU-A) channel 14 for the same purpose. In fact, Kobayashi et al. (2009) identified limitations in the radiative transfer model used to simulate SSU observations, by not properly accounting for changes that affected the SSU instrument over time (pressurized cell leaked, subsequently losing pressure). Improving the time consistency of the reanalysis record in this example requires to fix the sources of bias in the assimilation process, i.e., here an observation operator bias.

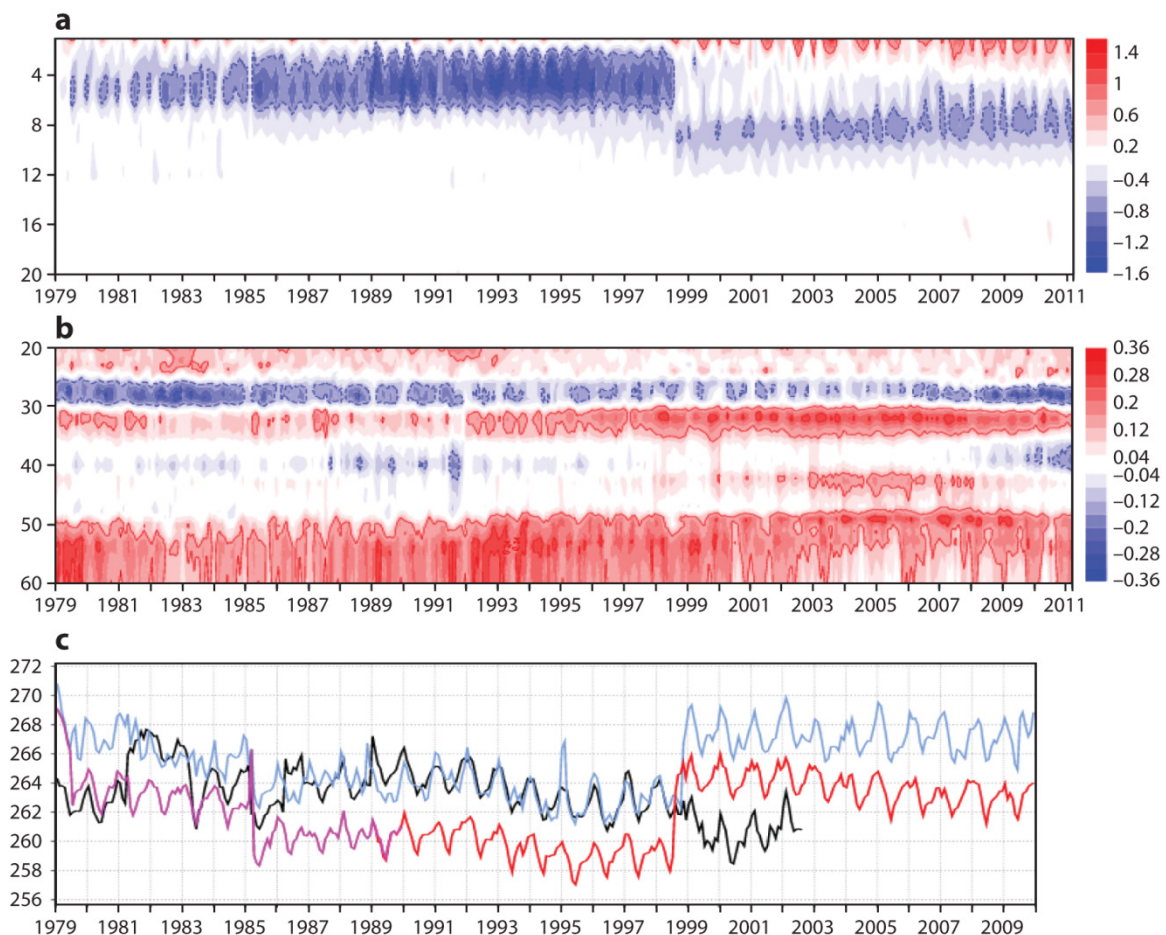


Figure 4: (a) Contours in time (horizontally) versus height (vertically) of analysis temperature increments for model levels 1 to 20 (approximately pressure level 0.1 hPa or 65 km altitude to pressure level 35 hPa or 23 km altitude, respectively) in ERA-Interim. (b) like (a), except for model levels between number 20 and the surface. (c) Time-series of ERA-Interim temperature analyses at 1 hPa (approximately model level number 5).

At other levels, such as near the tropical tropopause (model level number 28 in Figure 4b), one can see evidences of consistently negative biases indicating that the model tropical tropopause is consistently predicted as being too warm and observations act to correct this feature. These corrections vary over time. The strongest increments are applied when the observing system is the most complete (towards the end of the record). This is an example of model bias modulated by varying amounts of observations acting to correct this bias. The only proper solution to this problem would be to fix the bias in the model (aerosol forcing bias? radiation bias? gravity wave parameterization? other?). Until then, other solutions may be applied to mitigate the effect of such model bias on the reanalysis products. One solution would be to include additional degrees of freedom in the analysis to determine the most likely model errors, using for example a weak-constraint 4DVAR formulation (Trémolet, 2007).

4. Future plans for ECMWF reanalysis

Activities on reanalysis at ECMWF aim to provide the European capability to carry out regular global reanalyses to be continued in near-real-time, to serve the future Climate Services of Global Monitoring of Environment and Security (GMES). The idea is to build such capacity on previous investments already made by European countries in the meteorological infrastructure and capabilities, such as the ongoing continuous improvements in models. The European modelling community contributes via the ECMWF Integrated Forecasting System (IFS), which is to be opened in the near-future to the wider European research community (Open-IFS project).

Observations to be assimilated in reanalysis should include in situ weather observations recovered by national meteorological services from their long archives (reaching back to the 19th century in some cases), as well as observations reprocessed from satellite records (from EUMETSAT and ESA, as well as from other satellite agencies outside Europe).

To achieve all this, capacity building is ongoing under the auspices of a project funded by the European Union Framework Programme-7 (EU FP7). This project, called ERA-CLIM, involves nine partners, including two partners from countries outside Europe (Russia and Chile). The workplan includes: an ambitious data rescue effort, with a focus on upper-air observations such as from radiosondes before they were regularly exchanged on a regular basis after 1957, the reprocessing of selected important satellite datasets by EUMETSAT, the development of a user-friendly observation feedback data server and browser, and finally the production of two pilot reanalyses: a replacement to ERA-Interim (covering the satellite data-rich time period since 1979, probably an ensemble at horizontal resolution T511 or approximately 40 km), and a pendant of Gil Compo's 20th century reanalysis assimilating only surface observations, tentatively called "ERA-20C".

The development of a user-friendly interface to access the ECMWF reanalyses observation feedbacks will surely represent a major advancement for data assimilators, because such data are currently very difficult and time-consuming to access. They remain consequently so far largely under-exploited. It seems reasonable to foresee that such development could also benefit researchers trying to improve observation usage in operational NWP as well as assist satellite agencies better monitor the performance of their instruments or understand long-term behavior by having direct access to such observation feedback. Finally, such tool would open the possibility for the whole research community

(including academia) to download content in a simple form that allows to conduct various studies, whether that be for educational or research.

5. Data assimilation system for ERA-20C

As indicated above, the ERA-CLIM project includes the production of a 20th century reanalysis assimilating only surface observations (ERA-20C). While it is not clear whether we will have a consolidated observations input dataset for many geophysical variables (pressure, temperature, humidity, wind...), we can already benefit from the International Surface Pressure Databank (ISPD). Assimilating surface pressure observations will assist to determine the atmospheric circulation in the lower troposphere.

Various aspects of the data assimilation systems have to be configured to optimally conduct this century-long reanalysis. They are reviewed below.

5.1. Resolution

The production window of ERA-20C is 1 year. Reanalyzing 100 years in 1 year in a single, continuous production stream would require a production speed target of 100 days/day. This implies a low resolution, which we estimated cannot exceed T159 in the horizontal (approximately 125 km), unless we are prepared to split the production into several parallel streams.

Such horizontal resolution means that a model timestep of 1 hour is sufficient, instead of 30 minutes for the T255 resolution employed for ERA-Interim. This generates further additional computing savings. Further savings are also found by aligning the length of 4DVAR timeslots to that of the model timestep (again, instead of 30-minute-timeslots in ERA-Interim).

The analysis (4DVAR) is to be conducted with two minimizations, both at T95 resolution. The first analysis requires 35 iterations to generate a background error covariance matrix (randomization method), while the second minimization (also at T95) may be stopped as soon as convergence is reached.

5.2. Bias correction

A variational bias correction scheme for surface pressure observations has been developed. The groups of data to be corrected are identified by station name (for ships), location (for fixed stations), and pressure reporting practice (station level or sea level, as was more common before the 1980s).

This new bias correction scheme runs within the analysis, allowing observations to be converted from so-called “BUFR” format to the format that the assimilation system can ingest (called “ODB”) ahead of time, without waiting for the previous analysis to finish.

The new bias correction scheme reproduces the behaviour of the current scheme for surface pressure observations as now used by ECMWF Operations (Vasiljevic, 2005), except that all stations get corrected (instead of only those with large biases), and time variations are subject to a greater stiffness to avoid unrealistic changes in estimated biases. Figure 5 illustrates that the estimations from both

bias correction schemes are consistent with one another, though the variational bias correction scheme presents smaller time variability.

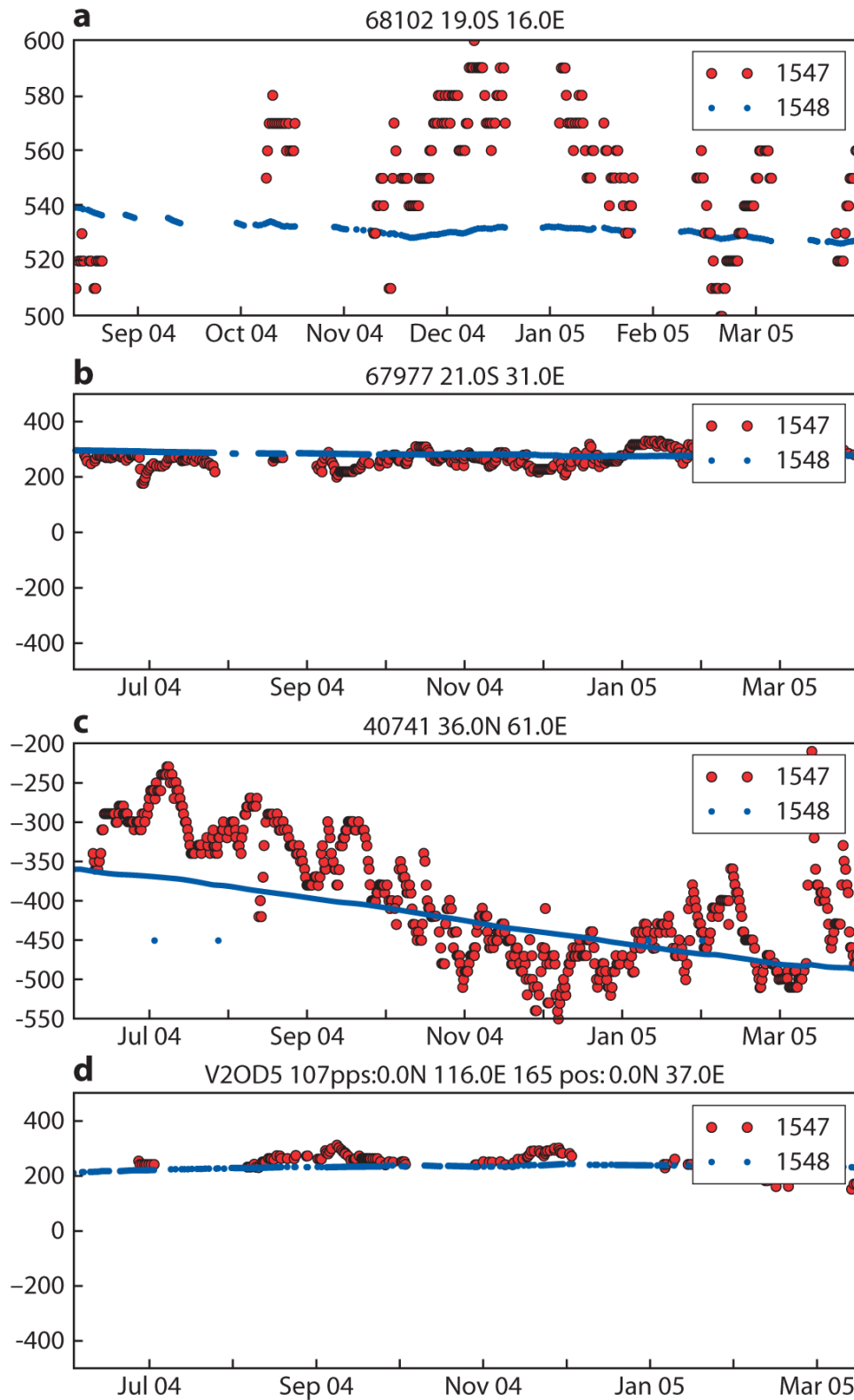


Figure 5: Time-series of bias corrections (in Pa) for surface pressure observations at four selected stations in remote areas: (a) Namibia, (b) Zimbabwe, (c) Iran, (d) a 168-meter cargo ship sailing the tropical seas. Red dots: current operational bias correction scheme; blue dots: variational bias correction scheme.

5.3. Surface-pressure-only assimilation

A next logical step in the preparation of the data assimilation system for ERA-20C is the determination of the quality of the products to be expected from surface-pressure assimilation. Figure 6 shows time-series of temperature forecast Root Mean Square Errors (RMSE) from a reference experiment (configured to reproduce ERA-Interim, at T255 resolution, assimilating all types of observations) and from a surface-pressure-only experiment at T159 resolution, verified against the operational analysis at the time, for forecasts at days 3 and 6. In the Northern Hemisphere extratropics (NH), the accuracy of a 6-day forecast from the fully observed reanalysis is as good (in a RMSE sense) as that from a 3-day forecast from the surface-pressure-only reanalysis. This indicates an equivalent loss of forecast skill of 3 days by withdrawing all observations other than surface pressure in the assimilation.

Approximately the same result is observed in SH (Figure 6b), though with greater accuracy loss. This is consistent with the greater scarcity of in situ observations in the Southern hemisphere, and the greater reliance on satellite data to get a good forecast and reanalysis in that region.

At the 200 hPa pressure level (Figure 6c), the first few days of the time-series exhibit an increase of forecast errors in the surface-pressure-only reanalysis. It looks like the assimilation system loses the memory of the background stratosphere within about 1-2 weeks. After that, the level of error is quite higher than in the fully observed reanalysis. There remains a gap between the 3-day and 6-day forecast RMSEs, indicating that the data assimilation system still produces an initial state that is good enough to generate better forecasts at day 3 than at day 6.

At the 100 hPa pressure level (not far above, but in fact above the tropopause, Figure 6d), the picture is quite different. The level of noise has jumped to much higher levels, and the RMSE of a 3-day forecast is about the same as the RMSE of a 6-day forecast, indicating that there is no forecast skill at in the system, which produces its own variability independently of the forecast lead time. In February 2005 we also see the trace of a sudden stratospheric warming event, apparently largely missed by the surface-pressure-only reanalysis (RMSE up to 10 K). This seems to indicate that in the stratosphere the surface pressure observations alone are insufficient for the analysis to generate a temperature structure consistent with observations.

Although in a different region, we find about the same conclusion for the whole of the Tropics (only shown here: near-surface, Figure 6e). Yet, the reasons are different; there is no geostrophic balance at the Equator and the information content of surface pressure observations for constraining the circulation becomes thus negligible; the temperature structure in that region is dominated by a radiative-convective equilibrium, to which surface pressure observations are not able to add in realism.

Overall we may conclude from this simple pair of experiments that a surface-pressure-only reanalysis may produce stratospheric and tropical temperature fields that will be more representative of model variability than of observed variability; greater realism will mostly be found in tropospheric temperatures in the well-observed areas.

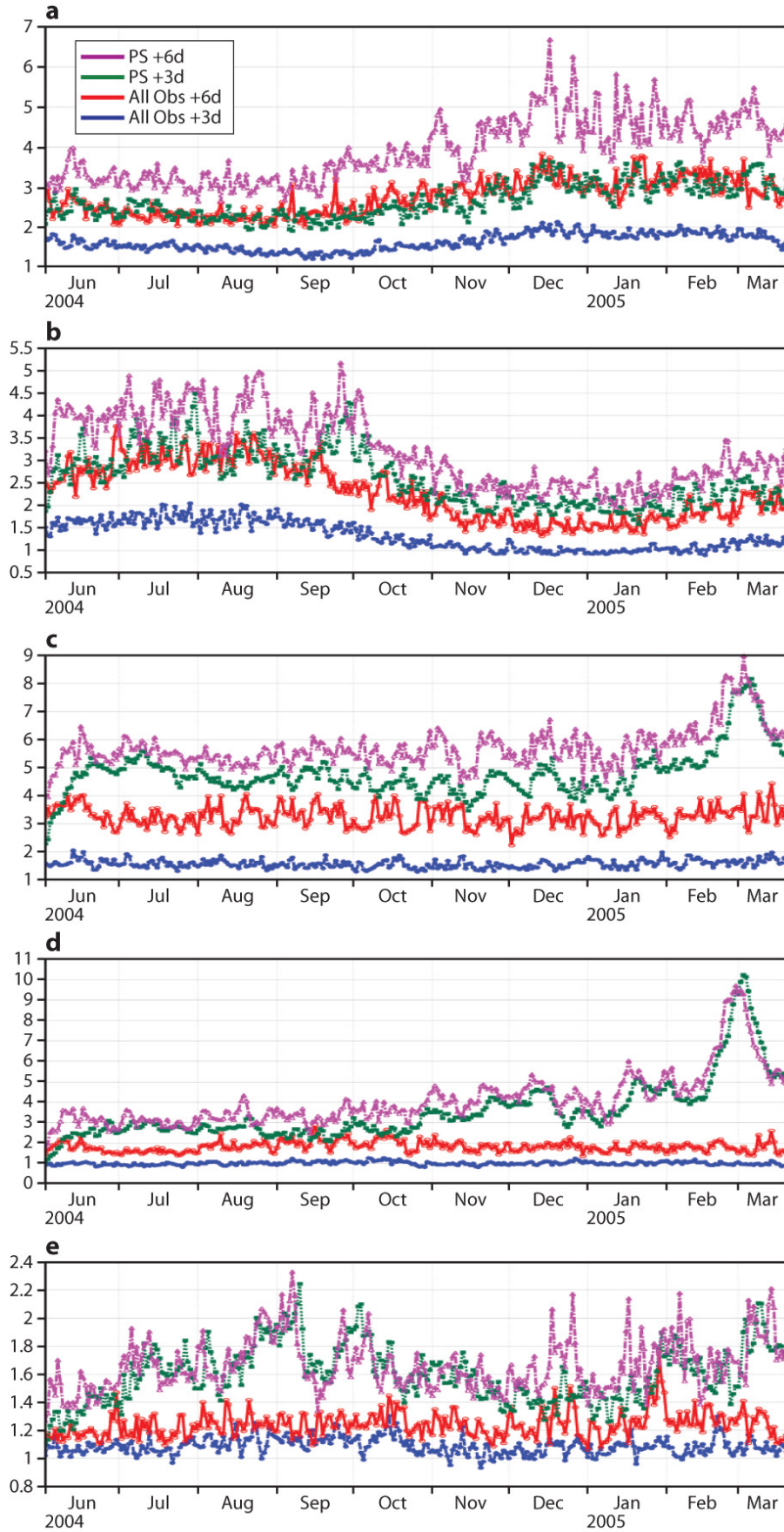


Figure 6: Temperature forecast RMSE (a) 1000 hPa Northern Hemisphere (NH), (b) 1000 hPa Southern Hemi., (c) 200 hPa NH, (d) 100 hPa NH, (e) 1000 hPa Tropics.

5.4. Retrospective analysis: 24-hour 4DVAR

One particularity of reanalysis is the retrospect knowledge of the truth (as reported by observations). This information is unavailable to operational NWP where observations of the future are unknown. Such information can be used in a retrospective analysis to generate analyses that best fit observations close to the analysis time as well as after the analysis time.

In a variational data assimilation framework, one can take advantage of this by extending the length of the assimilation window. Y. Trémolet at ECMWF has made modifications to the baseline version of IFS to allow 24-hour windows, instead of the standard 12-hour window, such as used in ERA-Interim. The rest of this section reports on experiments that were conducted to explore this possibility, with a low-resolution surface-pressure-only configuration.

Figure 7 shows four possible configurations of 4DVAR windows for ERA-20C. The 12-hour configuration relies on a background drawn from a 3-hour forecast, extending until 15 hours forecast lead time. The 24-hour configuration also relies on a 3-hour-old forecast, except it extends until 27 hours. In the overlapping 24-hour configuration, each observation set is analyzed two times: the first time in conjunction with a background that is a 15- to 27-hour- forecast, and the second time with a background that is a 3- to 15-hour-forecast; it is important to note that this second forecast is in fact initialized from an analysis that was determined the first time, having already used this set of observations, and so comparisons between observations and this second background are more like comparisons between observations and the last trajectory of the first analysis. Finally, a last configuration is considered, where each 4DVAR consists of one minimization only (instead of two), in order to benefit from the fact that all observations are already considered twice as indicated just before, and to reduce the computing cost.

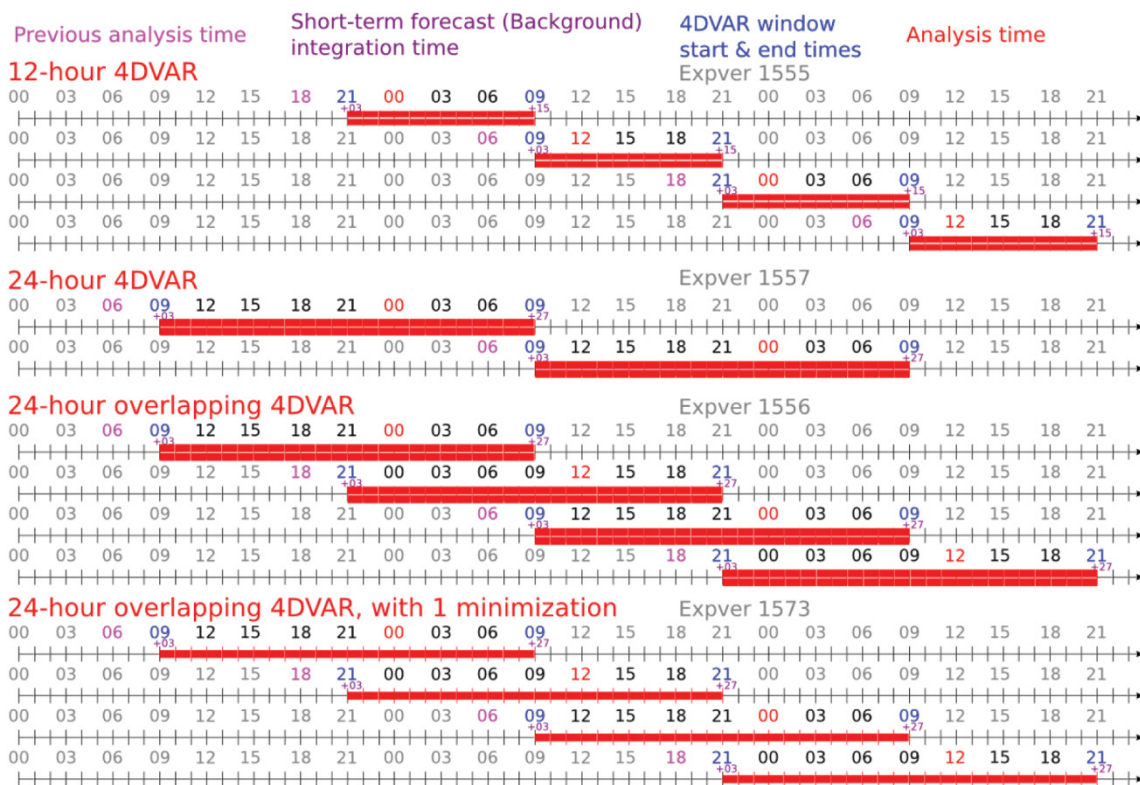


Figure 7: Configurations of the 4DVAR windows considered for ERA-20C

Each of the above experiment was conducted for several months, starting on 1 June 2004. We now show results of the fit of the background to observations calculated over the time period 1 June 2004-31 July 2004. Figure 8 shows time-series of standard deviation of observation minus background for all assimilated surface pressure observations, as a function of the 4DVAR timeslot forecast lead time. In the first few timeslots (up to 6 hours), the 12-hour 4DVAR background better fits the observations than the 24-hour 4DVAR background, very likely because the analysis from which the 24-hour 4DVAR background is drawn is degraded as compared to which the 12-hour 4DVAR background is drawn. However, the 12-hour 4DVAR background errors grow faster than those of the 24-hour 4DVAR and at some point the curve for 12-hour 4DVAR crosses that of the 24-hour 4DVAR, so that the 24-hour 4DVAR background better fits observations at forecast lead times 6-12 hours. This is probably because fitting observations over a longer window (24 hours instead of 12 hours), may help to better capture information related to large scale circulation; this possibly translates into a better forecast capability beyond 6 hours. Another way to consider this is that the 24-hour 4DVAR may project the information that it extracts from observations onto lower wave-numbers than the 12-hour 4DVAR.

For forecast lead times 12-24, the overlapping 24-hour 4DVAR background better fits the observations than the other two experiments do for forecast lead times 1-12. This indicates a clear superiority of the overlapping 24-hour 4DVAR analysis since it generates forecasts that appear more consistent with observations before they are assimilated.

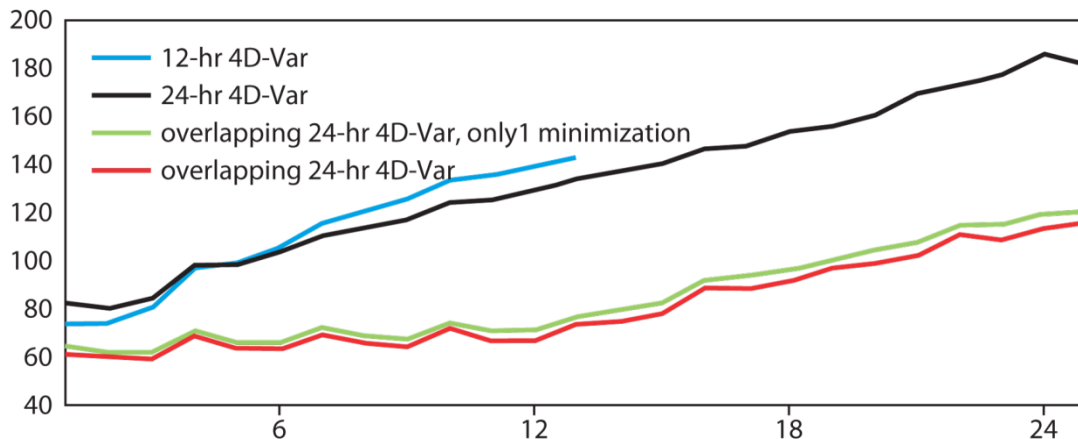


Figure 8: Standard deviation of observation minus background departures (in Pa), for assimilated surface pressure observations, as a function of 4DVAR timeslot forecast lead time (in hours)

The cost of the various 4DVAR configurations explored here is reported in Table 1. In terms of cost, the most promising option for a fast ERA-20C production would be the 24-hour 4DVAR (non-overlapping, with 2 minimizations).

4DVAR configuration	12-hour	24-hour	24-hour, overlapping	24-hour, overlapping, 1 minimization
Production speed	36 days/day	52 days/day	26 days/day	33 days/day

Table 1: Reanalysis production speed that can be achieved using the four different 4DVAR configurations explored in this paper, for surface-pressure-only experiments at T159 resolution (T95 analysis, 1 hour timestep)

Reduced observing system experiments offer other ways to diagnose the performances of data assimilation system configurations, e.g. by inspecting the fit to non-assimilated observations. Figure 9 shows the fit of the background (and analysis) drawn from the 12-hour and 24-hour 4DVAR configurations to non-assimilated meridional winds from radiosondes and temperatures from aircraft in selected areas.

Figure 9 indicates that tropospheric analyses better fit the observations than the background in a standard deviation sense, even though those observations were not assimilated. As expected, this indicates some redundancy (or consistency) between information extracted from surface pressures and from tropospheric temperatures and winds. Figure 9 also shows that the 24-hour 4DVAR backgrounds and analyses fit the observations better than the 12-hour backgrounds and analyses, in a standard deviation sense. This suggests that using a 24-hour window may generate reanalysis products with more realistic tropospheric variability.

However, this remark for the troposphere variability is mitigated by the mean fits to aircraft temperatures and all stratospheric fits, which are degraded in the 24-hour configuration as compared to the 12-hour configuration. These degradations may result in fact from model biases, which are reduced when the assimilation is conducted twice as often, preventing maybe the model biases to develop too much. Since the earlier investigations reported above have suggested that the quality of the stratosphere may not be a reasonable target in ERA-20C, these degradations may in the end not affect our choice of the 4DVAR configuration for ERA-20C.

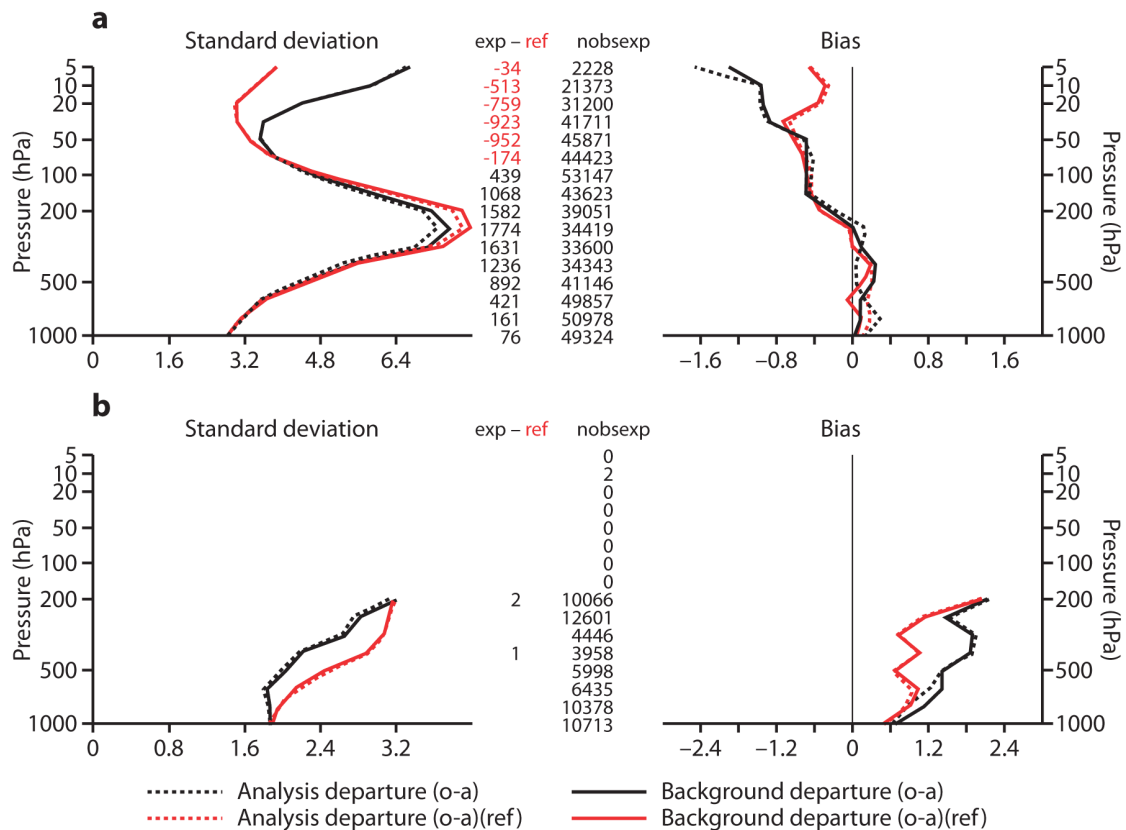


Figure 9: Comparison between background (and analyses) and non-assimilated observations, for the 12-hour and 24-hour 4DVAR experiments. (a) radiosonde meridional wind in the Northern Hemisphere extratropics; (b) aircraft temperature in the Southern Hemisphere extratropics

Other aspects of the data assimilation system will need configuring, and have not yet been looked at. Specifying the background error covariance matrix should be done in a way that allows reflecting the increasing quality of the reanalysis as the observing system improves (over a century, from a few hundred observations per day to tens of thousands). To achieve this, an Ensemble of Data Assimilation (see lecture by M. Bonavita) will be used to capture the spread of the short-term forecasts used as background for the next analysis.

Using an ensemble will also allow to generate equally-likely realizations of the reanalysis, whose spread may be used by reanalysis users as a proxy for random errors.

Finally, observation errors will also need tuning, in particular for the early period (1900-1950).

6. Conclusions and perspectives

Not far from the original promises, global reanalyses of the atmosphere have delivered datasets that have helped all kinds of users investigate climate variability and predictability, but also modelers and data assimilators track the progress of their developments in improving NWP forecasts. In fact reanalyses are becoming increasingly used for climate studies, though challenges remain for many geophysical variables (such as precipitation – not discussed here). However, regarding the second reanalysis goal, much more progress could be done to better understand discrepancies between models and observations, by exploiting more the observation feedbacks generated by reanalyses. So far, such data have been very difficult to access, even within the reanalysis community, let alone from outside. Great progress is expected in this area thanks to the ERA-CLIM project, which will deliver an interface to access and browse the observation feedback from ECMWF reanalyses as well as others (likely also 20-CR).

The long-term goals of generating reanalysis datasets that are free of discontinuities, while at the same time improving our understanding of NWP quality changes using as many possible types of observations, are by nature irreconcilable. However, the gap between the two could be bridged by improving on the following aspects:

- in the data assimilation component: better specifying background and observation error covariances (ideally, space/type and time-varying),
- in the model component: reducing model biases (or solving for them in data assimilation, using a weak-constraint formulation),
- in the observation component: understanding sources of biases and homogenizing long time-series whenever possible to remove spurious breaks related to equipment changes for example.

One additional aspect to remember in reanalysis is the simple fact that observations collected in the past will deliver better value for science once reanalyzed with state-of-the-art tools (models and data assimilation systems). Any model and data assimilation improvement (including observation operators) today or tomorrow will help realize the potential of all old data, in a more powerful way than originally thought at the time. This should be seen as an encouragement to collecting more observations, even though their impact on today's NWP systems may appear today difficult to realize.

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