Capturing trends and low-frequency variations in reanalyses

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1. Reanalysis and climate trends

Comprehensive reanalyses derived by processing multi-decadal sequences of past meteorological observations using modern data assimilation techniques have found widespread application in many branches of meteorological and climatological research. Care is needed, however, in using them to help document and understand climatic trends and low-frequency variations. Atmospheric data assimilation comprises a sequence of analysis steps in which background information for a short period, typically of six- or twelve-hour duration, is combined with observations for the period to produce an estimate of the state of the atmosphere (the “analysis”) at a particular time. The background information comes from a short-range forecast initiated from the most-recent preceding analysis in the sequence. Problems for climate studies arise partly because the atmospheric models used to produce these “background forecasts” are prone to biases (as indeed are the models used for climate simulation and prediction). If observations are abundant and unbiased, they can correct the biases in background forecasts when assimilated.

In reality, however, observational coverage varies over time, the 1970s transition of southern-hemisphere observing system being the most substantial change in the period following the establishment of the radiosonde network in the 1940s and 50s. Observations themselves are prone to bias, either instrumental or through not being representative of their wider surroundings, and these biases can change over time, as in the case of the daytime warm bias in radiosonde measurements of stratospheric temperature, for example. Moreover, the data assimilation process can introduce biases that depend on observational coverage and other factors, as seen in the problems with humidity and rainfall over tropical oceans in ERA-40 (Uppala *et al.*, 2005). These factors can result in trends and low-frequency variations in reanalyses that are mixed with true climatic signals. Nevertheless, as illustrated below with several examples from ERA-40, reanalyses can provide depictions of trends and low frequency variations in quite reasonable agreement with independent studies of the observational record, depending on region, variable and time period. Discrepancies can be informative not only of problems in the reanalysis itself, but also of problems in the observational data. Moreover, reanalyses provide a comprehensive and largely self-consistent picture of anomalies in temperature, humidity, rainfall and circulation over land and ocean that is difficult to piece together otherwise from the disparate sets of observational records.

2. Temperature trends and low-frequency variability in ERA-40

Trends and low frequency variability of surface air temperature from ERA-40 and from the monthly climate station data analysed by Jones and Moberg (2003) are in generally good agreement from the late 1970s onwards, and earlier for well-observed regions. Monthly and twelve-month running mean temperature anomalies for Europe are compared in Fig.1, for example. Twelve-month running mean anomalies are compared for Europe, North America and Australia in Fig. 2.

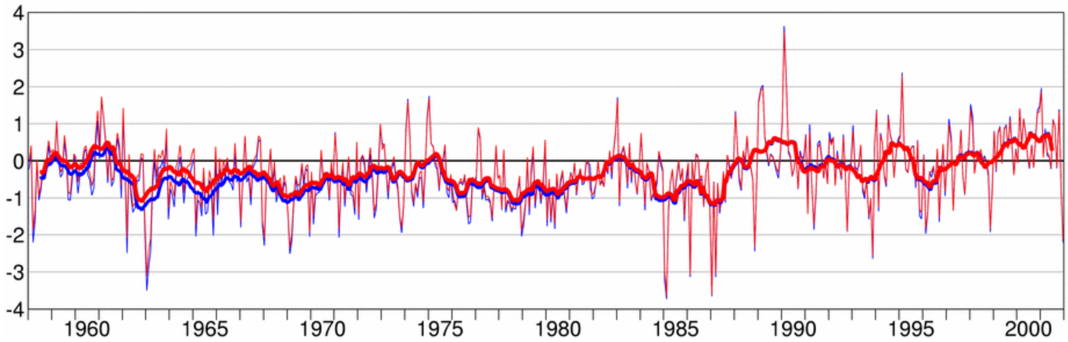

Figure 1: Monthly and 12-month running mean temperature anomalies (K) with respect to the period 1987-2001, averaged over Europe, from ERA-40 (red) and from the CRUTEM2v analysis (blue) of Jones and Moberg (2003). See Simmons et al. (2004) for details.

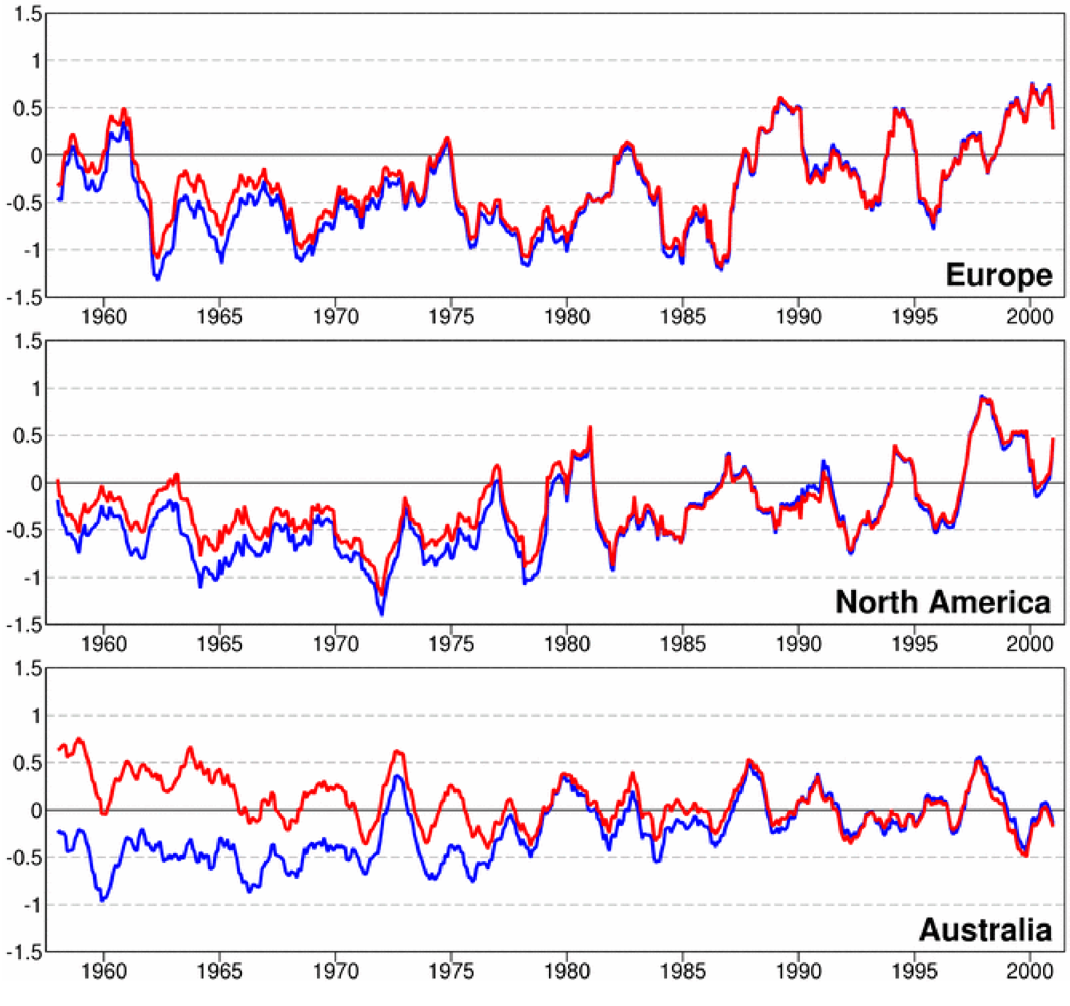

Figure 2: 12-month running mean temperature anomalies (K) with respect to the period 1987-2001, averaged over Europe, North America and Australia, from ERA-40 (red) and from the CRUTEM2v analysis (blue) of Jones and Moberg (2003). See Simmons et al. (2004) for details.

Temperatures from ERA-40 vary quite coherently throughout the planetary boundary layer from the late 1970s onwards, and earlier for regions with consistently good coverage by both surface and upper-air observations (Simmons *et al*., 2004). Discrepancies between ERA-40 and climate-station data for surface air temperature have been shown to be due in part to bias in the upper-air temperature analysis prior to the satellite era, and are in general are more marked for regions in the southern hemisphere than in the northern hemisphere, as in the examples shown in Fig. 2. Poorer agreement prior to 1967 for Europe and North America seen in this figure is a consequence of inadequate availability of synoptic data for ERA-40 in the early years. Detailed examination of local discrepancies later in the period has identified some specific problems in the archive of station data in addition to cases of suspect performance of the reanalysis system.

The combination of sparse radiosonde data over the extratropical southern hemisphere and a cold bias of the assimilating model causes a cold tropospheric bias in the ERA-40 analyses in early years, giving a tropospheric warming trend that is clearly too large when taken over the full period of the reanalysis (Bengtsson *et al*., 2004; Simmons *et al*., 2004). Fig. 3 shows that in the mean the ERA-40 analysis provides a very close fit to 500hPa radiosonde temperatures in the extratropical northern hemisphere throughout the period of the reanalysis, but a poorer fit (and cold bias in early years) for the southern hemisphere. ERA-40 exhibits a general middle-tropospheric warming since the 1970s at middle- and high-latitudes of both hemispheres, and a middle-tropospheric cooling over most of the tropics and subtropics that is almost certainly too strong due to a warm bias in the analyses for the early satellite years.

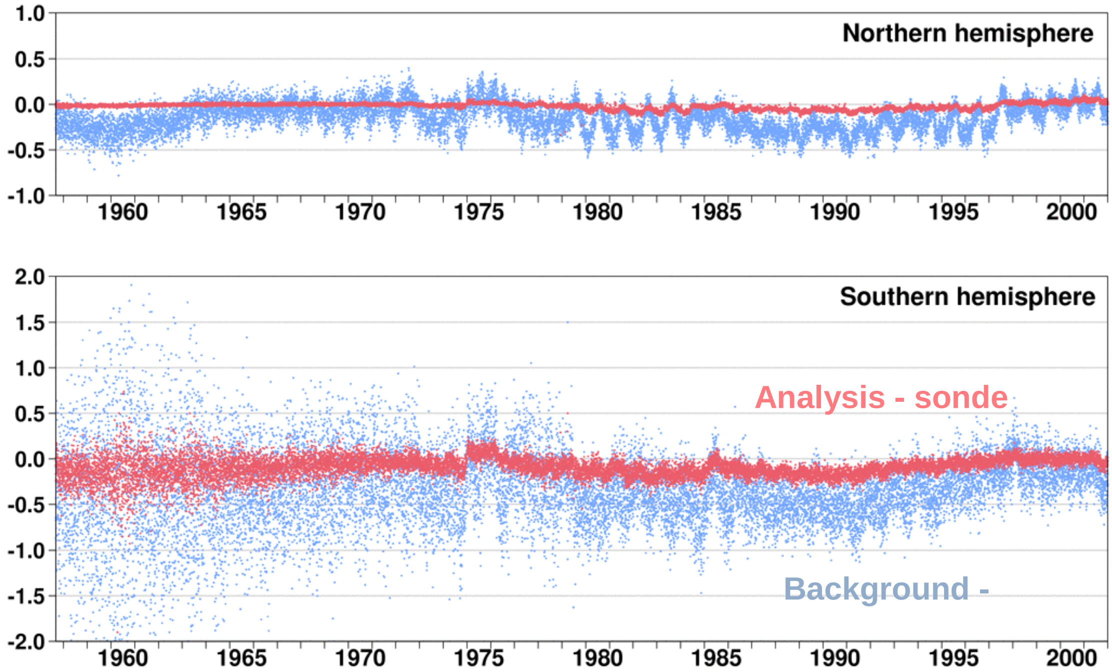

Figure 3: Daily values of the mean fit (K) of the ERA-40 background (blue) and analysis (red) to 12UTC 500hPa radiosonde temperatures for the extratropical northern and southern hemispheres.

Processed MSU records of bulk temperature have been compared with equivalents derived from the ERA-40 analyses (Santer *et al.*, 2004). In ERA-40 the temperature analysis is determined multivariately, using not only MSU data but also data from a variety of other satellite-based sensors, radiosondes, aircraft and surface observation. The MSU data are corrected for estimated biases (Harris and Kelly, 2001; Uppala *et al*., 2005), but the assimilation procedure itself takes account of orbital drift and change in satellite height, factors that have to be addressed in direct processing of MSU data for climate studies (e.g. Christy *et al.*, 2003; Mears *et al.*, 2003). Fig. 4 shows global-mean indicators of middle- to upper-tropospheric temperature (T2) and lower-stratospheric temperature (T4) from ERA-40 and from the MSU record as processed by Mears *et al.* (2003). Agreement between ERA-40 and the alternative MSU version derived by Christy *et al.* (2003) is less good, as can be seen in the linear trends for the period 1979-2001 shown in Table 1. The ERA-40 analyses are biased cold in the upper troposphere and lower stratosphere relative to radiosonde data in the early satellite years, and biased slightly warm at the end of the period, consistent with a T4 cooling rate that is smaller in ERA-40 than in the two MSU datasets.

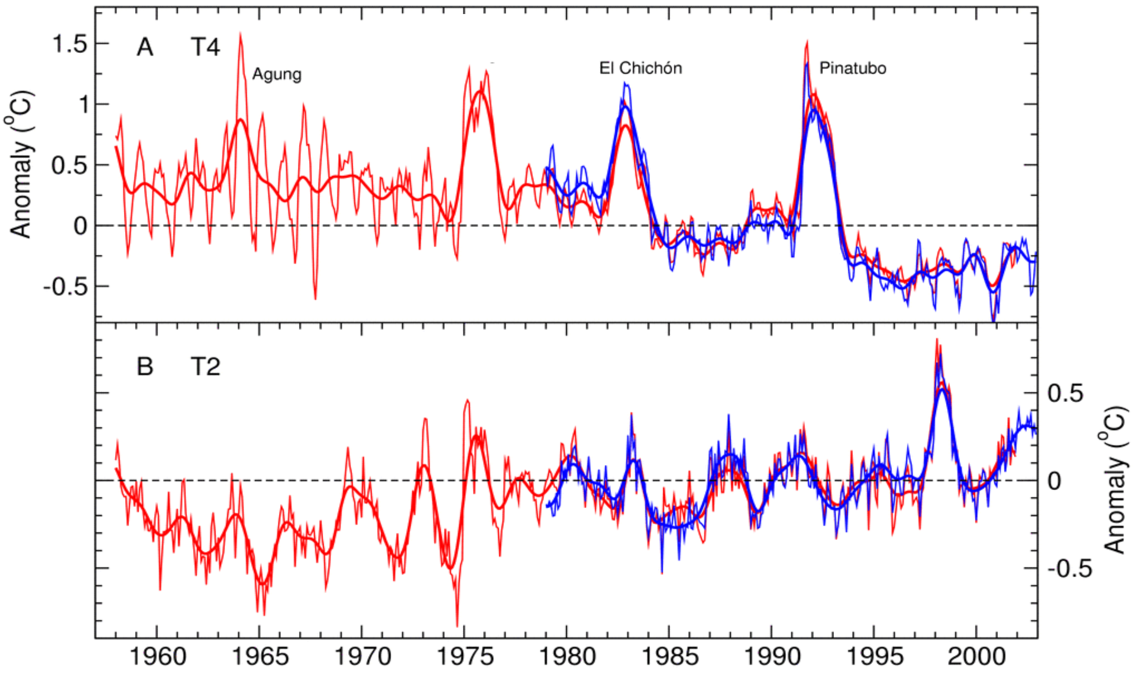

Figure 4: Equivalent global- and monthly-mean MSU bulk tropospheric (bottom panel) and lower-stratospheric (top panel) temperature anomalies relative to 1979-2001 derived from ERA-40 analyses (red) compared with actual MSU data (blue) processed by Mears et al. (2003). Adapted from Santer et al. (2004).

T4	ERA-40	-0.30 K/decade
	Mears *et al.* (2003)	-0.39 K/decade
	Christy *et al.* (2003)	-0.49 K/decade
T2	ERA-40	0.08 K/decade
	Mears *et al.* (2003)	0.09 K/decade
	Christy *et al.* (2003)	0.01 K/decade

Table 1: Least-squares linear rate of change of bulk tropospheric (T2) and lower-stratospheric (T4) temperature over the period 1979-2001 from ERA-40 (Santer et al., 2004) and from MSU data processed by Mears et al. (2003) and Christy et al. (2003).

Geographical patterns of the linear trend in tropospheric temperature (T2) are qualitatively similar in ERA-40 and the two MSU datasets. All show coherent warming over most of the northern hemisphere and cooling over the central Pacific and northern Siberia. Tropospheric temperature trends in these three datasets differ substantially only south of 45S, where Christy *et al.* indicate marked cooling, Mears *et al.* indicate moderate cooling, and ERA-40 indicates no net cooling. These differences are not fully understood, although the treatment of surface emissivity effects over snow- and ice-covered surfaces is a likely contributory factor. Elsewhere, patterns of trend over the oceans are generally consistent with those in sea-surface temperature (Simmons *et al.*, 2004). The large-scale patterns of stratospheric cooling are similar in ERA-40 and the MSU datasets, with maximum cooling at high latitudes in the southern hemisphere, and cooling minima (or even slight warming) over the central Pacific and several smaller regions (Santer *et al.*, 2004).

The ERA-40 analyses reproduce well the low-frequency variability seen in the MSU (and radiosonde) data record. The tropospheric warming associated with the 1998 El Niño is particularly marked, as are the warm periods in the lower stratosphere following the volcanic eruptions of Agung in 1963, El Chichón in 1982 and Pinatubo in 1991, as can be seen in Fig. 4. The warm period shown for 1975/76 in the figure is, however, spurious, related to a problem in bias correction of radiance data from the NOAA-4 satellite. The effect of this can also be seen at 500hPa in the southern hemisphere in the fit of analysis to radiosonde shown in Fig. 3. The pronounced annual cycle in global-mean lower stratospheric temperature seen in Fig. 4 for the early years, particularly before 1969, is also an artefact; the reanalyses are too cold in winter and spring over Antarctica for years with insufficient data to correct a pronounced model bias. The relatively low tropospheric values early in the period stem from the cold model bias in the extratropical southern hemisphere noted earlier.

In the upper stratosphere, biases in the background model fields of ERA-40 are relatively large and data coverage varies substantially, with no data assimilated early in the period and increasing coverage subsequently from the VTPR, SSU and AMSU-A satellite-borne instruments. Assimilation of upper stratospheric radiance data was especially problematic in those periods (from 1987 to 1997 in particular) when data were available from only one SSU instrument in sun-synchronous orbit, as it was difficult for the data assimilation system to distinguish a background error in the semi-diurnal tide from an overall bias in the background forecast. There are consequently substantial shifts in upper stratospheric temperature analyses over the period of ERA-40. Compared with the consensus of climatologies examined by Randel *et al.* (2004), the ERA-40 temperatures are biased warm by several K early in the reanalysis period, oscillate substantially in the middle of the period as data availability varies and radiance-bias adjustments change, and are biased cold by up to 5K later in the period.

3. Variability in atmospheric humidity in ERA-40

Andersson *et al*. (2004) discuss how the ERA-40 analyses were generally moistened over tropical oceans by the assimilation of satellite data. The infrared VTPR and HIRS data were assimilated only in regions judged to be cloud-free, and SSM/I data were assimilated only in regions judged to be rain-free. Background forecasts in these regions were drier than indicated by the data, and moistening increments resulted. The problem of excessive rainfall arose in part from the way the humidity analysis spread increments in the horizontal, which not only moistened regions that the data indicated were too dry, but also added moisture in neighbouring regions that were already close to saturation, increasing rainfall there. It is also likely that the resulting excess latent heating in moist regions increased the tropical circulation, producing additional drying in descent regions that in turn led to additional moistening by the data assimilation. As rainfall was enhanced where it tended to occur naturally, the overall patterns of wet and dry regions appear to be realistic, not only climatologically and but also for seasonal anomalies (Betts and Beljaars, 2003).

Estimates of monthly-mean precipitation rates from the Global Precipitation Climatology Project (GPCP; Adler *et al.*, 2003) are compared with estimates from ERA-40 in Fig. 5 for two extratropical regions and two tropical regions. Although biases are evident, especially for the tropical regions, the alignment of points is largely parallel to the diagonal, indicating similar temporal variability in the two datasets. Related time series can be seen in Kållberg’s presentation to this workshop.

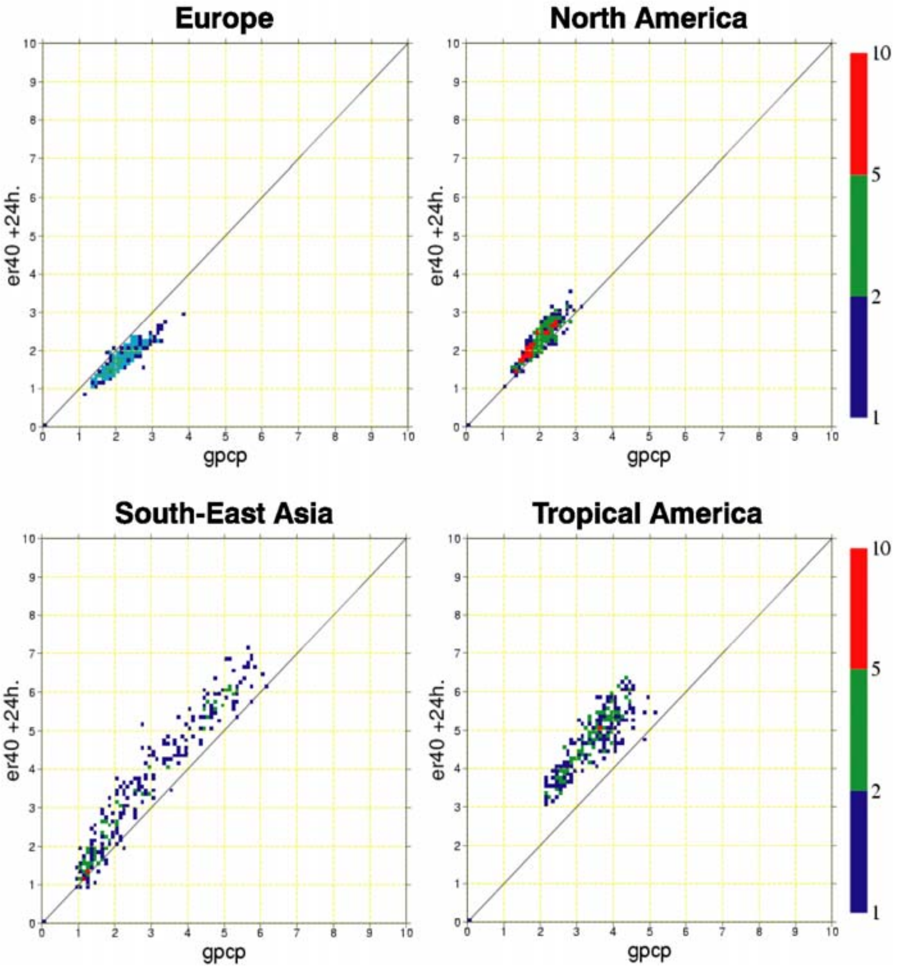

Figure 5: Scatter plots comparing ERA-40 and GPCP monthly-mean precipitation rates (mm/day) averaged over Europe, North America, South-east Asia and Tropical America. Colour shading indicates the number of points per pixel. ERA-40 values are from the range 12-24h from forecasts run from 00 and 12UTC. Figure courtesy of Per Kållberg.

Larger rainfall rates over the tropical oceans from the second half of 1991 onwards in ERA-40 were due in part to effects of volcanic aerosols on HIRS infrared radiances following the eruption of Mt. Pinatubo. These effects were not included directly in the forward radiative transfer model used in the variational analysis. Instead they needed to be absorbed into the bias corrections applied to the radiance measurements. This was a particular problem for data from the NOAA-12 satellite as it became operational close to the time Mt. Pinatubo erupted. Inadequately corrected infrared radiance biases tend to result in humidity changes in the tropical troposphere, since the relatively low background errors in temperature force analysis changes to be predominantly in humidity. 1991 was a difficult year in this regard because there was no data available from two SSM/I channels, which reduced a control on the humidity analysis.

The excess moisture added by the analysis of satellite data tends to fall out early in the forecast range, and Uppala *et al.* (2005) found quite good agreement between time series of 24h-forecast humidity with independent retrievals from the satellite data. This is illustrated in Fig. 6, which compares time series from 1979 onwards of 24-hour forecast values of total column water vapour (TCWV) averaged over the tropical oceans with corresponding tropical oceanic averages of gridded monthly-mean retrievals from SMMR data for the period 1979-1984 (Wentz and Francis, 1992) and SSM/I data from July 1987 onwards (Wentz, 1997; Wentz and Spencer, 1998). SMMR data were not assimilated in ERA-40. Some of the radiance data from rain-free regions used to produce the SSM/I retrievals were assimilated in ERA-40, but via a quite different processing.

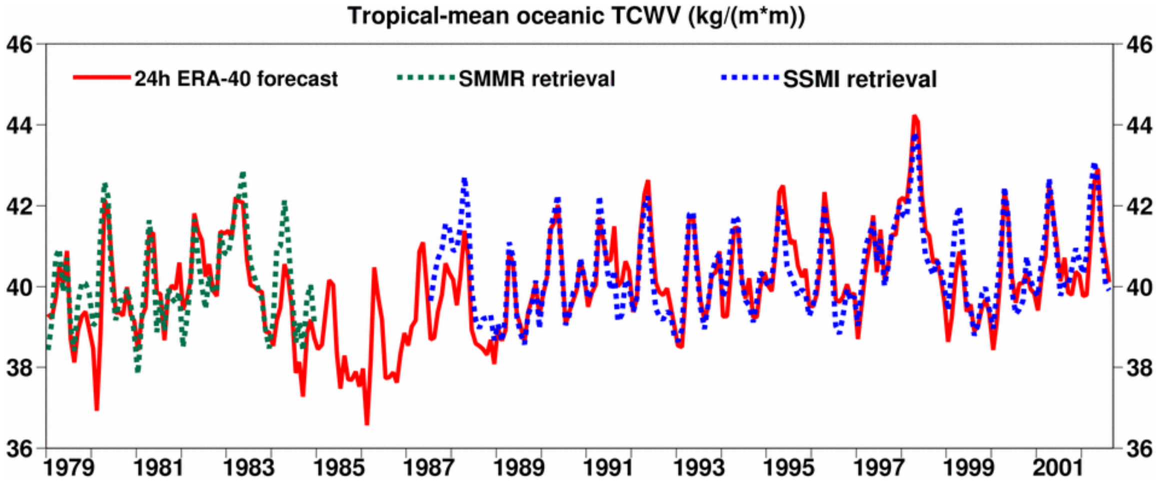

Figure 6: Monthly averages of 24h ERA-40 forecast (red) total column water vapour (kg m-2) and of corresponding retrievals from SSMR (green dotted) and SSM/I (blue dotted) radiances, averaged over oceans in the tropical belt from 23.5N to 23.5S from January 1979 to August 2002. Retrievals from SMMR data were downloaded from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory, California Institute of Technology, and those from SSM/I data are all-satellite averages of version-5 retrievals downloaded from Remote Sensing Systems.

Fig. 6 shows month-to-month and year-to-year variations are similar in the 24h forecasts and retrievals. Analysed values are larger than SMMR values for much of 1982 and the first half of 1983, which may be related to an uncorrected effect of aerosol from the volcanic eruption of El Chichón on the HIRS radiances. The 24h forecasts fit the SMMR data well during this period. Both analysed and forecast values are lower than SMMR values for a spell beginning in mid-1979 and in 1984. Further discussion of the comparison of TCWV analyses and retrievals is given by Allan *et al.* (2004).

Variations in the 24h forecast TCWV averaged over tropical oceans during the SMMR and SMM/I periods correlate well with variations in the tropical-mean sea-surface temperature analyses used in ERA-40. This is shown in Fig. 7, where time series are presented for the whole of the reanalysis period. The figure shows that relatively low values of TCWV occur prior to assimilation of the first satellite data at the beginning of 1973, and the comparison of these values with the SST time series and with TCWV later in the period suggests that the amplitude of the annual cycle of TCWV is underestimated in the early period, with particularly low values from March to May each year. The TCWV time series matches the SST series well from 1973 to 1978, giving some confidence in ERA-40's extraction of humidity information from the VTPR radiances. TCWV is lower than suggested by SST in late 1979 and early 1980, and in 1984, consistent with the comparison with SMMR data. The comparison with SST suggests that too-dry ERA-40 values extend from 1984 until 1988.

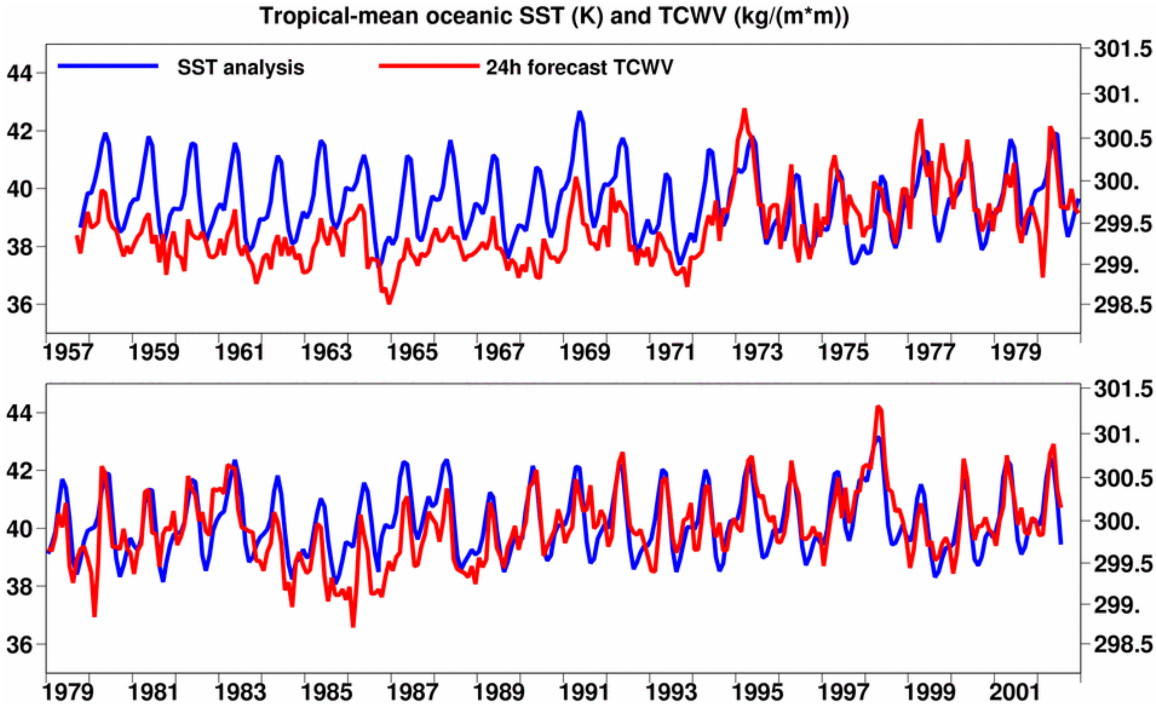

Figure 7: Monthly averages of 24h forecast total column water vapour (red; kg m-2; scale shown left) averaged over tropical oceans and the mean tropical sea surface temperature (blue; K; scale shown right). The temperature scale is linear in saturation specific humidity for a reference surface pressure 1013.25hPa, and chosen to make the mean and standard deviation of the two time series equal for the SSM/I period from July 1987 onwards.

Examination of global mass statistics provides a measure of consistency over time of the analysed water content of the atmosphere (Trenberth and Smith, 2005). Fig. 8 shows time series of the global-mean analyzed surface pressure, the contribution from atmospheric water vapour (derived from the humidity analyses) and the difference between the two. The latter is a good approximation to the surface pressure of dry air, and should be almost independent of time. Results are shown over the period from 1979 to 2001; variations over time in the inferred mass of dry air are significantly larger for earlier years.

Not only is there a degree of consistency over the final two decades of ERA-40 between the directly analysed annual cycle in net atmospheric water-vapour content and the analysed annual cycle in global-mean surface pressure, there is also a degree of consistency in the analyses of longer-term variations. The analysed total surface pressure and the analysed humidity content both decrease to a minimum at the end of 1985, and rise thereafter. Such agreement as there is must come from the analysis of observations as the assimilating model's governing equations do not account for changes in surface pressure due to imbalance between precipitation and evaporation, and the model would thus give uniform global-mean total surface pressure were it not for truncation error.

4. Improvement of reanalyses

Progress in reanalysis stems largely from the general improvement of data assimilation systems that results from research programmes in numerical weather prediction. Many of the improvements of ERA-40, ECMWF's second-generation reanalysis, over ERA-15, its first-generation reanalysis, arise directly from changes made to the underlying operational data assimilation system over the seven-year interval between the two reanalyses (Uppala *et al.*, 2005). ERA-40 also improves on many aspects of the earlier, first-generation NCEP/NCAR reanalysis (Santer *et al.*, 2004; Simmons *et al.*, 2004; Uppala *et al.*, 2005). Early results from the new ERA-Interim reanalysis show considerable further improvements due to another five years of development of the data assimilation system, allied with the availability of higher performance computing that has enabled use of four- rather than three-dimensional variational data assimilation and use of higher horizontal resolution. Further progress can be expected, with confidence, to be made. Moreover, several key areas of development of data assimilation for numerical weather prediction are also key areas for climate applications of reanalyses: handling of biases, representation of the hydrological cycle and land surface, and coupled atmosphere/ocean systems, for example. Research is nevertheless needed to ensure that reanalysis systems make best use of sparse early data, as direct application of assimilation systems developed to work effectively in the comparatively data-rich present may not be the best approach when data coverage is poor. A further need is for comprehensive observing system experiments to be carried out as an integral part of each major new reanalysis, so as to define better the dependence of reanalysis products on changes to the observing system.

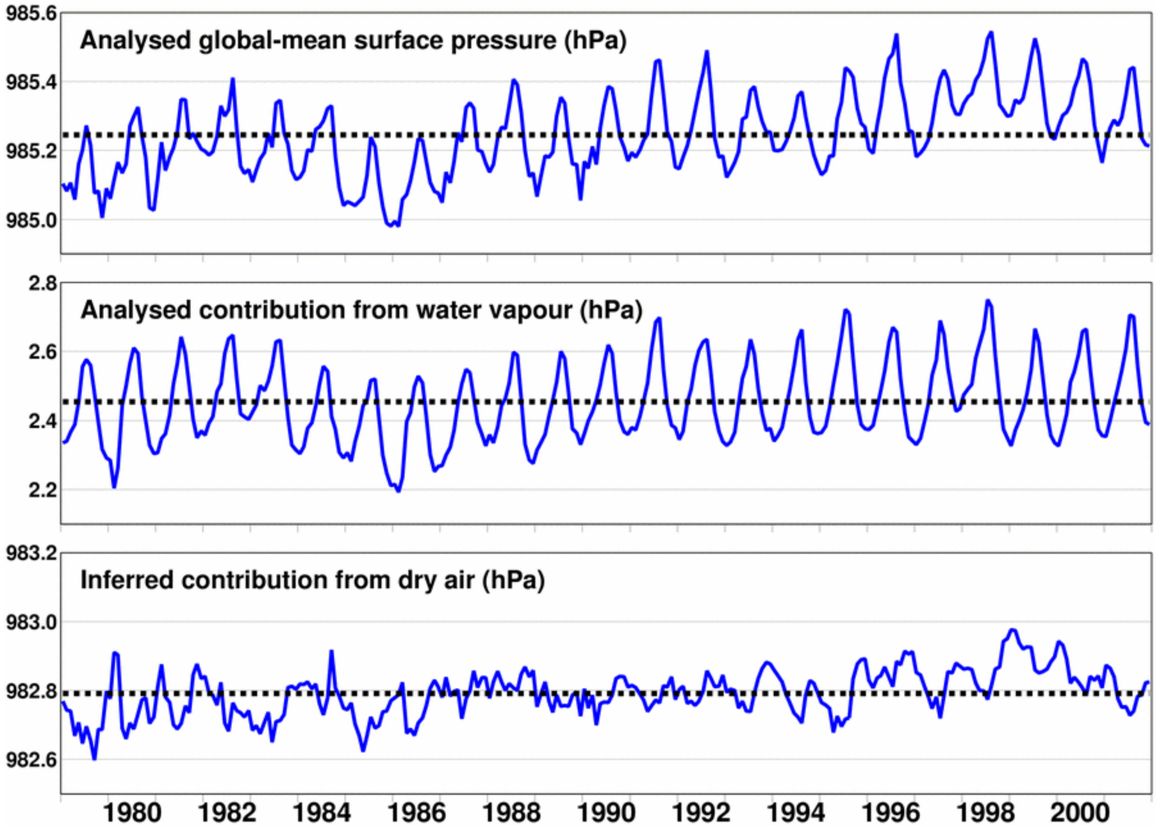

Figure 8: Global means of (top) analysed surface pressure (hPa), (middle) the contribution from water vapour as deduced from the humidity analyses, and (bottom) the difference between the two, for the period 1979 to 2001. The difference provides an estimate of the contribution from dry air. Totted lines indicate average values over the period.

Several factors can be identified that will lead to better trends in future reanalyses:

The passage of time

This will limit impact (or enable avoidance) of the early-satellite period for which biases in temperature proved problematic in ERA-40. It will also see gradually increasing impact from new and improved observations, such as from radio occultation.

Reduction of bias in background forecasts

This is likely to stem primarily from ongoing work to improve the realism of the climate of the assimilating model, work that is basic to the development programme for an assimilation and forecasting system that it applied over forecasts ranges from weeks to seasons. Slowly varying bias in the background forecasts for long-term reanalyses will also be reduced by better specification, or analysis, of the variations over time of radiatively active constituents of the atmosphere in addition to water vapour and ozone. Likewise, benefit should accrue from improved specification or analysis of surface conditions. Lower biases in the background forecasts may also result from improvements to the data assimilation process, to avoid effects such as caused in ERA-40 by assimilating humidity-sensitive satellite data only in clear or rain-free areas.

Better handling of remaining model biases in data assimilation

Initial work on this has been reported by Trémolet at this workshop.

Better correction of biases in observations

Homogenization of time series of temperature data from individual radiosonde stations (discussed by Haimberger at this workshop), refinement of radiosonde temperature corrections dependent on solar zenith angle, and variational correction of radiance biases (discussed by Dee) are important developments in this regard that will be evaluated in ERA-Interim. ERA-Interim will also use an adaptive scheme for correction of biases in surface-pressure observations (discussed by Vasiljevic at the 2005 ECMWF/NWP-SAF Workshop on Bias Estimation and Correction in Data Assimilation[1]). There is a need for further developments in this area, for a variety of observation types.

Better observation operators

Examples here are improved forward radiative transfer modelling for SSU radiances (discussed by Kobayashi at the 2005 ECMWF/NWP-SAF Workshop on Bias Estimation and Correction in Data Assimilation) and incorporation of volcanic aerosol effects for HIRS radiances.

Better quality control of observations

One key decision that has to be made in reanalysis is when and when not to use data from specific satellite-borne instruments or from specific channels of a particular instrument, but other quality-control choices made within data assimilation systems can influence systematic characteristics of the resulting analyses.

Better collection of observations

Filling gaps in pre-1967 SYNOPS and improving pre-1977 snow-cover data are two examples based on experience from ERA-40.

Time-variation in observation/background error variances

Larger background error variances than used in ERA-40 for the pre-satellite southern hemisphere would increase the weight given to radiosonde data. Evidence of the importance of revising the error specification when data coverage is radically reduced is provided by Thépaut's presentation to this workshop.

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