ERA-40 hydrological cycle

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The second ECMWF ReAnalysis, ERA-40, is now well underway. The centres first 15-year ReAnalysis, ERA-15, was successfully concluded in 1998. However, in the meantime, the ECMWF data assimilation system had been developed further to such an extent that it was decided to embark on a second longer reanalysis already in 1999. In particular, the ERA-15 optimum interpolation (O/I) analysis technique had been replaced by a variational technique, either 3-dimensional (3D-Var) or 4-dimensional (4D-Var). The variational analysis eliminates the need for local selection of observations in separate 'analysis boxes', something that caused irrelevant box-scale noise in ERA-15. Another big step forward is the direct assimilation of raw satellite radiances, rather than derived [in a separate 1D-Var step] layer mean temperatures.

Due to computer capacity 3D-Var was selected for ERA-40, with a resolution of T159 (~125 km.) and 60 vertical levels up to 0.1 hPa (~65 km.) The production is run in three different 'Streams' defined by the availability of satellite data. Stream 1 began in 1989 and uses a comprehensive set of satellite data: TOVS, SSM/I, Scatterometer and Cloud Motion Winds. Stream 2 began in 1957 when no satellite data existed. Stream 3 runs from 1972 and makes use of raw IR soundings from the VTPR system on early NOAA satellites. It is believed that this is the first time those radiances have been used directly in a modern data assimilation.

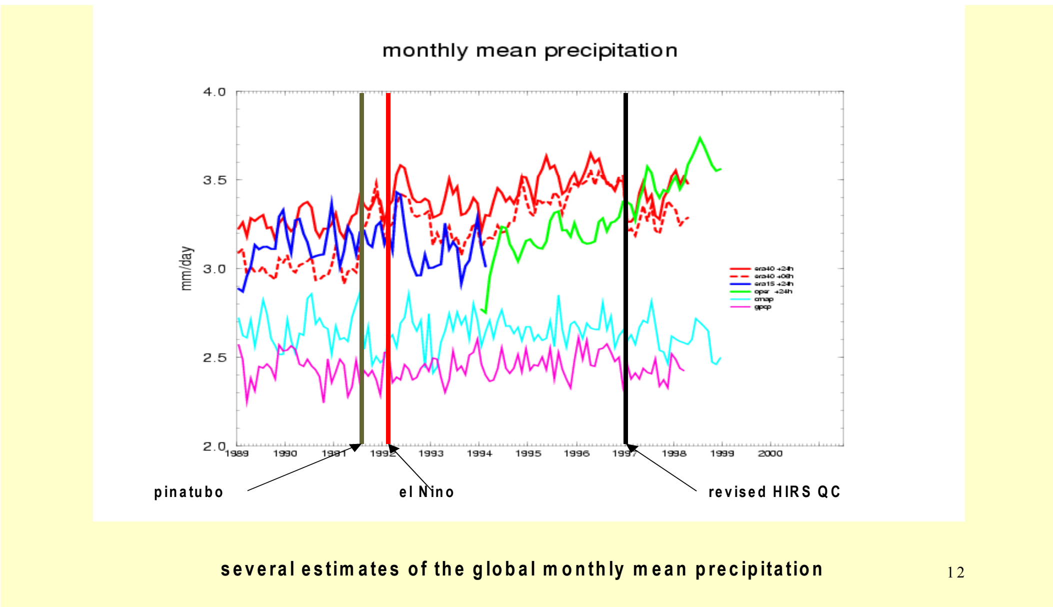

Figure 1. Global monthly mean precipitation in mm/day from ERA-40 +6h (red dashed), ERA-40 +12h -> +24h (red, full), ERA-15 +12h -> +24h (blue), ECMWF operations (green), CMAP (cyan) and GPCP (magenta). The Pinatubo eruption, the 1992 El Niño and a change in the use of HIRS data are indicated.

The analyses and the short range forecasts are monitored closely, both at ECMWF and by our validation partners. Hopefully the monitoring should detect problems at an early stage, so that corrections and remedies can be applied before too much valuable production time has been lost. The monitoring makes use of many tools, such as statistics on observation availability, use and rejection; time series of the bias corrections applied to the satellite brightness temperatures; maps and time series of analyses and analysis increments increments; and a comprehensive set of monthly mean statistics.

Perhaps the most serious problem found by the monitoring, here at ECMWF and especially by the Max Planck (MPI) group in Hamburg where the global hydrological cycle is of particular interest, is the excessive precipitation over the tropical oceans. At the time of this workshop the reason(s) is (are) not known, hence in this presentation we will concentrate on diagnosis of the problem, leaving possible explanations and remedies for further work.

Soon after Stream 1 had passed 1991, the MPI group pointed out that the precipitation increased considerably after the Mount Pinatubo volcanic eruption in June that year. In figure 1 the ERA-40 global mean precipitation (in mm/day), from +6 hour forecasts and (in order to elucidate precipitation spin-up) from forecasts accumulated from +12 hours to +24 hours, are shown in red. They are compared with the previous reanalysis (ERA-15, in blue) and the ECMWF operations at the time (in green). Two independent estimates, GPCP (Gruber & Huffman) and CMAP (Xie & Arkin) are also included. Although absolute rain amounts over the tropical oceans are difficult or impossible to estimate correctly, the large differences and the increasing trend in ERA-40 are hard to accept as being realistic.

A complicating factor is that a new NOAA satellite, NOAA-12, was launched close to the Pinatubo event. Before a new HIRS infrared instrument can be used in the assimilation, its bias characteristics have to be determined in so called ‘passive mode’. The radiances are going through all the processing and quality control and their bias characteristics are collected, but they are not used in the final analysis. The bias tuning for this instrument was done in an atmosphere heavily contaminated by volcanic ash. These aerosols have their own IR emission in addition to the CO2 and the resulting bias correction coefficients may become less than perfect.

After thorough investigation and much testing, modifications were introduced in Stream 1 from January 1997. They included revised data thinning, channel-selection and quality control of HIRS and SSM/I radiances, and gave a reduced, though still relatively high, tropical precipitation, as seen in figure 1. The short-range forecast verifications were also slightly improved.

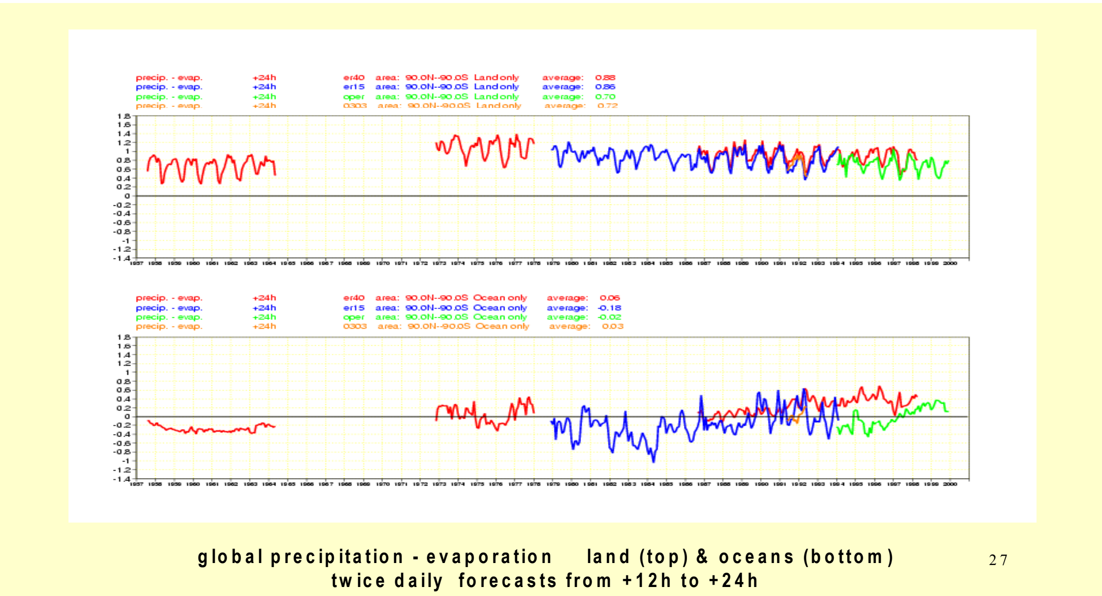

Figure 2. Monthly mean Precipitation - Evaporation over land (top) and the oceans (bottom) . Red is ERA-40, blue is ERA-15, green is ECMWF operations and the short orange curve is from experiment 303, a test for the ‘1997’ revision which is not discussed here.

The global precipitation minus evaporation (P-E) trend in figure 2 is obviously quite unrealistic with positive values over the global ocean in Stream 1 and to some extent also in Stream 3. During the 1960’s, when no satellite measurements were available (Stream 2), on the other hand, the oceanic P-E has the correct sign, and the global land & sea mean is close to zero as it should be.

The monthly mean analysis increments of the tropical total column water vapour (TCWV), in figure 3, show that the analysis adds net water. In stream 1 the added amount averages to some 0.5 kg/m^2, hence about ½ mm of water is added in each analysis cycle. Much, but not all, of this water rains out in the following 6-hour background forecast for the next cycle. The result is unrealistically high precipitation over the oceans in the ITCZ. And, maybe worse, since all the added water ‘has not had time to rain out’ when new observations are added in the next 3D-Var analysis, there might be a slow but consistent gradual moistening of the atmosphere.

Furthermore we note that the increments are close to zero over land where the satellite data are not used. Likewise, in Stream 2, when no satellite data were available, the mean TCWV increments are very close to zero both over sea and land. In Stream 3 (VTPR but no SSM/I) we can note a similar problem as in Stream 1.

Observing system experiments (OSE) with the ERA-40 system where either the HIRS or the SSM/I or both sets of satellite radiances were excluded, indicate that both of them contribute to the moistening.

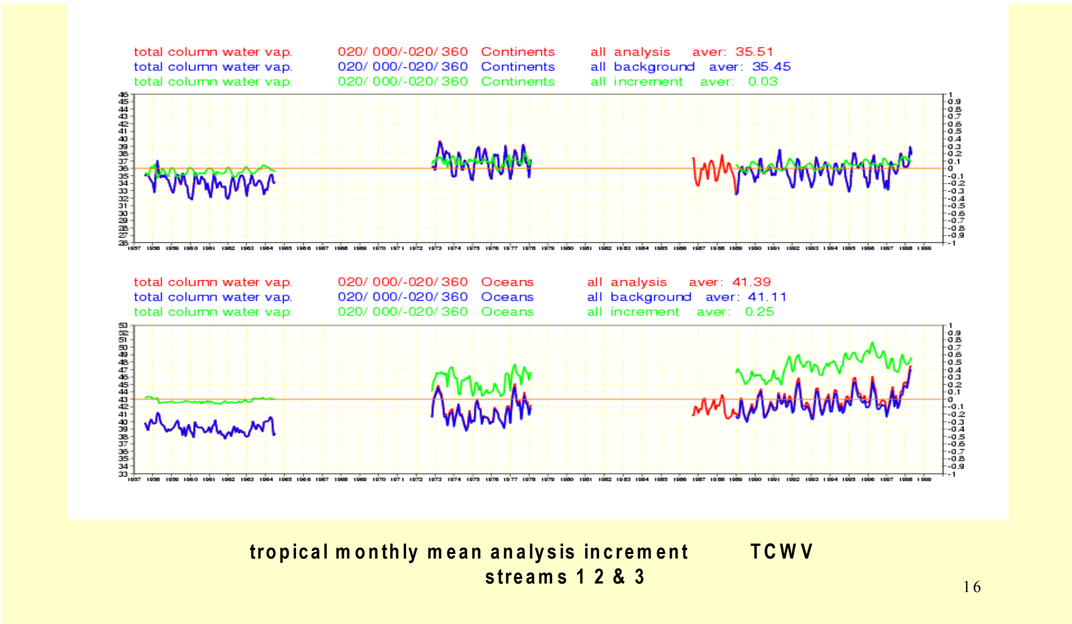

Figure 3. Monthly mean analysis increments of the tropical total water content in ERA-40. The blue curves are the background, and the red are the analyses. The scale - in kg/m^2 - of these two curves is on the left side of the diagrams. The difference between analysis and background, (the increment), is shown in green with the scale to the right. Land is above, ocean below.

Next, the vertical distribution of the moisture increments in a typical Stream 1 month is shown in figure 4. The water is added evenly in a 25-30 degree wide area somewhat north of the equator (this is July!) and below 500 hPa with a maximum of 0.2 g/kg around 700 hPa. There are drying increments in both the northern and southern subtropics and mid-latitudes. A similar cross section from the no-satellite Stream 2 (not shown in this write-up) does not exhibit any moistening, while drying is again seen over the northern mid-latitudes, the only area well covered with radiosondes in those years. The radiosonde humidity observations thus have a tendency to dry the analyses.

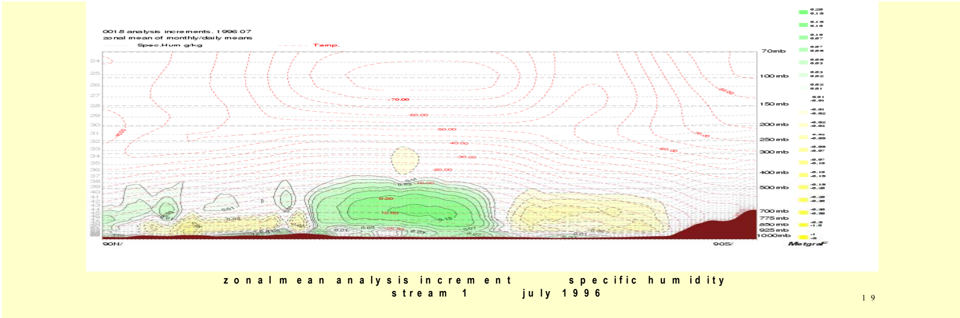

Figure 4. A cross section, pole to pole, of the zonally averaged monthly mean specific humidity analysis increment in July 1996.

For a few years within the ERA-40 assimilation, full 10-day forecasts have been run. They are made twice daily, from 00 UTC and from 12 UTC, and the prime purpose is to study how the predictability in the medium-range depends on observation availability and quality. So far we have three full years, one in each of the three Streams. The daily mean hydrological fluxes have been extracted from these forecasts for all the different forecast lengths up to D+10.

Concentrating on 'P-E' in figure 5, the red curves show that the global precipitation exceeds the evaporation by about ½ mm per day at the beginning of the forecasts in both Stream 1 and Stream 3. Stream 1 reaches its balance only after 4-5 days, and Stream 3 even later. The no satellite Stream 2, on the other hand, is in complete balance already after a day, beginning from a negative P-E balance.

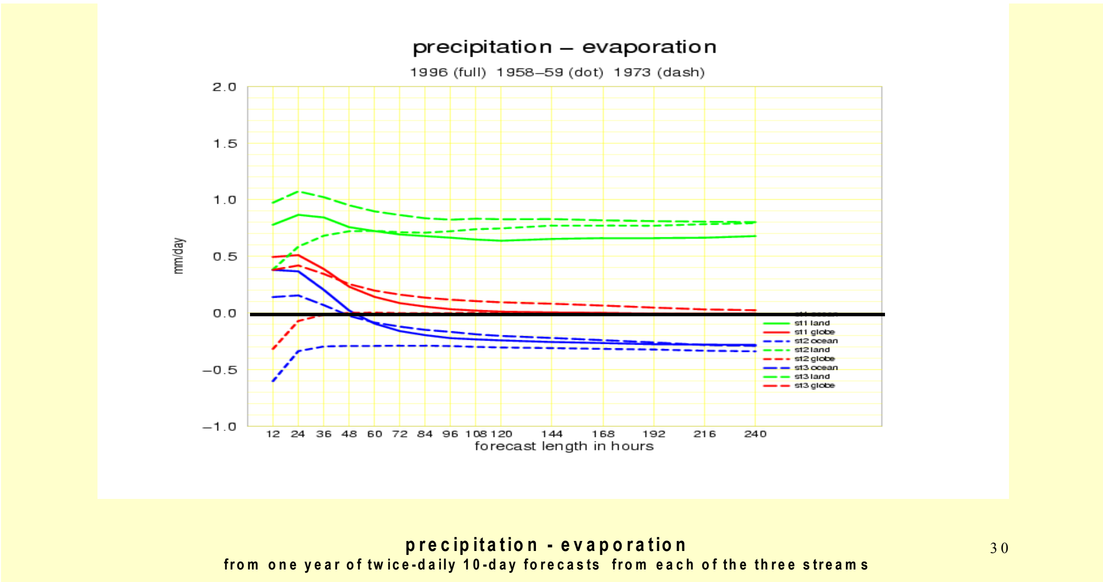

Figure 5. One year mean P-E from Stream 1 (full lines), Stream 2 (dotted) and Stream 3(dashed). Green is over land, blue is over oceans and red is over the entire globe.

Conclusions:

- The short-range forecasts in ERA-40 Stream 1 and Stream 3 produce excessive amounts of rain over the tropical oceans, leading to positive 'P-E' over the global ocean.
- The analysis adds about ½ mm of precipitable water to the tropical atmosphere every 6th hour.
- Radiosondes have a tendency to remove water vapour from the analyses.

- The forecast model is not able to get rid of all water added in the analysis within the 6 hour forecast. It may need 4-5 days to reach full hydrological balance (Global P-E . 0.).
- The pre-satellite Stream 2 does not have the problem. OSE tests hint at both TOVS and SSM/I as contributors.
- A set of modifications to tighten the HIRS and SSM/I quality control had limited but positive effects.
- A full explanation - and remedy - for the wet ERA-40 analyses is not yet found.