ECMWF reanalyses: Diagnosis and application

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1 Introduction

Reanalysis uses a modern data assimilation system to reprocess past observations. This produces a detailed description of the atmospheric evolution over an extended period of time, consisting of gridded fields of observed meteorological parameters (surface pressure, temperature, winds, humidity, and ozone), as well as many additional parameters generated by a forecast model (e.g. rainfall, cloud parameters, boundary layer height, etc.). The data assimilation ensures that the reanalysed fields are constrained by the available observations, in a manner consistent with laws of physics as expressed by the forecast model.

Reanalysis is performed with a single data assimilation system. This ensures that the reanalysed data products are not affected by model upgrades, resolution changes, or any of the other modifications to the data processing algorithms that are periodically introduced in operational forecasting systems. The representation of long-time scale variability in reanalysis data is therefore more homogeneous than that which can be obtained from operational analyses. Furthermore, the use of a recent version of the data assilimation system means that the quality of reanalysed fields for earlier dates tends to be higher than that of the original operational analysis.

For these reasons, reanalysis data have become extremely popular for many different types of applications. They provide convenient access to the observational record, in terms of a comprehensive set of global geophysical parameters. ECMWF has produced several atmospheric reanalyses in the past; most notably ERA-15 (Gibson *et al.* 1997) and ERA-40 (Uppala *et al.* 2005). Additional global atmospheric reanalysis data sets are available from NOAA, JMA, and NASA. More specialised reanalyses are being produced as well, e.g. high-resolution regional reanalyses; long-term reanalyses using only surface information; shorter-term reanalyses for chemical composition.

The most recent atmospheric reanalysis project at ECMWF is ERA-Interim (Simmons *et al.* 2007; Uppala *et al.* 2008), which covers the period from 1989 to present and continues to be updated in real time. The primary goal for ERA-Interim has been to address certain difficult data assimilation problems encountered during the production of ERA-40. These are related to the representation of the hydrological cycle, the quality of the stratospheric circulation, and the consistency in time of reanalysed geophysical fields. A second, related, objective for ERA-Interim was to improve on various technical aspects of reanalysis such as data selection, quality control, bias correction, and performance monitoring.

The configuration of the ERA-Interim reanalysis system is based on a December 2006 release (Cy31r2) of ECMWF's Integrated Forecast System (IFS). This release represents more than five years of accumulated progress in modelling and data assimilation since ERA-40, which used a June 2001 version of the IFS. In addition, many technical changes related to data handling and performance monitoring have been implemented during this period. The most important scientific improvements in the ERA-Interim system are:

- Use of four-dimensional variational (4D-Var) analysis within 12-hourly intervals
- Significant improvements in model physics
- Increased spatial resolution, based on T255 spherical-harmonic truncation
- Improved formulation of the atmospheric humidity analysis
- Revised background error covariances using wavelet transforms
- Variational bias corrections for satellite radiance data
- Various improvements in radiative transfer modelling

With some exceptions, the observations used in ERA-Interim consist of input data originally prepared for the ERA-40 reanalysis, supplemented with data used in ECMWF's operational forecast system. Only modest efforts were made to optimise the data selection for use in ERA-Interim, or to take advantage of improved input data sets which are now available for reanalysis, e.g. from climate centres, space agencies, and other data providers.

All ERA-Interim data, including daily and monthly analyses and forecasts, are accessible to ECMWF's Member State users via MARS. A large subset of the products is available on $1.5^\circ \times 1.5^\circ$ regular latitude-longitude grids for research purposes, and can be downloaded from the internet at http://data.ecmwf.int. These include 3-hourly surface parameters, 6-hourly upper-air parameters on pressure levels extending vertically to about 50 km altitude, and monthly averages for all parameters. See Berrisford *et al.* (2009) for a complete description of the ERA-Interim data archive.

2 Reanalysis quality requirements and diagnostics

The primary requirement for reanalysis data is that they faithfully represent the existing observational record. In fact, many users regard reanalysis products as equivalent to observations, even if this is not always justifiable. Reanalysis fit to observations can be verified with analysis departures. However, it is more meaningful to consider statistics of background departures, because these provide an indication of the information content of the reanalysed fields by measuring how well observations that have not yet been assimilated can be predicted.

A further requirement concerns the physical coherence of the reanalysed fields, in the sense that they should be consistent with the laws of physics as well as with the observations. One way to diagnose this is to produce forecasts using the reanalysis as initial conditions. The skill of these re-forecasts depends on the accuracy, completeness, and consistency of the reanalysed fields, as well as on the quality of forecast model. Other diagnostics that test the physical coherence of reanalysis data include assessments of the global mass, energy, and momentum budgets, and of the hydrological cycle.

3 Biases and trends

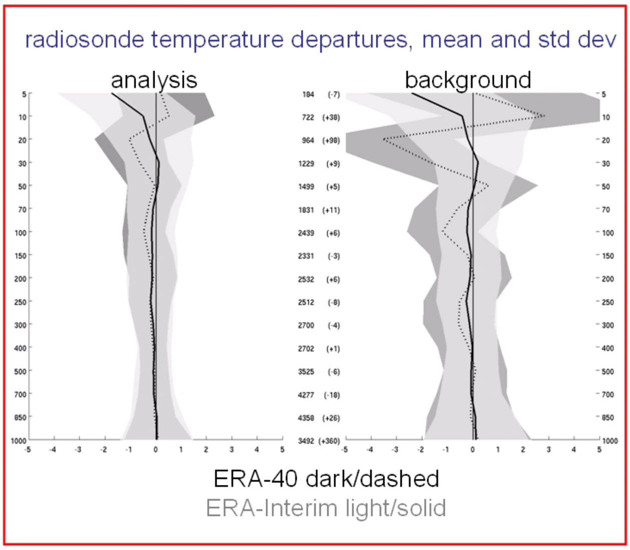
Possibly the most ambitious goal for reanalysis is to accurately represent long-term signals, trends and variability. The difficulties involved in this are fundamental and not specific to reanalysis. The climate system, even today, is incompletely and inaccurately observed; the extent of the data coverage, the measurement techniques, and the associated uncertainties are continually changing. Any such changes can generate or modulate systematic errors in estimates of climate variables. The challenge is to make optimal use of all available information, from models and observations, in order to expose the underlying uncertainties and reduce them as much as possible.

Upper-air temperatures in the Arctic (Jan 2000)

Reduced bias

Improved vertical consistency

Improved consistency between background and analysis



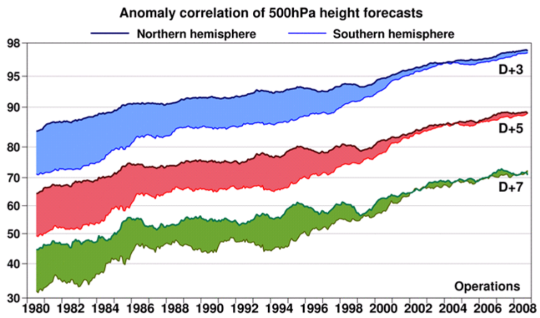
ERA-Interim achieves similar accuracy with smaller analysis increments

Quality of (re-)forecasts

Updated from
Simmons & Hollingsworth (2002)

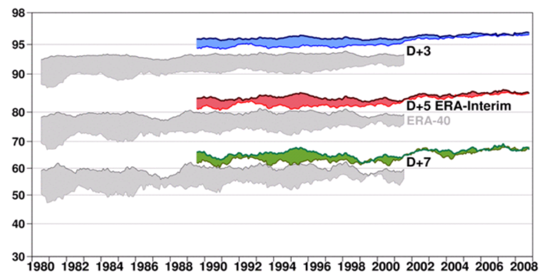
Operational forecasts from ECMWF:

- improvements over time due to system upgrades (model and data assimilation)



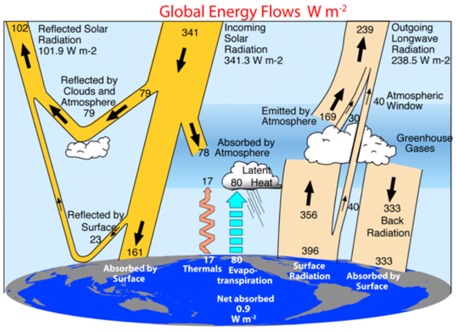
Re-forecasts produced with ERA-Interim:

- quality is more uniform globally and in time
- improvements relative to ERA-40 reflect 5 years of IFS development

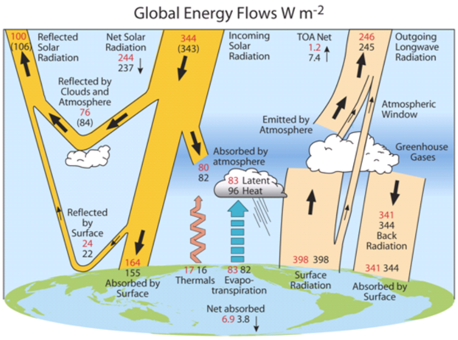


Energy budget

Trenberth *et al.* 2009:
Earth's global energy budget

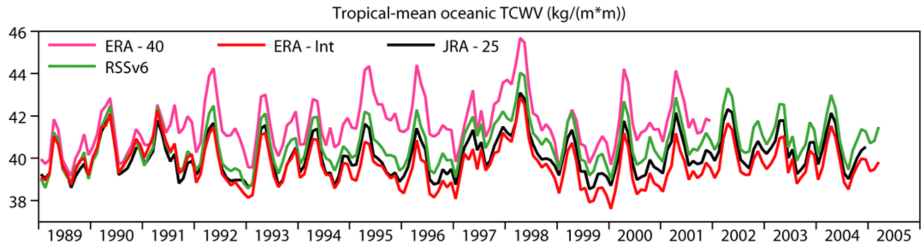


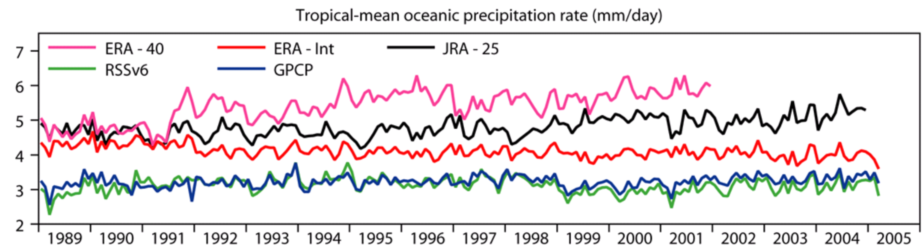
ERA-Interim 1989-2008 ERA-40 1989-2001



- TOA balance improved in ERA-Interim
- Surface energy balance worse, esp. over oceans

Water





Improvements in ERA-Interim, due to:

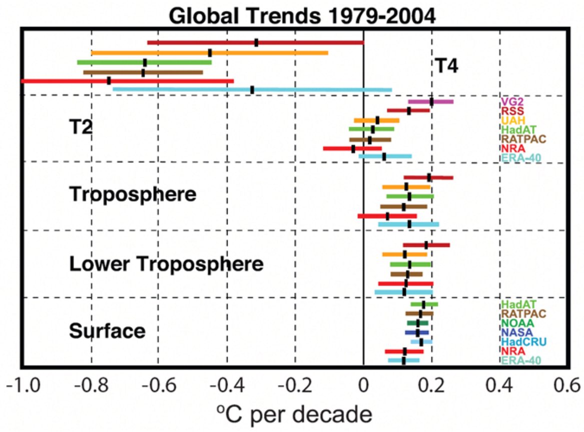
- Revised humidity analysis
- Better model physics
- 4D-Var
- Improved bias corrections for radiance data

Biases and trends

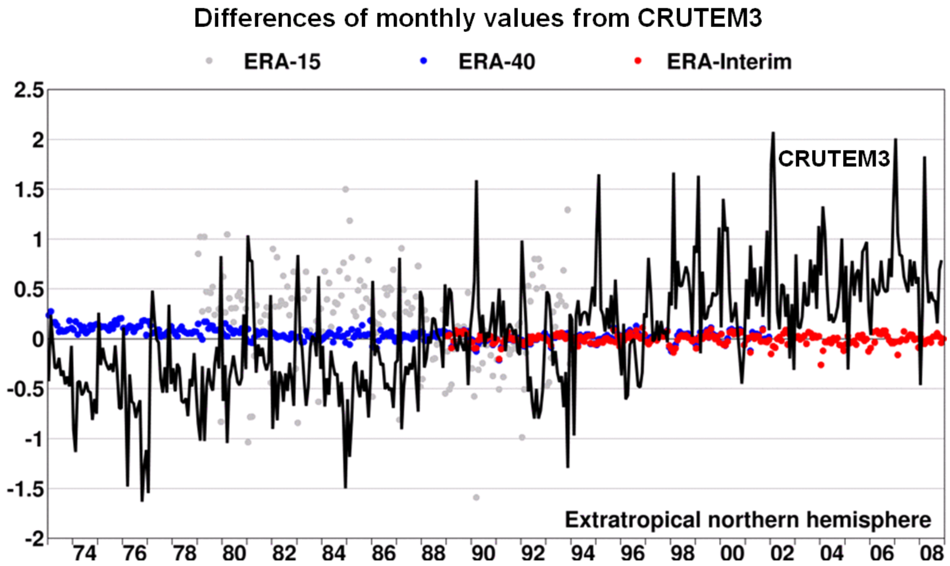
Reanalysis is considered unsuitable for trend estimation (IPCC AR4)

In theory, temperature trends from reanalysis should be superior

In practice, this requires dealing with biases in models and observations



Time series of 2m land temperature anomalies (K)

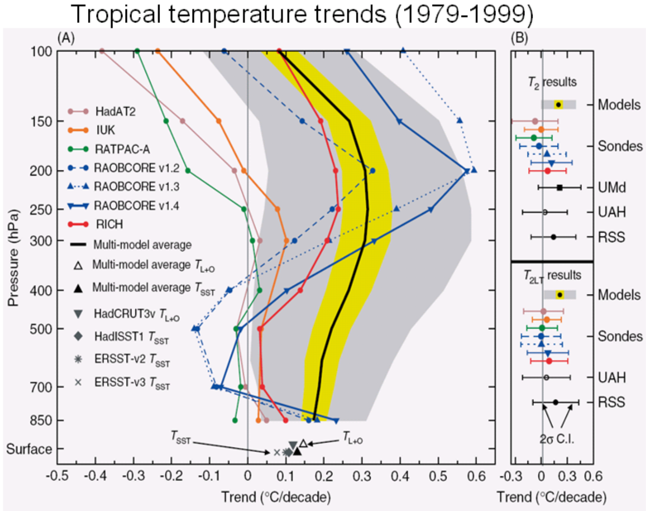


ERA sampled as CRUTEM3 (Brohan et al., 2006) following Simmons et al. (2004)

Can we do as well for upper-air trends in reanalysis?

Problem: There is no single true reference data set

Tropical temperature trends (1979-1999)

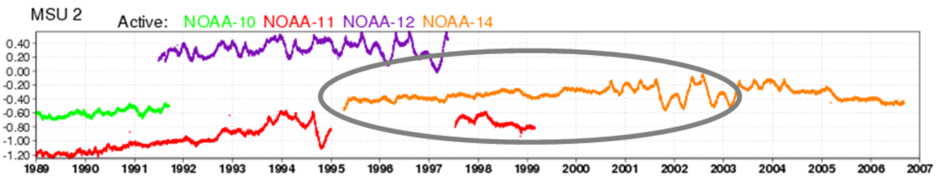


Santer *et al.* 2008, Int. J. Climatology

Reanalysis can be used to remove biases from observations

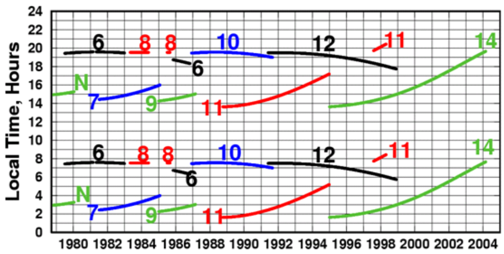
Variational bias correction of satellite radiances in ERA-Interim
Dee and Uppala 2009 (QJRMS, in press)

Global mean bias corrections for MSU channel 2 (lower troposphere)

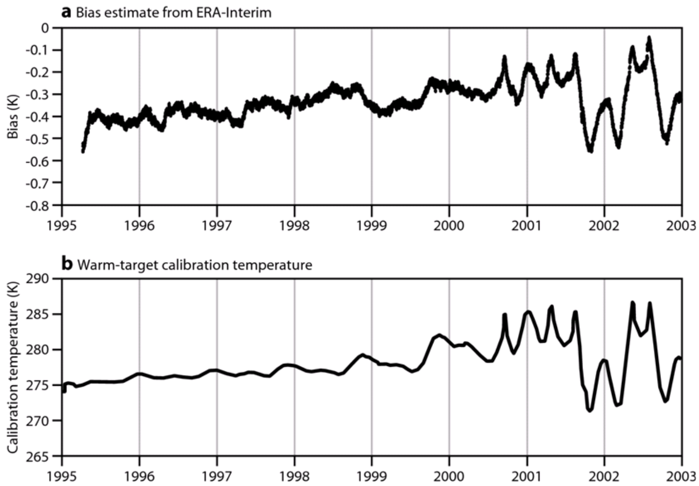


Equator crossing times for
NOAA Polar Orbiting satellites

- Drift in polar orbit causes changes to the total heat budget of the satellite
- This affects instrument self-calibration



MSU instrument bias due to warm-target fluctuations



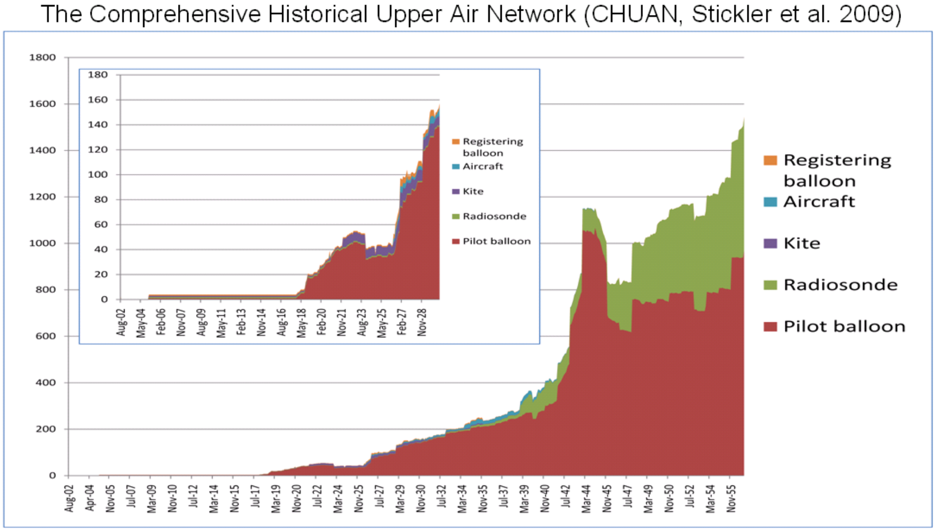
Variational bias estimates for NOAA-14

Actual warm-target temperatures on board NOAA-14 (Grody *et al.* 2004)

MSU instrument errors are identified based on all information available to the reanalysis

Upper-air observations pre-1957

The Comprehensive Historical Upper Air Network (CHUAN, Stickler et al. 2009)



Can we get *both* high accuracy *and* meaningful trend estimates?

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