Experience and estimation of biases in ECMWF reanalyses

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Graeme Kelly
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Contents

- Reanalyses in general
- Bias estimation ERA-15 and ERA40
- How successful?
- ERA-Interim
- Conclusions
General

- Reanalyses, a sequence of atmospheric and surface conditions over a long period
- Time consistency important
- Quality of reanalyses are affected by
  - The quality of the assimilation system (model and analysis)
  - The characteristics of the observing system
    - Changes
    - Coverage and gaps
  - Boundary conditions
  - Systematic and random errors in the previous
Before reanalyses

• Operational analyses were successfully used in general circulation studies especially in the Tropics and Southern Hemisphere, but due to the improving forecasting system it was difficult to study interannual variations and impossible to study climate change.

• Reanalysis efforts proposed e.g. by Bengtsson & Shukla (1988)
There has been an increasing need to understand trends:

- MSU-2 data compared with ECMWF operational analyses revealed discontinuities related to major system changes by Hurrell & Trenberth (1991)
- Upper-air temperature trends Oort & Liu (1992) GFDL data vs MSU-2 and MSU-4 in good agreement, high expectations on reanalyses & trends
- Temperature trends and inadequate spatial sampling Karl et al. (1993)
- ...
ECMWF reanalyses

ERA-15 1979-1993

- Data assimilation system
  - Model T106L31
  - Optimum Interpolation
- TOVS Cloud Cleared Radiances (HIRS/ MSU) through 1D-Var retrieval
- Bias corrections applied to satellite radiances and radiosonde heights
- ECMWF operational data the main source of conventional observations, added by COADS, FGGE, ALPEX
• **NCEP Reanalysis**
  - Period 1948 and continues as Climate Data Assimilation System (CDAS)
  - NCEP reanalysis has used the original NESDIS retrievals
  - Retrievals of SSMI data have not been used

• **ECMWF Operations**
  - Direct assimilation of radiances started in 1996
Use of TOVS data in ERA-15
<table>
<thead>
<tr>
<th><strong>Input radiance</strong></th>
<th><strong>ERA-15</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Cleared and nadir corrected Radiances</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Method</strong></th>
<th><strong>ERA-15</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Static J. Eyre based on W. Smith &amp; H. Woolf</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th><strong>Scan bias</strong></th>
<th><strong>ERA-15</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Global offset with 0 at center</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Air-mass dependent bias</strong></th>
<th><strong>ERA-15</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Data selected in 5 latitude bands</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Predictors:</strong> MSU-2,3 and 4, which are unaffected by clouds</th>
<th><strong>ERA-15</strong></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th><strong>Update frequency</strong></th>
<th><strong>ERA-15</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly</td>
<td></td>
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</tbody>
</table>
ERA-15 Tropical temperature

Fig. 2. Time series of the monthly mean tropical (20°N to 20°S) 2LT temperatures from NCEP, MSU, and ERA-15. The standard deviation of each is given in the insets. A low-pass smoothing spline has been fitted to the data to show the decadal variations.

Trenberth et al. (2000)
Fig. 3. Difference in time series of the monthly mean tropical (20°N to 20°S) 2LT temperatures from MSU and ERA-15, as ERA–MSU. A straight line fit has been added to the series to show the two discontinuities.

Trenberth et al. (2000)

NOAA-9 MSU-3 problem
November 1986
**ECMWF reanalyses**

**ERA-40 1957-2002**

**ERA-15 1979-1993**

- Improved data assimilation system
  - Assimilating model T159L60
  - 3D-Var FGAT
  - Analysis of O₃
- More extensive use satellite radiances
- ERA-15 experience ➔ ERA-40 blacklist
- More comprehensive use of conventional observations
- Use of Meteosat reprocessed winds, CSR data passive
- Improved SST & ICE dataset
- Ocean wave height analysis
Model levels

**ERA-15/ L31**  **ERA-40/ L60**

- **13 LEVELS**
  - 0.1 hPa
  - 64 km
  - 10 hPa
  - 100 hPa

- **9 LEVELS in PBL**

**Levels added**

- **13 LEVELS**
- **7 LEVELS**
- **9 LEVELS in PBL**
Observing Systems in ERA-40

CONVENTIONAL SURFACE AND UPPERAIR OBSERVATIONS
NCAR/ NCEP, ECMWF, JMA, US Navy, Twerle, GATE, FGGE, TOGA, TAO, COADS, ...

AIRCRAFT DATA

1957
1973
1979
1982
1988
2002

1973 VTPR
1979 TOVS: HIRS/ MSU/ SSU Cloud Motion Winds
1987 SSM/I
1991 ERS-1
1995 ERS-2
1998 ATOVS: AMSU-A

METEOSAT Reprocessed Cloud Motion Winds

1973 TOMS/ SBUV

1979 TOMS/ SBUV

1987 TOVS: HIRS/ MSU/ SSU

1988 ERS-1

1995 ERS-2

1998 ATOVS: AMSU-A
Handling of biases in ERA-40

- Radiosonde temperature biases 1980 onwards (Andrae et al. 2004)
- VTPR, TOVS, SSMI and ATOVS radiances
- ERS scatterometer wind bias correction
Radiosonde temperature bias, OB-FG
(4 solar elevation angle intervals and the mean)
all year 1994, South West Canada

Uncorrected

Corrected
Use of radiances in ERA-40

- **VTPR**  8 channel IR sounder instrument
  PAOBs, bogus observations (BOM) from cloud imagery

- **TOVS**  3 sounder instruments
  - HIRS  20 channel IR
  - MSU  4 channel MW
  - SSU  3 channel IR

- **SSMI**  7 channel MW imager

- **ATOVS**  3 sounder instruments
  - HIRS  20 channel IR
  - AMSUA  20 channel MW
  - AMSUB  5 channel MW
VTPR Radiance Sensitivity

Radiance sensitivity to atmospheric temperature changes

Radiance sensitivity (Tropical) to atmospheric moisture changes

Temperature

Humidity
Image created from VTPR CH 2 for all orbits on 28/12/1972
TOVS/ATOVS satellite data 1978-2002

Hernandez et al. (2004)
Radiance sensitivity to atmospheric temperature changes
MSU channels on NOAA-14 (*not used over land)
**VTPR/ TOVS/ ATOVS bias correction**

<table>
<thead>
<tr>
<th>Input radiance</th>
<th>ERA-40</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Level-1c calibrated at ECMWF from Level-1b</td>
</tr>
<tr>
<td>Method</td>
<td>Static</td>
</tr>
<tr>
<td></td>
<td>B. Harris &amp; G. Kelly</td>
</tr>
<tr>
<td>Scan bias</td>
<td>18 latitude bands</td>
</tr>
<tr>
<td>Air-mass dependent bias</td>
<td>Predictors:</td>
</tr>
<tr>
<td></td>
<td>Model values</td>
</tr>
<tr>
<td></td>
<td>DZ(1000-300)hPa</td>
</tr>
<tr>
<td></td>
<td>DZ(200-50)hPa</td>
</tr>
<tr>
<td></td>
<td>(T_{\text{skin}}) and TCWV</td>
</tr>
<tr>
<td>Update frequency</td>
<td>Once per satellite life time or after a jump in instrument based on about two week statistics</td>
</tr>
</tbody>
</table>
VTPR Radiance monitoring 1972/73
Analysis Increments at the start of VTPR radiance assimilation

**500hPa**

**VTPR**

Analysis increments, exp: 0030  500hPa Temp C.  Bias  mean bias =  0.00  st.dev. mean st.dev =  0.58
Region: Land and Sea  limited by:  90.0/  0.0  -  -90.0/357.5

Analysis / Background exp: 0330  500hPa Temp C.  Analysis, mean  -15.80  Background, mean = -15.80
Region: Land and Sea  limited by:  90.0/  0.0  -  -90.0/357.5
Analysis Increments at the start of VTPR radiance assimilation

Precipitable water

VTTPR

Analysis Increments. exp: 0030  PWC kg/m**2  Bias  mean bias=  0.18  st.dev. mean st.dev.=  1.33
Region: Land and Sea  limited by:  20.0/ 0.0  -20.0/357.5

Analysis / Background exp: 0030  PWC kg/m**2  Analysis. mean=  40.49  Background. mean=  40.31
Region: Land and Sea  limited by:  20.0/ 0.0  -20.0/357.5
<table>
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<th></th>
<th>ERA-40</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input radiance</strong></td>
<td>Calibrated Level-1c from F. Wentz →1998 and then on from ECMWF. Satellite to calibration with reference to the 1st satellite done by F. Wentz</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td>Static B. Harris &amp; G. Kelly</td>
</tr>
<tr>
<td><strong>Scan bias</strong></td>
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</tr>
<tr>
<td><strong>Air-mass dependent bias</strong></td>
<td>Predictors: Model values 10 m wind speed, T\text{skin} and TCWV</td>
</tr>
<tr>
<td><strong>Update frequency</strong></td>
<td>Once per satellite life time or after a jump in instrument</td>
</tr>
</tbody>
</table>
How successful?
Global-mean 3hPa temperature (°C)

Year: 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 00 01 02

Pressure levels:
- 1 mb
- 2 mb
- 5 mb
- 10 mb
- 20 mb
- 30 mb
- 50 mb
- 70 mb
- 100 mb
- 150 mb
- 200 mb
- 300 mb
- 500 mb
- 700 mb
- 1000 mb

Legend:
- Temperature range
- Color scale
Ascension Island (8S,14W)
Independent rocketsonde data and ERA-40
Zonal wind at 30km

(Agathe Untch)
Trend and variability in lower stratospheric temperature

Linear trend:
- MSU-4: -0.39°C/decade
- ERA-40: -0.30°C/decade
- NCEP: -0.82°C/decade

MSU-4 data analyzed by Mears et al. (2003)
ERA-40 equivalent from Ben Santer
Comparison of reanalysis and land-station values

Based on monthly station data (Jones and Moberg, 2003)

Based on ERA-40 reanalysis of synoptic data

Surface air temperature anomaly (°C) with respect to 1987-2001

Northern hemisphere

Based on monthly station data (Jones and Moberg, 2003)

Based on ERA-40 reanalysis of synoptic data

Simmons et al. (2004)
Recents trends (1985-2001) in Antarctic snow accumulation from simulations based on ERA-40 and NCEP boundary conditions agree well with the ice core measurements

Andrew J. Monaghan et al. (2005)
500hPa temperature differences

Mean fit (K) of analysis and background to 12UTC 500hPa radiosonde temperatures

Analysis - sonde  Background - sonde  Northern hemisphere

Southern hemisphere
(Maximum energy contribution 700 hPa)

Mean and STD OB-FG MSU_Tb Ch 2 Global

![Graphs showing data for different years and satellites](image-url)
(Maximum energy contribution 300 hPa)

Mean and STD

OB-FG MSU_Tb Ch 3 Global

Year
(Maximum energy contribution 90 hPa)

Mean and STD OB-FG MSU_Tb Ch 4 Global
Operational monitoring 6/9/2001-6/10/2001
- Spacecraft manoeuvre causing instrument heating

AMSU A NOAA-16

MSU NOAA-14
Mean and STD

Maximum energy contribution 400 hPa

OB-FG  HIRS_Tb Ch 4 Global
Mean and STD

(Maximum energy contribution 1.5 hPa)
(Maximum energy contribution 4 hPa)

Mean and STD

OB-FG SSU_Tb Ch 2 Global

[Graph showing time series data with different datasets represented by various colors. The x-axis represents years from 1980 to 2002, and the y-axis shows values ranging from -2.0 to 2.0. Different datasets include NOAA-6, NOAA-7, NOAA-9, TIROS-N, NOAA-11, and NOAA-14.]
Mean and STD

(Maximum energy contribution 15 hPa)
Mean and STD

(Maximum energy contribution 700 hPa)

OB-FG  HIRS_Tb Ch 11 Global
ECMWF reanalyses

ERA-Interim 1989 ➔ Continues as CDAS ➔

ERA-40 1957-2002

(Planned to start in Dec 2005)

- Data-assimilation system
  - T159L60 ➔ T319L91 ?
  - Improved assimilating model CY30R1+
  - Use of 12 hour 4D-Var
  - New humidity analysis
- Satellite Level-1c radiances
  - Better RTTOV and improved use of radiances especially IR
  - Adaptive bias correction
  - Direct assimilation of SSMI radiances
  - Updating blacklist based on JRA-25 experience
- Improved use of radiosondes
  - Bias correction and homogenization based on ERA-40
- Correction of SHIP/ SYNOP surface pressure biases
- Use of reprocessed Meteosat winds and radiances 1989→
- New set of Altimeter wave height data 1991→
Static(Red) and Variational (Black) bias correction
Static and Variational bias correction

0469: TEMP-T 50 hPa S_PolarC
St.dev. and bias (K) OB-FGOB-AN

Static

Adaptive
Static (Red) and Variational (Black) bias correction
(Satellite Data : TOVS/AMSU-A (NOAA-15))

0469: TOVS-1C_noaa-15_AMSU-A_Tb  Ch 7  Tropics
St.dev. and bias (K) OB-FGOB-AN

0470: TOVS-1C_noaa-15_AMSU-A_Tb  Ch 7  Tropics
St.dev. and bias (K) OB-FGOB-AN
Adaptive

Static
Static (Red) and Variational (Black) bias correction
(Satellite Data: SSMI)
Static(Red) and Variational (Black) bias correction (Satellite Data: SSMI)

St.dev. and bias (K) OB-FGOB-AN

0469: SSMI-1C_dmsp-15_SSMI_Tb Ch 3 Tropics

0470: SSMI-1C_dmsp-15_SSMI_Tb Ch 3 Tropics

St.dev. and bias (K) OB-FGOB-AN
Conclusions

- In ERA-40, for the first time, the satellite radiances been extensively assimilated over a long period
- The ERA-40 bias corrections are much more stable than in ERA-15
  - Level 1c versus CCR
  - Direct radiance assimilation, RTTOV, new bias correction predictors
- Detection of realistic climate change signals from ERA-40
- Adaptive bias correction offers many advantages
- Potential for improving the bias estimation in future reanalyses
  - Use of a longer assimilation window
  - Exploit the statistics from ERA-40 (feedback & ODB) to understand satellite biases and possible instrument drifts
  - Accounting model biases
  - Correction of biases in Atmospheric Motions Vectors?
  - More accurate metadata from data producers
  - Integration of different bias corrections