Satellite data in reanalyses

Sakari Uppala & colleagues

ECMWF

Seminar on Development in the Use of Satellite Observations in NWP, 3-7 Sept 2007
Contents

- Motivation of reanalyses
- Observing system: reanalysis perspective
- Evolving analysis schemes
- Observing system changes → analysis quality
- The impact of satellite data:
  - ERA-15 → ERA-40 → ERA-Interim
- Future directions
Motivation of reanalysis
Zonal mean vertical velocity mPa/s 1979-1993

ERA-15 reanalysis

(Stendel & Arpe, ERA-15 Report series No 6)
Application of reanalyses (1)

To improve understanding of

- Weather and climate
- General circulation of atmosphere
- Long term variability and trends
- Tele-connections
- Atmospheric transport
- Hydrological cycle
- Surface processes
- Predictability studies: daily → seasonal
- Extreme weather, storm tracking, tropical cyclones, ...
Application of reanalyses (2)

To provide:

Initial states, external forcing or validation data for

- Climate model integrations
- Ocean models
- Monthly and seasonal forecasting
- Chemical transport models
- DEMETER, ENSEMBLES, ENACT, CANDIDOZ, ...

A substitute for “observed statistics”
Reanalysis projects

- NCEP/ NCAR 1948 → ... CDAS
- NASA/ DAO 1980 - 1995
- ECMWF, ERA-15 1979 - 1993
- ECMWF, ERA-40 1957 - 2002
- ECMWF, ERA-Interim 1989 → ... ECDAS
- JMA, JRA-25 1979 → ... CDAS
- In preparation
  - NASA/ MERRA 1979 →
  - New coupled NCEP reanalysis 1979 →
  - US Arctic Reanalysis System 2000 → 2010
  - New JRA reanalysis 1957 →
Operational forecast performance 1980-2007

Northern Hemisphere
500 hPa geopotential
ANC reaching 60%

Northern Hemisphere
500 hPa geopotential
ANC reaching 60%

Tropics
850 hPa wind vector
ABC reaching 70%

Southern Hemisphere
500 hPa geopotential
ANC reaching 60%

Monthly time series
Moving average

ERA-15
ERA-40
Reanalysis quality depends on:

1) The available observational information:
   - Conventional
   - Satellite
   - The spatial and vertical distribution of the previous
   - Boundary forcing fields: SST and ice dataset

2) The data assimilation system:
   - The analysis method and the assimilating forecast model
   - The observation and background model errors
Analysis product quality improves in time

Observing systems including SST/ICE improves:
Better quality, more data types, higher time frequency

Data-assimilation system, model and analysis, unchanged through the period

Reanalysis schematically
Observations for reanalysis
Surface observations

1958 March

1998 March
Radiosonde coverage for 1958

1°1° average in 3 categories: > 1 per week -> 0.5 per day: 0.5 per day -> 1.5 per day: > 1.5 per day

Average number of soundings per day: 1609
Radiosonde coverage for 1979

1°1° average in 3 categories: > 1 per week -> 0.5 per day: 0.5 per day -> 1.5 per day: > 1.5 per day

Average number of soundings per day: 1626
Radiosonde coverage for 2001

1°1° average in 3 categories: > 1 per week -> 0.5 per day: 0.5 per day -> 1.5 per day: > 1.5 per day

Average number of soundings per day: 1189
Year 2000

mobile ships, Dropsondes and radiosondes

A single analysis time
Daily number of radiosondes in the Northern Hemisphere

Pressure (hPa)

ERA-15 / L31

ERA-40 / L60

Level number
Zonal mean number of radiosondes

ERA-15 / L31

ERA-40 / L60

Pressure (hPa)

Level number

3 - 6
6 - 11
11 - 16
16 - 45
45 - 118
118 - 225
225 - 545
545 - 562
GARP
THE GLOBAL ATMOSPHERIC RESEARCH PROGRAM (1969)

MAIN OBJECTIVES

- Improved understanding of the physical processes of the general atmospheric circulation
- Formulation of improved physico-mathematical models of the atmosphere
- Optimum design for a global observing system

Program components: Tropical (GATE), Global, other (MONEX, POLEX, …)

Research projects | Numerical experimentation | Technological developments

FIRST GARP GLOBAL EXPERIMENT
FGGE
December 1978 → November 1979
GATE EXPERIMENT  15 June → 19 September 1974
Example day
19740710
850 hPa
Pilot & Temp
First Garp Global Experiment
FGGE 1979
Definition of the observing system
Satellites with VTPR instruments
ERA-40 TOVS 1C RADIANCES
NOAA-9 198411 - 198811
90 S - 90 N  Central scan

- Failure of channel 2
- Drifting of channel 3
- Bad earth location
Technological advances

In the past
Thousands of tapes/ cartridges

Today
1 Super DLT capacity ~800GB
Observing Systems in ERA-40

1957

1973 VTPR

1979 TOVS:
HIRS/ MSU/ SSU Cloud Motion Winds

1979 TOMS/ SBUV

1982 Reprocessed Cloud Motion Winds

1987 SSM/I

1991 ERS-1

1995 ERS-2

1998 ATOVS: AMSU-A

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

AIRCRAFT DATA
Quality of Cloud Motion Winds improves

Moving average of daily $\sqrt{U_{\text{rms}}^2 + V_{\text{rms}}^2}$

Latitude band 30N-15N (OB–AN, OB–FG) levels 300-200 hPa
METEOSAT Reprocessed Winds

a) Old operational IR data

b) Reprocessed ELW data, IR and VIS
Sea Surface Temperature and Ice data

Before November 1981 (HADISST1, Met Office)
- Monthly SST analysis based on ship and buoy measurements
- Sea ice extent has large uncertainty

From November 1981
- Retrievals of SST from Advanced Very High Resolution Radiometer after cloud clearing
- Buoy and ship data
- OI or 2D-Var weekly SST analysis (R. Reynolds, NCEP)
- Background is the previous SST analysis
- Bias correction applied to satellite SSTs
- Sea ice extent determined from ice concentrations retrieved from SSMR and SSMI instruments

Interpolation to daily values
NOAA/NCEP weekly 2D-Var
Satellite, Ship and buoy
Met Office monthly HADISST1
Ship and buoy

Nov 1981

El Nino
La Nina

(F. Wentz, Remote Sensing Systems)
ECMWF reanalyses

ERA-40 1957-2002

ERA-15 1979-1993

- Improved data assimilation system
  - Assimilating model T159L60
  - Optimum Interpolation → 3D-Var FGAT
  - Analysis of O₃
- More extensive use satellite radiances (from CCR → Level 1c 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

Levels added

13 LEVELS

7 LEVELS

9 LEVELS in PBL
## Use of atmospheric satellite data in reanalyses

<table>
<thead>
<tr>
<th></th>
<th>VTPR/ TOVS/ ATOVS</th>
<th>DMSP</th>
<th>GEO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SSU VTPR HIRS MSU</td>
<td>AMSU</td>
<td>SSM/I</td>
</tr>
<tr>
<td><strong>NCEP 1948 →</strong></td>
<td></td>
<td></td>
<td>Oper AMWs</td>
</tr>
<tr>
<td></td>
<td>NEDSIS operational T &amp; q retrievals</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ERA-15 1979-1993</strong></td>
<td>- - 1D-Var retrievals of T &amp; q using CCR. Above 100hPa NEDSIS retrievals.</td>
<td>-</td>
<td>Oper AMWs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ERA-40 1957-2002</strong></td>
<td>1c 1c 1c 1c 1c</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1D-Var retrievals of TCWV &amp; wind speed</td>
<td>Oper+reprocessed AMWs, CSR passively</td>
<td></td>
</tr>
<tr>
<td><strong>JRA-25 1979 →</strong></td>
<td>1c - 1c 1c 1c</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>JMA retrievals of TCWV</td>
<td>Oper+reprocessed AMWs</td>
<td></td>
</tr>
<tr>
<td><strong>ERA-Interim 1989 →</strong></td>
<td>1c - 1c 1c 1c</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1c radiances and 1D-Var retrievals of rainy radiances</td>
<td>Oper+reprocessed AMWs, CSR passively</td>
<td></td>
</tr>
</tbody>
</table>
Use of TOVS data in ERA-15
Handling of biases in ERA-40

- Radiosonde temperature biases 1980 onwards
- VTPR, TOVS, SSMI and ATOVS radiances
- ERS scatterometer wind bias correction
<table>
<thead>
<tr>
<th></th>
<th>ERA-15</th>
<th>ERA-40</th>
<th>SSMI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input radiance</strong></td>
<td>Cloud Cleared and nadir corrected Radiances</td>
<td>Level-1c calibrated at ECMWF from Level-1b</td>
<td>Level-1c data from RSS &amp; ECMWF. Satellite to satellite calibration with reference to the 1st satellite, F. Wentz</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td>Static</td>
<td>Static</td>
<td>Static</td>
</tr>
<tr>
<td></td>
<td>J. Eyre based on W. Smith &amp; H. Woolf</td>
<td>B. Harris &amp; G. Kelly</td>
<td>B. Harris &amp; G. Kelly</td>
</tr>
<tr>
<td><strong>Scan bias</strong></td>
<td>Global offset with 0 at center</td>
<td>18 latitude bands</td>
<td>18 latitude bands</td>
</tr>
<tr>
<td><strong>Air-mass dependent bias</strong></td>
<td>Predictors: MSU-2,3 and 4, which are unaffected by clouds</td>
<td>Predictors: Model values , DZ(1000-300), DZ(200-50), Tskin and TCWV</td>
<td>Predictors: Model values ,10 m wind speed, Tskin and TCWV</td>
</tr>
<tr>
<td><strong>Update frequency</strong></td>
<td>monthly</td>
<td>Once per satellite life time or after a jump in instrument based on about two week statistics</td>
<td>Once per satellite life time or after a jump in instrument</td>
</tr>
</tbody>
</table>
NOAA-11

ERA-40 Radiance Monitoring

-2 -1.5 -1 -0.5 0 0.5 1 1.5 2

M_4


MEAN UNCORRECTED DEPARTURE
MEAN CORRECTED DEPARTURE
MEAN OBSERVED: ANOMALY

Northeast

Pinatubo

NOAA-12

-2 -1.5 -1 -0.5 0 0.5 1 1.5 2

M_4

ERA-15 Tropical temperature

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
Quality of Analysis & Background
Global 500 hPa Temperature analysis mean increment and STD

VTPR introduced
Tropical TCWV analysis **mean increment and STD**

**VTPR**

Tropical mean TCWV (kgm$^{-2}$) **background and analysis**
Input observations

Conventional
• Surface
• Upperair
• Aircraft
• Satellite products

TOVS radiances

SSMI radiances

AIRS radiances

O3 data

Bias modules

NWP system
Observations and observation equivalents from the model and analysis in database
⇒ Quality and departure information

Conventional feedback
• Surface
• Upperair
• Aircraft
• Satellite products

TOVS feedback

SSMI feedback

AIRS feedback

O3 feedback

- Input and feedback observations in BUFR code as well as as the runtime database, ODB, through the period)
RMS fit (hPa) of analysis and background to 12UTC SYNOP and SHIP surface pressures

Northern hemisphere

Southern hemisphere

VTPR

FGGE

background

analysis
ERA-40: SATOB U-Wind 850 00 UTC Tropics RMS (m/s) OB-FG OB-AN 15 days MA

Number of used observations per day

Meteosat Reprocessed winds
Analysis of ozone

The three-dimensional ozone field is consistent both with available ozone observations and the dynamical state of the atmosphere.
ERA-40 analysis

Ground-based measurements
From NOAA/ CMDL and not used in analysis.

Monthly mean values

No data assimilated in 1989 and 1990.
Moisture analysis
Aspects of tropical humidity analysis in ERA-40

Tropical-mean TCWV (kg/(m$^2$m))

Tropical-mean TCWV increment (kg/(m$^2$m))

Tropical-mean precipitation (mm/day)
Tropical oceans: SST ↔ TCWV

- 24h forecast Total Column Water Vapour
- SST analysis
- kgm$^{-2}$
- Monthly SST HADISST1
- Reynolds weekly SST
- no satellites
- VTPR
- TOVS
- TOVS + SSMI
- TOVS + SSMI + ATOVS

Graph showing changes in SST and TCWV from 1987 to 2001, with different satellite datasets indicated.
Detection of tropical cyclones

- ERA-40 – SMMR TCWV 1979-1984

(from Richard Allan)
Climate variability and trends
Detection of tropical cyclones

Models: ERA-40(e40) | Taus: 1) 0; 2) 72
Basins: 1) NHEM; 2) SHEM | Veri Rules: Hetero JTWC(mod)
Debate on the trends in tropical cyclone intensity

Ryan L. Sriver and Matthew Huber, 2006, Geophysical Research Letters
“Low frequency variability in globally integrated tropical cyclone power dissipation”
- R. N. Maue and R. E. Hart, 2007, comment to the previous
- Ryan L. Sriver and Matthew Huber, 2007, Reply to comment

(Note: No TC bogus data in ERA-40 or NCEP!)

TOVS starts
One of the most important and difficult to characterize sources of long-term drift in the data is due to the evolution of the local observing time due to slow changes in the orbital parameters of each NOAA platform, which can alias diurnal temperature changes into the long-term time series. To account for this effect, we have constructed monthly diurnal climatologies of MSU Channel 2 brightness temperature using the hourly output of a general circulation model as input for a microwave radiative transfer model.

(Carl A. Mears et al: Correcting the MSU Middle Tropospheric Temperature for Diurnal Drifts, Remote sensing Systems)
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
Satellite radar altimeter 1992-2003
(Davis et al. Science 2005 Vol 308 No. 5730)

Surface elevation change rate (cm per year):
1992 → 2003

Precipitation change (cm of snow per year):
ERA-40 Atlas 1979-2001

http://www.ecmwf.int/research/era/ERA-40_Atlas/docs/index.html
Quasi-Biennial Oscillation

Equatorial band 2S-2N
Monthly mean zonal wind anomaly (m/sec) to 1979-2001 climate
FORECAST PERFORMANCE

1957-2002
Anomaly correlations of 500hPa height forecasts

Northern Hemisphere

Ops 1980

Ops 2001

Ops 2003

ERA 2001

Day

%
Anomaly correlations of 500hPa height forecasts

Australia/New Zealand

Ops 1980

Ops 2003

Ops 2001

ERA 2001

%
ERA-Interim 1989 → to continue as CDAS →

ERA-40 1957-2002

- Data-assimilation system
  - T159L60 → T255L60 / 12 hour 4D-Var
  - New humidity analysis and improved model physics
- Satellite level-1c radiances
  - Better RTTOV and improved use of radiances especially IR and AMSU
  - Assimilation of rain affected radiances through 1D-Var
  - Variational bias correction
- Improved use of radiosondes
  - Bias correction and homogenization based on ERA-40
- Correction of SHIP/ SYNOP surface pressure biases
- Use of reprocessed
  - Meteosat winds
  - GPS-RO data CHAMP / UCAR 2001 →, GRACE and COSMIC
  - GOME O3 profiles 1995 →
- New set of Altimeter wave height data 1991→
Mean daily precipitation rate

- **a** ERA-Interim minus GPCP
- **b** ERA-40 minus GPCP
- **c** ERA-Interim minus ERA-40

Mean total column water vapour

- **d** ERA-Interim minus RSS
- **e** ERA-40 minus RSS
- **f** ERA-Interim minus ERA-40
Anomaly correlation of 500hPa height forecasts

- ERA-Int
- ERA-40
- OPS

Northern Hemisphere

Improvement: NH ~ 0.5d  SH ~ 1d
Could start ~ 2011 depending on resources

~ 1938 → 2013 and continue as CDAS

Important components

- Recovery, organization and homogenization of observations
- Improved SST & ICE dataset
- Variational analysis technique aimed for reanalysis
- Comprehensive adaptive bias handling
- Handling of model biases
- Coupled atmospheric-ocean reanalysis?
Summary

- Reanalyses have, in part, reached the level required for climate studies
- Satellite data have an increasing role in reanalysis
- The composite observing system improves over time
- Due to the use of satellite data reanalysis has substantially better and more uniform quality after 1978 especially over the Southern Hemisphere
- Reanalysis is seen as an iterative process, where improvements in the data assimilation/ bias adjustment/ increasing resolution bring new qualities to reanalyses and therefore to the applications
- Reprocessing/ recalibration of satellite data improves reanalysis quality and should also be done iteratively
- Improving the homogeneity of satellite data record is important
- Satellite missions with long period and overlapping important for reanalyses