Progress achieved on assimilation of satellite data in NWP over the last 30 years

John Eyre
Met Office, UK

ECWMF Seminar on “Recent Development in the Use of Satellite Observations in NWP, 3-7 Sept 2007
Progress achieved on assimilation of satellite data in NWP over the last 30 years

sub-title: Ancient Developments in the Use of Satellite Observations in NWP

Structure of talk

• Satellite soundings (passive IR/MW soundings of temp/humidity profiles)
  • Early instruments
  • Assimilation experience: 1970s and 1980s
  • Problems with assimilation of retrievals
  • Direct assimilation of radiances: 1990s

• Atmospheric Motion Vectors (AMVs)

• Scatterometry
  • Early instruments
  • Early assimilation experience

• More recent advances
  • TOVS → ATOVS, AIRS and IASI, other data types
  • Radio occultation

• Strategies for various data types
Weather satellites – early milestones

- TIROS-1 1960 1st satellite giving images of Earth
- NIMBUS-1 1964 1st meteorological research satellite
- ATS-1 1966 1st geostationary weather satellite
- ESSA-1 1966 1st operational weather satellite
- NIMBUS-3 1969 1st temperature sounders
- ITOS-1 1970 1st APT system – improved imagery
- NOAA-2 1972 1st operational temperature sounder
- SMS-1 1974 1st USA operational geostationary satellite
- GMS-1 1977 1st Japanese operational geostationary satellite
- Meteosat-1 1977 1st European operational geostationary satellite
- TIROS-N 1978 New generation of operational polar satellites
- FGGE 1979 First GARP Global Experiment
Satellite soundings

- passive infra-red/microwave soundings of temperature/humidity profiles
Satellite sounding instruments

Nimbus series – temperature/humidity sounders
- Nimbus-3 1969-70  **SIRS, IRIS**
- Nimbus-4 1970-71  **SIRS, IRIS, SCR**
- Nimbus-5 1972  **ITPR, SCR**
- Nimbus-6 1975  **HIRS, SCAMS, PMR, LRIR**
- Nimbus-7 1978-94?  **LIMS, SAMS**

NOAA series – temperature/humidity sounders
- NOAA 2-5 1972-79  **VTPR**
- TIROS-N 1978-80  **TOVS = HIRS, MSU, SSU**
- NOAA-6/14 1979-  **TOVS = HIRS, MSU, SSU**
- NOAA-15+ 1998-  **ATOVS = AMSU-A, AMSU-B, HIRS**
VTPR Radiance Sensitivity

- Radiance sensitivity to atmospheric temperature changes
- Radiance sensitivity (Tropical) to atmospheric moisture changes

temperature  humidity
Fig. 3 TOVS normalised weighting functions (from Smith et al., 1979).
TOVS – scan patterns

HIRS and MSU scan patterns
Assimilation experience: 1970s (1)

Australian experience
See W. Bourke, “History of NWP in Australia – 1970 to the present”, BMRC Workshop, October 2004

• Importance of satellite cloud imagery interpretation for analysis of surface pressure (PAOBs) and 1000-500 hPa thickness in SH.

• From 1972, Kelly used NOAA-2,3,4 VTPR data – retrievals from cloud-cleared radiances.

• 1976, Kelly demonstrated within a continuous data assimilation system benefits of assimilating VTPR and PAOBs.

• Kelly, Mills and Smith (BAMS, 59, 393-405, 1978) “Impact of Nimbus-6 temperature soundings on Australian regional forecasts”:
  • 14 days assimilation. Average improvement of >5 skill scores points on 24h geopotential forecasts (surface $\rightarrow$ 200 hPa)

In this story, this chap Kelly appears everywhere!
UK experience


- SIRS data impact study
- Used operationally, at discretion of Chief Forecaster.
Summary paper:

Summarised results from several OSEs
• Desmarais et al (1978) VTPR + Nimbus 6
• Halem et al (1978) VTPR + Nimbus 6
• Bonner et al (1976) VTPR
• Atkins and Jones (1975) SIRS
• Druyan et al (1978) VTPR
• Kelly (1977) VTPR
• Kelly et al (1978) Nimbus 6
Summary paper:

Summary:
• “on average, a small improvement in numerical forecasts”
• “beneficial but modest impacts”
• “hesitate to claim that satellite data changed a poor forecast to an accurate one”
• Greater improvements in forecasts in S Hem.

Problems:
• Differences between retrievals and collocated radiosondes of 2-3 deg
• Analyses using satellite data have lower eddy potential energy
• Satellite soundings not point observations – have their own error characteristic – improved analysis schemes may enhance impact
• Improvements in retrieval methods likely - but basic problem is poor vertical resolution – “the statistical/climatological nature of retrieval techniques may suppress horizontal structure”
FGGE:
First GARP Global Experiment

(GARP = Global Atmospheric Research Programme)

General observational period:
01.12.1978 - 30.11.1979

Special observational periods:
05.01.1979 - 05.03.1979
01.05.1979 - 30.06.1979
Halem M, E Kalnay, W E Baker and R Atlas,
“An assessment of the FGGE Satellite Observing System during SOP-1”
BAMS, 63, 407-426, 1982

• OSEs for several obs types
• 6-hour forecast errors reduced downstream of data sparse areas by including satellite observations
• over N.America and Europe, small improvements in forecast skill
• over Australia, positive impact of satellite data is much larger

From the summary:

• 4 centres, 11 experiments, 85 forecast-days
• 3 periods: SOP-1, SOP-2, Nov 79 (2 NOAA satellites)

• ECMWF: NOSAT: “useful predictability reduced from 5.5 to 4.5 days in NH and from 5 to 3 days in SH
• GLAS: NOSAT: Large impact over S.America and Australia. Smaller but +ve impact over N.America and Europe
• ANMRC: NO-SATEM: Substantial +ve impact in SH
• GLAS: NO-SATEM: +ve impact over Australia. Europe and N.America, less impact and variable
• NMC: NO-SATEM: +ve impact on one cycle at T+3.5 over E.USA
• ECMWF: space-based only. “surprisingly good skill at T+4”, SH: small differences
ECMWF Seminar 1984. “Data Assimilation and observing system experiments, with particular emphasis on FGGE”.

Summary:

• Accuracy of satellite temperature soundings … 2-3 deg below 850 hPa, 1.5-2 deg above … satisfactorily assimilated … important role in analysing large scale weather systems at high and mid latitudes, in particular in SH

• “(satellite) atmospheric soundings … are an essential element of the GOS”

• Uppala et al
  • AMVs important for analysis of tropics
  • SATEMs of paramount importance for extra-tropical analysis over ocean areas

• Layering of retrievals:
  • Change from 14 layers: 1000-850, 850-700, 700-500, 500-400, 400-300, 300-250, 250-200, 200-150, 150-10, 100-70, 70-50, 50-30, 30-20, 20-10 hPa
  • To 11 layers in 1985,
  • To 7 layers in 1987: 1000-700, 700-500, 500-300, 300-100, 100-50, 50-30, 30-10
• SH: +ve impact, NH: mixed
• QC problems (cloud and rain)
• Improvements in stratosphere
• Reduced impact in NH compared with Uppala et al (1984)
Late 1980s: problems (2)

Andersson et al. “Global observing system experiments on operational statistical retrievals of satellite sounding data”, MWR, 119, 1851-1864 (1991)

- The neutral impact of SATEMs with the 1987 system gave way to a negative impact in the 1988 system. “In the present study the overall impact of SATEM data in the NH is negative”.
- Synoptically correlated biases


- “the new physical retrievals have much the same problems of bias and noise that were noted with the statistical retrievals”
- Improved QC to mitigate the worst problems
Late 1980s: problems - synoptically correlated biases

Problems with assimilation of sounder data

Problem No.1 - RADIOSONDES

Suomi’s 11th commandment:
“Thou shalt not worship the radiosonde”

- early NWP systems designed to make use of sondes
- satellite sounders and sondes have opposite strengths and weaknesses
- treating satellite soundings as “poor-quality sondes” is flawed
The history and future of data assimilation (1)

… backwards … and in 2 slides
Bayesian:
• What is the probability of atmospheric state, $x$, given observations, $y^o$? 
• Evaluate: $P(x|y^o) = P(y^o|x).P(x)/P(y^o)$

Variational (VAR):
• What is the most probable atmospheric state, $x$, given observations, $y^o$? 
• To maximise $P(x|y^o)$,
  • maximise: $\ln\{P(x|y^o)\} = \ln\{P(y^o|x)\} + \ln\{P(x)\} + \text{constant}$ 
• If PDFs are Gaussian, then minimise a PENALTY FUNCTION, 
  • $J[x] = \frac{1}{2} (x-x^b)^T B^{-1} (x-x^b) + \frac{1}{2} (y^o-H[x])^T (E+F)^{-1} (y^o-H[x])$

$x^b$: background 
$B$: background error covariance 
$H[x]$: observation operator 
$E, F$: error covariances of observations and observation operator
Optimal Interpolation (OI)

- Linearising the VAR problem →
- \( x^a = x^b + K \cdot (y^o - H[x]) \)
  - where \( K = B \cdot H^T \cdot (H \cdot B \cdot H^T + E + F)^{-1} \)
  - \( H \) is the Jacobian of the observation operator \( H[x] \)

Empirical

- \( x^a = x^b + K \cdot (y^o - H[x]) \)
- but with \( K \) as empirically-derived weights

Key issues for satellite soundings

- VAR provides method on handling large numbers of observations
- … linked to analysis variables in a non-linear way
• Linearized retrieval equation: \( x^a - x^b = K.(y^o - H[x^b]) \)

• Linearized forward equation: \( y^o - H[x^b] = H.(x-x^b) + \varepsilon \)

• Combine: \( x^a - x^b = K.H.(x-x^b) + K.\varepsilon \)

or \( x^a - x^t = (I-K.H).(x^b-x^t) + K.\varepsilon \)

retrieval error error error
background error error measurement error

where \( t \) denotes truth, \( I = \) unit matrix, \( H = \nabla_x H[x] \)

• This equation shows why assimilating retrieved temperature/humidity profiles into NWP models is more problematic than assimilating radiances directly
Variational equations: for 1D-Var, 3D-Var, 4D-Var

Minimize:

\[ J[x] = \frac{1}{2} (x-x^b)^T B^{-1} (x-x^b) + \frac{1}{2} (y^o-H[x])^T (E+F)^{-1} (y^o-H[x]) \]

where

- \( x \) contains the NWP model state
- \( x^b \) is background estimate of \( x \) (short-range forecast)
- \( B \) is its error covariance,
- \( y^o \) is vector of measurements
- \( H[...] \) is “observation operator” or “forward model”, mapping state \( x \) into “measurement space”
- \( E \) is error covariance of measurements,
- \( F \) is error covariance of forward model.

\[ \nabla_x J[x]^T = B^{-1} (x-x^b) - \nabla_x H[x]^T (E+F)^{-1} (y^o-H(x)) = 0 \]
Direct assimilation of radiances: 1990s

TOVS in NWP via 1D-Var
- **Eyre et al**, QJRMS, 119, 1427-1463 (1993) “Assimilation of TOVS radiance information through one-dimensional variational analysis”
- main advance over assimilation of SATEMs: 1D-Var produces no analysis increments when measured radiances agree with forecast radiances
- still needs care over assimilation because of use of forecast background in 1D-Var retrieval
  - operational ECMWF, June 1992

TOVS in 3D-Var
  - operational at NCEP, October 1995
  - operational at ECMWF, January 1996

TOVS in 4D-Var
- Operational at ECMWF, November 1997
Atmospheric motion vectors

• winds derived by tracking features in imagery
Scatterometry
<table>
<thead>
<tr>
<th>year</th>
<th>satellite</th>
<th>instrument</th>
<th>freq GHz</th>
<th>views</th>
<th>res km</th>
<th>swath km</th>
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<tbody>
<tr>
<td>73-74</td>
<td>Skylab</td>
<td>MRSA</td>
<td>13.9 (Ku-band)</td>
<td>1*</td>
<td>15</td>
<td>185</td>
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<tr>
<td>78</td>
<td>SEASAT</td>
<td>SASS</td>
<td>14.6 (Ku-band)</td>
<td>2</td>
<td>25</td>
<td>1000</td>
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<tr>
<td>91-00</td>
<td>ERS-1</td>
<td>AMI</td>
<td>5.3 (C-band)</td>
<td>3</td>
<td>25</td>
<td>500</td>
</tr>
<tr>
<td>95-</td>
<td>ERS-2</td>
<td>AMI</td>
<td>5.3 (C-band)</td>
<td>3</td>
<td>25</td>
<td>500</td>
</tr>
<tr>
<td>96-97</td>
<td>ADEOS-I</td>
<td>NSCAT</td>
<td>14.0 (Ku-band)</td>
<td>3</td>
<td>50</td>
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<tr>
<td>99-</td>
<td>Quikscat</td>
<td>Seawinds</td>
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<td>25</td>
<td>1800</td>
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<tr>
<td>06-</td>
<td>Metop</td>
<td>ASCAT</td>
<td>5.3 (C-band)</td>
<td>3</td>
<td>25</td>
<td>1000</td>
</tr>
</tbody>
</table>

* dual polarisation
Scatterometry: ERS-1 and -2 (1)
ERS scatterometer:
the measurement cone in $\sigma^0$-space

Wind speed increases along the cone
Wind direction changes through 360º for twice around the cone
Scatterometry: early assimilation experience

• Baker et al (JGR, 89, 4927-, 1984) SEASAT
  • Impact negligible in NH (~2% in skill score in PMSL). Impact +ve in SH removed when VTPR included. (Low-resolution model with no PBL scheme.)

• Yu and McPherson (MWR, 112, 368-, 1984) SEASAT
  • Significant impact in SH, but not possible to assess if impact is positive.

• Andersson et al (JGR, 96, 2653-, 1991) SEASAT
  • Neutral

• Stoffelen and Cats (MWR, 119, 2794-, 1991) SEASAT
  • LAM, QE-2 storm. Positive impact.

• Hoffman (JGR, 98, 10233-, 1993) ERS-1
  • Neutral

• Breivik et al (DNMI Tech Rep 104, 1993) ERS-1
  • Norwegian LAM. Small positive impact.

• Bell (Proc 2nd ERS-1 Symp, 1994) ERS-1
  • Positive in SH at T+120

• Stoffelen and Anderson (QJ, 123, 491-, 1997) ERS-1
  • Positive in short-range.
    • Operational at ECMWF? (with 3D-Var, January 1996?)
More recent advances
More recent advances: TOVS $\rightarrow$ ATOVS

AMSU-A  AMSU-B  TOVS = HIRS + MSU + SSU
More recent advances: AIRS and IASI

IASI v. HIRS
More recent advances: other observation types

Other satellite data now assimilated in NWP:

• SSMI MW imagery (for surface wind, water vapour, cloud water)
• SSMI cloud-affected radiances (for precipitation)
• geo WV radiances
• geo retrieved cloud
• ozone (SBUV, SCIAMACHY)
• MIPAS limb radiances
• SSMIS MW sounder radiances
• GPS-WV (satellite-to-ground)

• GPS-RO (satellite-to-satellite)
Radio occultation: the technique (1)
Radio occultation: the technique (2)

\[ \ln(n(a)) = \frac{1}{\pi} \int_0^\infty \frac{\alpha(a')}{\sqrt{a'^2 - a^2}} da' \]

\[ N = (n - 1) \times 10^6 = \kappa_1 \frac{p}{T} + \kappa_2 \frac{e}{T^2} \]

Impact parameter

Bending angle

L₁: 1.575 GHz / 19.0 cm
L₂: 1.227 GHz / 24.4 cm

Refractive index

Refractivity
Refractivity gradients caused by gradients in:
- density (pressure and temperature)
- water vapour
- electron density
- (liquid water)

\[ N = \kappa_1 \frac{p}{T} + \kappa_2 \frac{e}{T^2} + \kappa_3 \frac{n_e}{f^2} + \kappa_4 W \]

"dry"  "moist"  ionosphere  "scattering"

\( N \) = refractivity = \((n - 1) \times 10^6\); \( n \) = refractive index
\( p \) = pressure
\( T \) = temperature
\( e \) = water vapour pressure
\( n_e \) = electron density
\( f \) = frequency
\( W \) = liquid water density
Radio occultation: characteristics

• globally distributed

• temperature in stratosphere and upper troposphere, and ...

• humidity on lower troposphere

• high vertical resolution: 0.5 - 1 km

• low horizontal resolution: ~ 200 km

• high accuracy:
  • random errors ~1K
  • systematic errors <0.2K (to be demonstrated in practice)

• “all-weather”

• space/time sampling determined by number of GPS receivers

• relatively inexpensive
Radio occultation missions (1)

Past:
- GPS/MET: 1995 - 1997 experimental, selected periods only

Present:
- CHAMP 2000 - … exptl, continuous since 2001; NRT since 2006
- SAC-C 2000 - … sporadic measurements, experimental
- GRACE-A 2002 - … exptl, continuous since 2003; NRT since 2006
- COSMIC 2006 - … demonstration mission, 6 satellites
- TerraSAR-X 2007 - …

Future:
- EQUARS 2007? emphasising equatorial region
- OCEANSAT-ROSA 2009? Italian / Indian mission
- COSMIC-2 ?
- CICERO ? 20-100 satellites
Radio occultation missions (2)

COSMIC

CHAMP

Metop/GRAS
Error analysis: radio occultation with IASI

Collard and Healy, 2003
Data Coverage: GPSRO (8/8/2007, 0 UTC, pu00)
Total number of observations assimilated: 246
... compared with sondes

Data Coverage: Sonde (8/8/2007, 0 UTC, pu00)
Total number of observations assimilated: 619

TEMP LAND (613) TEMP SHIP (5) TEMP MOBILE (1)
Options:

(1) assimilate retrieved profiles of temperature and humidity
(2) assimilate retrieved profile of refractivity, N(z)
(3) assimilate measured refracted angles, $\alpha(a)$, directly

Special problems with RO data:

• non-separability of temperature and humidity
  • addressed by (2) and (3)
• limited horizontal resolution / problems of horizontal gradients
  • partially addressed by (3)
Radio occultation: monitoring

COSMIC-1
3 Jul -2 Aug 2007

Statistics of observation increments in % refractivity

Statistics are remarkably stable:
• day to day
• satellite to satellite
Recent results
(M.Rennie, Met Office)

Temperature: mean difference (top) and RMS difference (bottom) from sondes, SH, T+24 CONTROL, COSMICx6

The assimilation of GPSRO reduces RMS errors in the upper troposphere and corrects model biases.

Similar patterns in NH and TR, but smaller impact
More recent advances: radio occultation

Recent results – bias and RMS v. forecast range

Temperature (Kelvin) at 250.0 hPa: Sonde Obs
Southern Hemisphere (CBS area 20S–90S)
Meaned from 27/11/2006 12Z to 27/12/2006 12Z

Wind (m/s) at 100.0 hPa: Sonde Obs
Southern Hemisphere (CBS area 20S–90S)
Meaned from 27/11/2006 12Z to 27/12/2006 12Z
Strategies for various data types
Direct assimilation of observations

- Raw observations
  - Pre-process
    - Pre-processed observations
      - Observed variables
        - NWP model variables
          - Observation operator
            - Interpolate to time/place of observations
              - Observation increments
                - Compare
                  - Forecast observations
                    - Forecast
                      - NWP fields
                        - Interpolate to NWP model variables
                          - Map back to atmospheric variables
                            - Observation operator
                              - Forecasts
                                - NWP fields
Assimilation of satellite data: strategies for various data types


Direct assimilation of “raw” observations

Advantages
• Within variational schemes, the “observation operator”, $H(x)$, can be nonlinear - important for many remotely-sensed observations
• In principle, we can use "raw" measurements - in the space of the observed variables - e.g. radiances, backscatter coefficients - simpler errors

Limitations
• $H(x)$ must simulate observation in the form in which it is presented to the system - $H(x)$ must be matched to any pre-processing
• Raw observations have more complex operators
• Some obs are affected by physical variables NOT contained in the control variable
• Logistical problem - need to develop/maintain expertise on all satellite observation operators and associated errors - STRATEGY NEEDED: improved links between "assimilation centres" and "satellite centres” → NWP SAF, JCSDA
Summary - Needs careful consideration for each obs type

- Passive temperature/humidity soundings
  - as radiances
- Winds
  - small-scale as AMVs, large-scale as radiances?
- Scatterometry
  - as retrieved “ambiguous” wind vectors
  - not backscatter, for subtle reasons - high degree of nonlinearity of obs operator
- MW imagery (water vapour, cloud water, precip, wind speed)
  - complex issues:
    - nonlinearity of multi-variate operators,
    - low vertical resolution (dependence on B-matrix)
- Cloud imagery
  - as retrieved cloud or as radiances?
- Radio occultation
  - as retrieved refractivity or bending angle