Progress achieved on assimilation of satellite data in numerical weather prediction over the last 30 years

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1. Introduction

This paper reviews progress on the use of satellite observations in numerical weather prediction (NWP) over the last 30 years, with emphasis on the earlier years; more recent progress is covered in detail by other papers in this volume.

Section 2 provides a summary of the major early milestones in satellite meteorology and their relevance for the developing field of NWP.

Satellite soundings (i.e. passive infra-red and microwave soundings of atmospheric temperature and humidity) are considered in some detail in section 3, including: the history of the contributing instruments, early progress on assimilation of these data into NWP models, the fundamental problems encountered when assimilating retrieved temperature/humidity profiles, and the solution to these problems through more direct assimilation of the measured radiances.

Atmospheric motion vectors (AMVs) derived from satellite imagery have been, and continue to be, an important source of information for NWP. This topic is covered fully by Forsythe (2007, this volume).

Scatterometers provide information on wind speed and direction over the sea. Section 4 reviews the history of these instruments and the early assimilation experience. More recent progress is covered by Janssen (2007, this volume).

Section 5 provides a brief summary of more recent advances – in the instrumentation for satellite soundings, and in the range of satellite data now used in NWP. Other papers in this volume expand on most of these topics. An exception is radio occultation, for which this paper provides a background to the technique and the use of its data in NWP. For further discussion on the role of radio occultation measurements in stratospheric data assimilation, see Dee (2007, this volume).

When assimilating satellite data into NWP models, choices arise as to the form in which the data are assimilated; the data can be heavily pre-processed prior to assimilation or they can be used in a more or less "raw" form. The resolution of these choices is different for each data type. Section 6 provides some discussion on these issues.

2. Early meteorological satellites

Table 1 presents some of the important milestones in the development of meteorological satellites.

The first satellite to provide images of the Earth, and hence the weather, was TIROS-1 launched in 1960. This was followed by very rapid development in the satellites and their instruments, and in the progression from demonstration and research missions to operational capability. The first weather satellites carried imaging instruments, which provided pictures of clouds. The introduction of geostationary satellites gave frequently updated pictures of the clouds and allowed winds to be derived from their motion.

TIROS-1	1960	1st satellite giving images of Earth
Nimbus-1	1964	1st meteorological research satellite
ATS-1	1966	1st geostationary meteorological 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-orbiting satellites
FGGE	1978-9	First GARP Global Experiment

Table 1: Early milestones in the development of meteorological satellites.

Sounding instruments, providing information on vertical profiles of atmospheric temperature, were first deployed on Nimbus-3 in 1969, and by 1972 were operational on NOAA-2. A new generation of operational polar-orbiting satellites started in 1978 with TIROS-N and continued with subsequent NOAA satellites. They carried infra-red and microwave sounders with improved capabilities for monitoring atmospheric temperature and humidity.

In parallel with this, developments in geostationary satellites continued: the USA began an operational capability in this orbit in 1974. Following this lead, in 1977 Europe and Japan both launched their first in series of geostationary weather satellites.

By the time of the First GARP Global Experiment (FGGE), which ran from December 1978 to November 1979, there was a complete ring of geostationary satellites providing AMVs, together with a new generation of polar-orbiting satellites providing temperature/humidity soundings. This was an important milestone, as it effectively marked the beginning of the space-based component of the Global Observing System of WMO. It also provided operational NWP with a new wealth of observational data. Although some years of progress were needed to exploit their potential, this allowed the state of the global atmosphere to be analysed with an accuracy and completeness not previously possible. Furthermore, it provided the basis for subsequent reanalyses of the global atmospheric state (see Uppala, 2007 – this volume).

3. Satellite soundings

3.1. Early instruments

Table 2 summarises the early history of the atmospheric sounding instruments of the USA's polar-orbiting satellites – both the Nimbus research series and the TIROS/NOAA operational series. These instruments are the most relevant to NWP because, in the main, their data were available internationally in near-real time for operational use. Instruments marked in bold are those which received most attention for NWP use. These fall into three broad categories:

(a) Infra-red filter radiometers: SIRS, VTPR and HIRS, providing information on temperature in the troposphere and lower stratosphere, and humidity in the troposphere.

(b) Infra-red pressure modulator radiometers, with PMR acting as the proto-type for SSU, providing information on temperature in the mid/upper stratosphere.

(c) Microwave radiometers: initially SCAMS and MSU, providing information on tropospheric and lower stratospheric temperature, and later AMSU-A and AMSU-B providing improved vertical resolution together with extensions to the mid and upper stratosphere and to tropospheric humidity.

Nimbus series		
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	1978-1994	LIMS, SAMS
TIROS/NOAA series		
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**

Table 2: Early satellite sounding instruments.

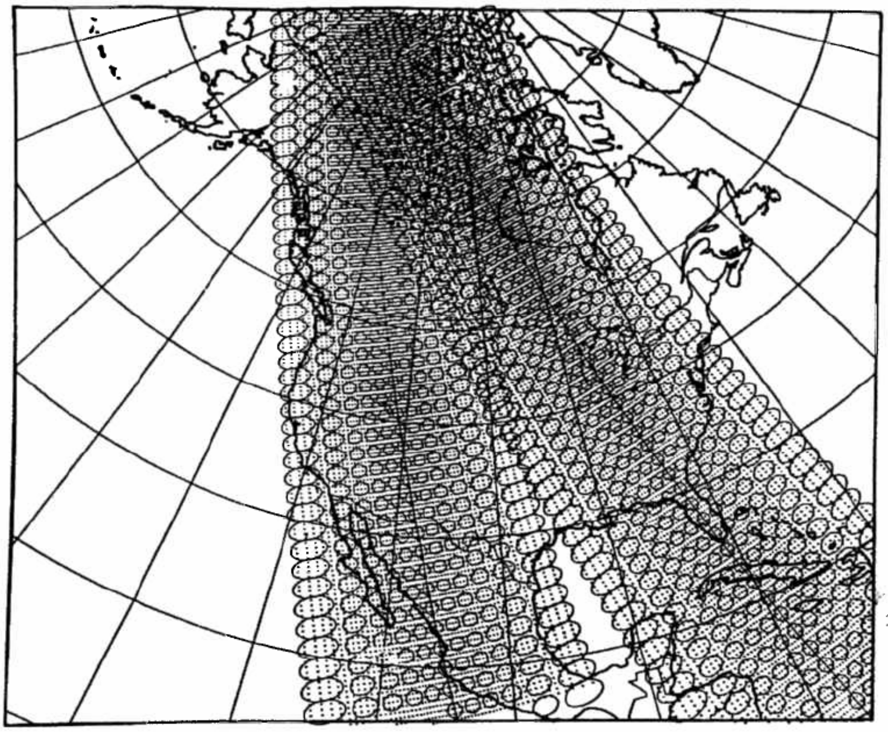

Figure 1: TOVS scan patterns for HIRS (small dots) and MSU (larger ellipses), from Smith et al. (1979).

The combination of HIRS, MSU and SSU is known as TOVS, and flew on many satellites starting with TIROS-N and ending with NOAA-14, until superseded by the Advanced TOVS (ATOVS) system from NOAA-15 onwards. TOVS therefore provided operational satellite soundings for over 20 years and was the focus of much research and development on the use of satellite data in NWP in the 1980s and 1990s.

The scan patterns of the HIRS and MSU instruments are shown in Fig.1 for parts of 2 consecutive orbits; TOVS provides complete global coverage at mid and high latitudes every 12 hours from one satellite. With a nominal 2-satellite system, near-global coverage is therefore available every 6 hours.

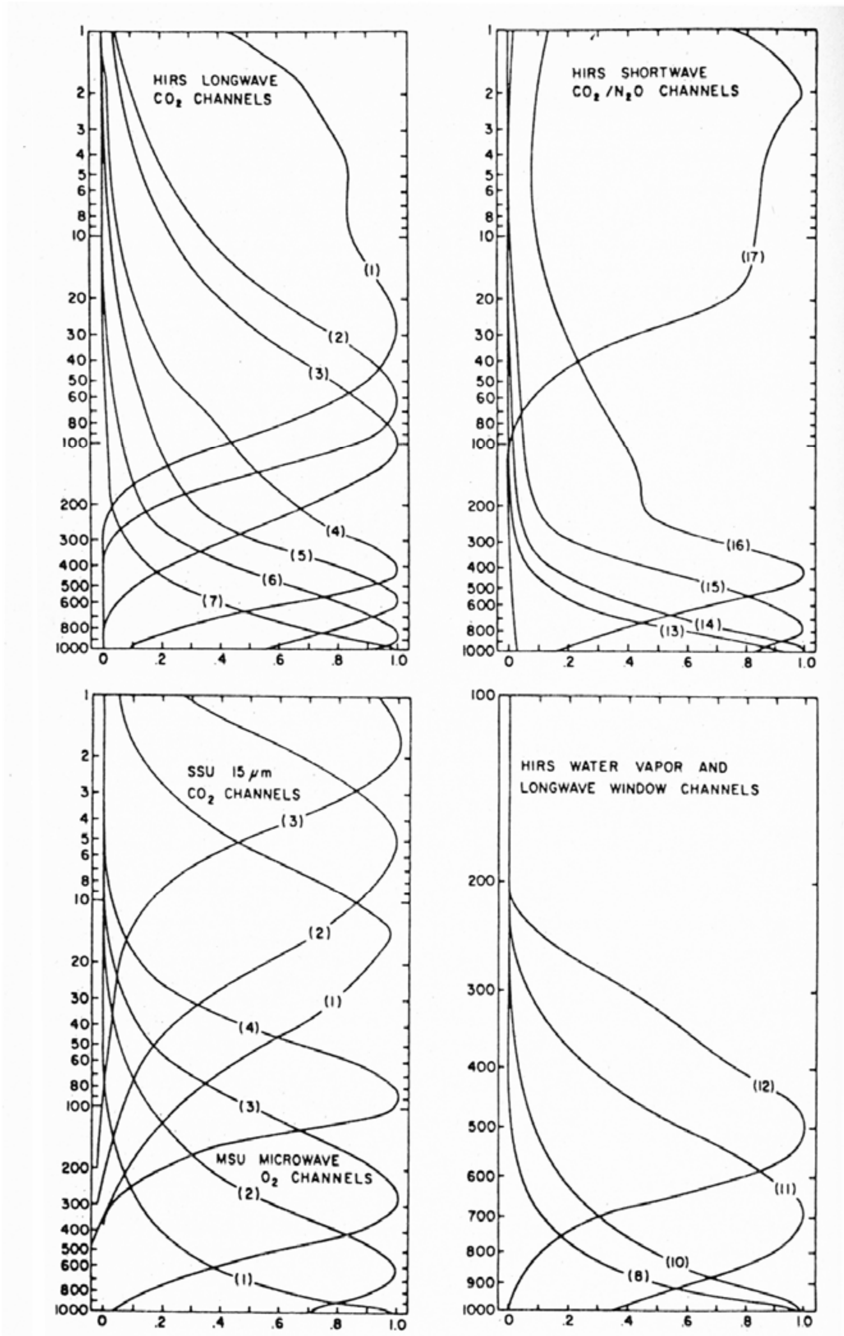

Figure 2: TOVS normalised weighting functions, from Smith et al. (1979).

Figure 2 shows the weighting functions for all the TOVS channels. The HIRS channels in the CO_2 bands around 15 and 4.3 μm provide temperature profile information in the troposphere and lower stratosphere with a spatial sampling of ~40 km. The HIRS channels in the 6 μm H_2O band provide tropospheric humidity profile information. MSU also provides temperature profile information in the troposphere and lower stratosphere with fewer channels and hence lower vertical resolution. However, the MSU provides information in cloudy conditions and is hence complementary. SSU extends coverage of temperature to the upper stratosphere. MSU and SSU have spatial samplings of ~160 and ~200 km respectively.

The main limitation of the TOVS system, even in cloud-free conditions, is its poor vertical resolution. Individual weighting functions have a width of 5-10 km. Combining channels with overlapping weighting functions increases the vertical resolution, but only to ~3 km. It is important to realise that this also limits the effective horizontal resolution of the TOVS system to well below the spatial sampling distance of HIRS (at least for mid-latitude baroclinic structures); atmospheric perturbations with small scale in the vertical also tend to have small scale in the horizontal.

3.2. Assimilation experience: 1970s.

Nimbus 3, carrying the first satellite temperature sounders, was launched in April 1969, and data from its SIRS instruments were first used very shortly afterwards; Smith et al. (1970) give the results of impact studies using data from June 1969. They reported on experiments in which retrievals from SIRS data were "bogussed" into the objective analysis of the USA's National Meteorological Center. They demonstrated cases of significant changes to analyses over the Pacific and subsequent forecasts over the USA.

Important early work on the assimilation of satellite data was performed in Australia, motivated by the relative scarcity of other observations in the S. Hemisphere. A summary is given by Bourke (2004). Before satellite sounding data became available, the Australian Bureau of Meteorology demonstrated the benefit of using satellite cloud imagery interpretation to estimate and then assimilate surface pressures (PAOBs) and 1000-500 hPa thicknesses in the S. Hemisphere. From 1972, Kelly assimilated VTPR data from NOAA-2, -3, and -4 in the form of retrievals from cloud-cleared radiances. In 1976 he demonstrated, within a continuous data assimilation system, the benefits of assimilating VTPR retrievals and PAOBs. Kelly et al. (1978) then demonstrated the impact of Nimbus-6 temperature soundings on Australian regional forecasts. Over 14 days of assimilation, they found an average improvement of >5 skill points on 24-hour forecasts of geopotential height, from 1000 to 200 hPa.

In the UK, Atkins and Jones (1975) reported an experiment to determine the value of SIRS data in numerical forecasting. The data had modest impact but were assimilated operationally, at the discretion of the chief forecaster.

The results of several data assimilation experiments in the late 1970s are summarised by Ohring (1979). The relevant papers and the sounding data to which they refer are summarised in Table 3.

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

Table 3: Data assimilation experiments summarised by Ohring (1979).

A few phrases from Ohring's paper summarise the state of the art at that time:

- "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 the S. Hemisphere".

Ohring identified the following problems that needed to be addressed before more impact could be expected:

- differences between retrievals and collocated radiosondes of 2-3 K,
- analyses using satellite retrievals had lower eddy potential energy,
- satellite soundings are not point observations; they have their own error characteristic, and improved analysis schemes may enhance impact,
- improvements in retrieval methods were likely, but the basic problem was poor vertical resolution; the statistical/climatological nature of the retrieval techniques may suppress horizontal structure.

3.3. Assimilation experience: early 1980s

The observational dataset from FGGE was the focus of several observing system experiments (OSEs) in the early 1980s. Typical data coverage during most of the FGGE period is shown in Fig.3. In the later part of FGGE, following the launch of NOAA-6 to complement TIROS-N, the coverage of satellite sounding data was considerably enhanced.

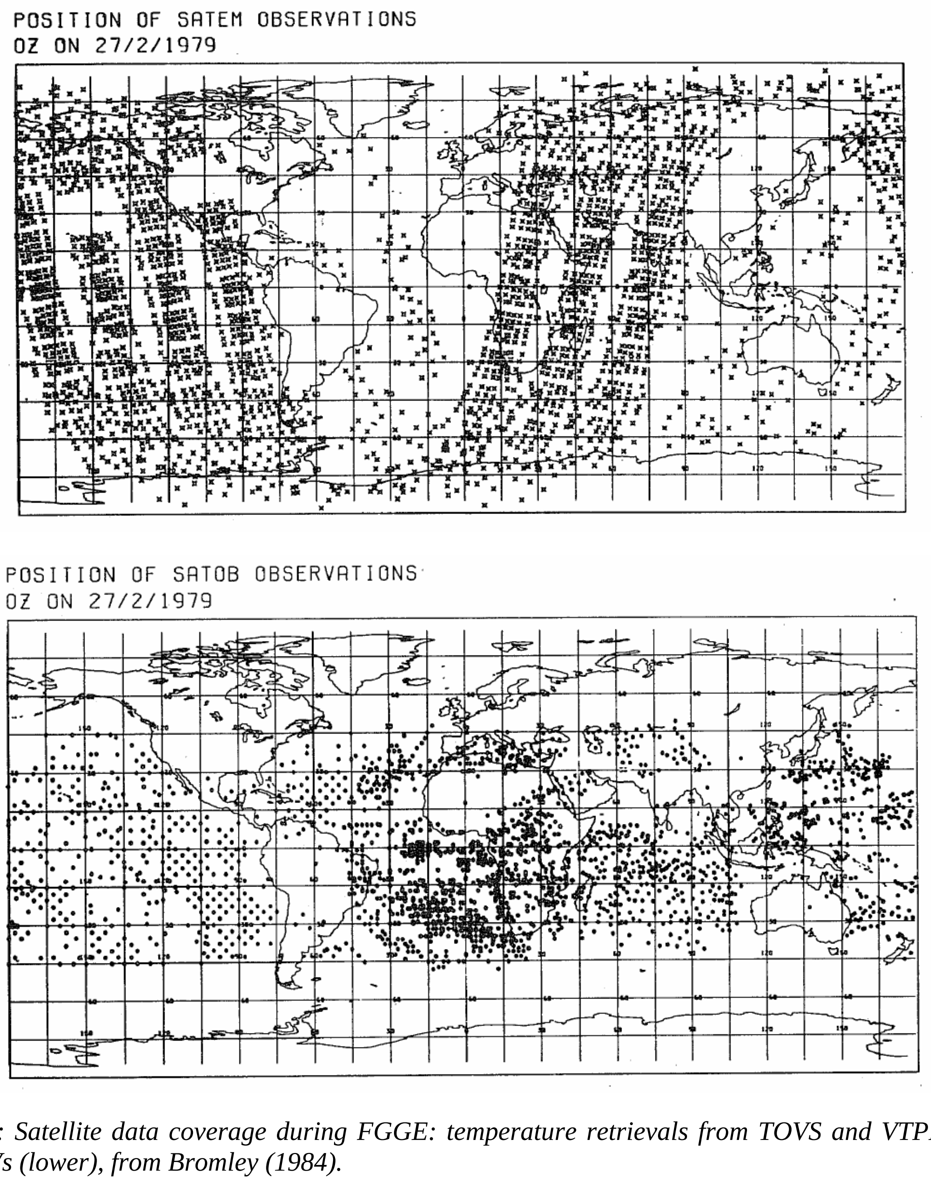

Figure 3: Satellite data coverage during FGGE: temperature retrievals from TOVS and VTPR (upper) and AMVs (lower), from Bromley (1984).

Halem et al. (1982) made an assessment of the FGGE satellite observing system. They reported on OSEs for several observation types, and their conclusions included:

- 6-hour forecast errors were reduced downstream of data sparse areas by including satellite observations,
- over N.America and Europe, small improvements were found in forecast skill,
- over Australia, positive impact of satellite data was much larger.

In 1982, a study conference on observing system experiments was held in Exeter (UK), and its main focus was on OSEs based on the FGGE dataset. Its report (Gilchrist, 1982) summarises results from 11 experiments conducted by 4 NWP centres and comprising 85 days of data assimilation. Experiments covered 3 periods: the Special Observing Periods of FGGE in January-March 1979 and May 1979, and a period in November 1979 during which TOVS sounding data from 2 NOAA satellites were available. The highlights from the workshop summary (from the perspective of satellite data impact) are summarised in Table 4.

Centre	Experiment	Impact
ECMWF	No satellite data	Useful predictability reduced from 5.5 to 4.5 days in NH and from 5 to 3 days in SH.
GLAS	No satellite data	Large impact over S.America and Australia. Smaller but positive impact over N.America and Europe.
ANMRC	No satellite sounding data	Substantial positive impact in SH.
GLAS	No satellite sounding data	Positive impact over Australia. Europe and N.America, less impact and variable.
NMC	No satellite sounding data	Positive impact on one cycle at T+3.5 over E.USA.
ECMWF	Satellite only	Surprisingly good skill at T+4. In SH, only small differences from all observations.

Table 4: Satellite data assimilation experiments summarised by Gilchrist (1982).

Another significant milestone was the ECMWF Seminar on “Data assimilation and observing system experiments, with particular emphasis on FGGE” in September 1984. The summary of this meeting (ECMWF, 1984) was notably optimistic:

- “accuracy of satellite temperature soundings … 2-3 deg below 850 hPa, and 1.5-2 deg above … satisfactorily assimilated … important role in analysing large scale weather systems at high and mid latitudes, in particular in the S. Hemisphere”,
- “(satellite) atmospheric soundings … are an essential element of the GOS”.

Uppala et al. (1984), summarising experiments at ECMWF, concluded that AMVs were particularly important for analysis of the tropics, and that satellite soundings were of paramount importance for extra-tropical analysis over ocean areas.

3.4. Problems arising in the late 1980s

By the late 1980s, the general performance of NWP systems had improved considerably. As a consequence the short-range forecasts were more accurate and the potential for damage through erroneous observations, or observations assimilated in an inappropriate way, was much greater. Some of the problems identified several years before (see 3.2 above) now became dominant and started to lead to satellite sounding data having either an average negative impact or at least an impact that was very variable from case to case.

Kelly and Pailleux (1988) paid particular attention to the form in which the retrieved profile was assimilated. They reduced the number of thickness layers used to represent the profile: from the 14 layers used in the early 1980s, to 11 layers in 1985, and then to 7 layers in 1987 (1000-700, 700-500, 500-300, 300-100, 100-50, 50-30, 30-10 hPa). In this way they attempted to represent only those vertical scales that the TOVS soundings were capable of resolving. Even with this improvement, and although the impact in the S. Hemisphere remained positive, they found that the impact in the N. Hemisphere was mixed. Indeed, in the N. Hemisphere that impact was considerably reduced compared to that reported by Uppala et al. (1984). Kelly and Pailleux also noted significant quality control problems caused by cloud and rain contamination.

Andersson et al. (1991) reported increased problems; they found that the neutral impact of TOVS retrievals with the 1987 system had given way to a negative impact in the 1988 system. They also found that the patterns of analysis increments resulting from assimilation of TOVS retrievals showed strong synoptically correlated biases, as illustrated in Fig.4. [During this period, the author recalls that, in addition to studying maps of analysis increments and of observation increments derived from TOVS retrievals, observations increments in the form of measured minus forecast radiances were also studied. The latter did not tend to show the synoptically correlated patterns evident in the former. The reason for this is discussed in section 3.5.3.]

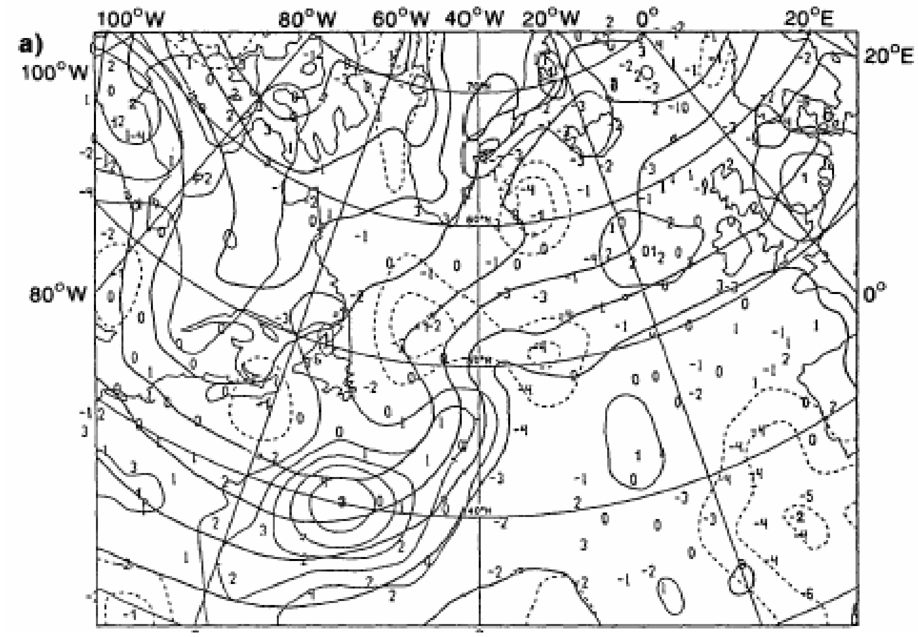

Figure 4: An example of synoptically correlated biases. Observed 1000-700 hPa TOVS layer-mean temperature retrieval deviations from background in K, 6 February 1987, 1200 UT. The background field is contoured with a 5K interval (solid lines) and the analysis increment with a 0.5K interval (thin lines: full lines positive, dashed lines negative). From Andersson et al. (1991).

In a companion paper, Kelly et al. (1991) explored quality control issues associated with the newly-available operational TOVS so-called "physical retrievals" (which replaced the "statistical retrievals" that had previously been available). They reported that the new physical retrievals had much the same problems of bias and noise that were noted with the statistical retrievals, and they showed how improved quality control could mitigate the worst problems.

3.5. Theoretical problems with assimilation of satellite sounding retrievals

3.5.1. Radiosondes and satellite soundings

One of the main problems with earlier strategies to assimilate satellite sounding data can be summarised in a saying of one of the pioneers of satellite meteorology, Verner Suomi, which has become known as Suomi's 11th commandment: "Thou shalt not worship the radiosonde". In the context of NWP this can be interpreted as follows.

Radiosonde data formed the back-bone of the observational base for early NWP systems, and these systems were designed to make best use of sondes: to exploit their strengths and to mitigate their weaknesses. When satellite soundings came along, it was natural to attempt to use them by making them look as similar as possible to sondes, i.e. by retrieving a temperature profile from the measured radiances, and then assimilating the retrieved profile, usually in the form of a profile of layer thicknesses. This procedure failed to do justice to the special characteristics of the satellite data and the information they contain. Radiosondes have very high vertical resolution. Satellite sounding data (from TOVS and earlier instruments) have relatively poor vertical resolution. When used at high vertical resolution, they consequently have low accuracy and complicated error characteristics (even though the measured radiances have high accuracy and rather simple error characteristics). On the other hand, the satellite soundings have uniform global coverage at a much higher density than the sondes, even in areas of the world were sondes are most numerous. Treating satellite soundings as "poor-quality sondes" was an ultimately flawed approach; a new approach was needed which was consistent with the true strengths and weaknesses of the satellite data.

3.5.2. Relevant aspects of data assimilation theory

To appreciate the problems of assimilating satellite sounding data, and how they have been tackled in recent years, it is necessary to consider some basic ideas in data assimilation and the history of how they have been implemented.

Ideally, in order to define the initial conditions in NWP, we might wish to solve the Bayesian problem: what is the probability of atmospheric state, x, given observations, y^o? or

- evaluate: $P(x|y^o) = P(y^o|x) \,.\, P(x) / P(y^o)$. (1)

It is far beyond the scope of present day computer power to estimate the full probability density function (PDF) and it probably always will be. Ensemble methods may be able to explore sufficient aspects of it to be useful.

At present, most operational NWP systems use a variational (or equivalent) approach, in which we ask the question: what is the most probable atmospheric state, x, given observations, y^o ? or

- maximise: $P(x|y^o) = P(y^o|x) \,.\, P(x) / P(y^o)$, (2)

which is equivalent to

- maximise: $\ln\{P(x|y^o)\} = \ln\{P(y^o|x)\} + \ln\{P(x)\} + \text{constant}$. (3)

If all the PDFs are Gaussian, then this is the same as minimising a **penalty or cost function**:

- $J[x] = ½\, (x-x^b)^T\, B^{-1}\, (x-x^b) + ½\, (y^o-H[x])^T\, (E+F)^{-1}\, (y^o-H[x])$ (4)

where x^b is the background field,

B is the background error covariance,

$H[x]$ is the observation operator,

and E and F are the error covariances of observations and observation operator. (See Lorenc, 1986).

The optimal analysis can be found by minimizing (4) or by solving its gradient equation:

- ∇xJ[x] T = B-1 (x-xb) + ∇xH[x]T (E+F)-1 (yo-H[x]) = 0 (5)

If we linearise the variational equation (5), we can derive the optimal interpolation (OI) formula:

- xa = xb + K . (yo-H[x]) (6)

where K = B.HT.(H.B.HT + E + F)-1 , (7)

and H is the Jacobian of the observation operator $H[x]$; $H = \nabla_x H[x]$.

Eq.(6) provides the "optimal" weights for the analysis, i.e. those which minimize the analysis error. Sub-optimal analyses can be obtained using other empirical weights, which may be simpler to derive and to apply, i.e.

- $x^a = x^b + K . (y^o - H[x])$ (8)

where K contains empirically-derived weights

Although the above derivation provides a framework for understanding the different approaches and the relationship between them, in a historical context they were actually developed in the reverse order. In general terms, empirical methods were superseded by OI (e.g. operational at ECMWF from 1980) and this was superseded by 3D-Var (e.g. operational at ECMWF in 1996).

The move to radiance assimilation starting in the 1990s tends to be associated with the introduction of variational (or equivalent) methods of data assimilation in operational NWP. It would have been possible to use radiances directly in OI, but two aspects of OI would have been limiting. Firstly, the OI weights equation (eq.(7)) involves the inversion of a matrix with a size equal to the number of observations. Computational limitations therefore restrict OI to using either a small subset of the potentially available observations or to analyse a small domain or both. This is particularly restrictive when we wish to assimilate many thousands of satellite radiances. Secondly, OI is based on linear theory and cannot easily handle observations which are related to the analysis variables in a nonlinear way. Variational methods overcome both of these limitations.

3.5.3. Characteristics of retrieval errors

Another fundamental problem with the assimilation of retrieved profiles can be understood by examining an error analysis for the retrieval problem. A general, linearised retrieval equation is the same as the general linear analysis equation, eq.(6) or eq.(8):

- $x^a - x^b = K . (y^o - H[x])$ (9)

A similar equation can be written for the forward (radiative transfer) problem:

- $y^o - H[x] = H . (x - x^b) + \varepsilon$ (10)

where ε is the measurement error.

Combining (9) and (10) gives an expression for the retrieval error:

- $x^a - x^t = (I - K.H) . (x^b - x^t) + K . \varepsilon$ (11)

where x^t is the true profile

and I is a unit matrix.

The second term on the right-hand side of (11) is easily interpreted; it represents the mapping of measurement error, through the retrieval operator K, into retrieval error. The first term on the right-hand side represents the mapping of "background" error into retrieval error. This shows that, when the background for the retrieval is systematically in error, then retrievals will also have systematic errors. For example, in a statistical regression retrieval, where the effective background is some climatological mean profile, background errors will be very similar for adjacent soundings and will lead to systematic retrieval errors which are locally and synoptically correlated, as found by Andersson et al. (1991).

This analysis shows why retrieval errors are complex; they are locally correlated/biased, and cannot easily be represented (locally) by an error covariance matrix. This shows, from a theoretical perspective, why the assimilation of retrieved temperature/humidity profiles into NWP models is fundamentally more problematic than the direct assimilation of radiances.

3.6. Direct assimilation of radiances: 1990s

The variational equations (4) and (5) can be applied in one-dimension (the vertical) to yield a "forecast first-guess" or 1D-Var retrieval, or they can be applied in 3 or 4 dimensions to the direct assimilation of radiances: 3D-Var or 4D-Var.

The 1D-Var approach was first implemented on TOVS data in operational NWP at ECMWF in June 1992 (Eyre et al., 1993), where it acted as an intermediate stage between the radiances and the OI analysis scheme. The main advantage of the method, compared with the assimilation of retrieved profiles, is that it produces no analysis increments when measured radiances agree with forecast radiances. However, care is still needed with the specification of the OI weights, to compensate for the use of forecast background in 1D-Var retrieval.

The 3D-Var approach for the direct assimilation of radiances was implemented operationally first at NCEP in October 1995 (Derber and Wu, 1987) and at ECMWF in January 1996 (Andersson et al., 1994). It was first used operationally in 4D-Var when ECMWF implemented this technique in November 1997. Since then, several other operational NWP centres have adopted this approach, either in 3D or 4D.

4. Scatterometry

4.1. History of the instruments

Wind scatterometers are radars which measure the backscatter of radiation from the sea surface from two or more viewing directions, from which can be deduced the wind speed and direction at the sea surface. Table 5 summarises the history of wind scatterometers.

The earliest satellite scatterometers flew on Skylab, as proof of concept for radar backscatter measurements. The first instrument designed for wind vectors was SASS on Seasat. Unfortunately this failed after a few months, and there was then a 13-year gap until scatterometer data became available from the AMI on ERS-1. However, Seasat provided useful data for assimilation experiments in the intervening years. AMI was also flown on ERS-2, and ASCAT on MetOp is essentially a double-sided version of this instrument. NSCAT on

ADEOS-I had a viewing geometry similar to ASCAT, whereas the Seawinds instrument on ADEOS-II and Quikscat uses a conically scanning geometry. This leads to a wider total swath than for the other instruments, although high-quality wind direction information is only achievable over about half the total swath. The other main difference between the instruments concerns the radar frequency: AMI and ASCAT use C-band frequencies whereas the other instruments use Ku-band. C-band is substantially less sensitive to rain contamination.

Year	satellite	instrument	frequency (GHz)	Views	resolution (km)	swath (km)
1973-74	Skylab	MRSA	13.9 Ku-band	1	15	185
1978	Seasat	SASS	14.6 Ku-band	2	50	1000
1991-2000	ERS-1	AMI	5.3 C-band	3	50	500
1995-	ERS-2	AMI	5.3 C-band	3	50	500
1996-97	ADEOS-I	NSCAT	14.0 Ku-band	3	50	1000
1999-	Quikscat	Seawinds	13.4 Ku-band	4	25	1800
2003	ADEOS-II	Seawinds	13.4 Ku-band	4	25	1800
2006-	MetOp	ASCAT	5.3 C-band	3	25	1000

Table 5: Wind scatterometers.

4.2. The measurement technique and the assimilation problems

Different scatterometers have used various viewing geometries, but their principle of operation is the same and is illustrated in Figure 5 for the viewing geometry of the AMI scatterometer. The satellite views the ocean surface from a number of directions, in this case 3. It views a given same patch of ocean 3 times within a period of a few minutes: first with the forebeam, then with the midbeam and last with the aftbeam. In this way, the observation at each location is a triplet of backscatter measurements.

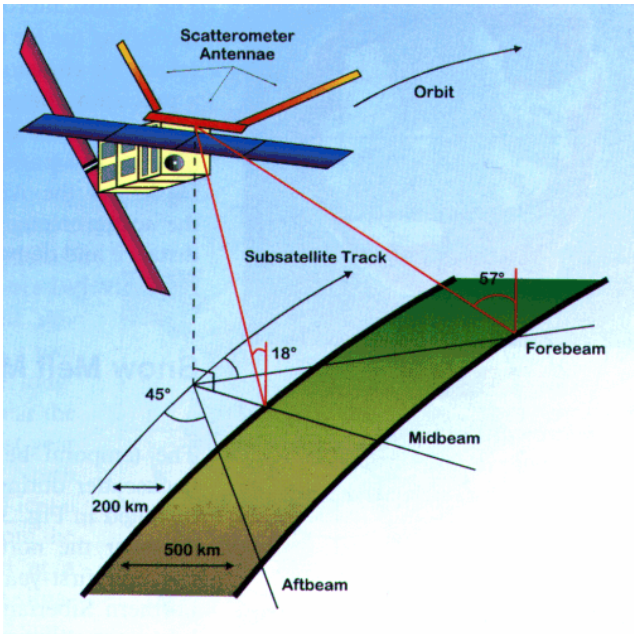

Figure 5. Illustrating the viewing geometry of the AMI scatterometer.

This triplet can be represented as a single point in 3-dimensional measurement space, as shown in Fig.6 (Stoffelen and Anderson 1997a). In this space, it is found that "good" measurements lie close to a cone.

Wind speed increases along the cone, and wind direction changes through 360 degrees in two circuits around the cone. “Bad” measurements, e.g. those contaminated by precipitation or sea-ice, tend to lie off the cone. This representation and the concept of “closeness to the cone” provide a useful framework for understanding both the retrieval problem (i.e. the retrieval of wind speed and direction from backscatter measurements) and the quality control problem. They also provide insight into the main assimilation problem; there are usually two wind directions, separated by ~180 degrees and associated with similar wind speeds, consistent with each set of backscatter measurements.

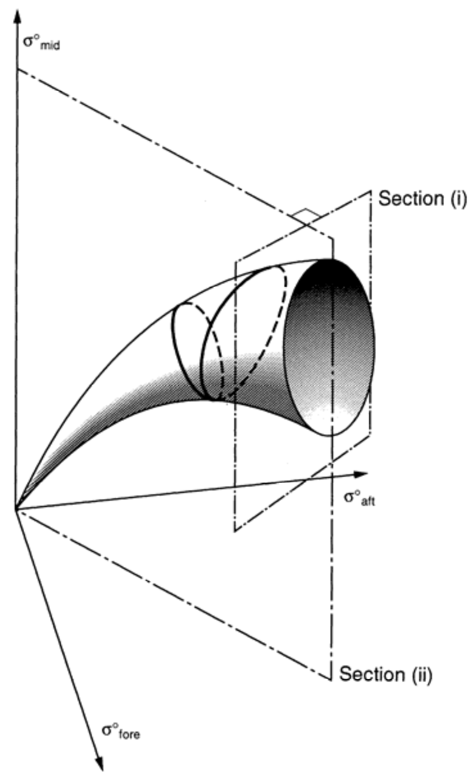

Figure 6: .Schematic representation of the measurement space for AMI scatterometer data, from Stoffelen and Anderson (1997a).

There have been two basic approaches to the assimilation of scatterometer data. The first approach is to retrieve the two (or more) wind vectors consistent with the measurements, and then to select the “best” for presentation to the assimilation system. The procedure for selecting the “best” can use horizontal consistency or closeness to a NWP background field or both. The use of a NWP background will tend to give accurate directions in most cases but the wrong direction in a minority of potentially important cases, e.g. when a small-scale low pressure centre is misplaced in the background field, in which case the erroneous retrieval will tend to reinforce the background error when assimilated. The second approach is to present all possible “ambiguous” wind vectors to the assimilation system and to allow it, implicitly, to make the selection. This is possible within a variational framework (Stoffelen and Anderson, 1997b) It is even possible, via dynamical consistency or support of other observations, for the analysis to choose a solution which reverses the direction of the background field (e.g. see Stoffelen and Anderson, 1997a).

By analogy with the experience of radiance assimilation, one might expect that the optimal way of assimilating scatterometer data would be through direct assimilation of the backscatter coefficients. However, Stoffelen (2000) has shown that this approach is highly problematic because of the particular nonlinear relationship between wind vectors and backscatter coefficients. At present, assimilation of ambiguous winds is widely preferred.

4.3. Asimilation experience

Despite its early demise, Seasat provided useful data for several impact studies. Baker et al. (1984) reported “very small” impact in the N. Hemisphere (2% in skill score in mean sea level pressure) and a larger positive impact in the S. Hemisphere, although the latter was lost when VTPR data were included in the assimilation. The authors commented that the low impact may have been influenced by their use of a lower resolution NWP model without a planetary boundary layer scheme. Yu and McPherson (1984) reported significant impact of Seasat data on the S. Hemisphere analysis, although they were unable to assess if the impact was positive. Anderson et al. (1991) reported an overall neutral impact through assimilation of Seasat data. Stoffelen and Cats (1991) showed a positive impact of Seasat data when used in a limited area NWP model for the case of the QE-II storm (September 1978).

With the advent of ERS-1 in 1991, renewed efforts were made to exploit scatterometer data in NWP. Hoffman (1993) reported a neutral impact with the ECMWF global system. Breivik (1993) found a small positive impact with the Norwegian regional model. Bell (1994) reported positive impact in the S. Hemisphere with the UK global model. Following the transition from OI to 3D-Var, Stoffelen and Anderson (1997a) found positive impact on short-range forecasts with the ECMWF global system. ERS scatterometer data became operational in global NWP at the Met Office (UK) in September 1992 and at ECMWF, as part of the transition to 3D-Var, in January 1996.

5. More recent advances

5.1. From TOVS to ATOVS

A substantial advance, both in the quality of satellite sounder data and in their impact on NWP performance, followed the replacement of TOVS by Advanced TOVS (ATOVS), first on NOAA-15 launched in 1998 and then on subsequent NOAA satellites and on MetOp. The infra-red sounder HIRS was retained, but the MSU and SSU of TOVS were replaced by the AMSU-A and AMSU-B of ATOVS. (AMSU-B was later replaced by the “look-alike” MHS.)

The weighting functions of AMSU are shown in Fig.7 and should be compared with the weighting functions of MSU and SSU in the lower left panel of Fig.2. The temperature sounding channels of AMSU-A are comparable in number and vertical range with those of HIRS+SSU, and the humidity sounding channels of AMSU-B with those of HIRS. Like MSU, the AMSU is able to provide sounding information from cloudy regions, but with a horizontal and vertical resolution comparable to HIRS. The introduction of AMSU provided sounding quality in cloudy areas that had only been available hitherto in cloud-free areas. Although the vertical resolution is still limited to ~3km, the improved performance in cloudy areas has proved crucial to the performance of NWP systems, with all major NWP centres quickly demonstrating substantial benefit from ATOVS data. This confirms the importance of improving the analysis in meteorologically active areas, which are predominantly cloudy.

Further details on the use of ATOVS data in NWP are given by Derber (2007, this volume).

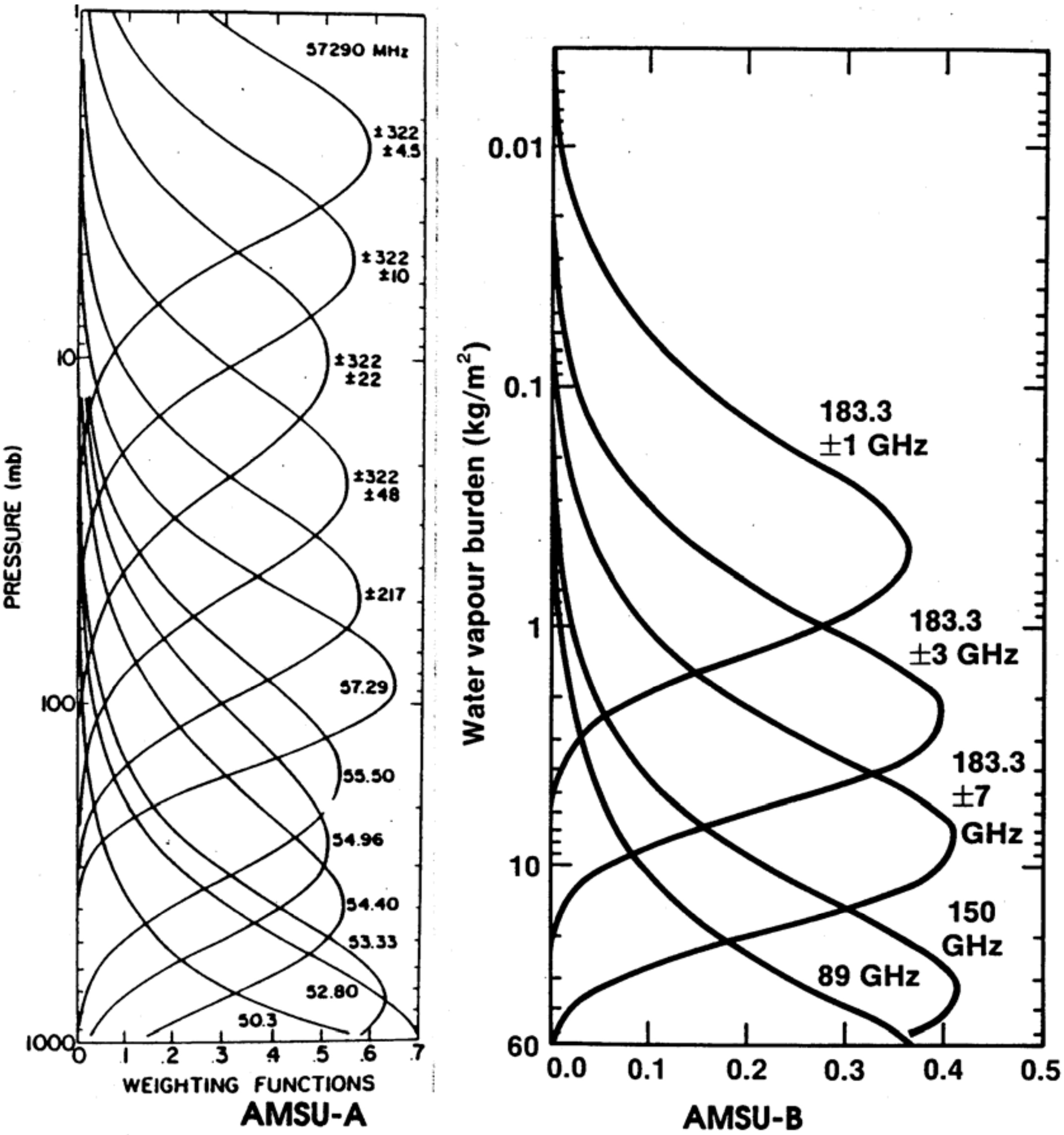

Figure 7: .Weighting functions for AMSU-A and AMSU-B.

5.2. Advanced infra-red sounders

A further advance in satellite sounders has been the introduction of advanced infra-red sounders – spectrometers and interferometers of significantly improved vertical resolution compared with filter radiometers such as HIRS. The first of these is the AIRS instrument on NASA's Aqua satellite. Although AIRS is a one-off research/demonstration instrument, its data are sufficiently similar to its operational successors – IASI on MetOp (from 2006) and CrIS on NPP and NPOESS (from 2009) – that the NWP community has invested substantially in the understanding and use of its data, with very encouraging results – see Collard (2007, this volume).

These instruments have thousands of spectrally narrow channels, compared with the 20 broad channels of HIRS. They have weighting functions for individual channels which are somewhat narrower and, more importantly, they have the combined power of thousands of overlapping channels, leading to a system vertical resolution of ~1 km (cf. ~3 km for HIRS).

5.3. Other data types

Early work on the assimilation of satellite data into NWP models focussed mainly on the 3 observation types discussed so far in this paper:

- passive infra-red and microwave soundings,
- atmospheric motion vectors,
- scatterometer data.

In recent years the number of observation types used in NWP has grown considerably and now includes:

- passive microwave imagery (for information on surface wind, total column water vapour, cloud and precipitation),
- water vapour channel radiances from geostationary imagers,
- cloud information retrieved from geostationary imagery data,
- ozone information (e.g. from SBUV and SCIAMACHY),
- limb sounder radiances (e.g. from MIPAS),
- GPS (satellite-to-ground) total zenith delays,
- GPS (satellite-to-satellite) radio occultation measurements.

Most of these data types are discussed further in other papers in this volume. In the next section we focus only on radio occultation data.

5.4. Radio occultation

5.4.1. Technique

Radio occultation (RO) is a measurement technique for obtaining information on the vertical gradient of atmospheric refractive index, which is related to the gradients of density (and hence of temperature and pressure) and of water vapour density (Melbourne et al., 1994). When a radio signal from a transmitter on a GPS satellite passes through the limb of the atmosphere, the signal is delayed and its path is bent by gradients in the refractivity field. If this signal is intercepted by a GPS receiver on another satellite, behind the Earth's limb, then the time of receipt and the direction from which the signal is received are different from those that would have been obtained from an unrefracted path. This is illustrated in Fig.8. The angle through which the ray is deflected – the "bending angle", α – is related in a simple way to the measured Doppler shift and phase delay of the received signal.

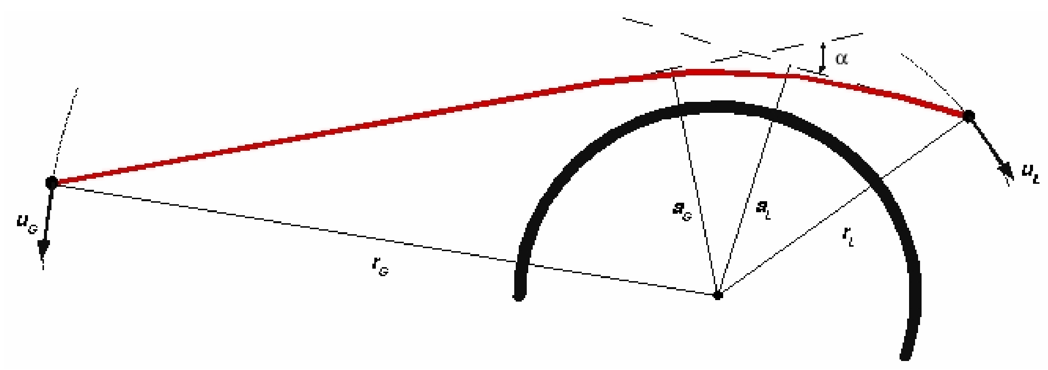

Figure 8: The geometry of a radio occultation measurement showing the refracted ray from a transmitting satellite (on the left) to a receiving satellite (on the right).

During an occultation event, the GPS satellite sets or rises relative to the receiving satellite, and the ray between them sweeps out a path of changing tangent height through the atmospheric limb; a typical occultation takes ~1 minute to profile the atmosphere (0-60 km) and thus provides a profile of bending angle against height (or, more strictly, impact parameter – a_G in Fig.8). The profile of refractive index can be derived from the profile of bending angle, analytically in the limit of a spherically symmetric atmosphere, using the Abel transform.

5.4.2. Physics

Refractive index and refractivity are related to meteorological variables as follows:

- $$N = \kappa_1 \, p/T + \kappa_2 \, e/T^2 + \kappa_3 \, n_e/f^2 + \kappa_4 \, W \tag{12}$$

where 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,

and κ_i, $i = 1 \rightarrow 4$, are coefficients.

The 4th term, caused by atmospheric scattering, is negligible at GPS frequencies. The 3rd term is significant but can be corrected by using measurements at the two GPS frequencies of 1.575 and 1.227 GHz. The 2nd term, caused by water vapour, dominates in the lower troposphere but becomes negligible in the upper troposphere and stratosphere, where the bending is dominated by density gradients.

5.4.3. Characteristics

RO measurements are globally distributed in a quasi-random manner. They provide temperature information for the stratosphere and upper troposphere, and humidity information for the lower troposphere. They have a high vertical resolution of 0.5-1 km, but low horizontal resolution of ~200 km. They provide information of high accuracy, equivalent to random errors in temperature of ~1K. Moreover their systematic errors are very low: <0.2K and probably better, as required for climate monitoring. RO measurements are “all-weather”, as they are negligibly affected by cloud and precipitation. The space/time sampling of the measurements is determined by the number of GPS receivers; a constellation of 6 satellites can provide ~3000 occultations per day. Furthermore, by the standards of space-borne remote sensing, they are relatively inexpensive.

The vertical information content from RO data is highly complementary to that from advanced infra-red sounders such as IASI, as illustrated in Fig.9.

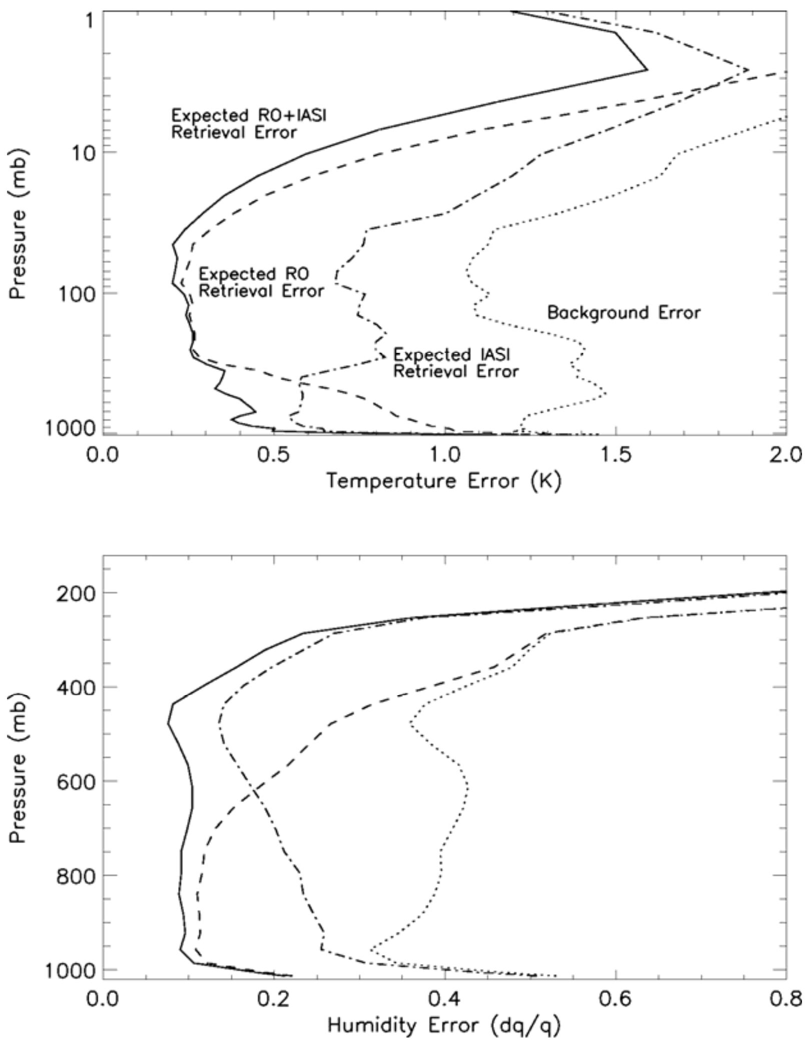

Figure 9: Simulated retrieval errors, assuming a 1D-Var retrieval technique with a forecast background, for profiles of temperature (above) and humidity (below) for RO (dashed), IASI (dot-dashed) and combined (solid). Assumed background errors are shown by the dotted lines. From Collard and Healy (2003).

5.4.4. Missions

RO was first demonstrated for the Earth's atmosphere with the GPS/MET mission from 1995 to 1997 (Kursinski et al., 1996; Rocken et al., 1997) and continued by the CHAMP mission from 2000 (Wickert et al., 2001). Missions from which data have been available to NWP centres are summarised in Table 6.

GPS/MET	1995-97	Experimental, selected periods only
CHAMP	2000-	Experimental, continuous since 2001; near-real time since 2006
SAC-C	2000-	sporadic measurements, experimental
GRACE-A	2002-	Experimental, continuous since 2001; near-real time since 2006
COSMIC	2006-	demonstration mission, **6 satellites**; near-real time since 2006
MetOp/GRAS	2006-	operational from 2007

Table 6: Radio occultation missions

The COSMIC constellation (Anthes et al., 2000) is of particular interest, with its 6 satellites providing a higher density of coverage.

5.4.5. Assimilation options

The assimilation options for RO data were first discussed by Eyre (1994) and can be summarised as follows:

(a) assimilate retrieved profiles of temperature and humidity,

(b) assimilate retrieved profiles of refractivity,

(c) assimilate bending angle profiles directly.

Option (a) has generally been rejected as it does not permit optimal treatment of one of the fundamental problems with RO: the non-separable effects of temperature and humidity on the refractivity (see eq.(12)). Options (b) and (c) have both been tried. From a theoretical perspective, option (c) is preferred as it allows one to address another fundamental problem: the limited horizontal resolution of RO data and hence the danger of destroying information that the NWP model already contains on horizontal gradients of atmospheric fields in the vicinity of the occultation. Option (c) allows this problem to be addressed partially (although not completely, because of the assumptions of path symmetry in the derivation of the bending angle profile – see Healy 2001). Option (b) does not address it, because the Abel transform, used to retrieve refractivities from bending angles, assumes that the atmosphere is spherically symmetric (i.e. contains no horizontal gradients). However, it may be possible to come close to the accuracy of bending angle assimilation by comparing measured refractivities with forecast refractivities, where the forecast profile is a carefully weighted average over the plane of the occultation.

5.4.6. Assimilation experience

Assimilation studies on RO data are summarised by Healy and Thépaut (2006) and include results from Liu et al. (2001), Zhou et al. (2004), Poli and Joiner (2003) and Healy et al. (2005). Further results are given by Healy et al. (2007). As expected, largest impacts are found in the upper troposphere and lower stratosphere, and particularly in the S. Hemisphere. Surprisingly large impacts have been found when comparatively small numbers of observations have been assimilated, suggesting that RO data are highly complementary to other components of the GOS.

The role of RO data in stratospheric data assimilation is discussed further by Dee (2007, this volume).

6. Assimilation strategies for various data types

For each satellite observation type to be assimilated into a NWP model, one is usually faced with a choice as to the form in which the data are best assimilated, and particularly the amount of pre-processing they undergo prior to assimilation. The common features of this choice can be illustrated using Fig.10, which shows schematically the main elements of the data assimilation process. At the bottom of the figure is shown the continuous cycle of forecast-assimilate-forecast operations. For each assimilation cycle, the NWP model background fields are interpolated to the space-time of each observation and then passed through an "observation" operator to create "forecast observations". The observations undergo some form of pre-processing, which can be more or less complicated. For example, satellite sounding radiances may be heavily pre-processed to generate a retrieved atmospheric profile, or they may be lightly pre-processed and presented to the assimilation system as radiances. The pre-processed observations are then compared with the "forecast observations"; their differences are called "observation increments". The data assimilation procedure then converts the observation increments, through a process of mapping and weighting, into "analysis increments" which are added to the NWP background field to generate the final analysis.

It is important that the observation operator and the pre-processing of observations are carefully matched, so that the observation increments are the result of comparing "like with like". This includes the very important treatment of biases in the observations and in the observation operators (see, e.g., Derber, 2007, this volume).

In general, if the observation operator is simple (e.g. not extending beyond simple interpolation of fields) then, for most satellite data types, the pre-processing must be complex. On the other hand, if raw or lightly pre-processed observations are assimilated, then the observation operator must be complex.

There are two principle advantages in assimilating observations close to their raw form. Firstly, the “observation operator”, $H(x)$, can be nonlinear and this is important for many remotely-sensed observations. Variational methods no longer restrict assimilation to approximate linearization of this relationship, and this allows the true information content of the observation to be properly represented. Secondly, "raw" measurements, in the space of the observed variables, tend to have simpler error characteristics (see section 3.5.3).

On the other hand, assimilation of raw observations presents some new problems. Firstly, raw observations tend to have more complex operators. Secondly, some observations are affected by physical variables not contained in the control variable (e.g. the stratosphere above the model top, or surface variables). Thirdly, there is a logistical problem: the need to develop and maintain expertise on all satellite observation operators and associated errors, requiring resources beyond the means of a single NWP centre. It was the recognition of this problem in the mid-1990s that stimulated the search for new strategies to improve links between "assimilation centres" and "satellite centres” and to share the necessary work on observation operators and satellite data pre-processing software. New collaborative activities, such as the EUMETSAT Satellite Applications Facility for NWP (NWP SAF) in Europe and the Joint Center for Satellite Data Assimilation (JCSDA) in the USA, have been the outcome.

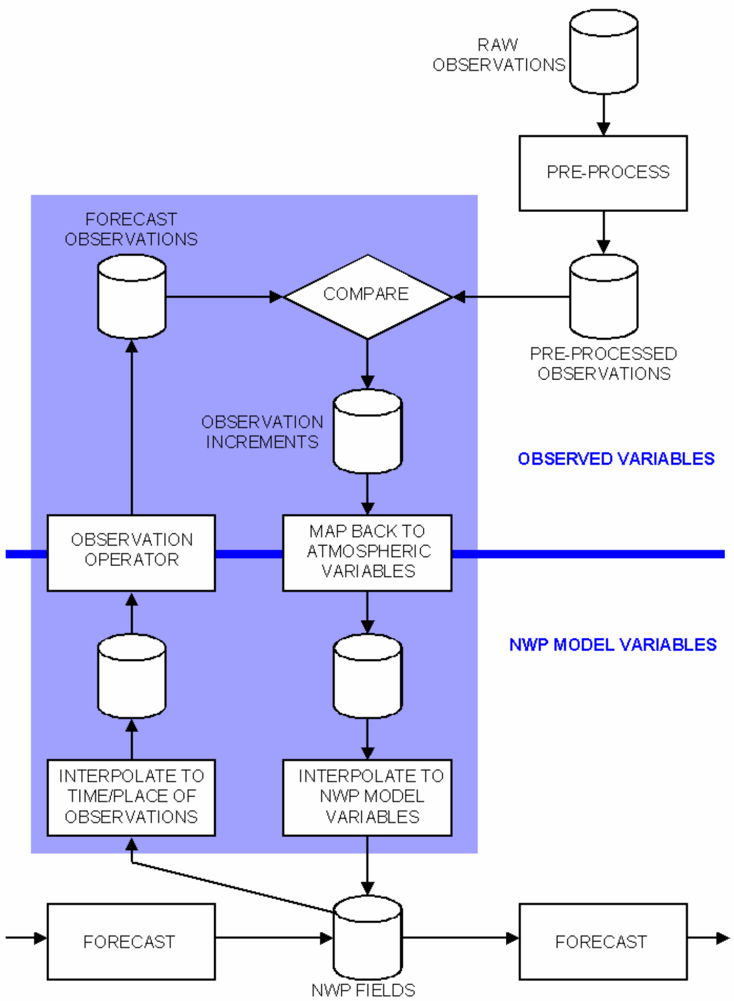

Figure 10: Illustrating schematically the assimilation of observations into a NWP model.

Preferred assimilation options for various data types were reviewed by Eyre (1997). An updated summary is given here:

- Passive temperature/humidity soundings – as radiances, for the reasons given in sections 3.4-3.6 of this paper.
- Wind information - as AMVs where the observation relies on the tracking of small-scale features that cannot be represented by the NWP model fields, but possibly by 4D assimilation of radiances for larger-scale features. For further discussion see Forsythe (2007, this volume). The resolution of the NWP model clearly has a bearing on this issue.
- Scatterometry - as retrieved "ambiguous" wind vectors, for the reasons given in section 4.2 of this paper.
- Microwave imagery (for information on water vapour, cloud water, precipitation and wind speed). There are many complex issues surrounding this data type and considerable development in thinking since 1997. See Bauer (2007, this volume) and English (2007, this volume) for recent ideas.
- Cloud imagery - as retrieved cloud variables (e.g. fractional coverage and cloud-top pressure) or as radiances. For microwave measurements, which are sensitive to cloud bulk properties, then the latter is likely to be preferred. For infra-red meaurements, which tend to be sensitive to cloud-top properties, a successful preferred method has yet to emerge.
- Radio occultation - retrieved refractivity or bending angle, for the reasons given in section 5.4.5 of this paper.

7. Summary and conclusions

Assimilation of satellite data into NWP models has come a long way since the first experiments to assimilate SIRS data in 1969-70. During the 1970s and early 1980s, progress was slow as a result of limitations both in the satellite measurements and in the assimilation systems. Nevertheless useful impact was found, particularly in the S. Hemisphere, and although problems were recognised, the general mood was optimistic. There was a crisis of confidence in the late 1980s, when demonstrated impacts in the N. Hemisphere became first neutral and then negative. This led to a major re-think around this time concerning the nature of the assimilation problems. Out of this emerged a general trend towards direct assimilation of radiances, which has been adopted by several NWP centres and has yielded consistent positive impact from these data in both hemispheres.

Alongside satellite sounding data, information on winds derived from satellite imagery (AMVs) have been important since the early days of satellite data information. From the 1990s, operational assimilation of other types of satellite data has expanded considerably; these include information from scatterometers, microwave imagers and several other types of instrument.

In recent years, the quality of satellite sounding information has improved considerably. The ATOVS instruments, through their improved microwave component, have provided enhanced soundings particularly in cloudy areas. The advanced infra-red sounders, AIRS and IASI, have enhanced the infra-red contribution to the system through their greatly improved vertical resolution. Both of these enhancements led to substantially increased forecast impact, to the extent that the satellite component of the GOS is now the main contributor to currently achieved levels of short- and medium-range forecast skill, even in N. Hemisphere mid-latitudes - see Kelly (2007, this volume). In addition, satellite data accumulated over the last 35 years are playing a major role in re-analyses of the atmospheric state – see Uppala (2007, this volume).

Acronymns

1D-Var	One-dimensional variational analysis / retrieval
3D-Var	Three-dimensional variational analysis / assimilation
4D-Var	Four-dimensional variational analysis / assimilation
ADEOS	Advanced Earth Observing Satellite (of Japan)
AIRS	Atmospheric InfraRed Sounder
AMI	Active Microwave Instrument
AMSU	Advanced Microwave Sounding Unit
AMV	Atmospheric motion vector
ANMRC	Australian Numerical Meteorology Research Centre
APT	Automatic Picture Transmission
ASCAT	Advanced Scatterometer
ATOVS	Advanced TOVS
ATS	Applications Technology Satellite (of the USA)
CHAMP	Challenging Mini-satellite Payload (of Germany)
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CrIS	Cross-track Infrared Sounder
ECMWF	European Centre for Medium-range Weather Forecasts
ERS	European Remote Sensing satellite (of ESA)
ESA	European Space Agency
ESSA	Environmental Science Services Administration satellite (of the USA)
EUMETSAT	European organisation for the exploitation of Meteorological Satellites
FGGE	First GARP Global Experiment
GARP	Global Atmospheric Research Programme
GLAS	Goddard Laboratory for Atmospheric Sciences, NASA, USA
GMS	Geostationary Meteorological Satellite (of Japan)
GNSS	Global Navigation Satellite System
GOS	Global Observing System (of WMO)
GPS	Global Positioning System
GPS/MET	GPS Meteorology satellite
GRACE-A	Gravity Recovery And Climate Experiment satellite
GRAS	GNSS Receiver for Atmospheric Sounding
HIRS	High-resolution Infrared Radiation Sounder
IASI	Infra-red Atmospheric Sounding Interferometer
IRIS	InfraRed Interferometer Spectrometer
ITOS	Improved TIROS Operational System
ITPR	Infrared Temperature Profile Radiometer
JCSDA	Joint Center for Satellite Data Assimilation (of the USA)

LIMS	Limb Infrared Monitor of the Stratosphere
LRIR	Limb Radiance Inversion Radiometer
MetOp	Meteorological Operational satellite (of EUMETSAT and ESA)
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MRSA	Microwave Radiometer / Scatterometer and Altimeter
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration (of the USA)
NCEP	National Centers for Environmental Prediction (of the USA)
NH	Northern Hemisphere
Nimbus	NASA series of experimental meteorological satellites
NMC	National Meteorological Center (of the USA)
NOAA	National Oceanic and Atmospheric Administration (of the USA), and the operational polar-orbiting satellites series of that agency
NPOESS	National Polar-Orbiting Environmental Satellite System (of the USA)
NSCAT	NASA Scatterometer
NWP	Numerical Weather Prediction
OI	Optimal interpolation (method of data analysis/assimilation)
OSE	Observing system experiment
PAOB	"Paid Observation" – pseudo-observation derived from a manual analysis
PDF	Probability density function
PMR	Pressure Modulator Radiometer
QE-II	Queen Elizabeth the Second (ocean liner)
Quikscat	Quick Scatterometer mission (of NASA)
RO	Radio occultation
SAC-C	Satelite de Aplicaciones Cientificas – C (of Argentina)
SAF	Satellite Application Facility (of EUMETSAT)
SASS	Seasat-A Satellite Scatterometer system
SATEM	WMO message format for satellite temperature and humidity retrievals
SAMS	Stratospheric and Mesospheric Sounder
SBUV	Solar Backscatter UltraViolet instrument
SCAMS	Scanning Microwave Spectrometer
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SCR	Selective Chopper Radiometer
Seasat	NASA satellite for remote sensing of the ocean
Seawinds	Scatterometer instrument on Quikscat and ADEOS-II
SH	Southern Hemisphere
SIRS	Scanning Infa-Red Spectrometer
Skylab	USA's first experimental space station

SMS	Synchronous Meteorological Satellite (of the USA)
SSU	Stratospheric Sounding Unit
TIROS	Television InfraRed Observation Satellite
TOVS	TIROS-N Operational Vertical Sounder
UT	Universal Time
VTPR	Vertical Temperature Profile Radiometer
WMO	World Meteorological Organisation

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