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

Met Office

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

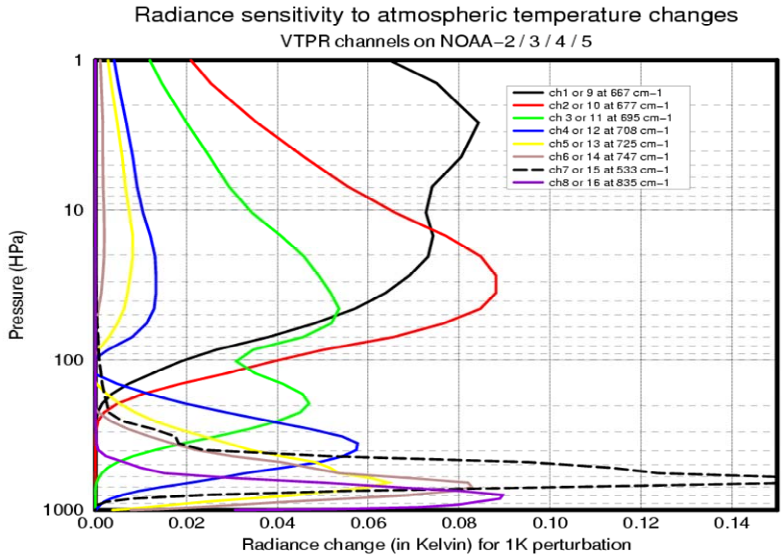
Nimbus series – temperature/humidity sounders

• 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

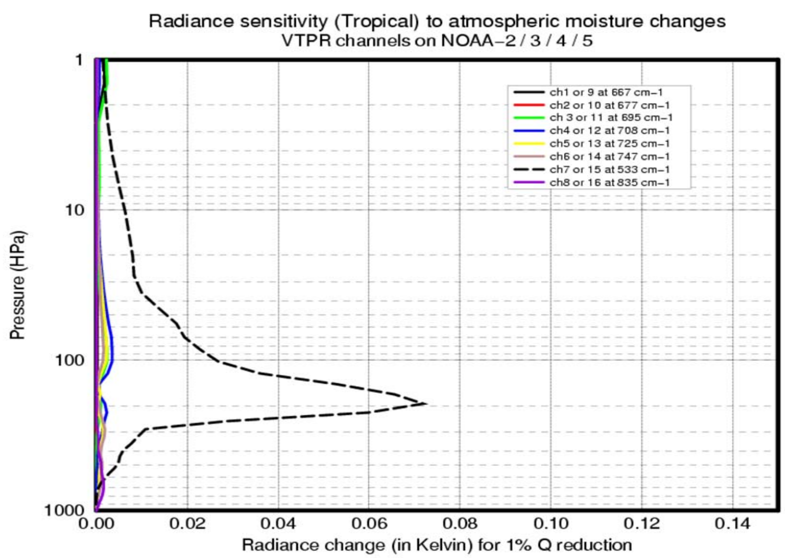
NOAA series – temperature/humidity sounders

• 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



temperature



humidity

TOVS – weighting functions

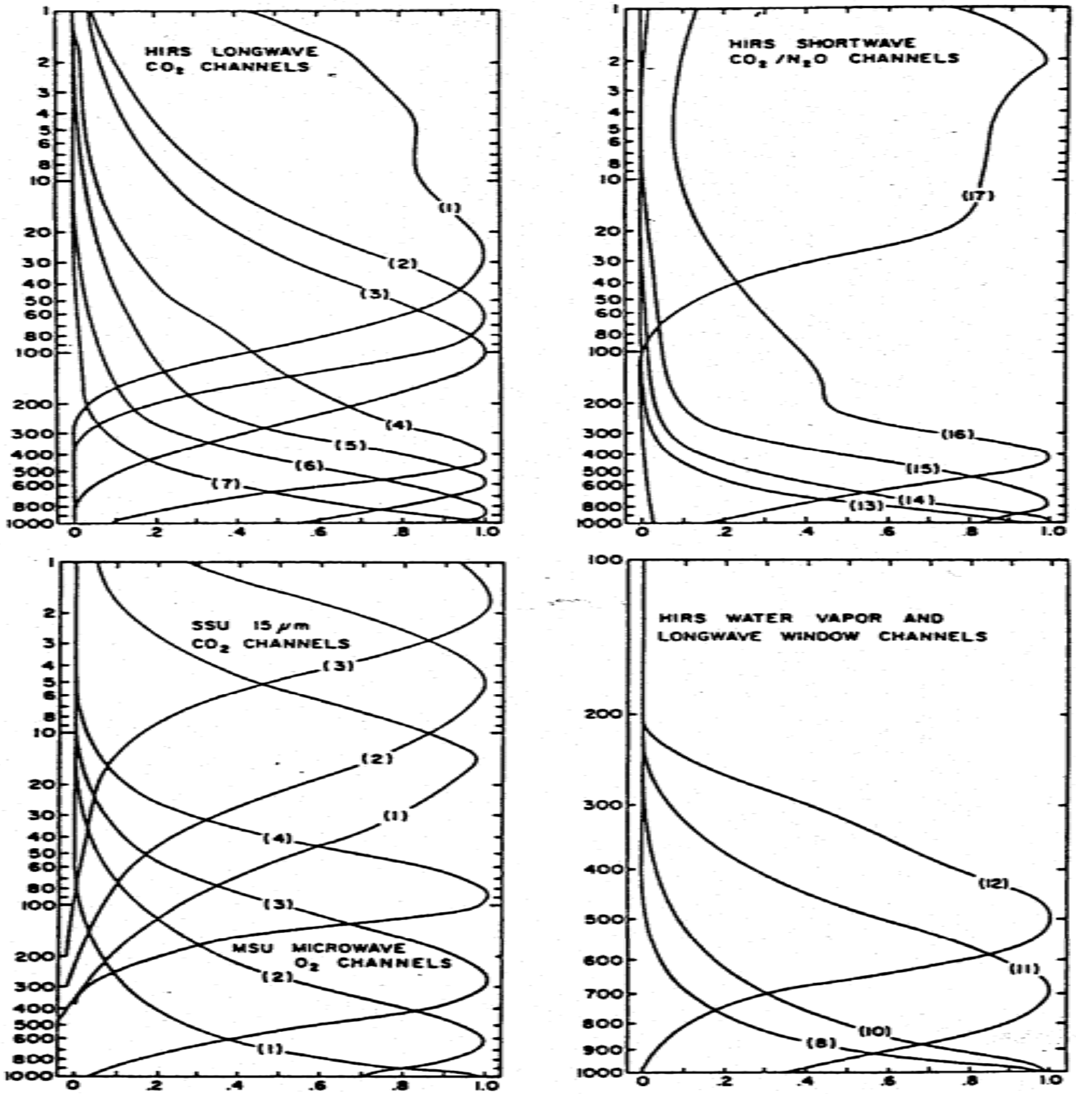
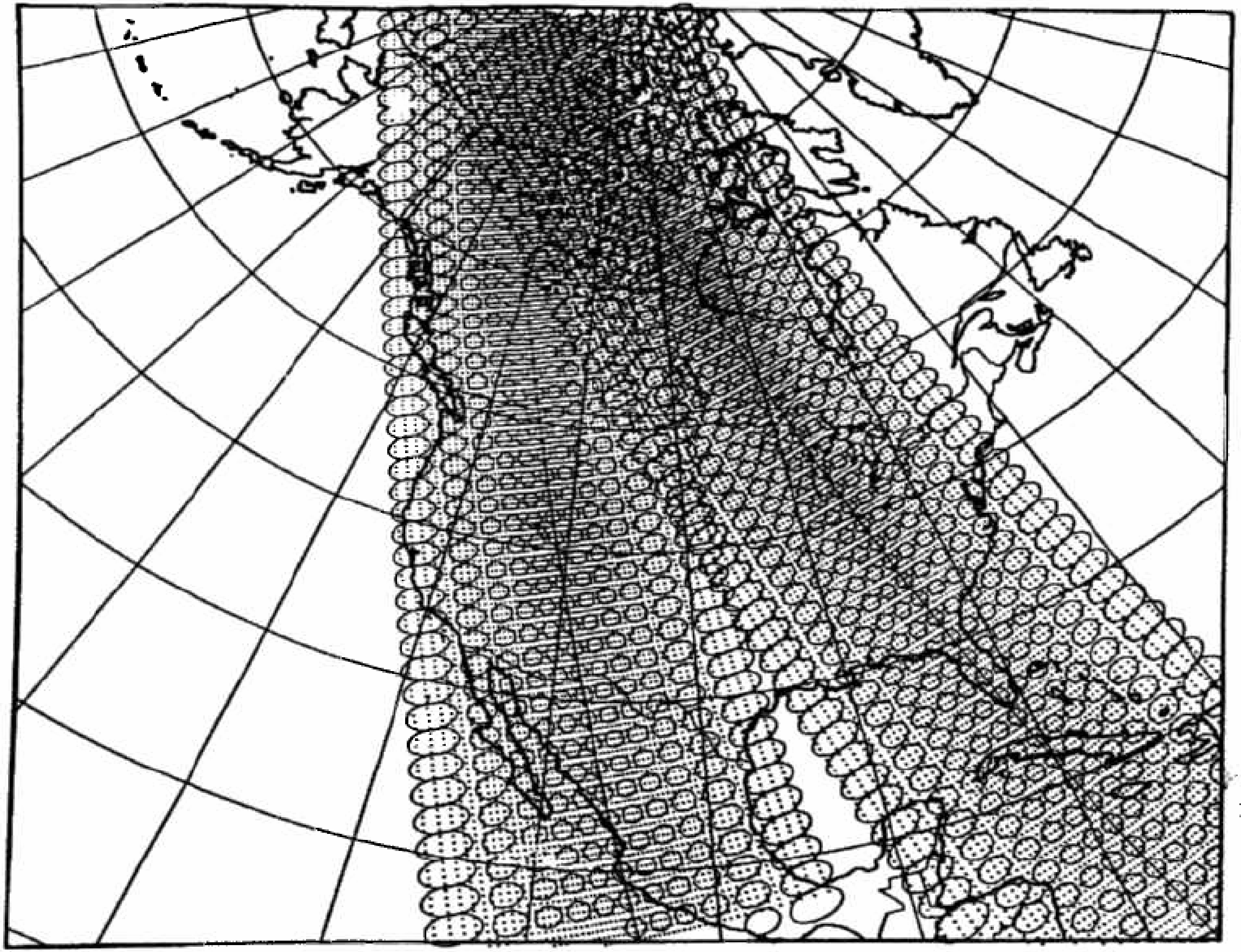


Fig. 3 TOVS normalised weighting functions (from Smith et al., 1979).

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 → 200 hPa)

In this story, this chap Kelly appears everywhere!

Assimilation experience: 1970s (2)

UK experience

Atkins and Jones, "An experiment to determine the value SIRS data in numerical forecasting", Meteorol Mag, 104, 125-142, 1975.

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

Assimilation experience: 1970s (3)

Summary paper:

Ohring G, “Impact of satellite temperature soundings on weather forecasts” (BAMS, 60, 1142-1147, 1979).

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

Assimilation experience: 1970s (4)

Summary paper:

Ohring G, “Impact of satellite temperature soundings on weather forecasts” (BAMS, 60, 1142-1147, 1979).

Summary:

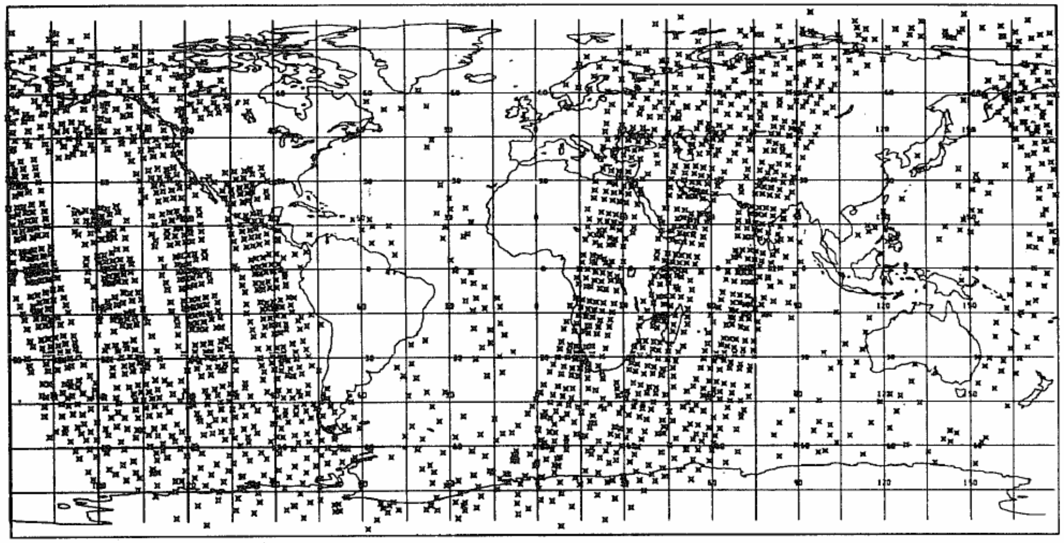
- “on average, a small improvement in numerical forecasts”
- “beneficial but modest impacts”
- “hesitate to claim that satellite data changed a poor forecast to an accurate one”
- Greater improvements in forecasts in S Hem.

Problems:

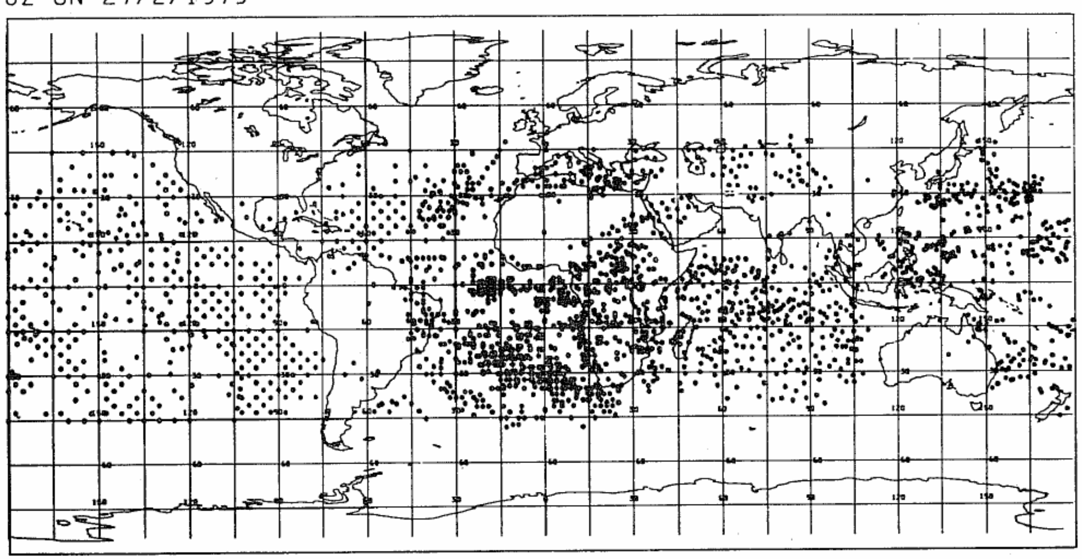
- Differences between retrievals and collocated radiosondes of 2-3 deg
- Analyses using satellite data have lower eddy potential energy
- Satellite soundings not point observations – have their own error characteristic – improved analysis schemes may enhance impact
- Improvements in retrieval methods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

FGGE – satellite data coverage

POSITION OF SATEM OBSERVATIONS
0Z ON 27/2/1979



POSITION OF SATOB OBSERVATIONS
0Z ON 27/2/1979



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

Assimilation experience: 1980s (1)

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

Assimilation experience: 1980s (2)

Met Office

Exeter Workshop 1982. Report of “JSC Study Conference on Observing System Experiments” (Gilchrist A,1982).

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

Assimilation experience: 1980s (3)

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

Late 1980s: problems (1)

Kelly and Pailleux(1988). "Use of satellite vertical sounder data in the ECMWF analysis system". ECMWF Tech Mem 143.

- 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)

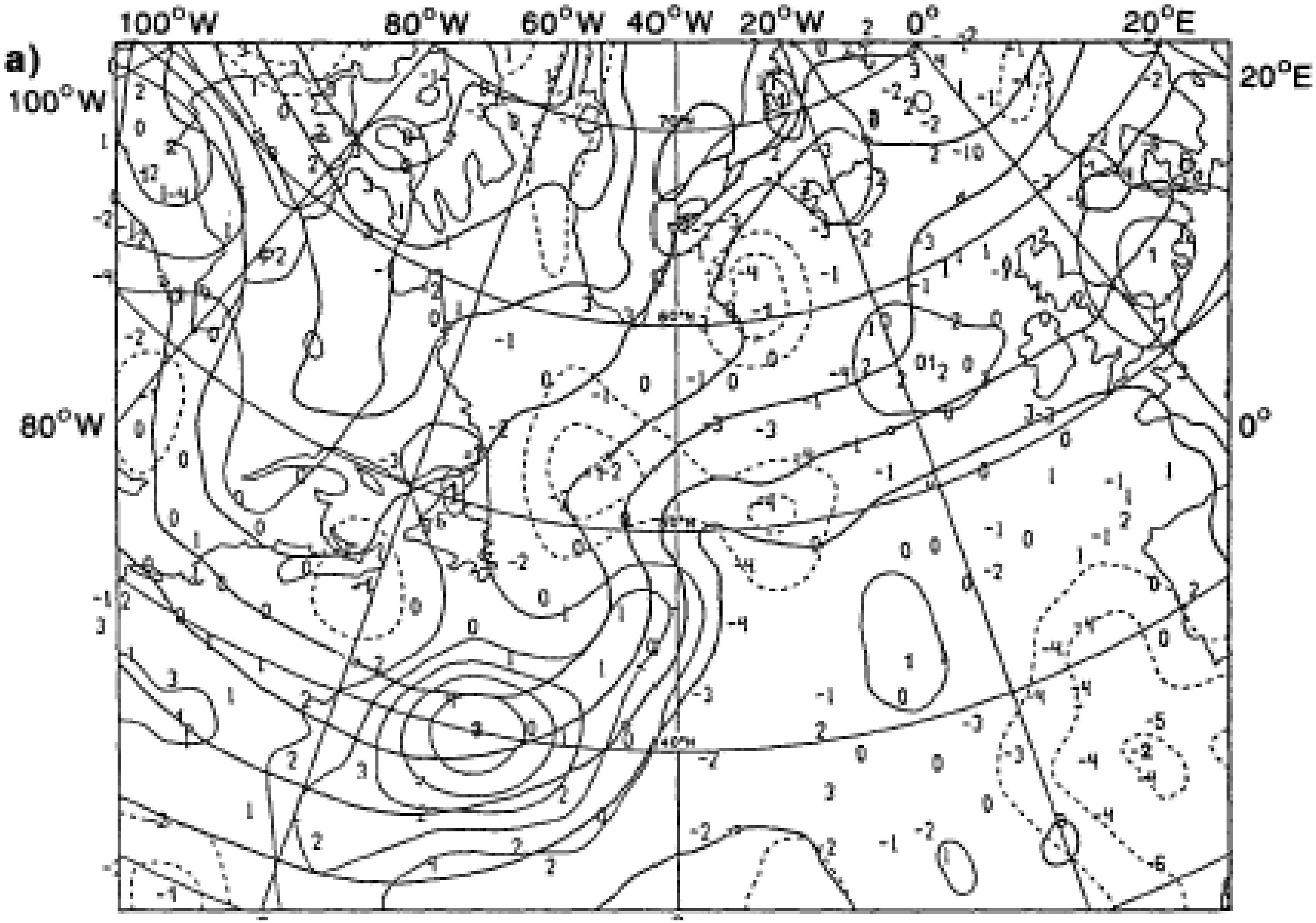
Andersson et al. "Global observing system experiments on operational statistical retrievals of satellite sounding data", MWR, 119, 1851-1864 (1991)

- 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

Kelly et al. "Quality control of operational physical retrievals of satellite soundings", MWR, 119, 1866-1880 (1991)

- "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



From Andersson et al (1991). Analysis increments and background,1000-700 hPa

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

The history and future of data assimilation (2)

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

The history and future of data assimilation (3)

Optimal Interpolation (OI)

- Linearising the VAR problem →
- $x^a = x^b + K . (y^o - H[x])$
  - where $K = B.H^T.(H.B.H^T + E + F)^{-1}$

  H is the Jacobian of the observation operator $H[x]$

Empirical

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

Retrieval error characteristics

- Linearized retrieval equation: $x^a - x^b = K.(y^o - \mathit{H}[x^b])$
- Linearized forward equation: $y^o - \mathit{H}[x^b] = H.(x - x^b) + \varepsilon$
- 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   background error   measurement error

where ^{t} denotes truth, I = unit matrix, $H = \nabla_x \mathit{H}[x]$

- This equation shows why assimilating retrieved temperature/humidity profiles into NWP models is more problematic than assimilating radiances directly

Direct assimilation of radiances: 1990s

Variational equations: for 1D-Var, 3D-Var, 4D-Var

Minimize:

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

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

- Derber and Wu, MWR, 126, 2287-2299 (1997). "The use of TOVS cloud-cleared radiances in the NCEP SSI analysis system".
    - operational at NCEP, October 1995
- Andersson et al, QJRMS, 120, 627-653 (1994). "Use of cloud-cleared radiances in three/four-dimensional variational data assimilation
    - operational at ECMWF, January 1996

TOVS in 4D-Var

- Operational at ECMWF, November 1997

Atmospheric motion vectors

- winds derived by tracking features in imagery

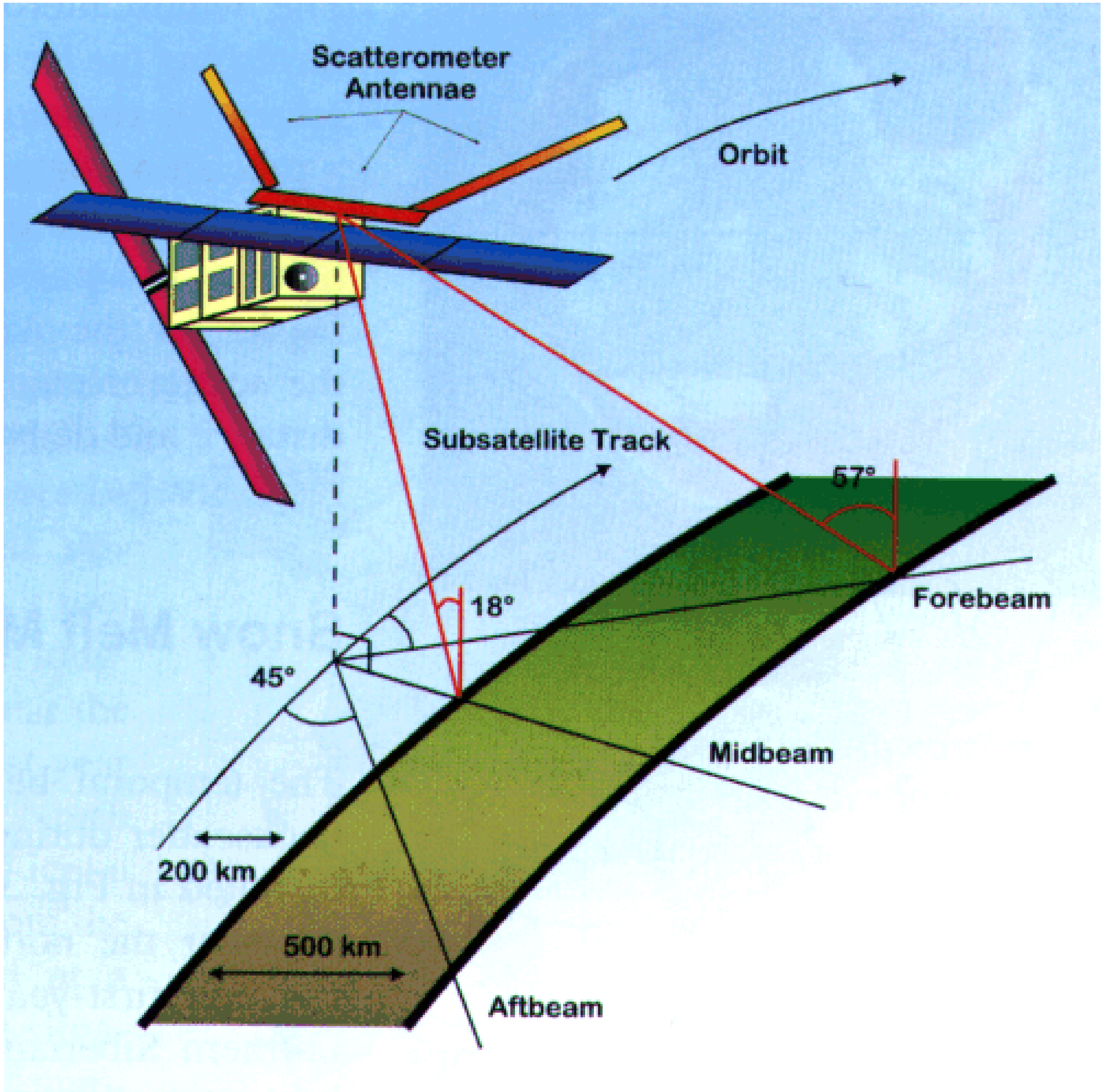
Scatterometry

Scatterometry: satellites and instruments

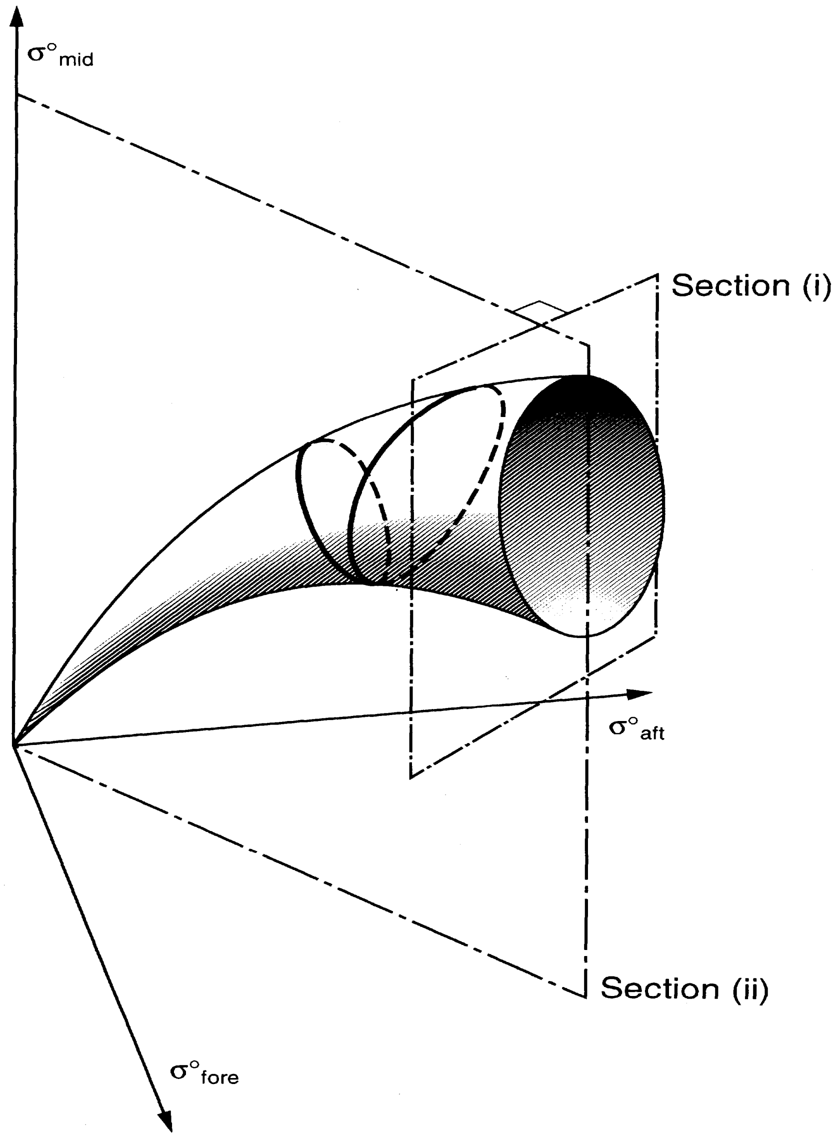
year	satellite	instrument	freq GHz	views	res km	swath km
73-74	Skylab	MRSA	13.9 (Ku-band)	1*	15	185
78	SEASAT	SASS	14.6 (Ku-band)	2	25	1000
91-00	ERS-1	AMI	5.3 (C-band)	3	25	500
95-	ERS-2	AMI	5.3 (C-band)	3	25	500
96-97	ADEOS-I	NSCAT	14.0 (Ku-band)	3	50	1000
99-	Quikscat	Seawinds	13.4 (Ku-band)	4	25	1800
06-	Metop	ASCAT	5.3 (C-band)	3	25	1000

* dual polarisation

Scatterometry: ERS-1 and -2 (1)



Scatterometry: ERS-1 and -2 (2)



ERS scatterometer:

the measurement cone in σ^0-space

Wind speed increases along the cone

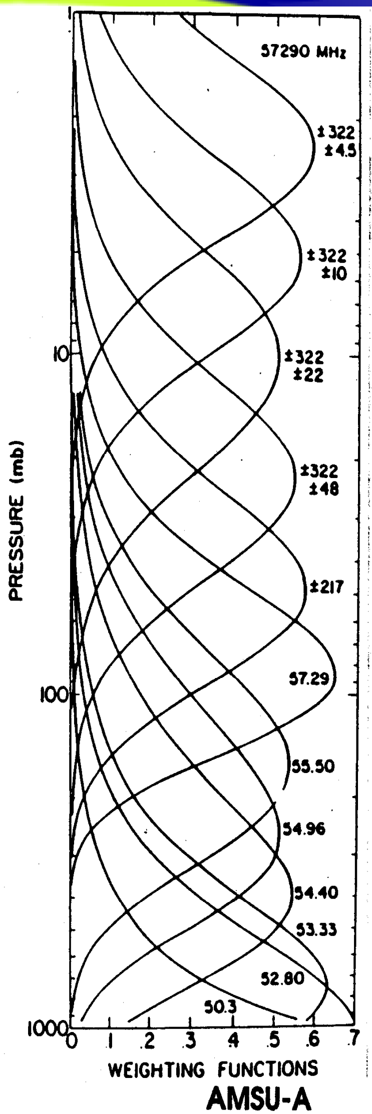
Wind direction changes through 360º for twice around the cone

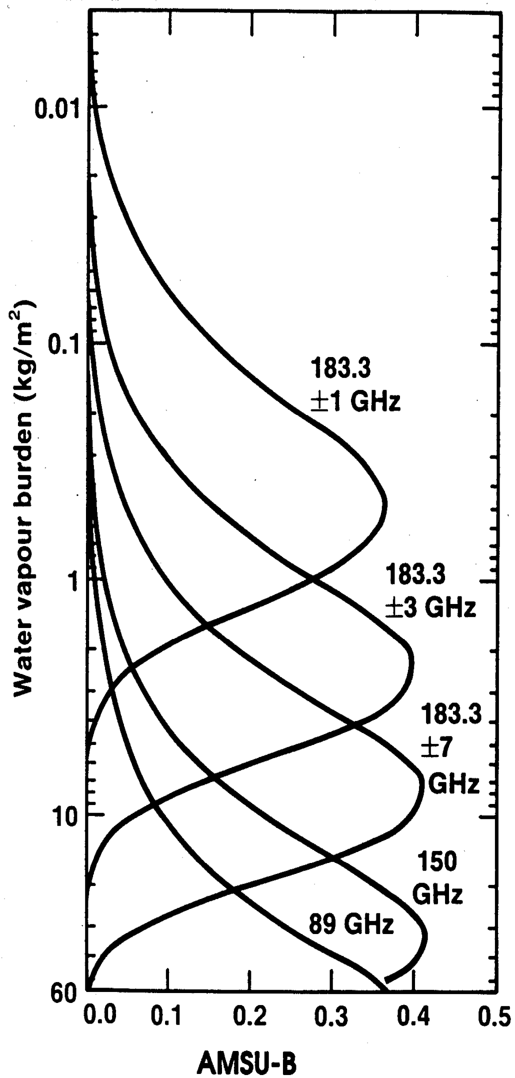
Scatterometry: early assimilation experience

- 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 → ATOVS





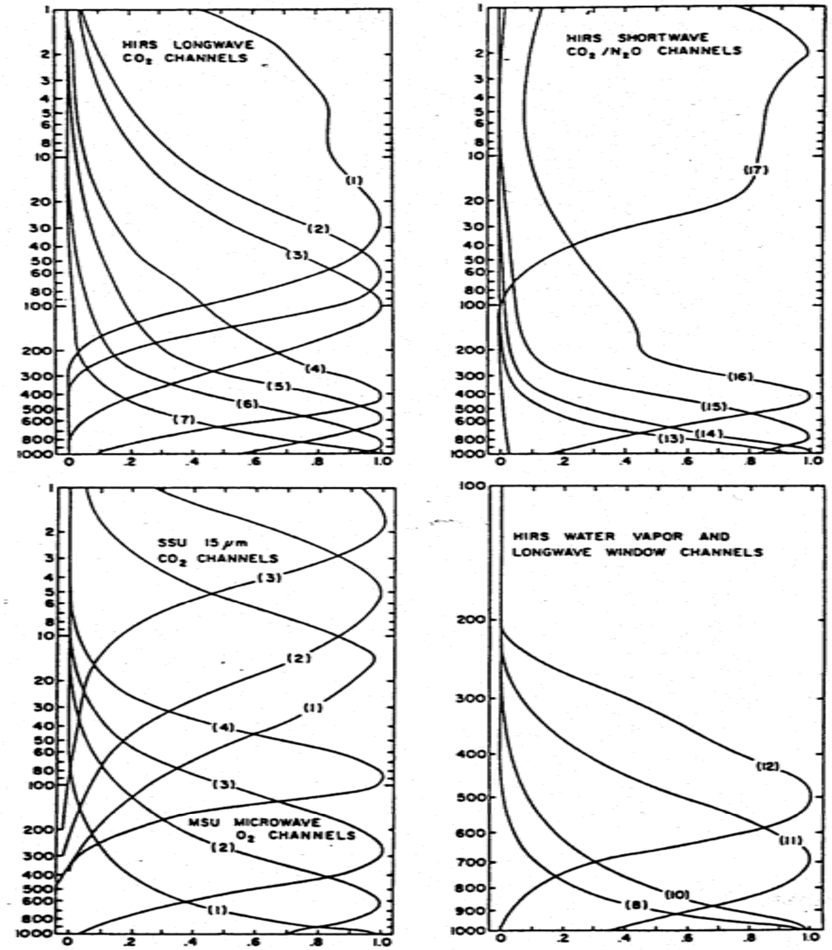
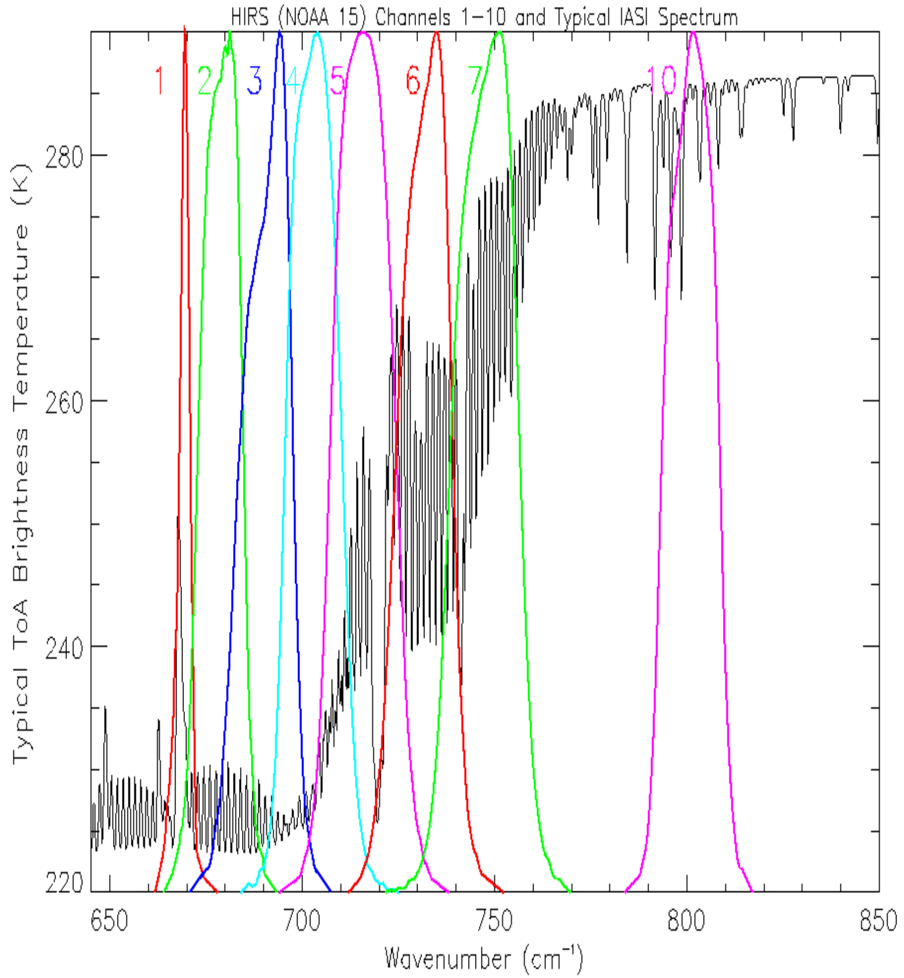
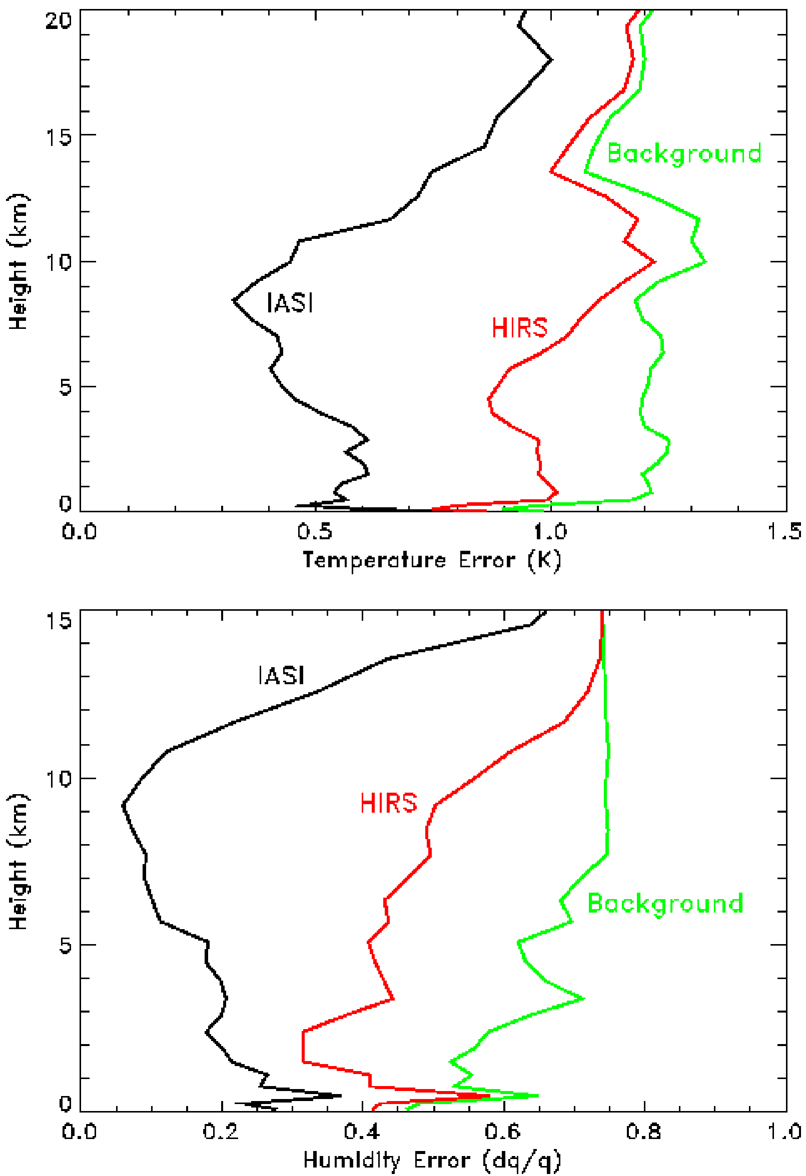


Fig. 3 TOVS normalised weighting functions (from Smith et al., 1979).

AMSU-A AMSU-B TOVS = HIRS + MSU+ SSU

More recent advances: AIRS and IASI





IASI v. HIRS

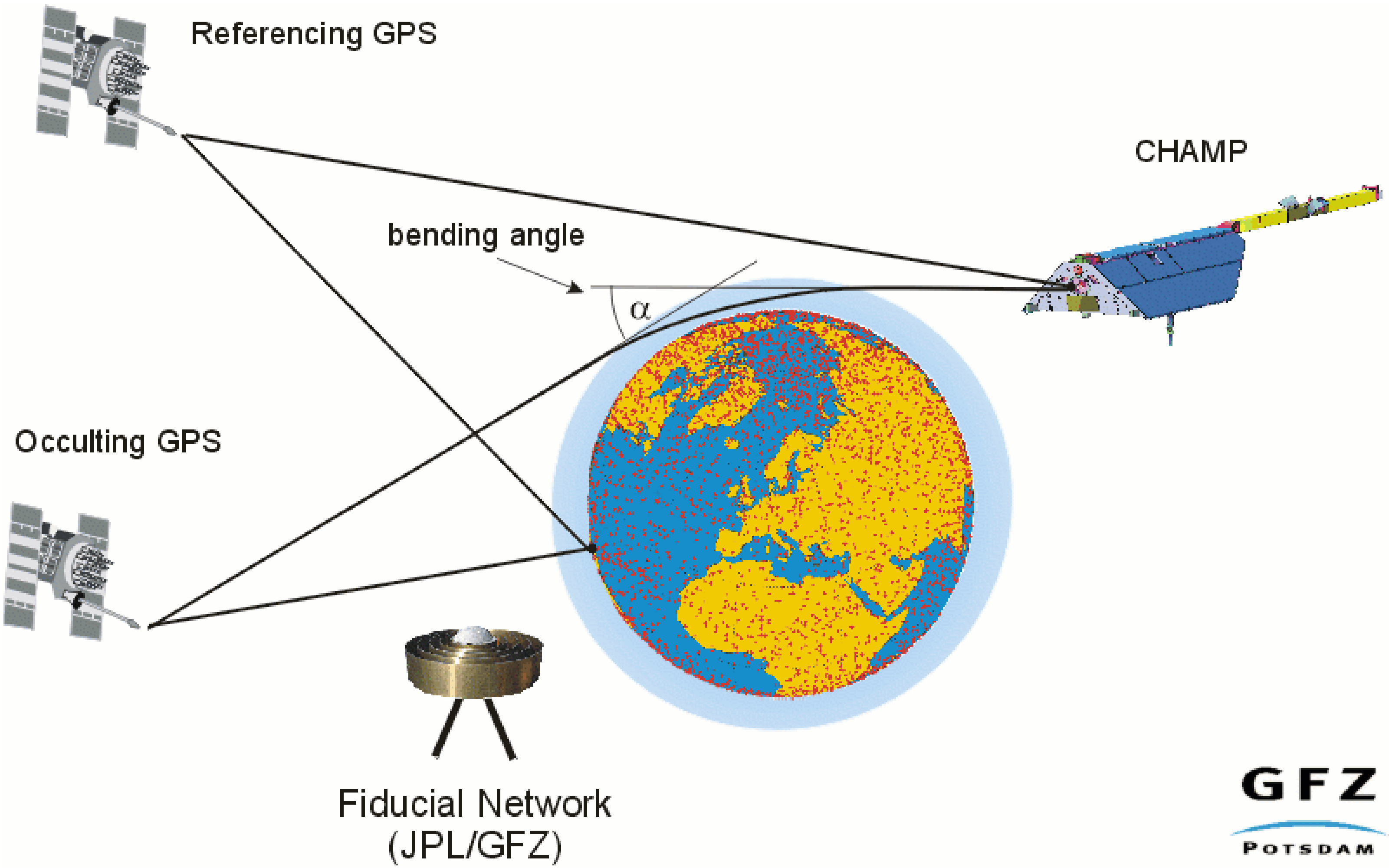
More recent advances: other observation types

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)

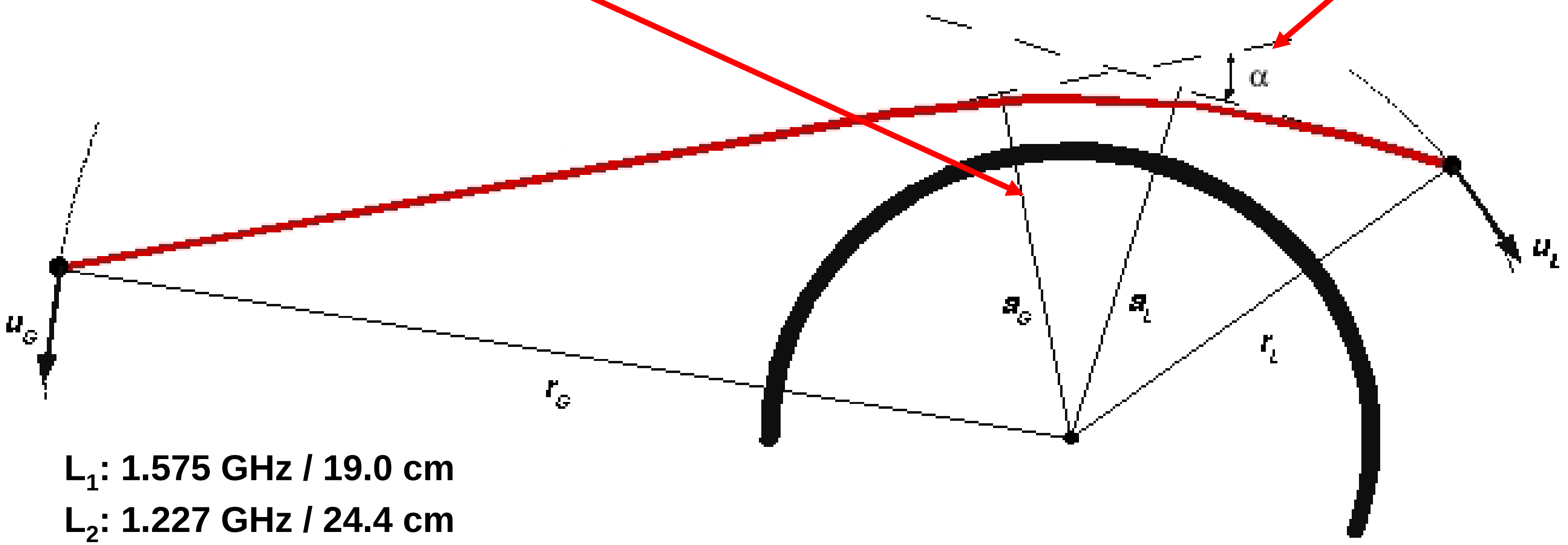
Radio occultation: the technique (1)



Radio occultation: the technique (2)

Impact parameter

Bending angle



L_1: 1.575 GHz / 19.0 cm

L_2: 1.227 GHz / 24.4 cm

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

Refractive index

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

Refractivity

Radio occultation: the physics

Refractivity gradients caused by gradients in:

- density (pressure and temperature)
- water vapour
- electron density
- (liquid water)

$$N = \kappa_1\, p/T + \kappa_2\, e/T^2 + \kappa_3\, n_e/f^2 + \kappa_4\, W$$

"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:

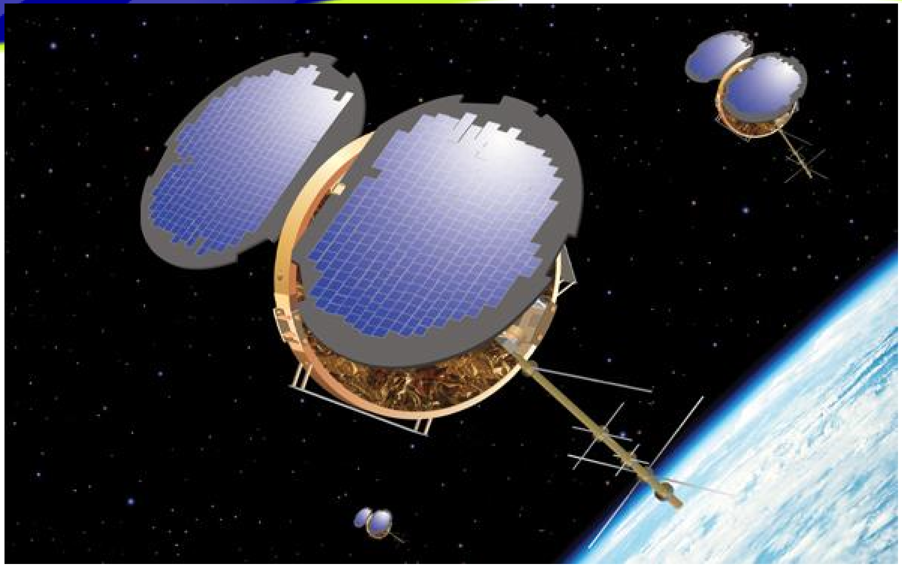
• CHAMP	2000 - …	exptl, continuous since 2001; NRT since 2006
• SAC-C	2000 - …	sporadic measurements, experimental
• GRACE-A	2002 - …	exptl, continuous since 2003; NRT since 2006
• COSMIC	2006 - …	demonstration mission, 6 satellites
• MetOp/GRAS	2006 - …	operational from 2007
• TerraSAR-X	2007 - …	

Future:

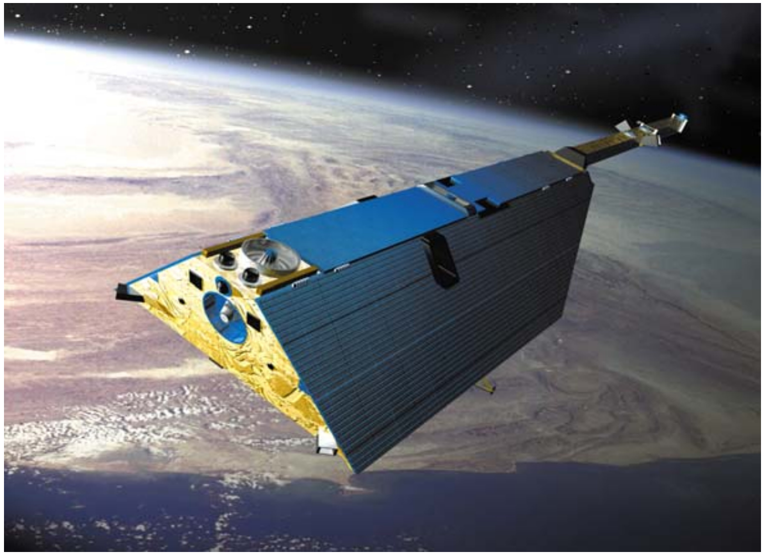
• EQUARS	2007?	emphasising equatorial region
• OCEANSAT-ROSA	2009?	Italian / Indian mission
• COSMIC-2	?	
• CICERO	?	20-100 satellites

Radio occultation missions (2)

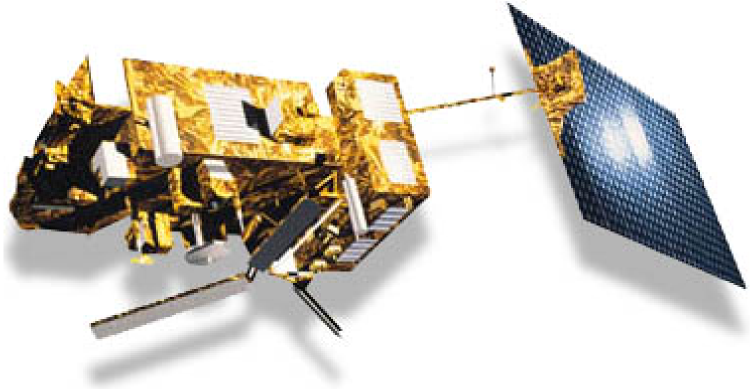
COSMIC



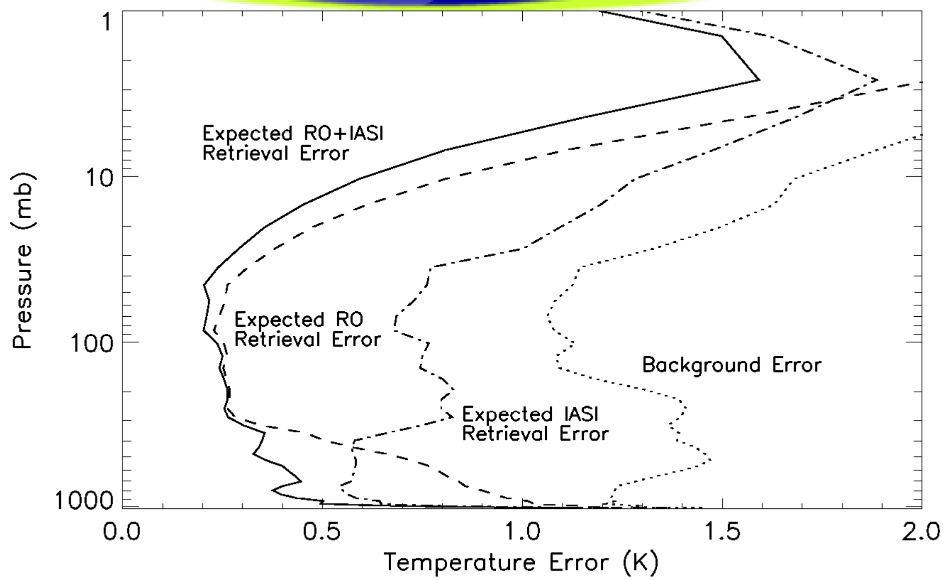
CHAMP

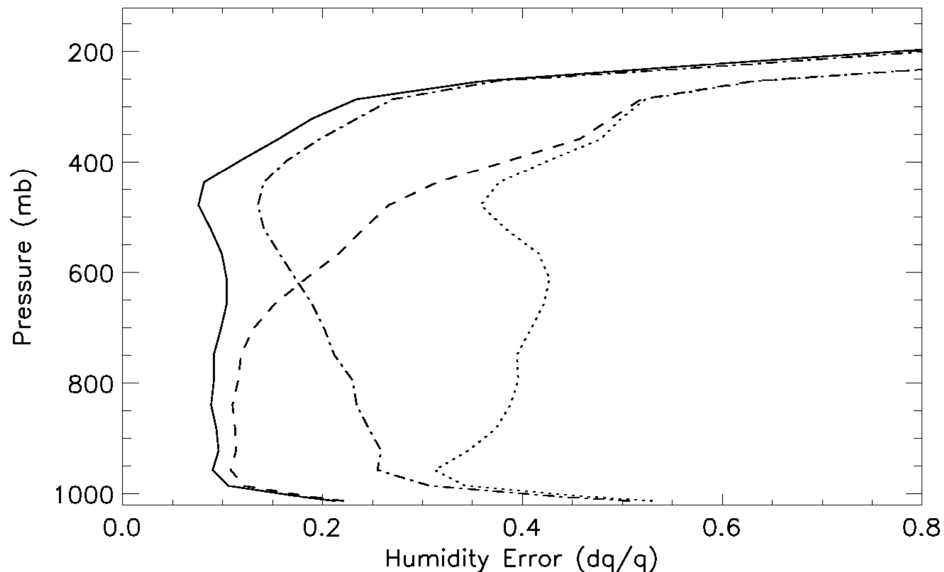


Metop/GRAS



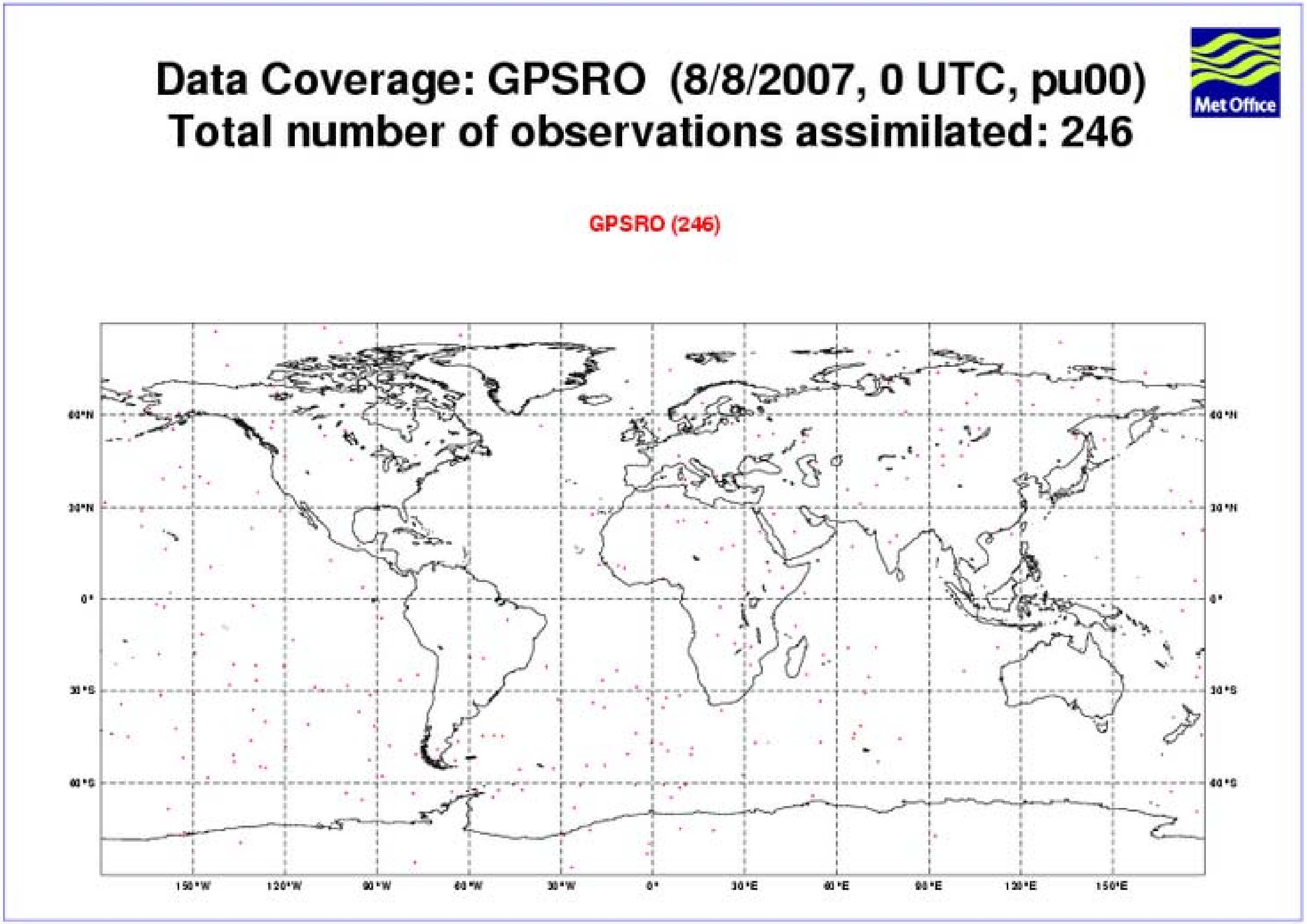
Error analysis: radio occultation with IASI



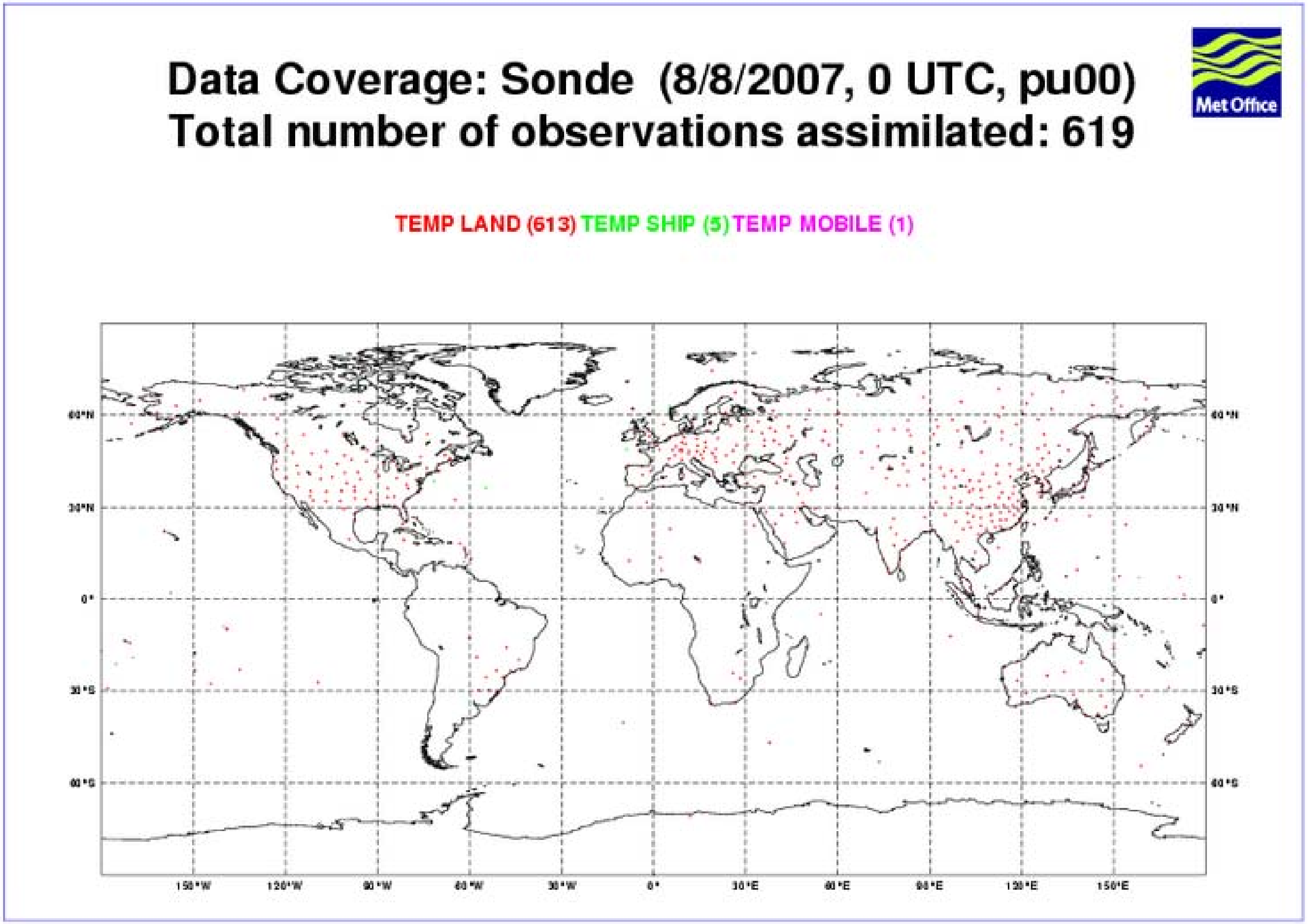


Collard and Healy, 2003

Radio occultation: data coverage in 6 h – 4 satellites



… compared with sondes



Radio occultation: assimilation options

Options:

(1) assimilate retrieved profiles of temperature and humidity

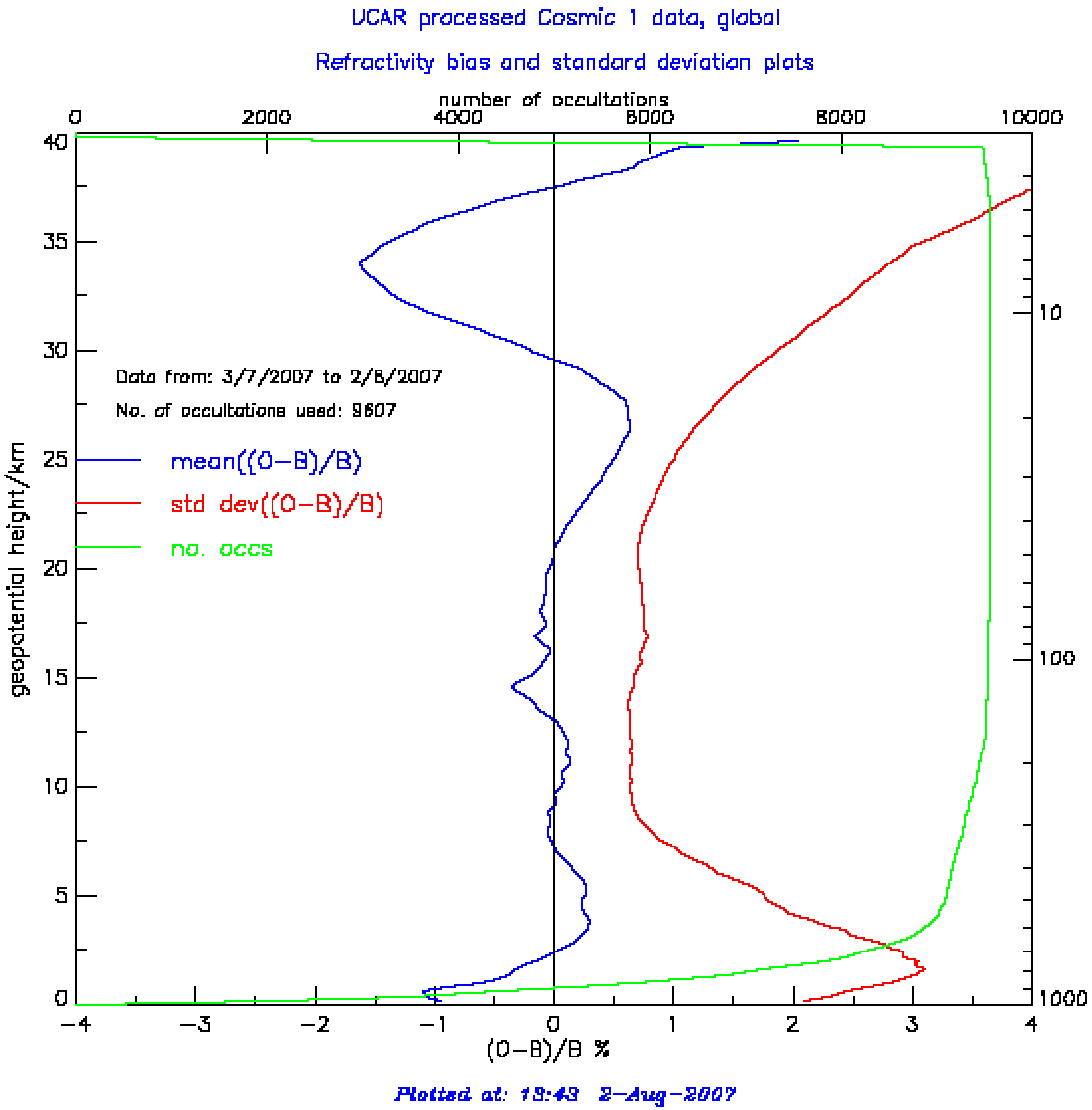
(2) assimilate retrieved profile of refractivity, $N(z)$

(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

More recent advances: radio occultation

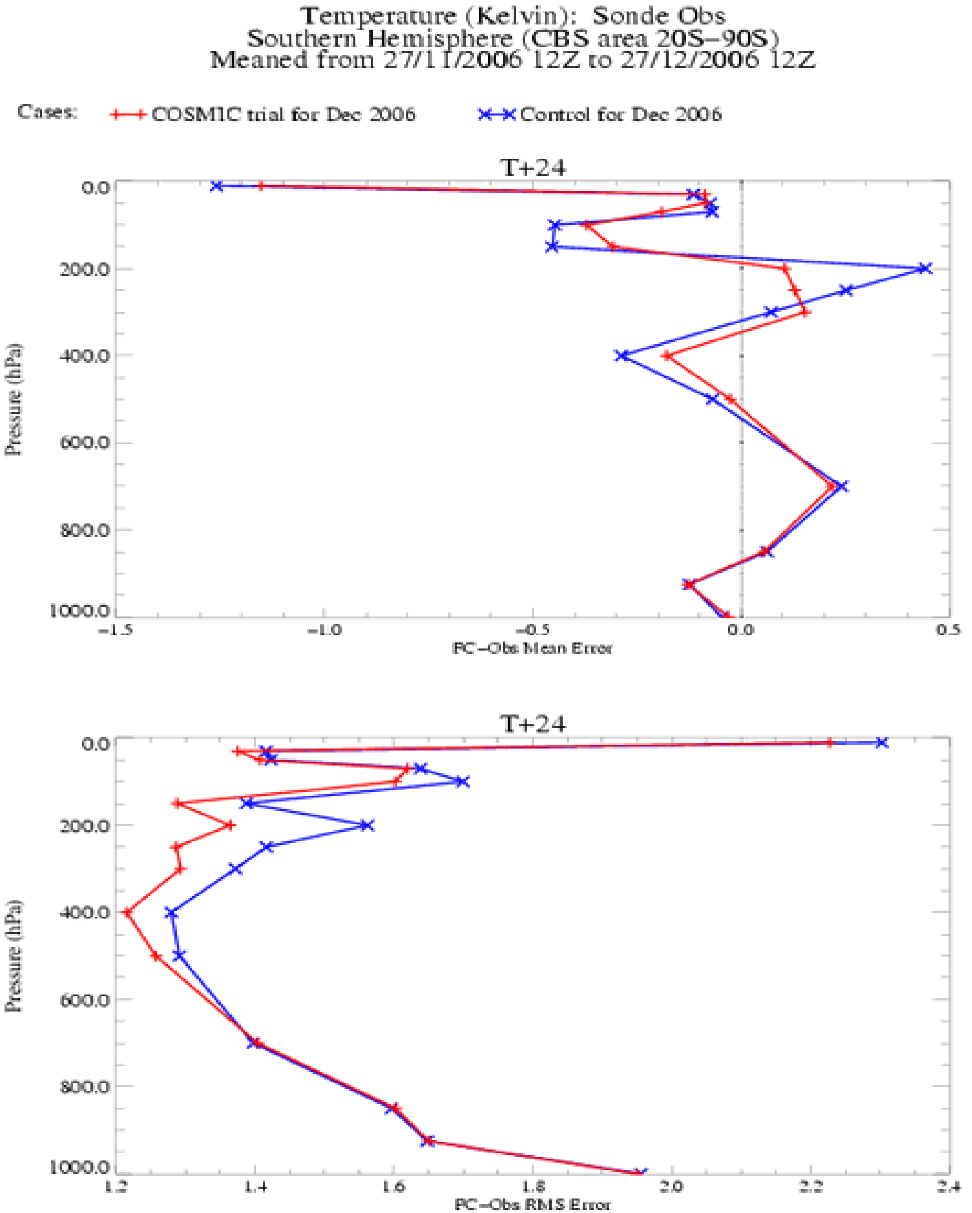
Recent results

(M.Rennie, Met Office)

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

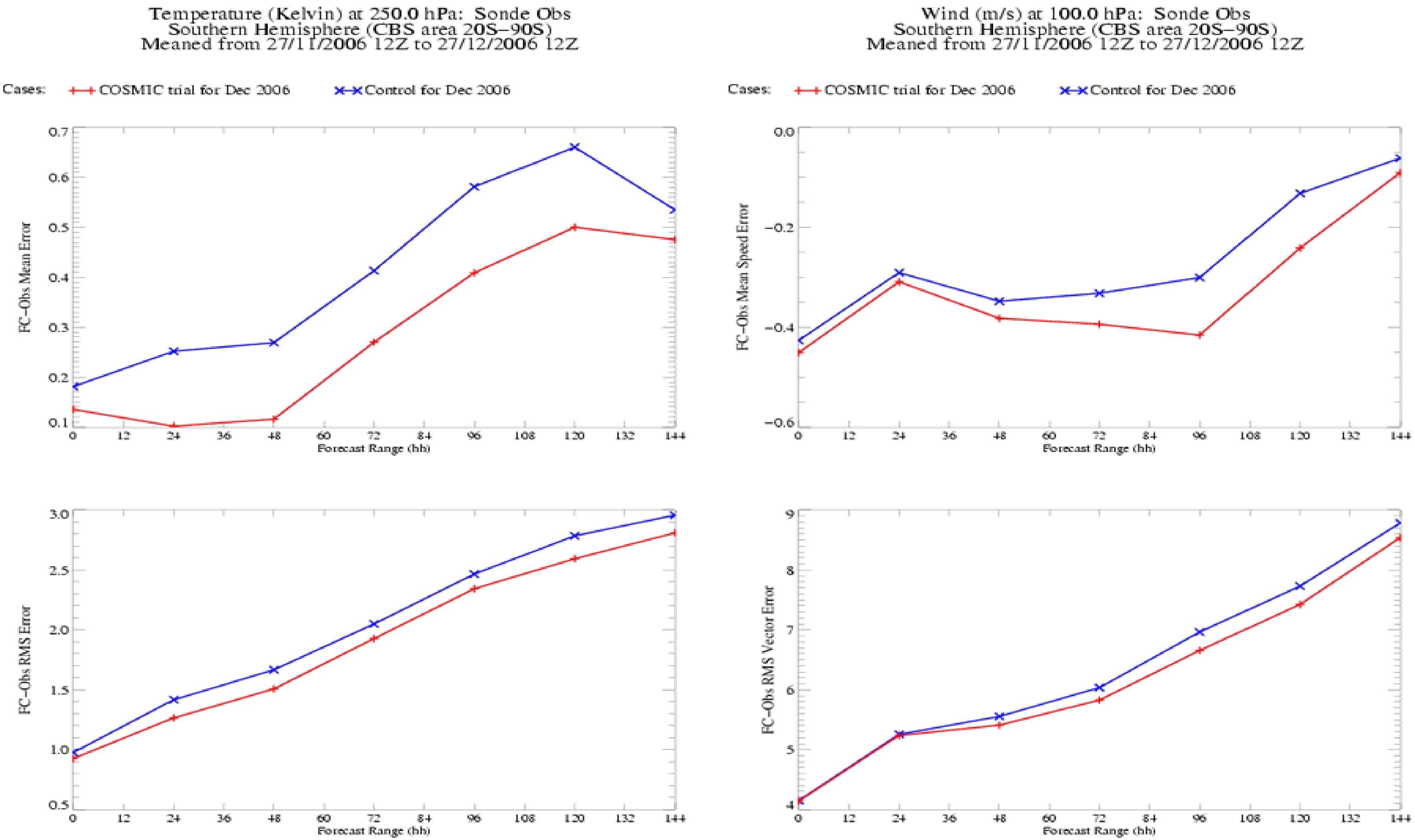
The assimilation of GPSRO reduces RMS errors in the upper troposphere and corrects model biases.

Similar patterns in NH and TR, but smaller impact



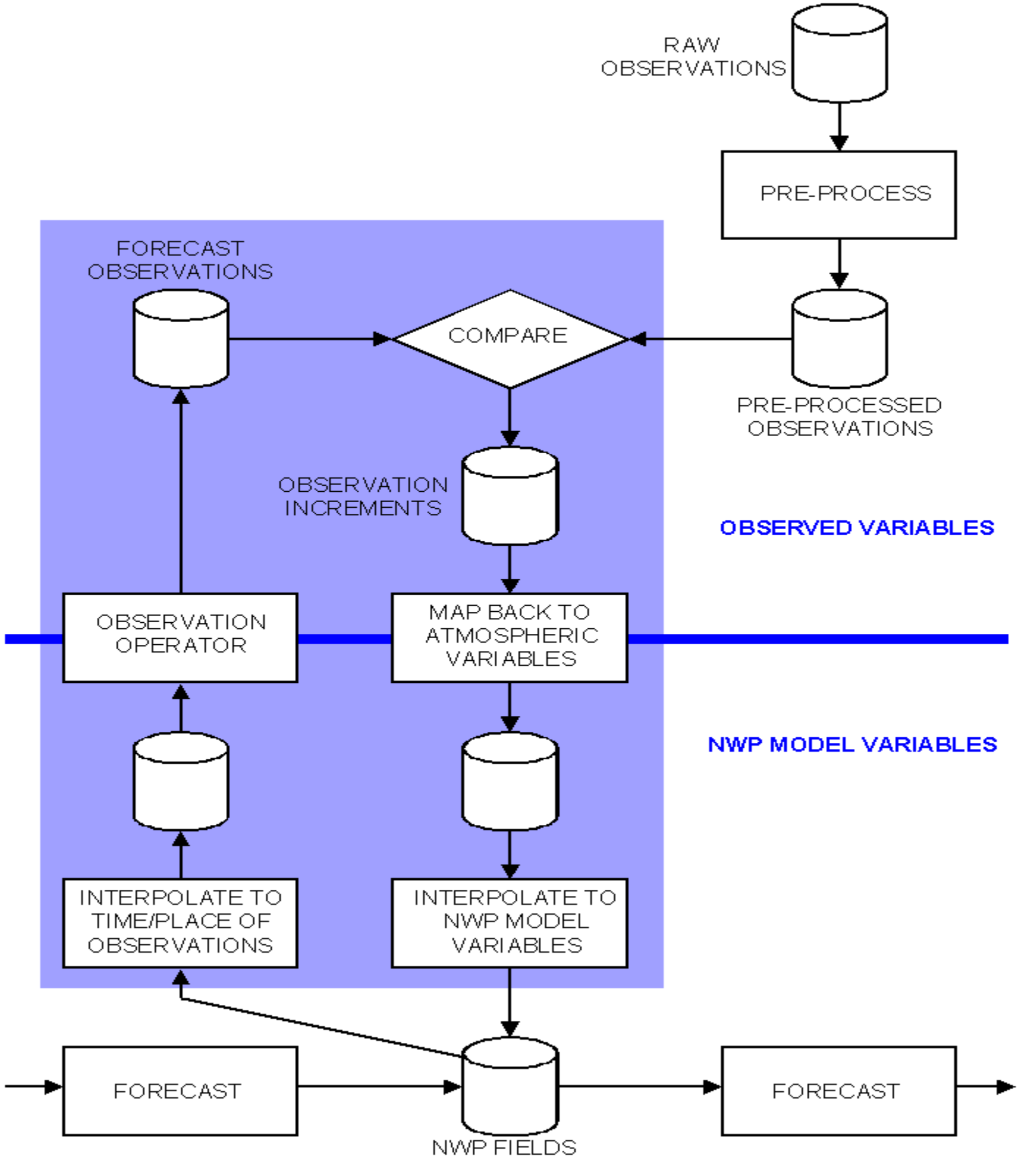
More recent advances: radio occultation

Recent results – bias and RMS v. forecast range



Strategies for various data types

Direct assimilation of observations



Assimilation of satellite data: strategies for various data types

Ref.: Eyre, "Variational assimilation of remotely sensed observations of the atmosphere", J Meteorol Soc Japan, 75, 331-338 (1997).

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

Met Office

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