Use of Advanced Infrared Sounder Data in NWP models

Roger Saunders (Met Office, U.K.)

- Why use advanced sounder data?
- How do we use advanced sounders in NWP?
  - Radiative transfer
  - Cloud detection
  - Bias tuning
  - Real time data monitoring
  - Data assimilation
- Impacts of sounder data

Demonstrate with AIRS data

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Why Do We Need Satellite Data for NWP ?

- Global coverage - main source of data over oceans and remote land areas.
- Measurements closer to scale of models grids.
- Has greater impact than radiosonde data on N. Hemisphere forecasts.
- Model validation (using data not assimilated) used for assessing impact of changes made and errors of the model analyses/forecasts.

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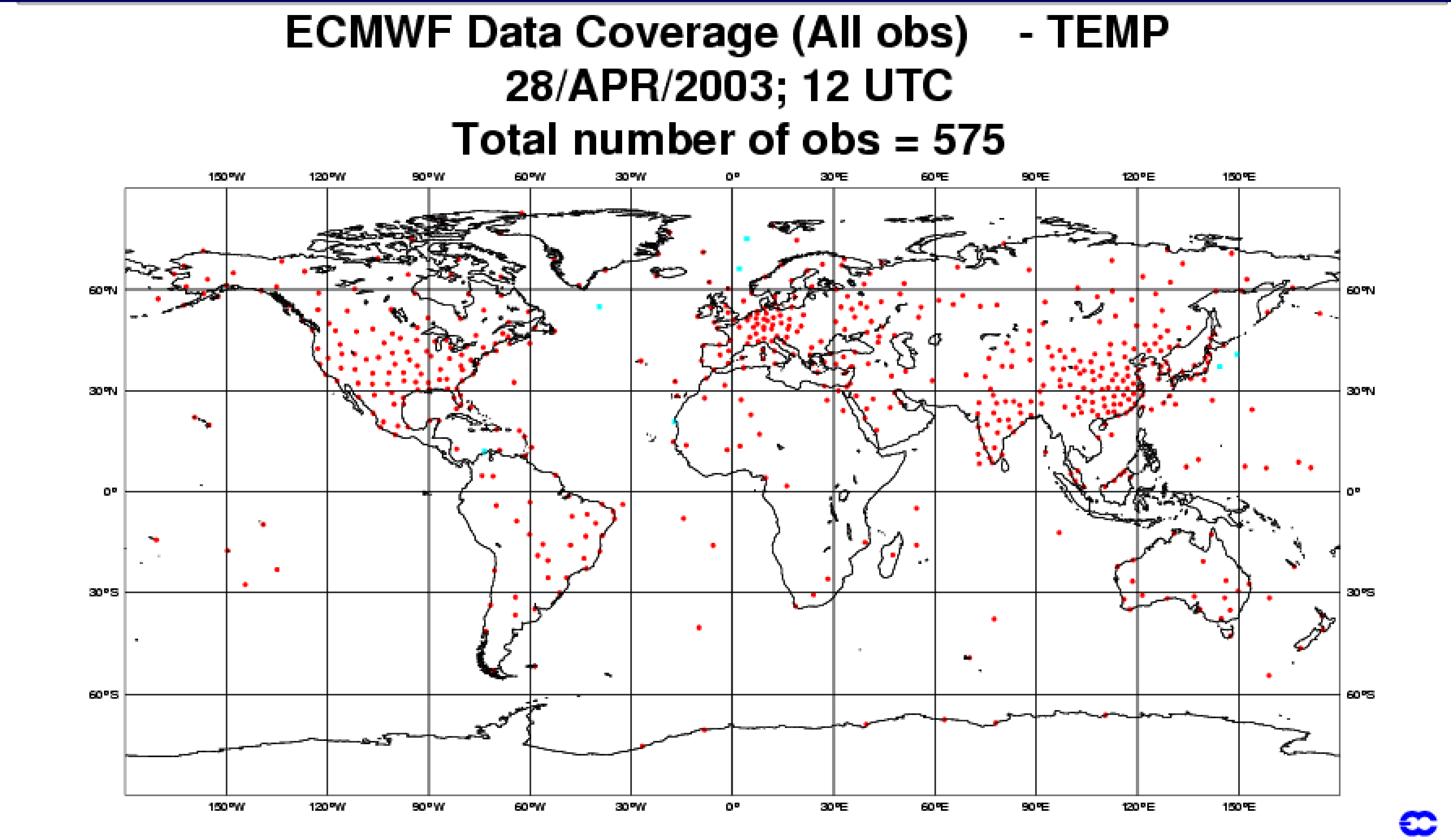
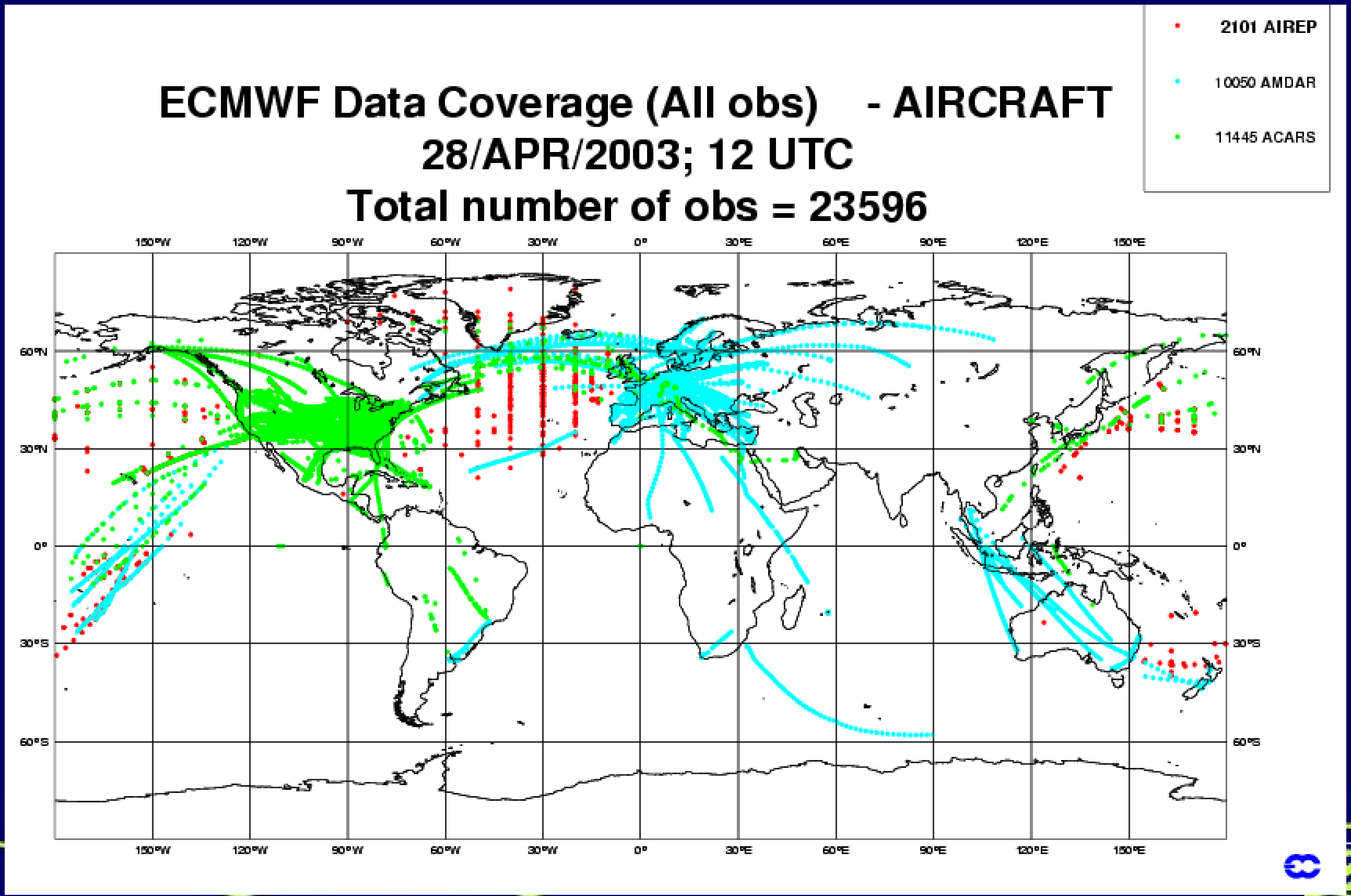
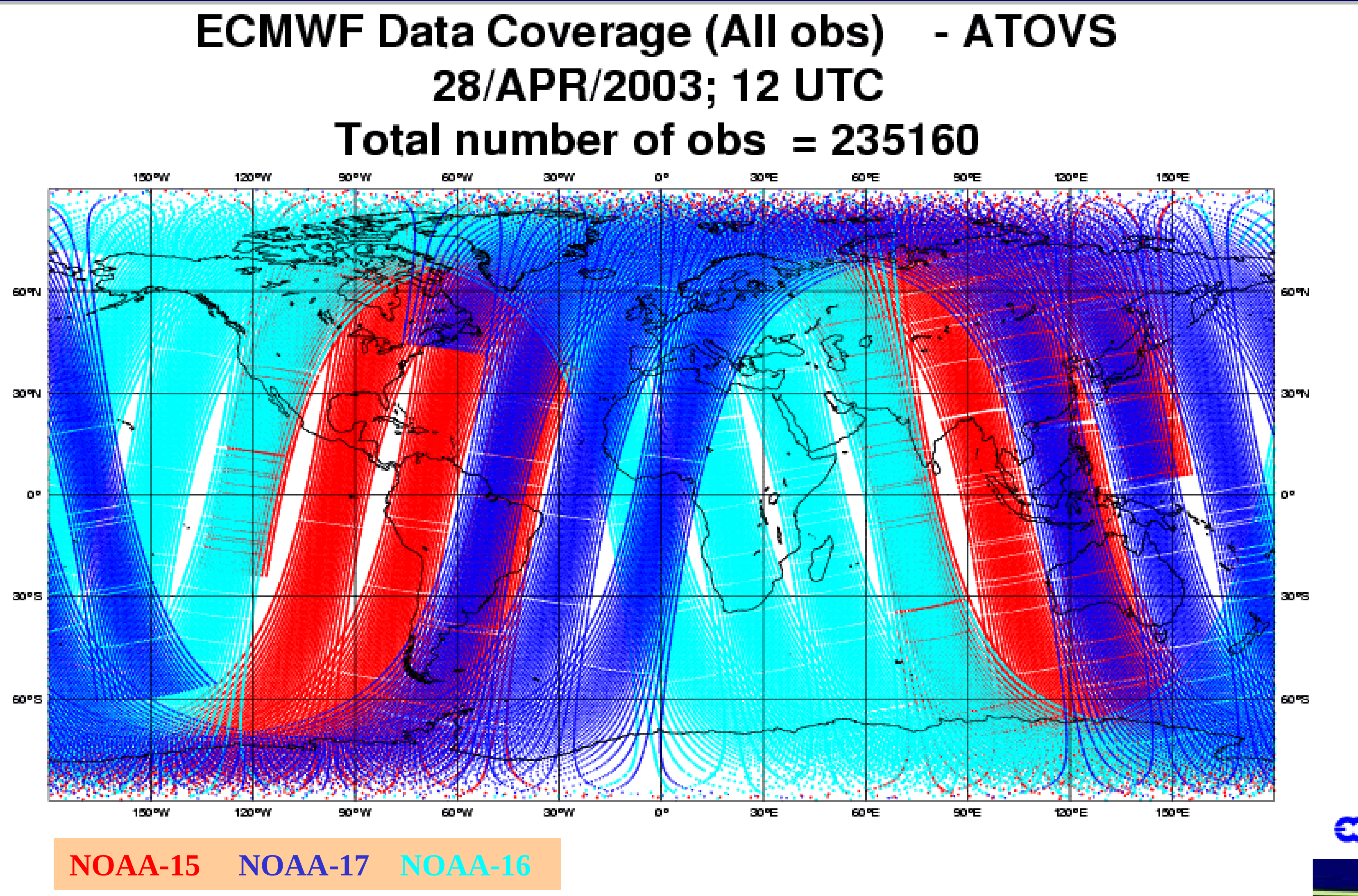
Global Coverage Plot: radiosondes



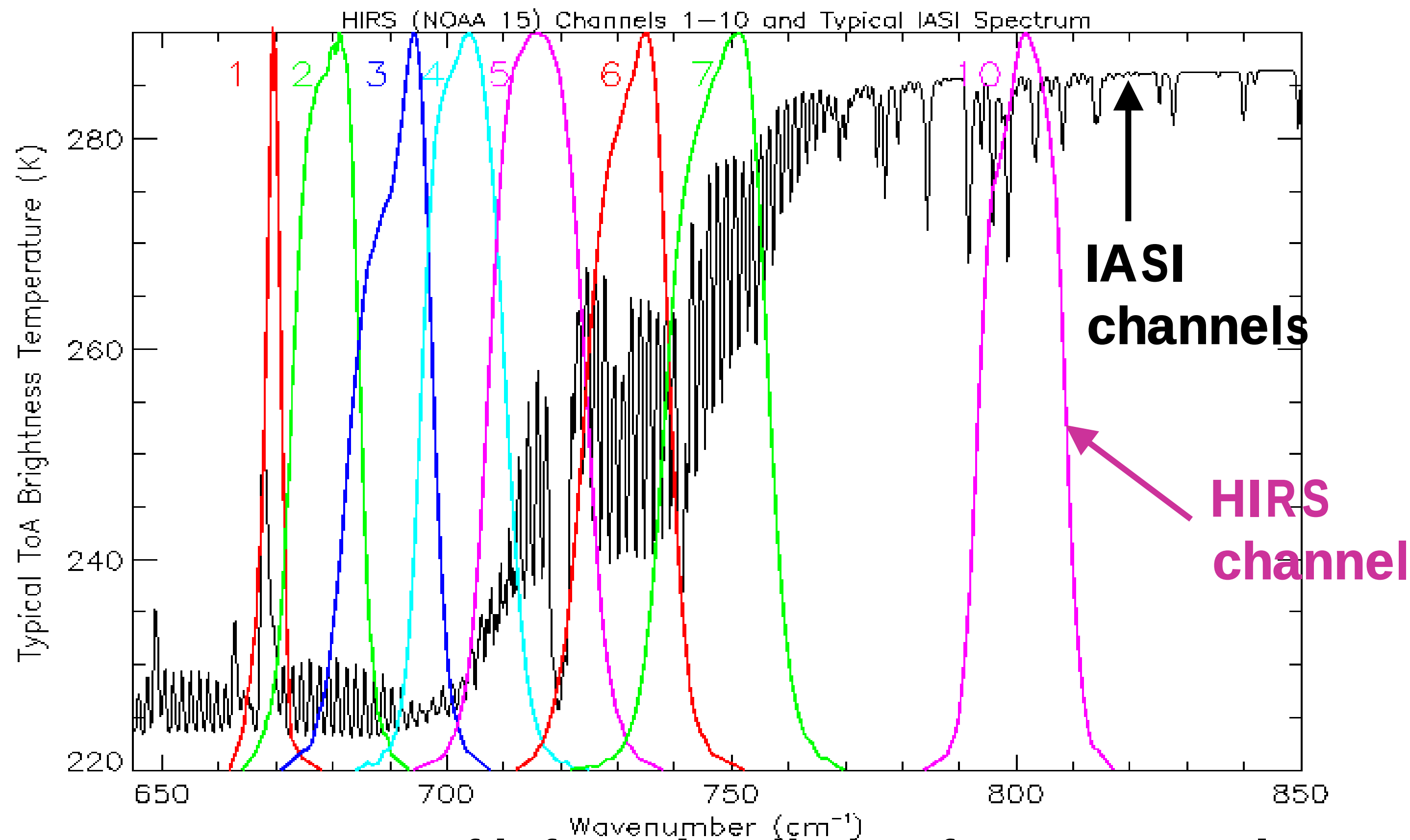
Global Coverage Plot: Aircraft



Global Coverage: Polar Satellite



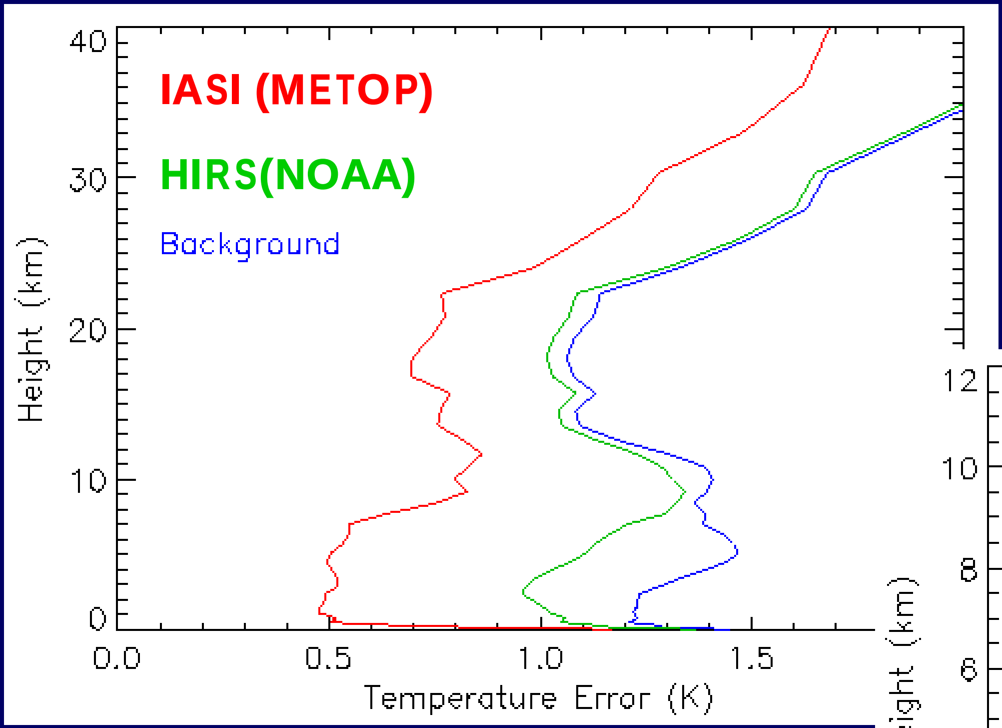
IASI vs HIRS



Spectrum of infrared radiation from atmosphere

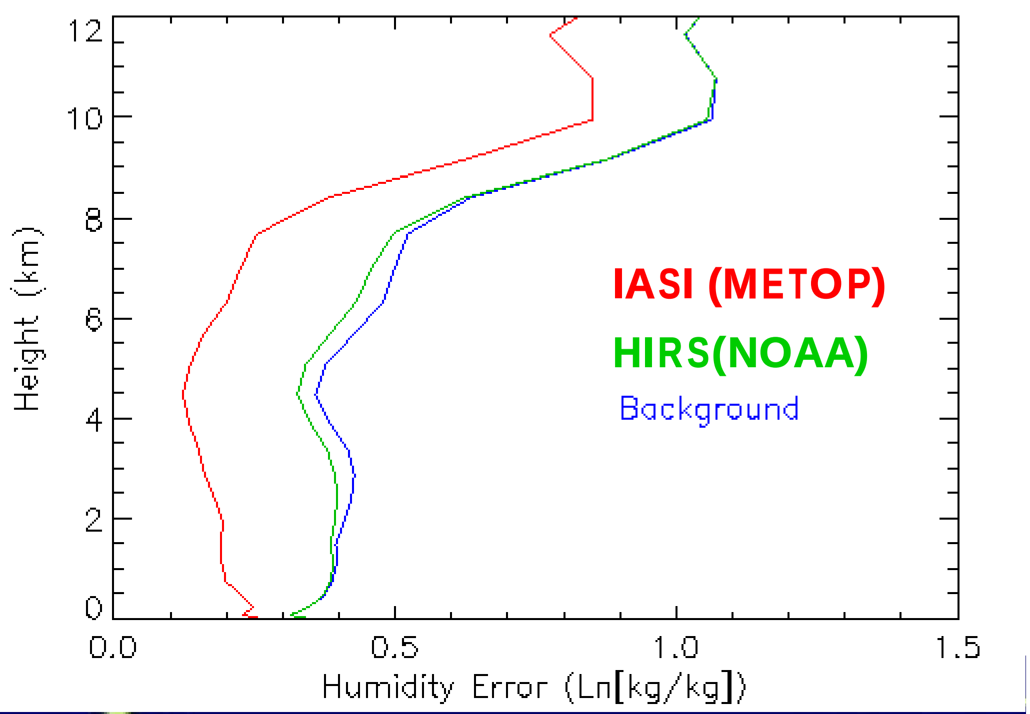
HIRS 19 channels vs IASI 8461 channels

Expected Retrieval Performance

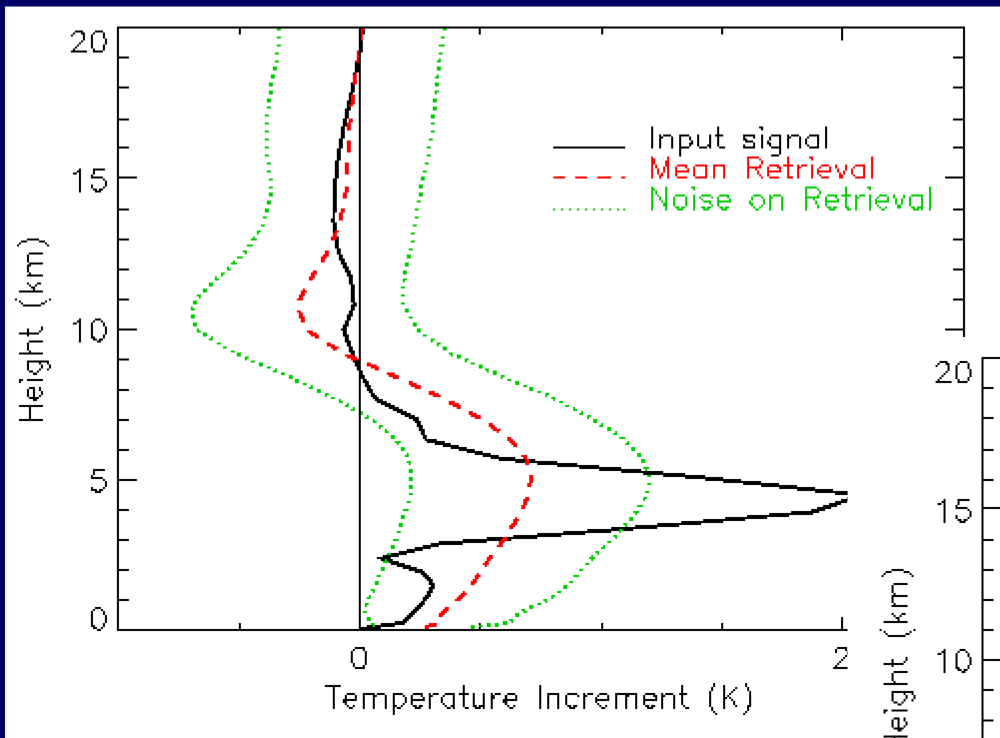


Temperature

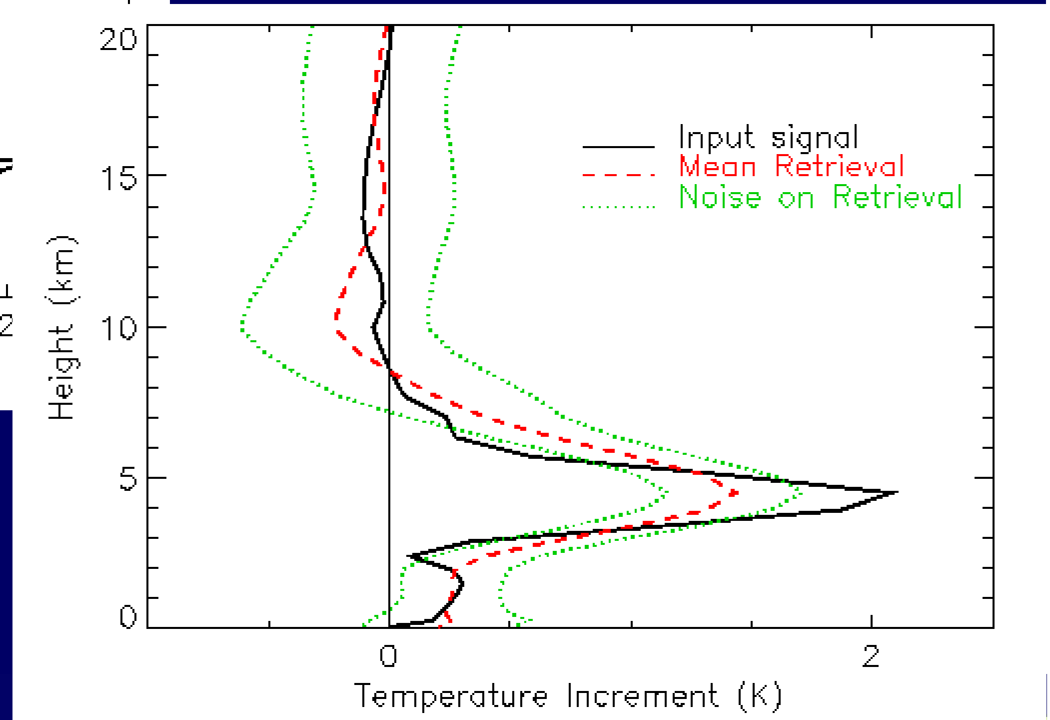
Humidity



Resolving Atmospheric Features



ATOVS



IASI

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Met Office NWP Models

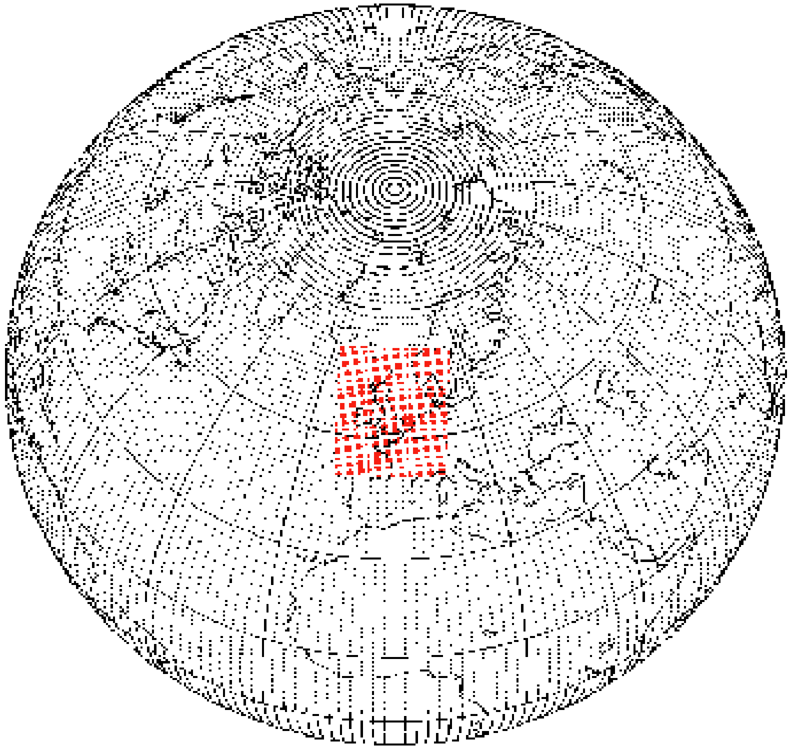

Figure 2: The grids used by the global and UK Mesoscale forecast systems.

	Horizontal Resolution	Horizontal Grid EW x NS	Vertical Levels
Global Forecast	0.83° x 0.56°	432 x 325	30
UK Mesoscale	12km	146 x 182	38
HADAM4	2.50° x 3.75°	96 x 73	38

Table 1: Resolutions used by main UM atmospheric configurations.

Model formulation:
Exact equations of motion in 3D, non-hydrostatic effects included, semi-Langrangian scheme, hybrid-eta in height.

Data Assimilation:
3DVar, FGAT, 6 hourly cycle 3hr cut-off with update runs for next cycle

Provides model background from 6 hour forecast

Observations Required for NWP

Primary	METOP	Current status
Wind	Sea Surface	*Sea surface*
Temp	Yes (1km vertical)	Yes (3km vertical)
Surface Pressure	Indirect	Indirect
Humidity	Yes (1km vertical)	Yes (3km vertical)
Secondary		
Ozone	Yes (profile)	Yes (total column)
Cloud Cover	Yes	Yes
Height	Yes	Yes
LWC/IWC	Yes	Yes
Surface SST/LST	Yes	Yes
Ice/snow	Partially	Partially
Vegetation	Yes	Yes
Soil Moisture	No	No

Polar Satellites for NWP

Period	1978-2006	2006-2020
U.S. satellites and *sensors*	NOAA-6-17 *HIRS,AMSU-A/B, (MSU, SSU), AVHRR, SBUV*	NPP+NOAA-N/N' *HIRS, AMSU-A, MHS, AVHRR, SBUV, CrIS, ATMS*
U.S. military	DMSP F8-F17 *SSM/I, SSMI(S)*	DMSP/NPOESS *SSMI(S), CMIS, VIRSS, ATMS, CrIS*
European satellites and *sensors*	ERS-1/2, Envisat *Scat, ATSR, GOME, AATSR, Schiamachy*	METOP-1 *HIRS, AMSU-A, MHS, IASI, AVHRR, GOME, ASCAT, GRAS*

IR Advanced sounders for NWP

Name	AIRS	IASI	CrIS	GIFTS
Instrument	Grating	FTS	FTS	FTS
Spectral range (cm^{-1})	649 –1135 1217–1613 2169 –2674	Contiguous 645-2760	650 –1095 1210 –1750 2155 –2550	685-1130 1650-2250
Unapodized spectral resolving power	1000 – 1400	2000 – 4000	900 – 1800	2000
Field of view (km)	13 x 7	12	14	4
Sampling density per 50 km square	9	4	9	144
Platform	Aqua	METOP	NPOESS	GIFTS
Launch date	May 2002	2005	2005 (NPP)	2008

How do we use advanced sounders in NWP?

1. Radiative transfer
2. Cloud detection
3. Bias tuning
4. Real time data monitoring
5. Data assimilation

Fast radiative transfer model used

- RTTOV-7 developed by EUMETSAT NWP SAF
  - Line database: HITRAN-96
  - LbL model GENLN2 at 0.001cm^{-1}
  - Water vapour continuum: CKD2.1
  - 43L fixed pressure level parametrisation
  - T, q, O_3 and surface from NWP model
  - Masuda for sea surface emissivity, 0.98 for land
  - Jacobians also computed *essential for radiance assimilation*

What is a fast RT model?

Estimate of atmospheric state and surface parameters for observation point X

View angle + sun angles

RT model for required sensor

Time ~ 1ms for 20 chans

Radiances for required satellite channels $y=H(X)$ and optionally jacobians $H \equiv \frac{\partial y_i}{\partial X_j}$

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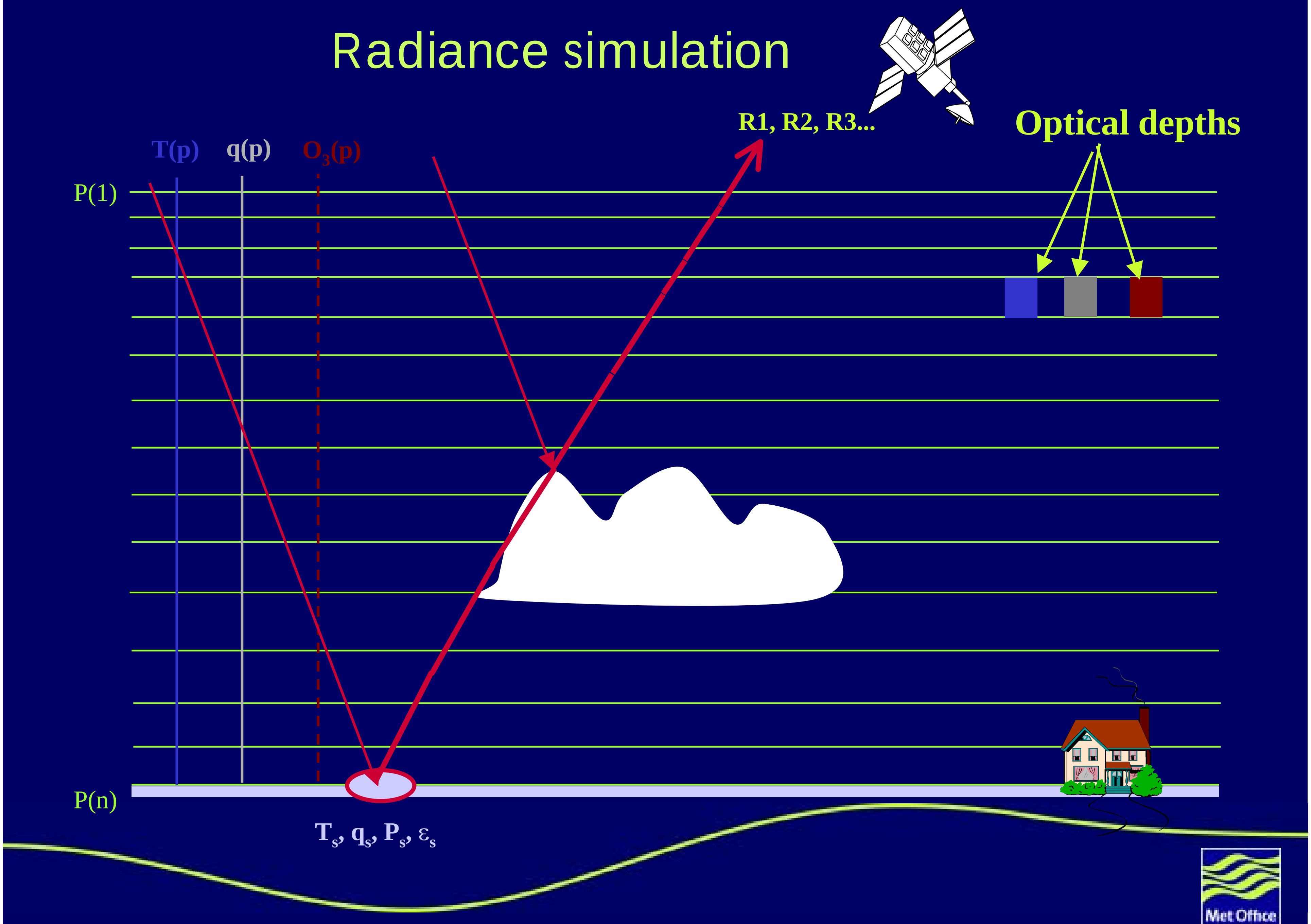
What is a fast RT model? (cont)

- Used to simulate top-of-atmosphere radiances as would be measured by infrared and microwave satellite radiometers within a few msecs.
- Also provides layer to space transmittances
- Also optionally provides jacobians
- ***Not*** part of model radiation scheme which provides SW/LW fluxes & heating and cooling rates (e.g. Edwards & Slingo UM-5)

Radiance simulation



Fast Model Approaches (profile ⇒TOA radiances)

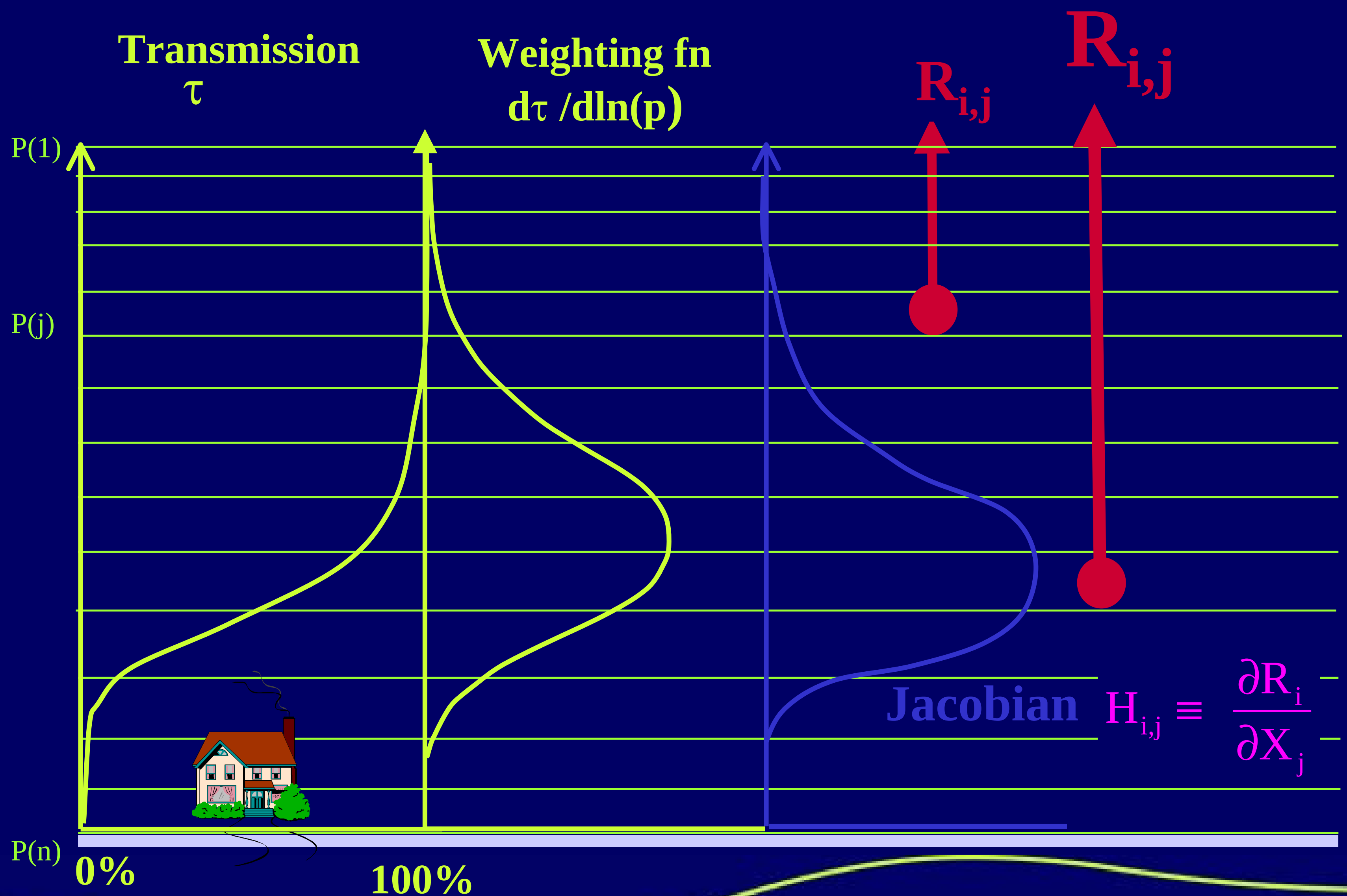
- Linear regression (profile ⇒ optical depth)
  - On fixed pressure levels
  - On fixed absorber overburden layers (OPTRAN)
- Physical method
- Look up tables
- Neural nets

Predictor	Fixed gases	Water vapour	Ozone
$X_{j,1}$	$sec(\theta)$	$sec^2(\theta) W_r^2(j)$	$sec(\theta) O_r(j)$
$X_{j,2}$	$sec^2(\theta)$	$(sec(\theta) W_w(j))^2$	$\sqrt{sec(\theta) O_r(j)}$
$X_{j,3}$	$sec(\theta) T_r(j)$	$(sec(\theta) W_w(j))^4$	$sec(\theta) O_r(j) \delta T(j)$
$X_{j,4}$	$sec(\theta) T_r^2(j)$	$sec(\theta) W_r(j) \delta T(j)$	$(sec(\theta) O_r(j))^2$
$X_{j,5}$	$T_r(j)$	$\sqrt{sec(\theta) W_r(j)}$	$\sqrt{sec(\theta) O_r(j)}\ \delta T(j)$
$X_{j,6}$	$T_r^2(j)$	$\sqrt[4]{sec(\theta) W_r(j)}$	$sec(\theta) O_r(j)^2 O_w(j)$
$X_{j,7}$	$sec(\theta) T_w(j)$	$sec(\theta) W_r(j)$	$\frac{O_r(j)}{O_w(j)} \sqrt{sec(\theta) O_r(j)}$
$X_{j,8}$	$sec(\theta) \frac{T_w(j)}{T_r(j)}$	$(sec(\theta) W_r(j))^3$	$sec(\theta) O_r(j) O_w(j)$
$X_{j,9}$	$\sqrt{sec(\theta)}$	$(sec(\theta) W_r(j))^4$	$O_r(j) sec(\theta) \sqrt{(O_w(j) sec(\theta))}$
$X_{j,10}$	$\sqrt{sec(\theta)}\ \sqrt[4]{T_w(j)}$	$sec(\theta) W_r(j) \delta T(j) \lvert \delta T(j) \rvert$	$sec(\theta) O_w(j)$
$X_{j,11}$	0	$(\sqrt{sec(\theta) W_r(j)}) \delta T(j)$	$(sec(\theta) O_w(j))^2$
$X_{j,12}$	0	$\frac{(sec(\theta) W_r(j))^2}{W_w}$	0
$X_{j,13}$	0	$\frac{\sqrt{(sec(\theta) W_r(j)} W_r(j)}{W_w(j)}$	0
$X_{j,14}$	0	$sec(\theta) \frac{W_r^2(j)}{T_r(j)}$	0
$X_{j,15}$	0	$sec(\theta) \frac{W_r^2(j)}{T_r^4(j)}$	0

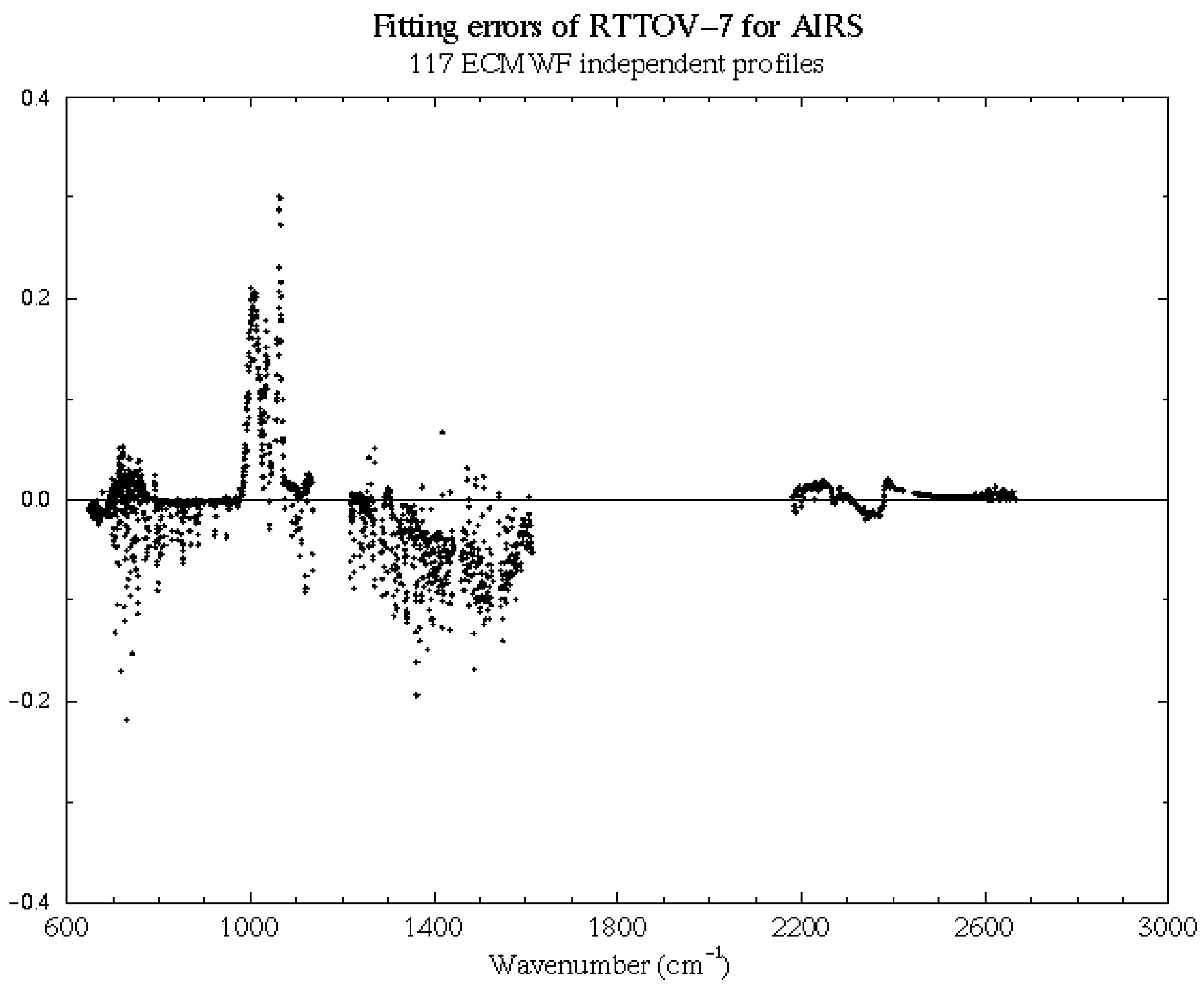
RTTOV-7 predictors

$$d_{i,j} = d_{i,j-1} + \sum_{k=1}^{K} a_{i,j,k} X_{k,j}$$

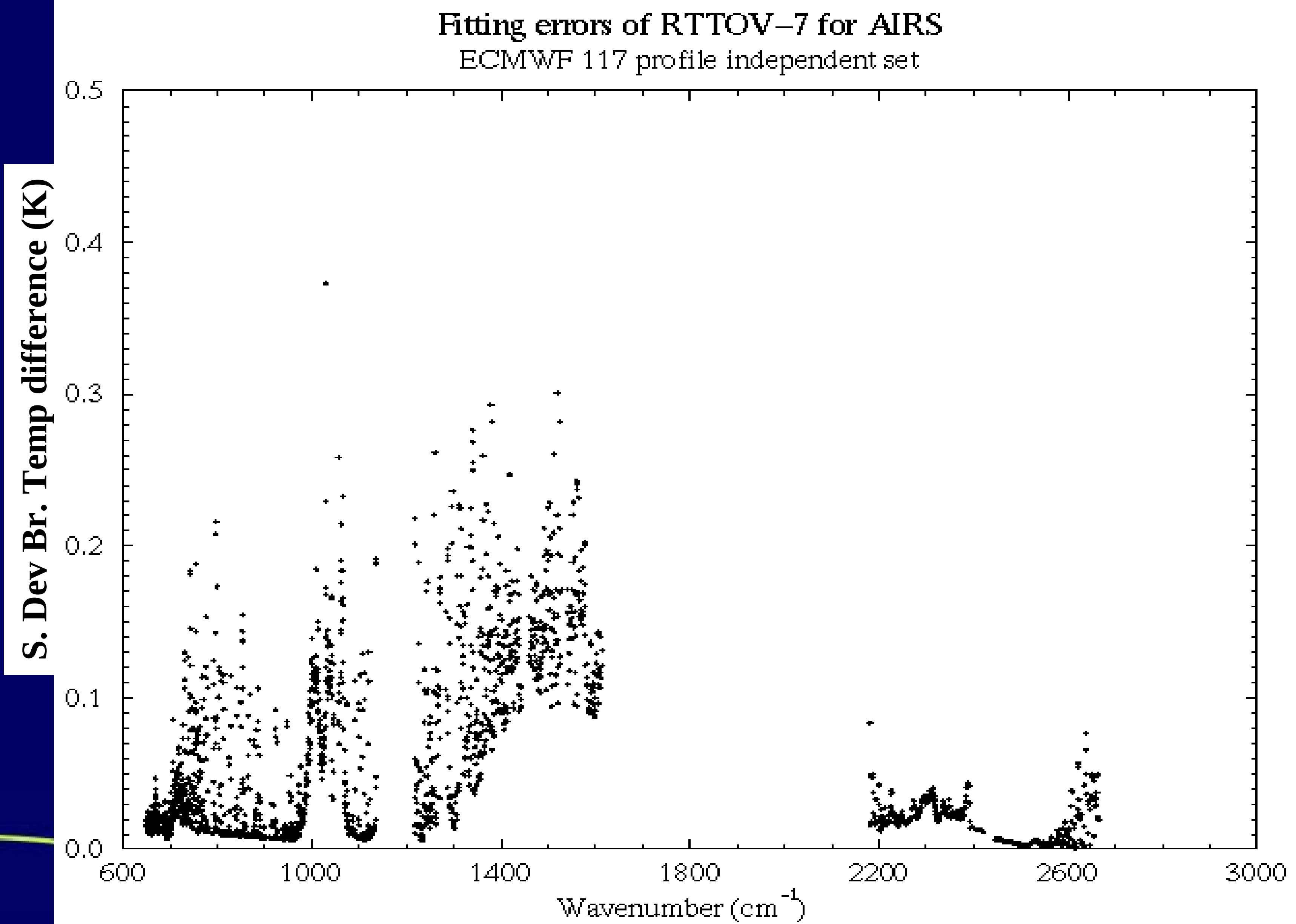
Jacobian matrix



RT model validation



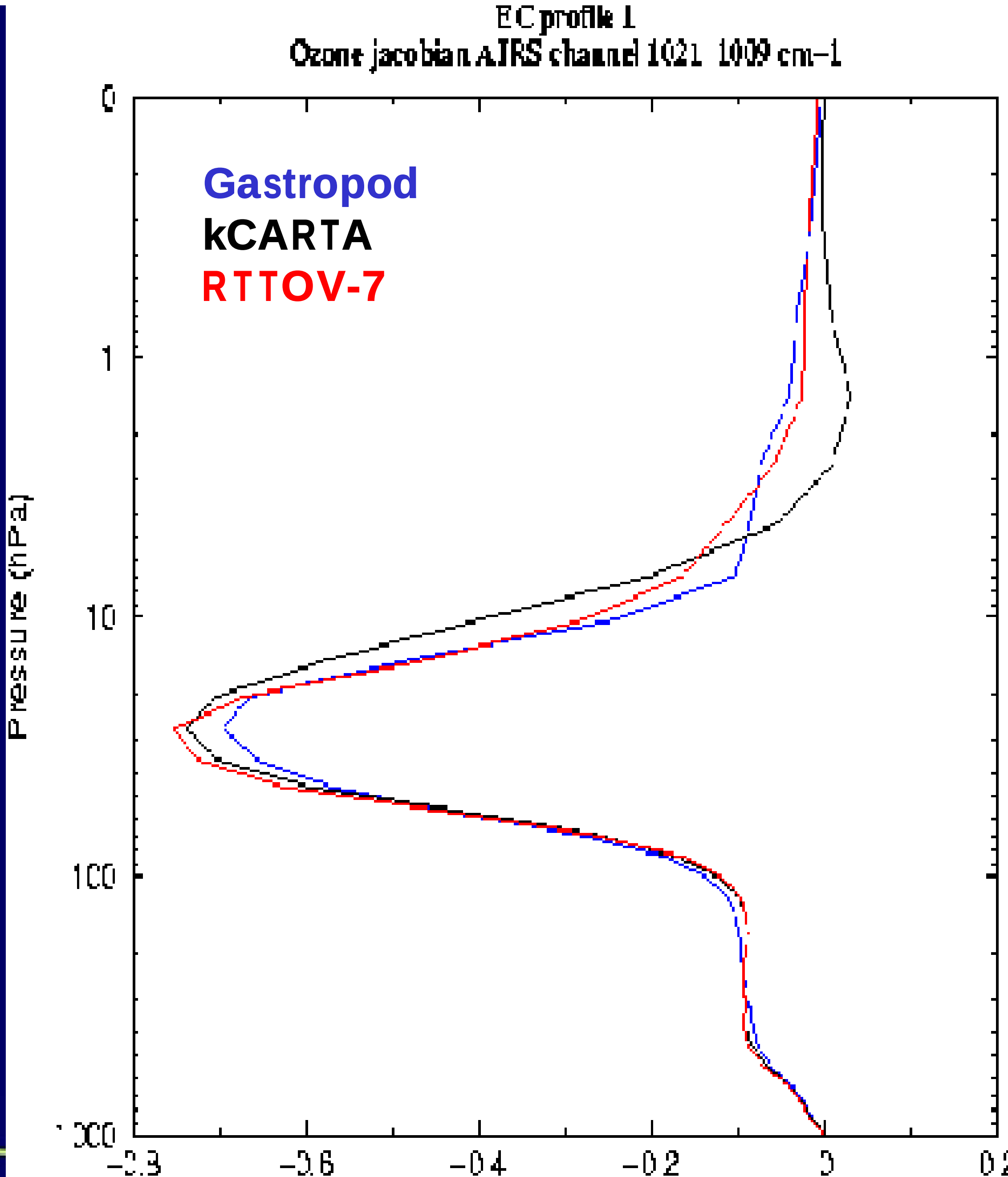
RT model validation



Work

RTTOV-7 model validation for AIRS

Ozone jacobian



Response to 10% change in ozone degK

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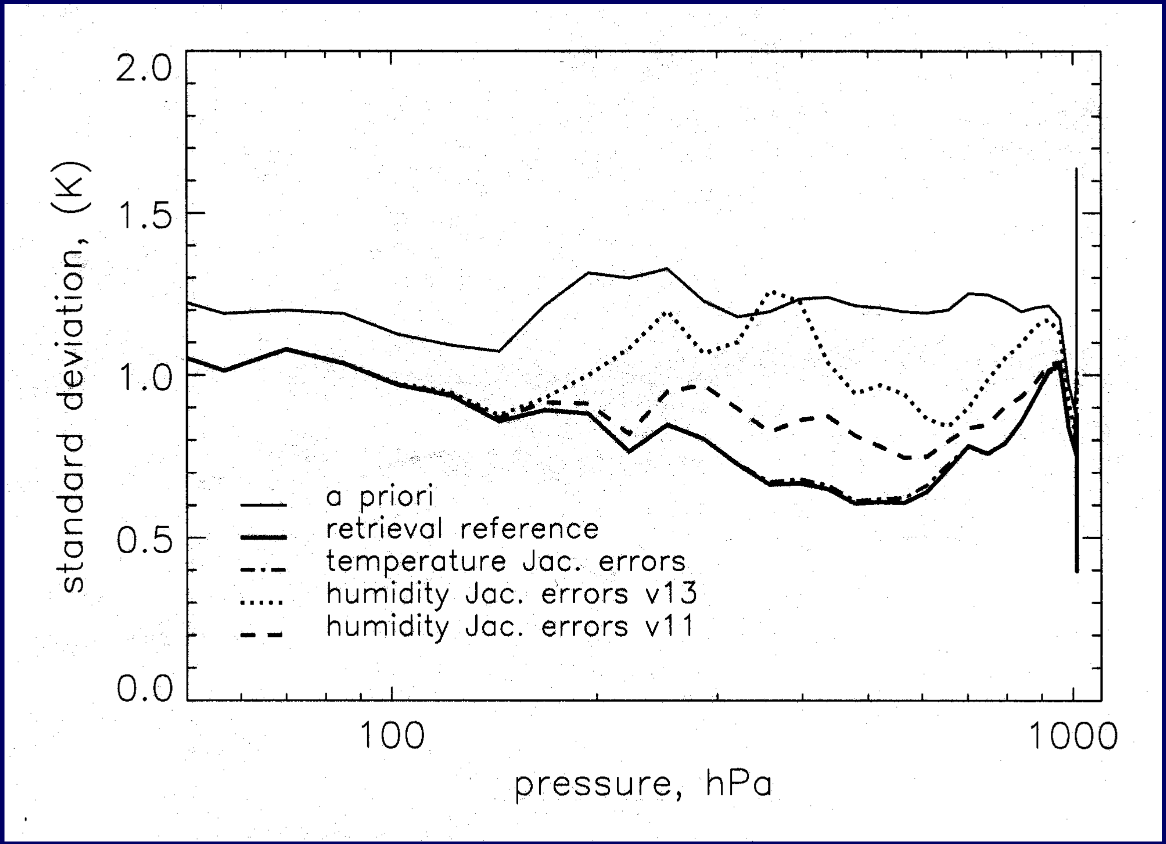
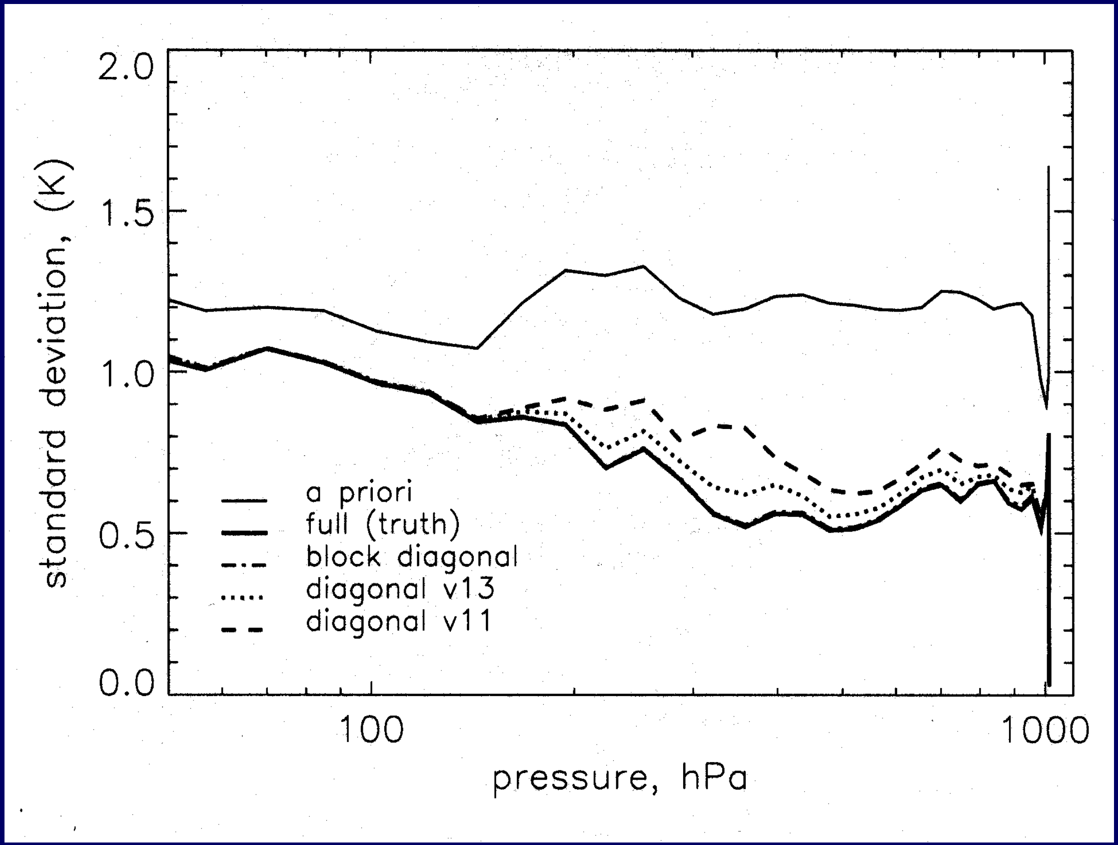
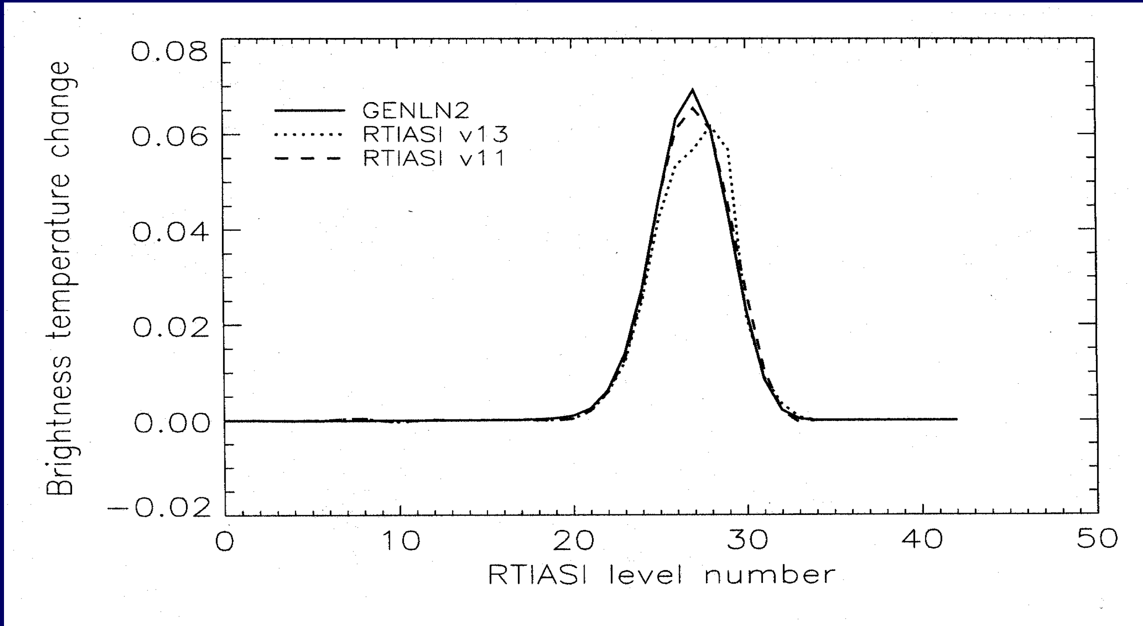
Effect of bad Jacobians



Effect of error correlation



Example of bad wv jacobian



To Prepare for Advanced IR sounders Aqua Has Been Launched!

- Aqua was launched from Vandenburg AFB, USA at 10.55am BST on 4th may 2002.
- It carries the AIRS spectrometer. The Met Office started to receive AIRS data in October 2002 to enable us to assimilate these data in NWP models.

How do we use advanced sounders in NWP?

1. Radiative transfer
2. Cloud detection
3. Bias tuning
4. Real time data monitoring
5. Data assimilation

Cloud detection

- Currently can only simulate accurately clear sky IR radiances as representation of clouds in NWP models and their radiative properties requires improvement.
- Therefore must identify those sounder fields of view which have significant cloud within them and screen them out.
- Several techniques developed to do this:
  - Inter-channel tests + SST check
  - Local spatial variance
  - Variational O-B checks → cloud cost
  - PCA

Var cloud cost (English et al.,1999)

$$J_C = (\Delta \mathrm{y})^{\mathrm{T}} \left\{ \mathrm{H}\left(\mathrm{x}^{\mathrm{b}}\right) \mathrm{B} \mathrm{H}\left(\mathrm{x}^{\mathrm{b}}\right)^{T} + \mathrm{R} \right\}^{-1} (\Delta \mathrm{y})$$

Principal Component Analysis (PCA) of the cloud cost

$$J_C = (\Delta \mathrm{y})^{\mathrm{T}} \mathrm{S}^{-1} (\Delta \mathrm{y})$$

$$= (\Delta \mathrm{y})^{T} \mathrm{U} \mathrm{X}^{-1} \mathrm{U}^{-1} (\Delta \mathrm{y})$$

$$= \sum_{i=1}^{N} (\Delta \mathrm{y}_i')^2$$

The i-th partial cloud cost

$$J_{Ci} \left[= \left(\Delta \mathrm{y}_i'\right)^2 \right]$$

Var scheme uses simple summation of all partial cloud cost

The i-th PCA components of $\Delta \mathrm{y}$

$$\Delta \mathrm{y}_i' \left(= \sum_{j=1}^{N} (\Delta \mathrm{y}_j)^{\mathrm{T}} \mathrm{U}_{ji} \Big/ \sqrt{\mathrm{X}_{ii}} \right)$$

S depends on profile by profile, then ...

PCA of simulated O-B difference

S is constructed from clear O-B statistics

Principal Component Analysis (PCA) of the cloud cost

$$S_{CLR} = \overline{(\Delta y_{CLR})(\Delta y_{CLR})^T}$$

$$= U_{CLR} X_{CLR} U_{CLR}^{-1}$$

The i-th PCA components of Δy for each profile

$$\Delta y_{CLR}' = (\Delta y_{CLR})^T U_{CLR} \sqrt{X_{CLR}}$$

$$\Delta y_{CLD}' = (\Delta y_{CLD})^T U_{CLR} \sqrt{X_{CLR}}$$

AIRS channel selection for cloud detection

- LW-IR, SW-IR, AMSU-A ch.3,15 are used for cloud detection

1) SOUND02 AIRS ch.261 13.80micron, ch.453 12.61micron,
ch.672 11.48micron, ch.787 10.90micron,
ch.843 10.66micron, ch.914 10.35micron,
ch.1221 8.96micron, ch.1237 8.90micron
AMSU-A ch.3 50.3GHz, ch.15 89.0GHz

2) MIX02 SOUND02 +
AIRS ch.2328 3.83micron, ch.2333 3.82micron

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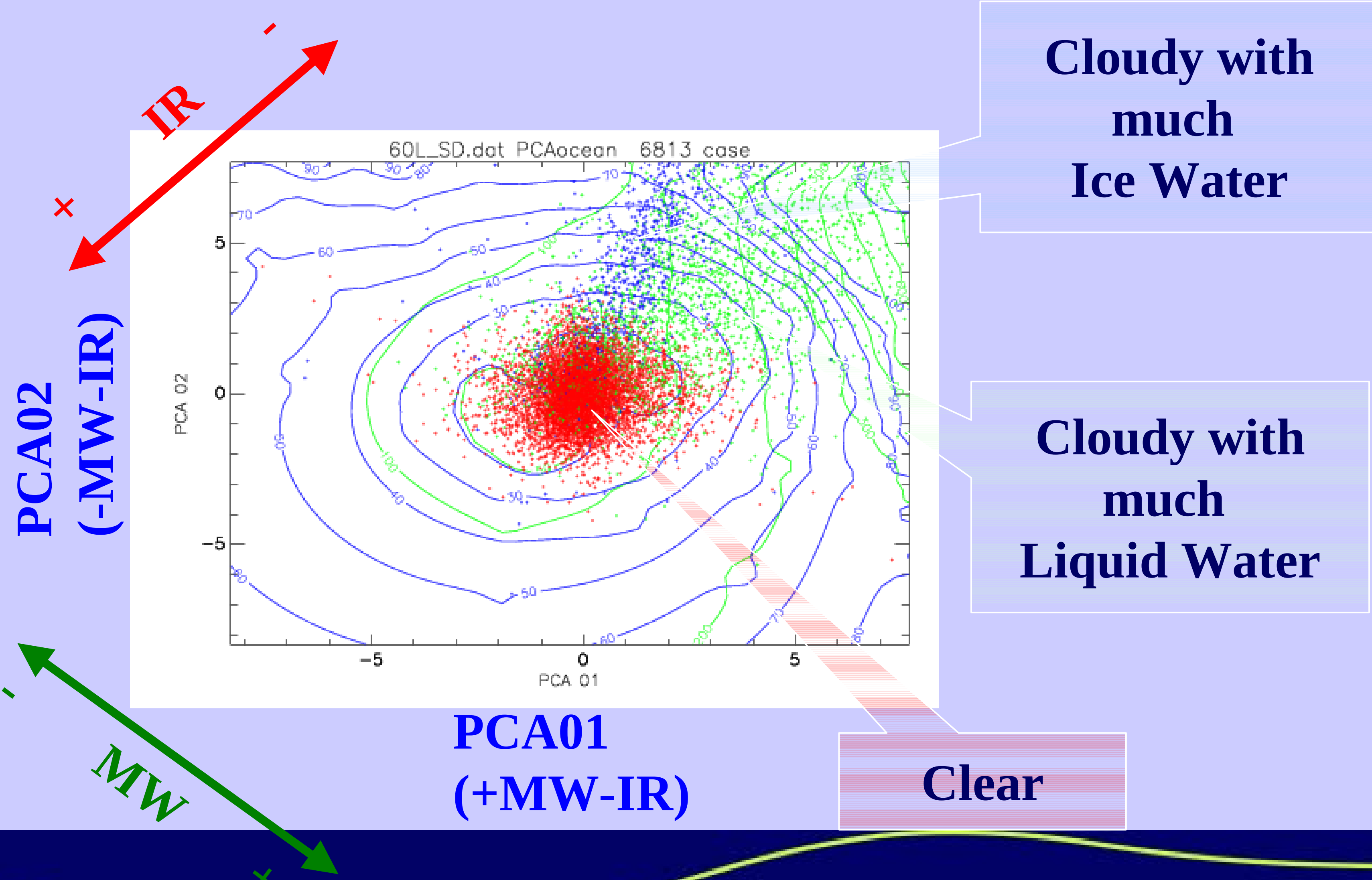
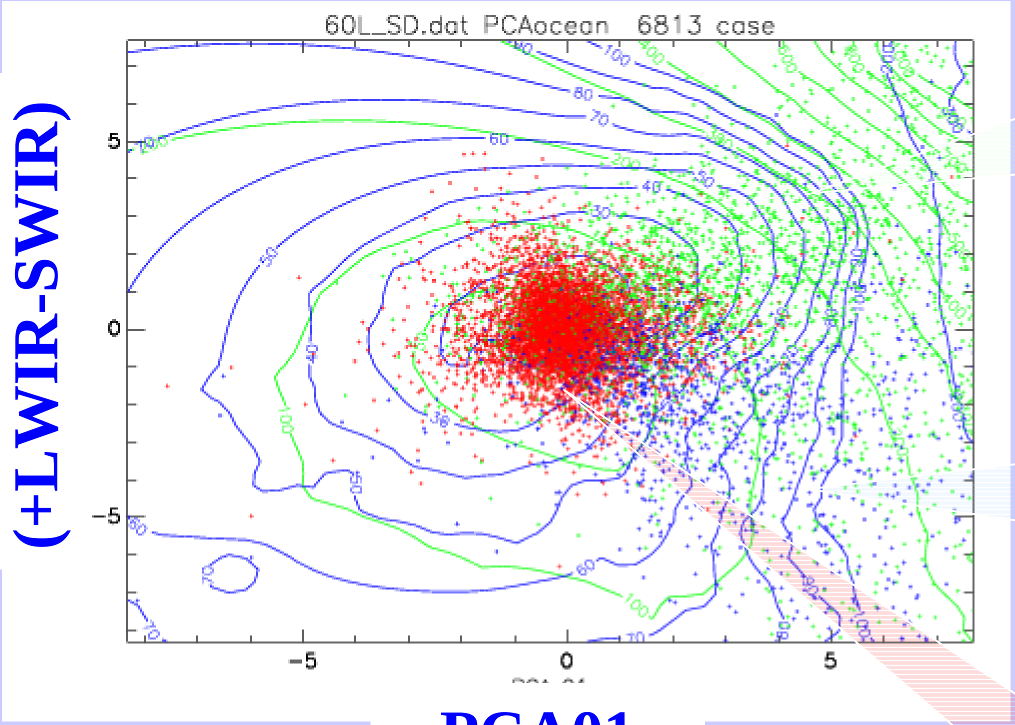
PCA components of O-B difference



PCA components of O-B difference



PCA04 (+LWIR-SWIR)

PCA01 (+MW-IR)

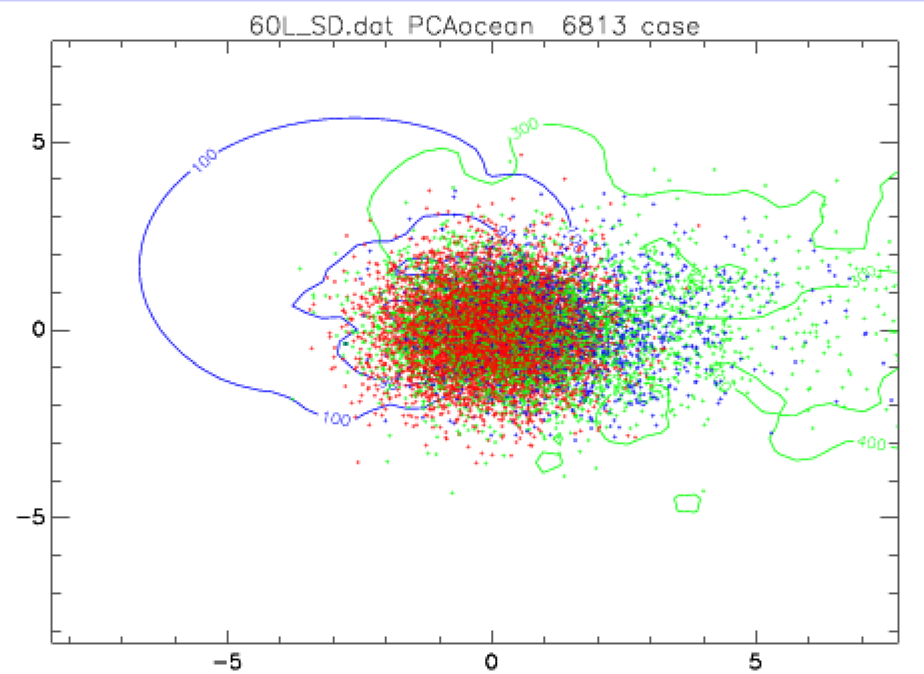
Cloudy with much Liquid Water

Cloudy with much Ice Water

Clear

Cloud distribution in O-B (and its PCA) space is inhomogeneous and asymmetric!!

PCA components of O-B difference

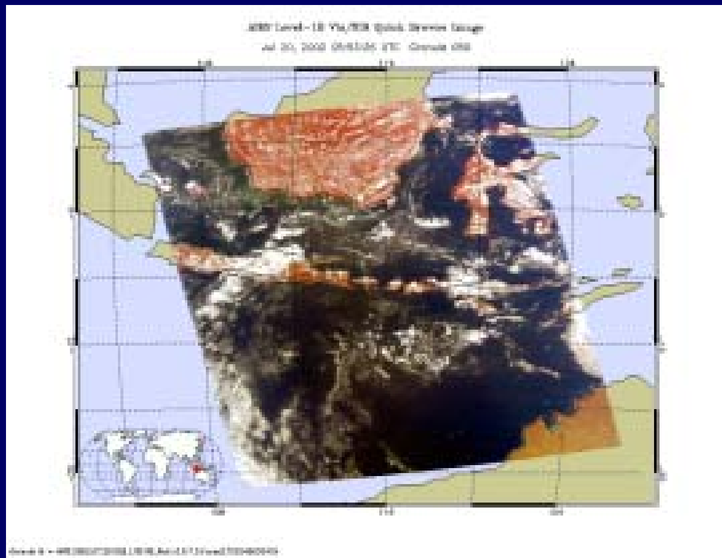


PCA12
(+ch.2328-ch.2333)

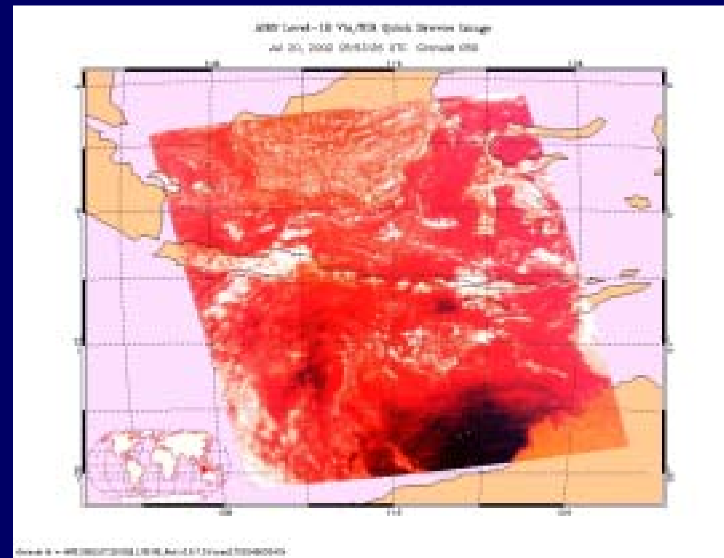
PCA11
(+ch.914-ch.843)

Higher components are no use for cloud detection !!

Cloud detection: Validation

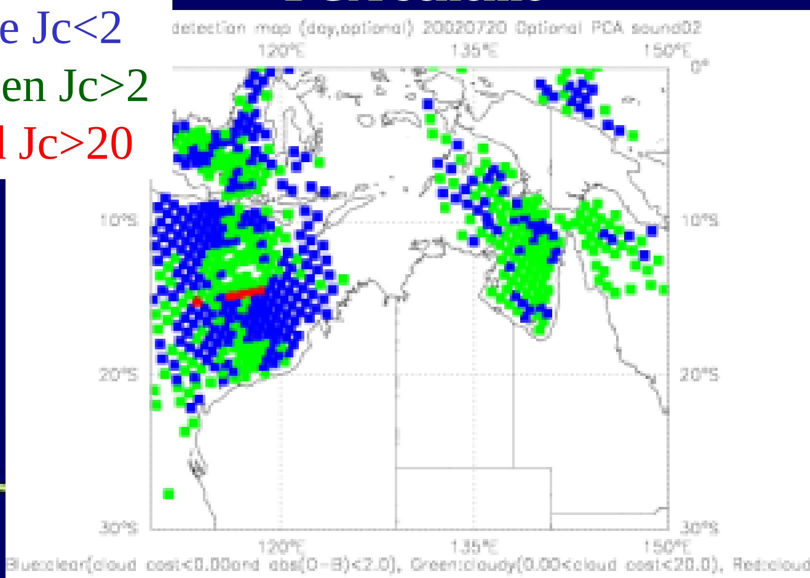


PCA scheme

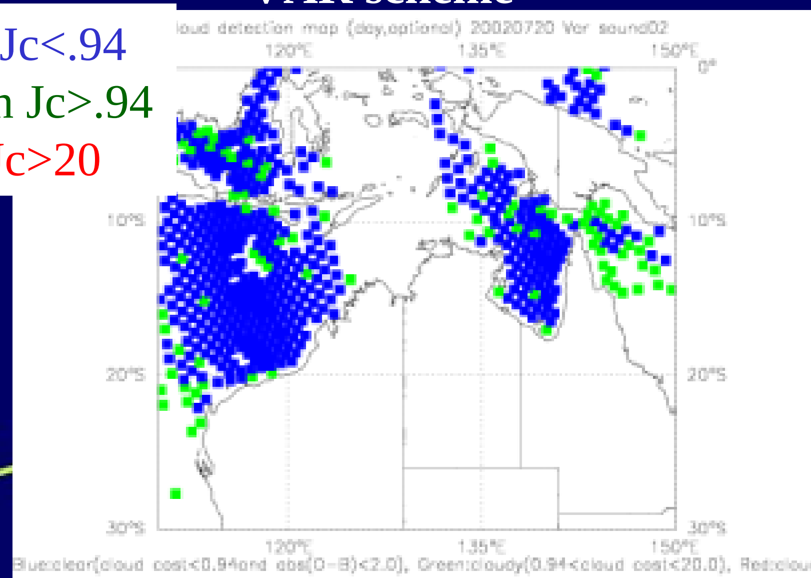


VAR scheme

Blue Jc<2
Green Jc>2
Red Jc>20



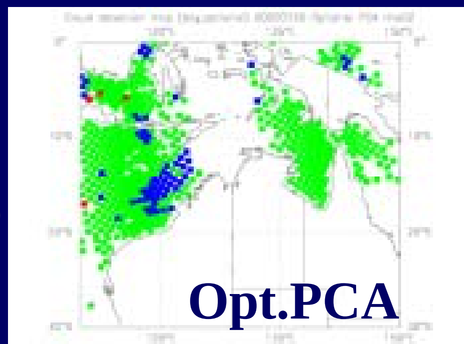
Blue Jc<.94
Green Jc>.94
Red Jc>20

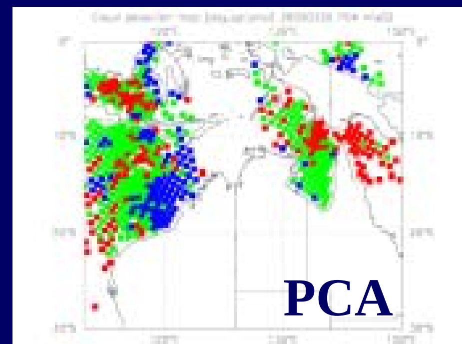


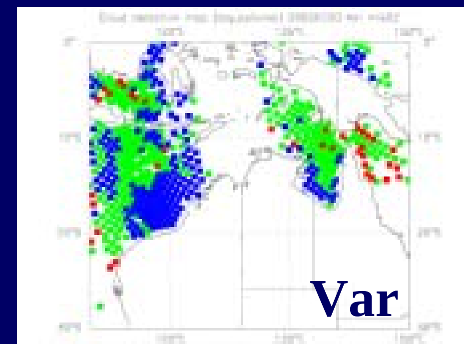
Case study -Australia-

- **Cloud detection results**

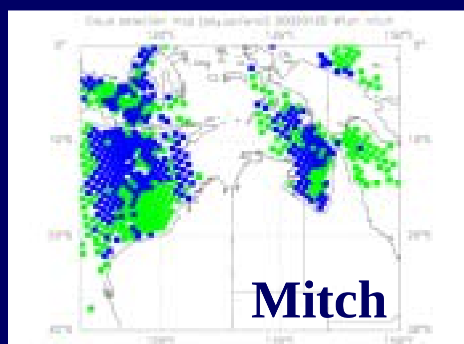
MIX02 (with SW-IR)

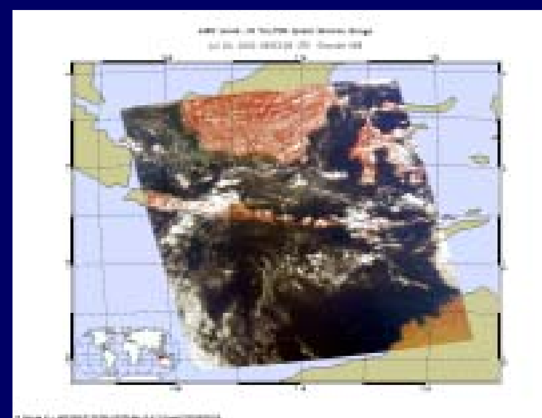


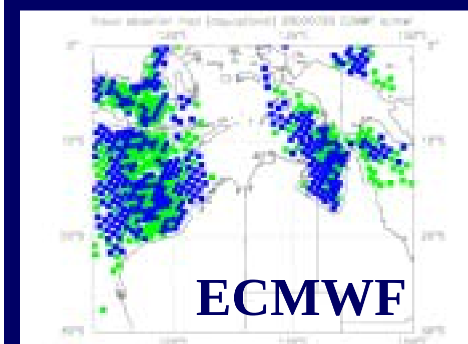




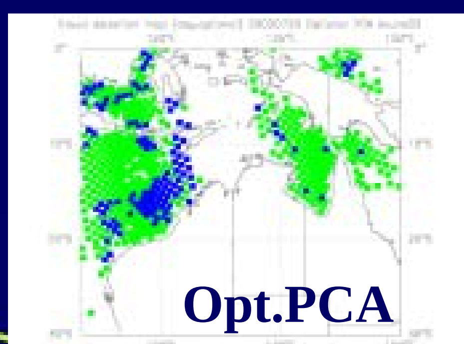
Blue Jc<2
Green Jc>2
Red Jc>20

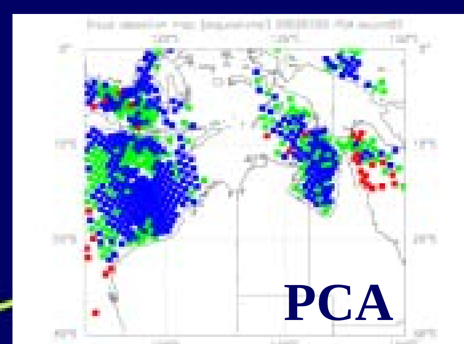


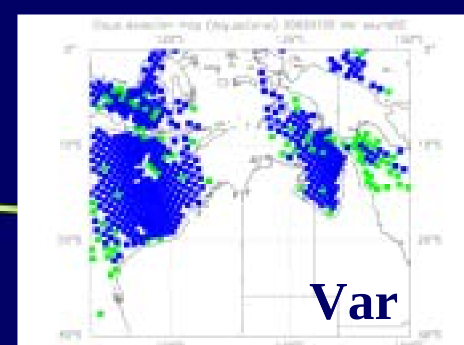




SOUND02 (without SW-IR)







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How do we use advanced sounders in NWP?

1. Radiative transfer
2. Cloud detection
3. Bias tuning
4. Real time data monitoring
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Bias tuning

- There are several potential sources of bias in the measured or simulated radiances due to:
  - i Instrument related biases (e.g. poor calibration)
  - ii Radiative transfer model biases (e.g. due to fast model, errors in spectroscopy....)
  - iii Biased NWP model temperature, water vapour or ozone values
- Should remove biases from (i) and (ii) but not necessarily (iii)
- Variational theory assumes observations are unbiased with gaussian error distribution

Bias tuning for AIRS

To remove biases, predictors from NWP model

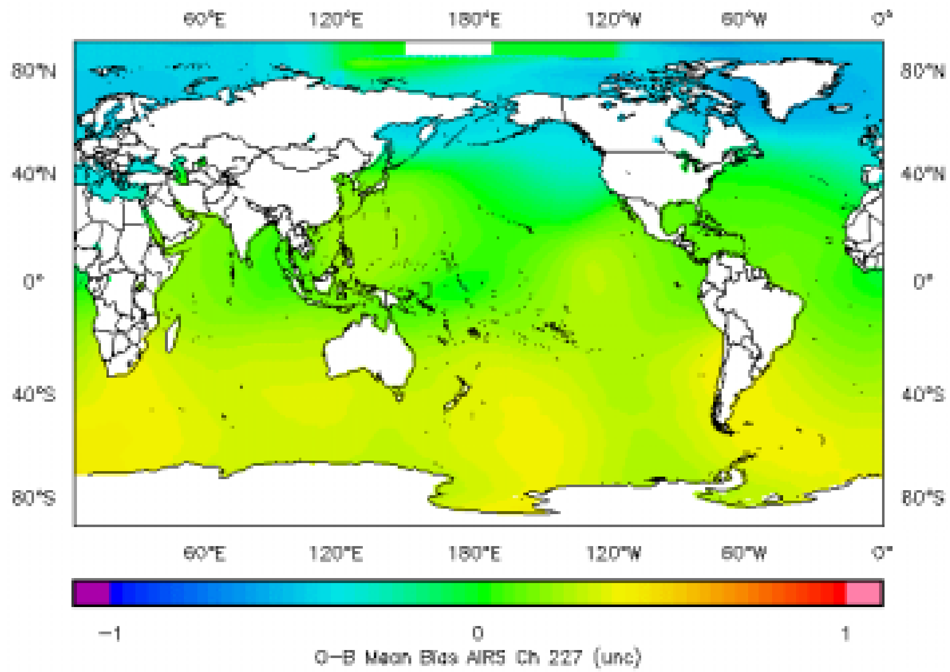
fields and/or instrument parameters are used.

Predictors for AIRS being used are:

- Scan angle
- Model T_{skin}
- Model Thickness 850-300 hPa
- Model Thickness 200-50 hPa
- Simulated brightness temperature

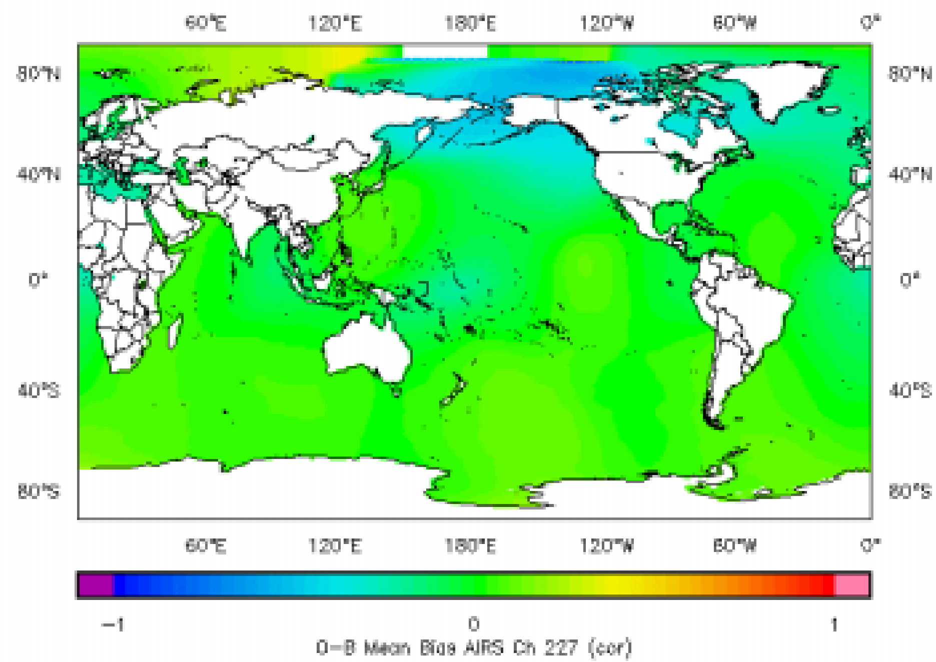
Example of AIRS bias tuning

Corrected biases

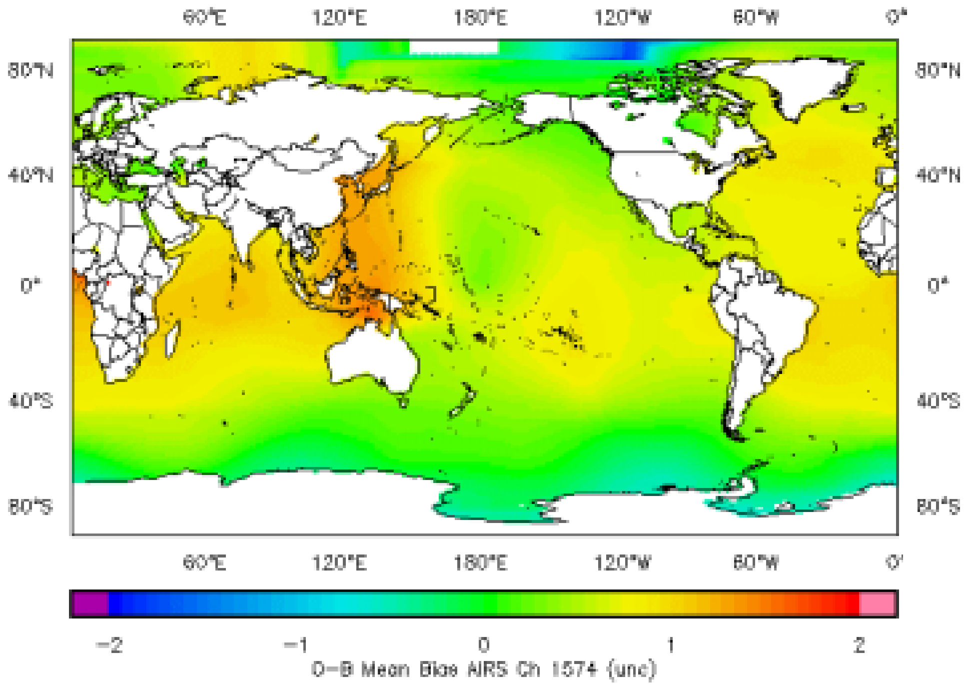


Uncorrected biases

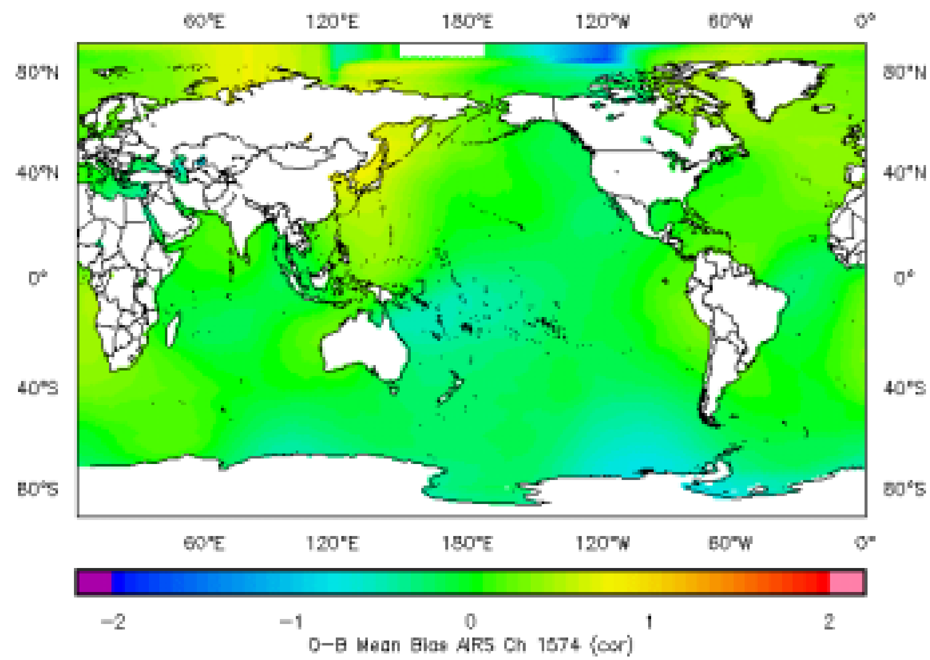
AIRS channel 227
Peaks at 700 hPA



Example of AIRS bias tuning



Uncorrected biases



Corrected biases

AIRS channel 1574
Upper trop wv

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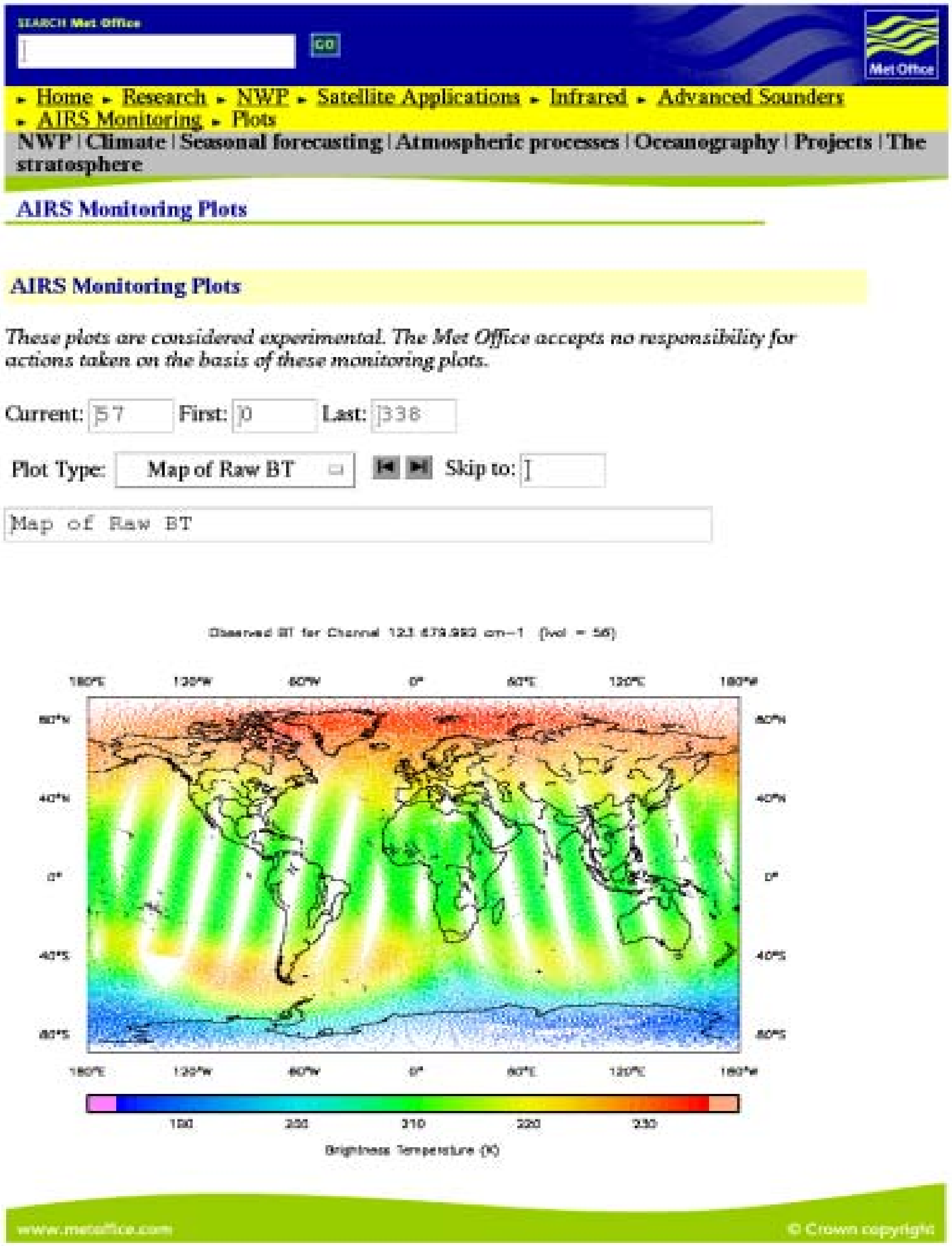
NWP Radiance Monitoring
Observed minus Simulated

- Continuous *global* view of data
- Good for spotting sudden changes in instruments

- Can compare with other satellites and in situ obs

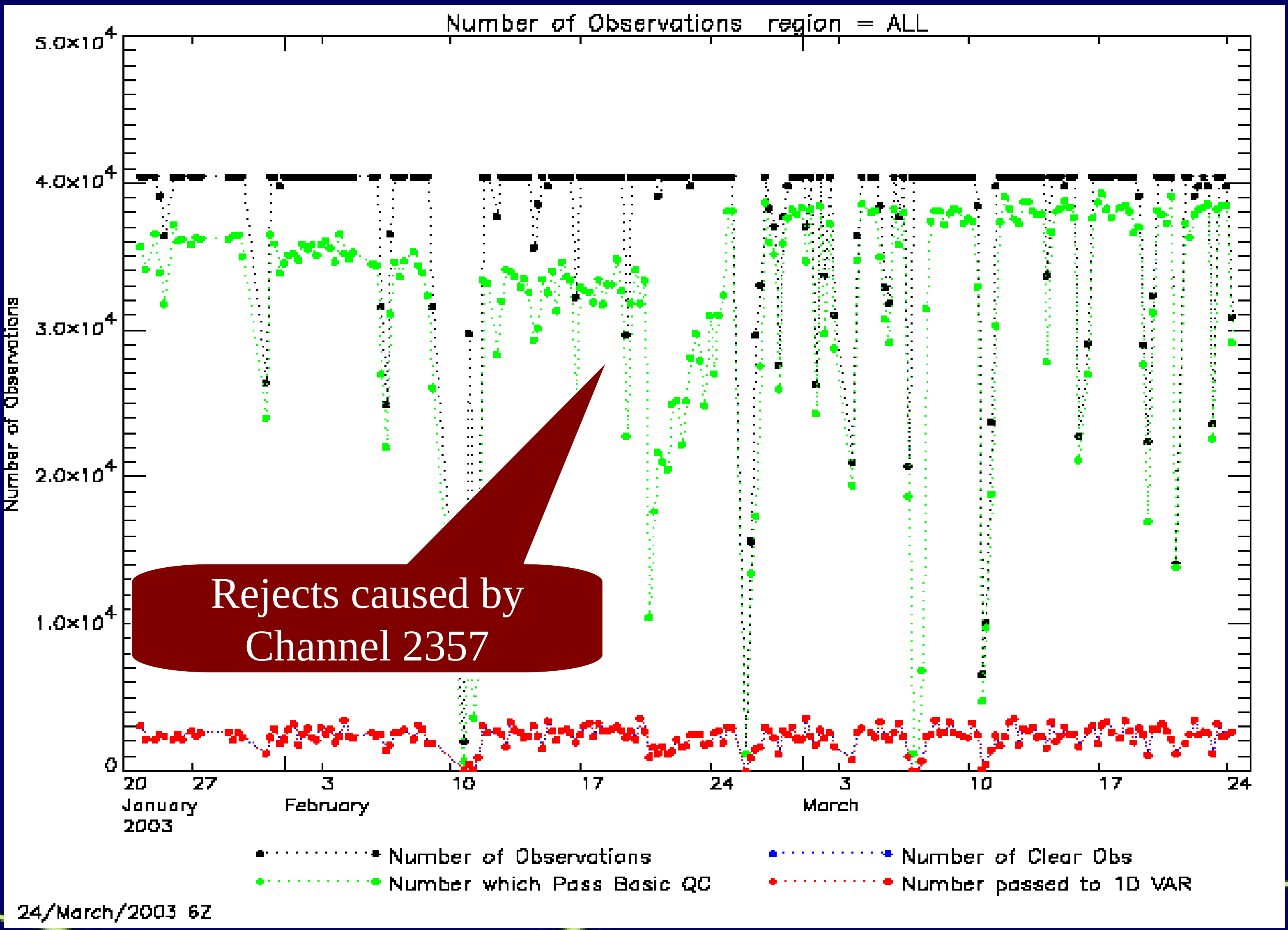
But NWP model has errors: (LST, water vapour, ozone, clouds, stratosphere) so bias correction and cloud detection important and care in interpretation



Monitoring web page

Available to the AIRS team in mid-December via password protected page on Met Office site.
http://www.metoffice.com/research/nwp/satellite/infrared/sounders/airs/index.html
Userid: airspage
Passwd: &Graces

Time series of observations

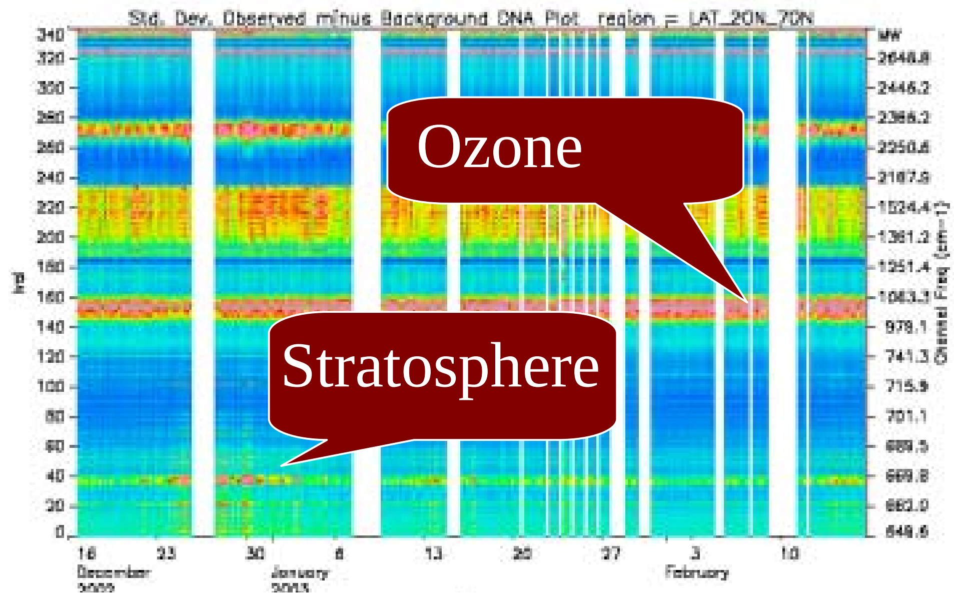


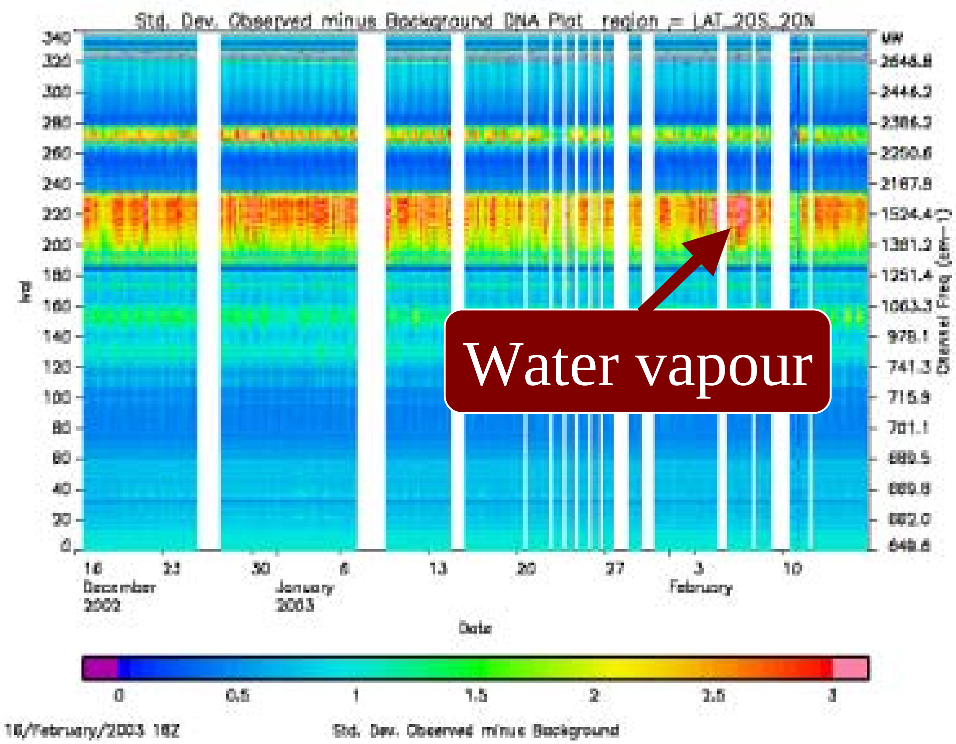
O-B st. dev plots

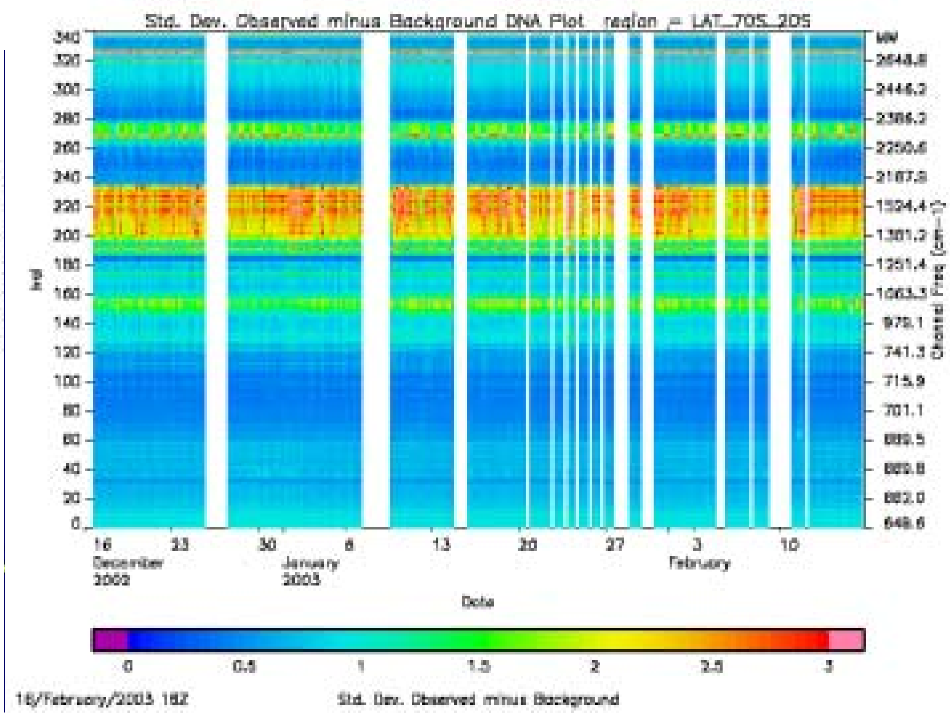
20-70N

20N-20S

20-70S

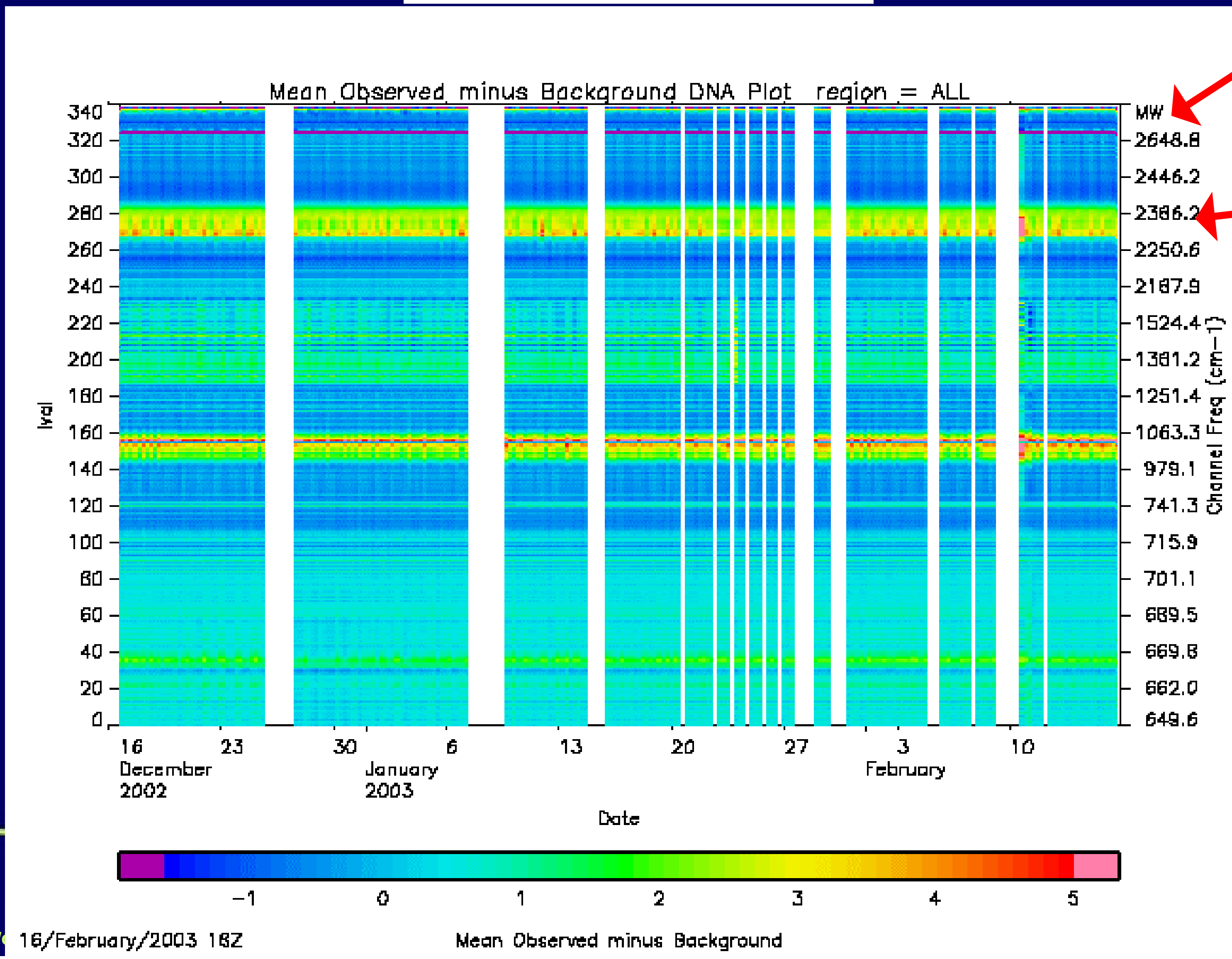






Tartan Plots: O-B clear mean bias

Global Observations



AMSU 1&2

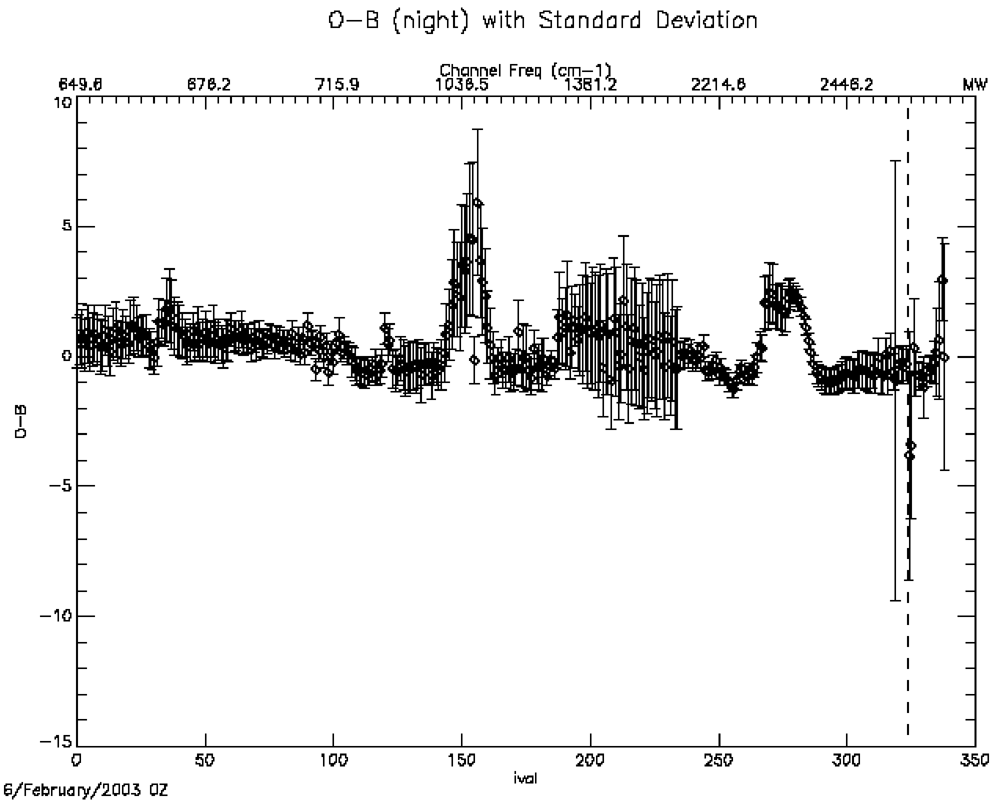
CO_2

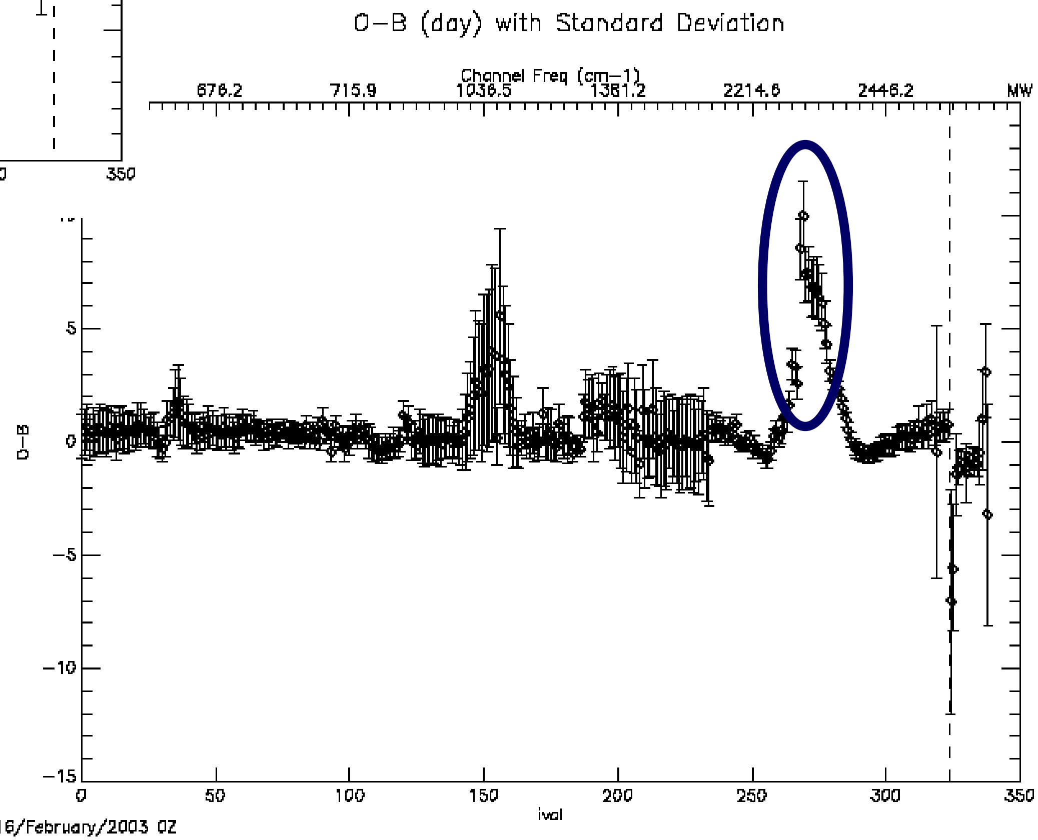
H_2O

O_3

CO_2

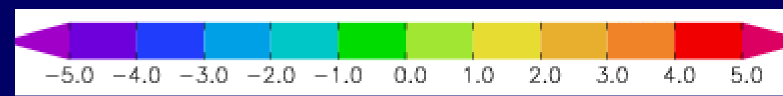
Day & Night spectra

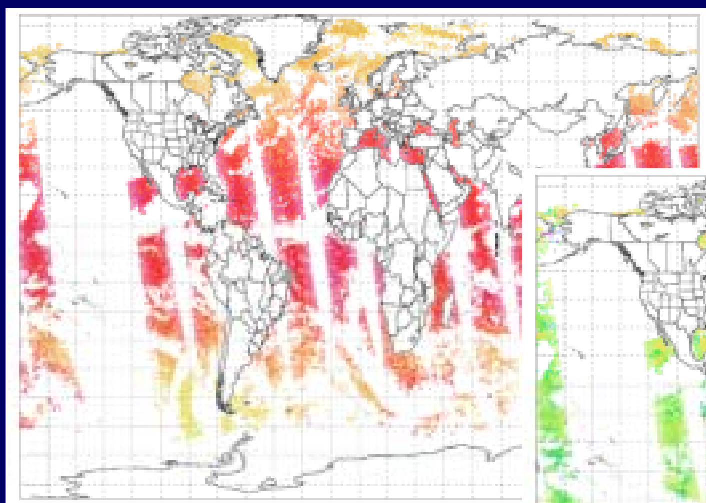




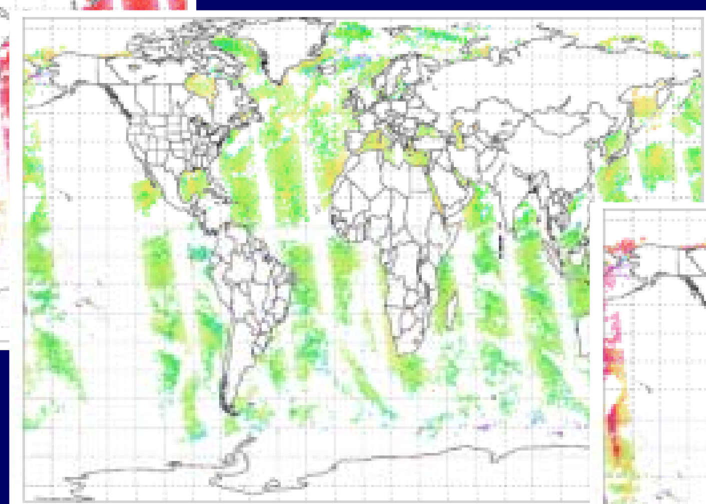
O-B difference

- **Large positive bias in the SW-IR in the day-time**
  due to Non LTE effect in upper sounding chs and sunglint in window

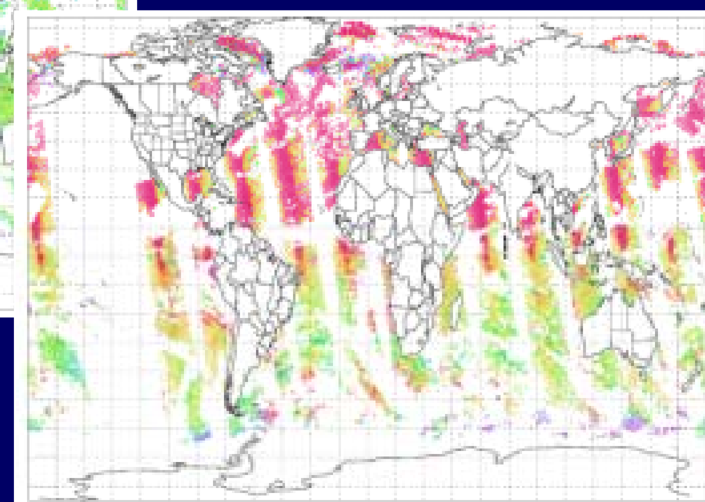




2387cm^{-1} (4.19micron)



2392cm^{-1} (4.18micron)



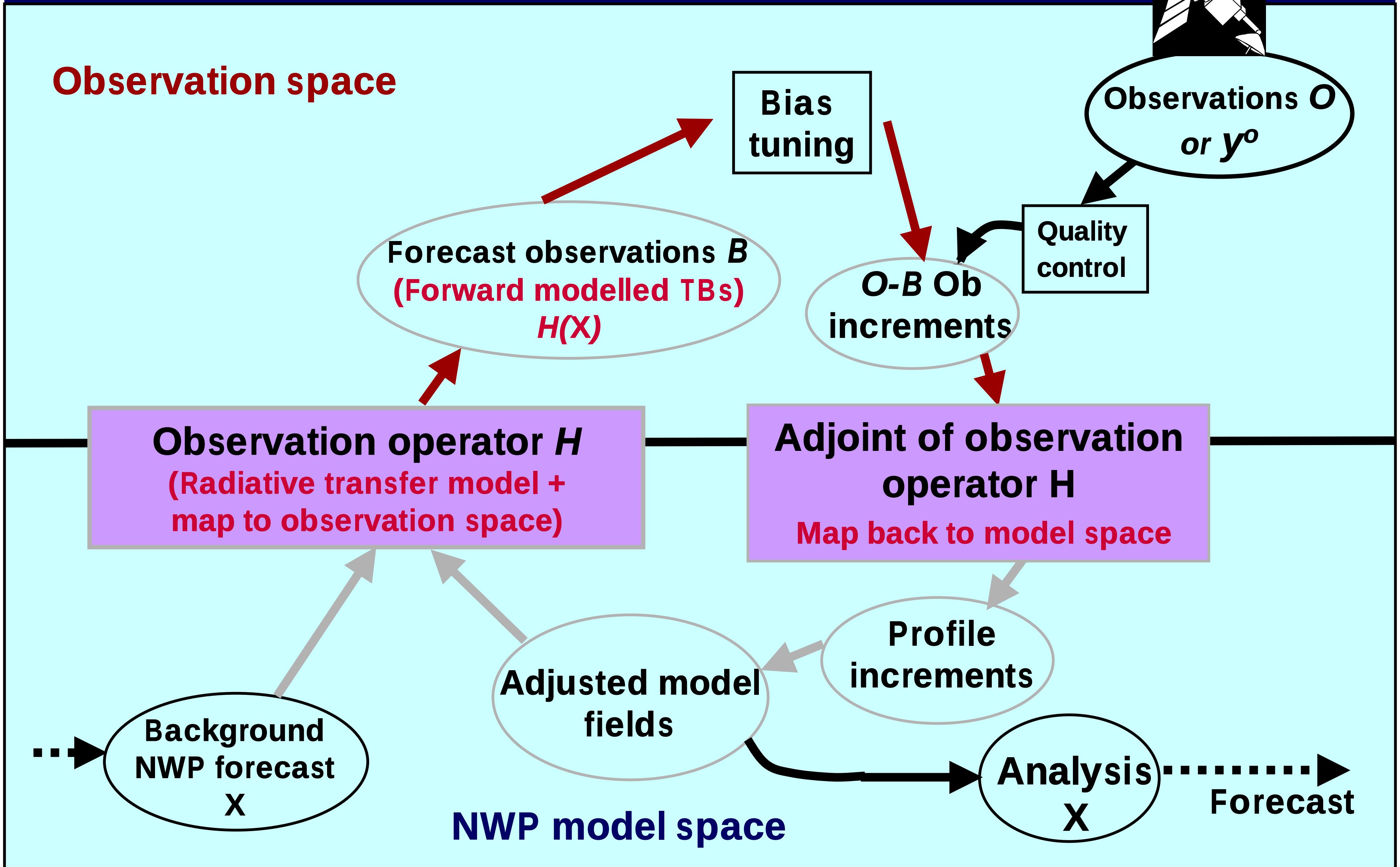
2618cm^{-1} (3.82micron)

SW-IR chans difficult to use for cloud detection

How do we use advanced sounders in NWP?

1. Radiative transfer
2. Cloud detection
3. Bias tuning
4. Real time data monitoring
5. Data assimilation

Assimilation of satellite data



Data assimilation

For variational assimilation we want to minimise a cost function *J*:

$$J(X) = 0.5(y^o - H(X))\,(O+F)^{-1}\,(y^o - H(X))^T + 0.5(X-X^b)\,B^{-1}\,(X-X^b)^T$$

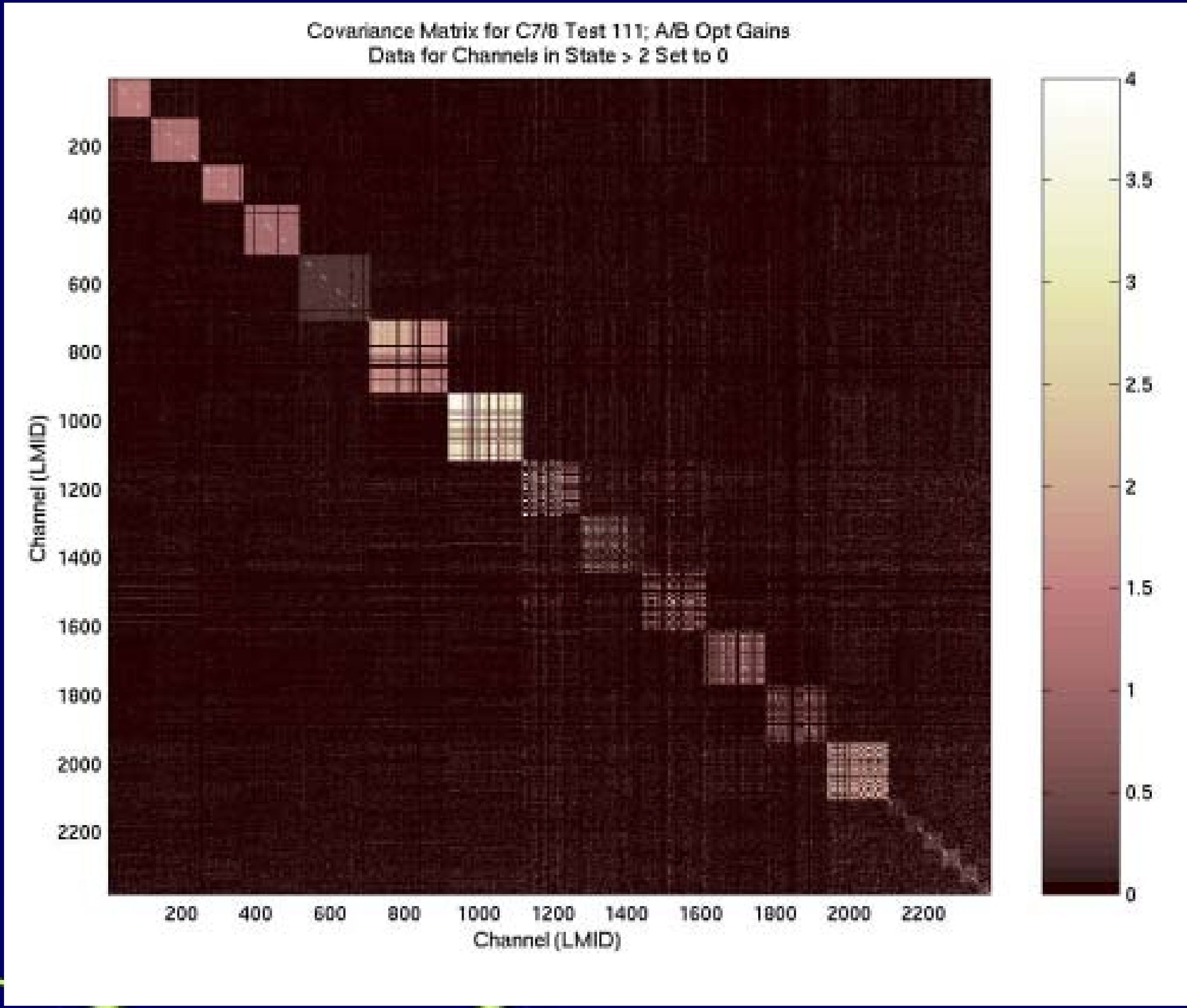
To minimise equation above, assuming the observations y^o to be linearly related to X then the minimum value for J(X) is when:

$$X = X^b + BH^T \cdot (H.B.H^T + O+F)^{-1} \cdot (y^o - H(X^b))$$

H is derivative of *H wrt* X often called jacobian matrix

$$\partial y = \mathrm{H}(X^b).\partial X$$

Observation errors: AIRS channel covariance



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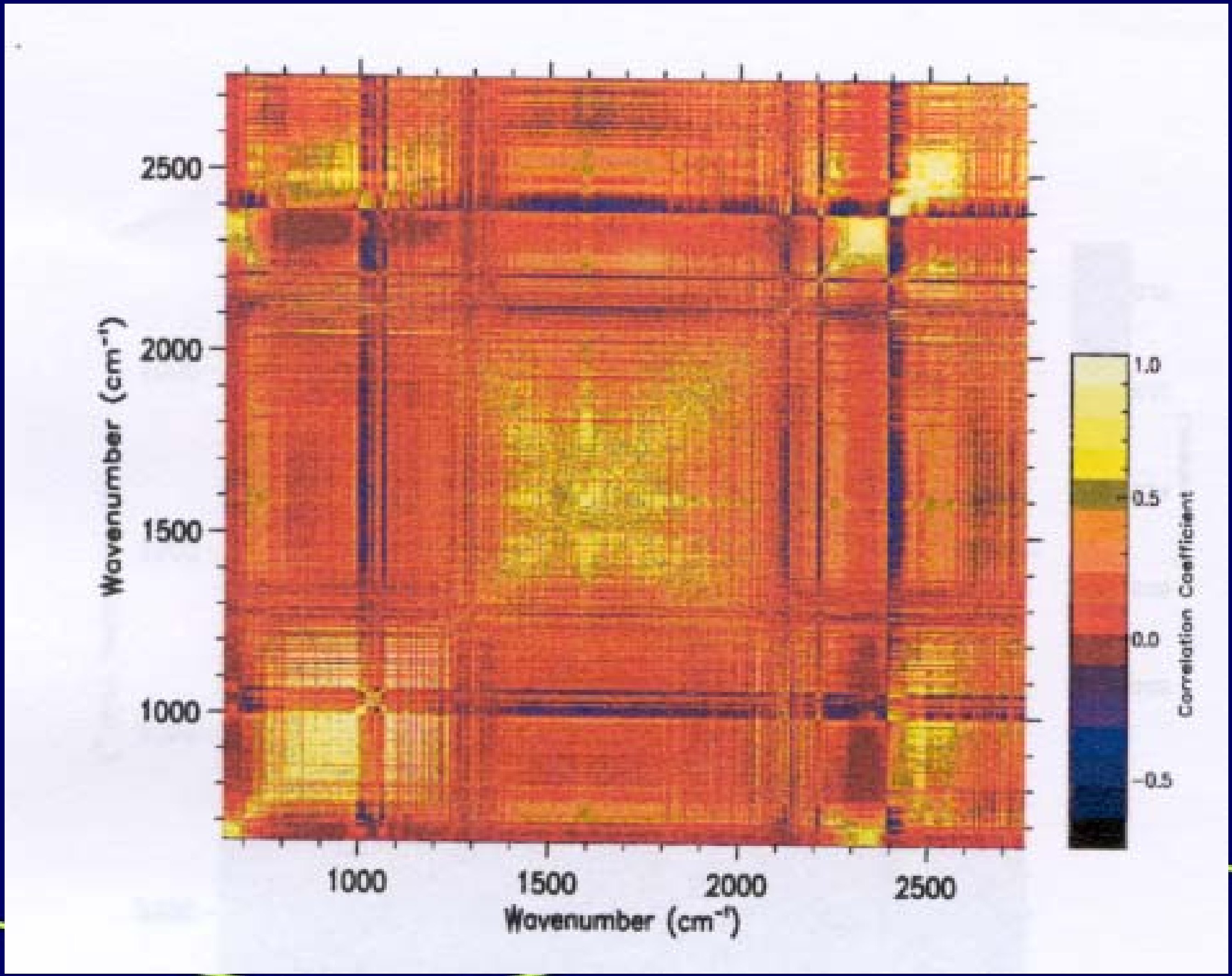
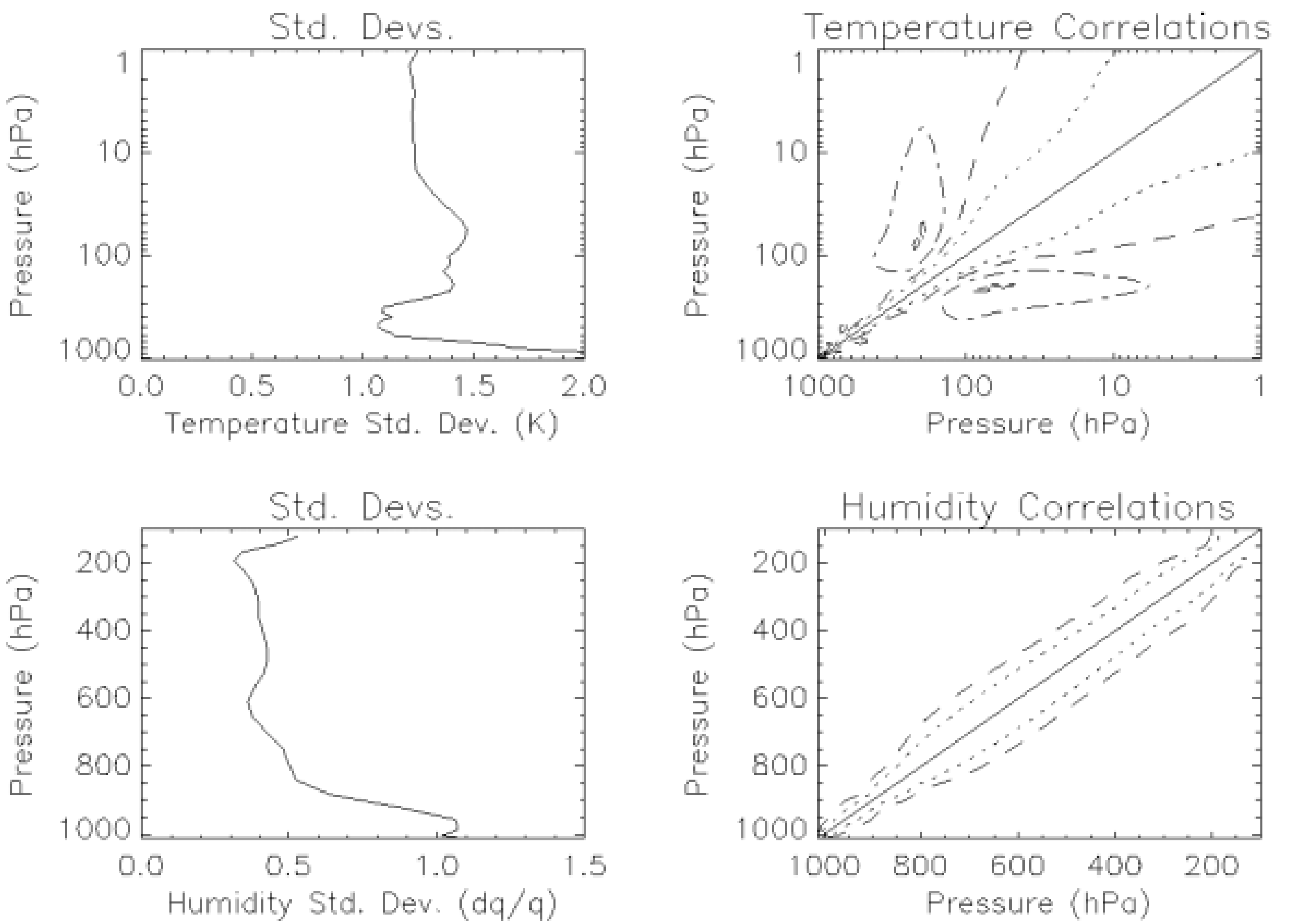
Forward model error correlation matrix for RTIASI



Background errors and correlation matrix for T and q



Options for Data Assimilation (1- type of observation)

- Assimilation of retrievals
  - T(p), q(p), O_3(p) *Lowest cost but inconsistent FG and no control of retrieval process. Must also have retrieval error covariance.*
- Assimilation of 1DVar retrievals
  - T(p), q(p), O_3(p) *More optimal but radiances used in isolation*
- Direct radiance assimilation in 3DVar or 4DVar
  - Radiances for limited number of channels *Most expensive but most optimal and is current operational use of ATOVS but only limited use of data*
- Use combination of channels
  - pseudo channels or EOFs *Possible for 'day-2' assimilation, needs more research*

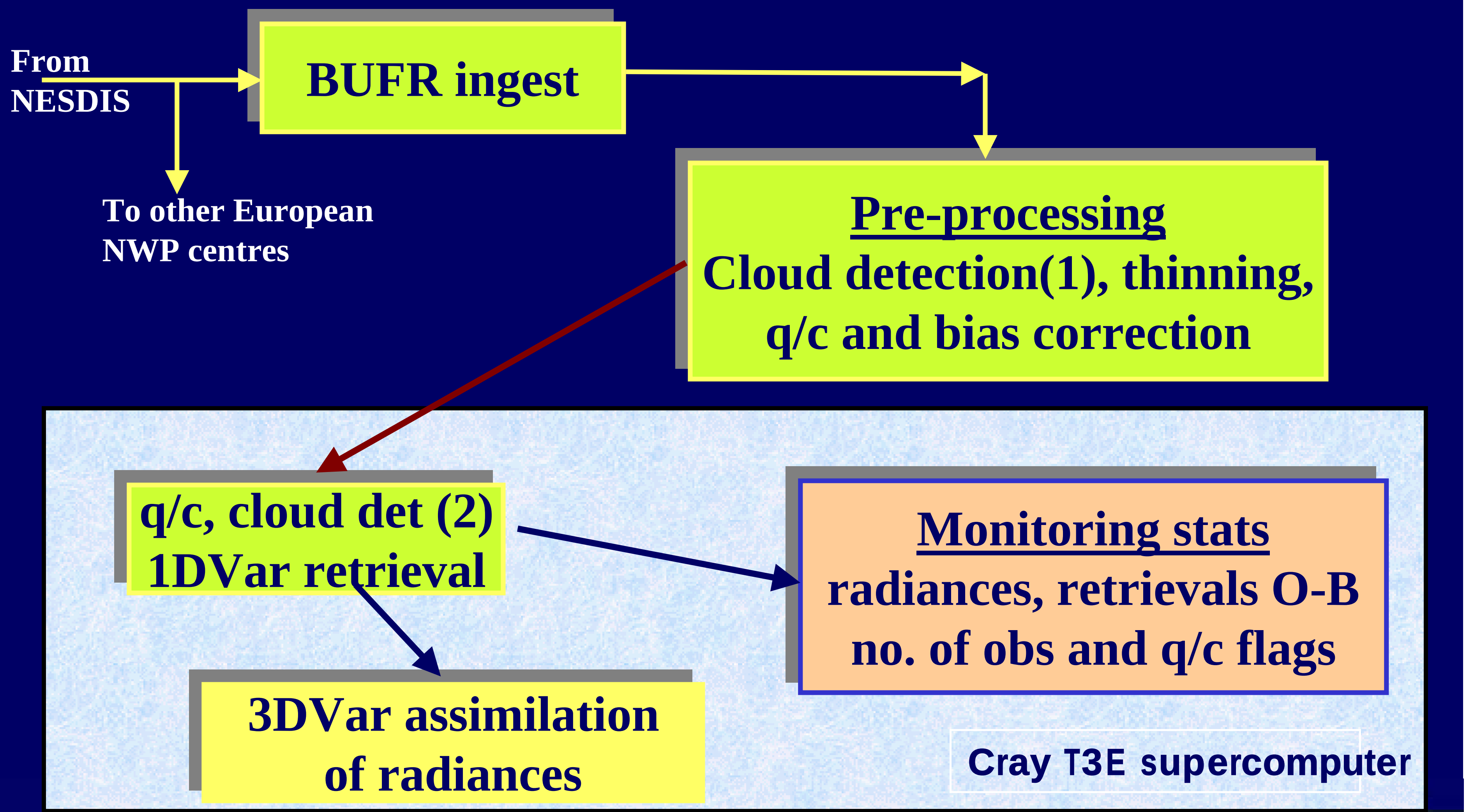
Met Office

Options for Data Assimilation (2 - coverage)

- Initially:
  - clear sky, tropospheric radiances over sea
  - stratospheric radiances globally
- Medium Term:
  - cloudy radiances over uniform low cloud
  - more radiances over land and sea-ice
- Longer term:
  - include cloud fully in state vector and provide cloud variables back to model

Met Office

AIRS processing at Met Office



Measuring Impact of Satellite Data on Forecasts

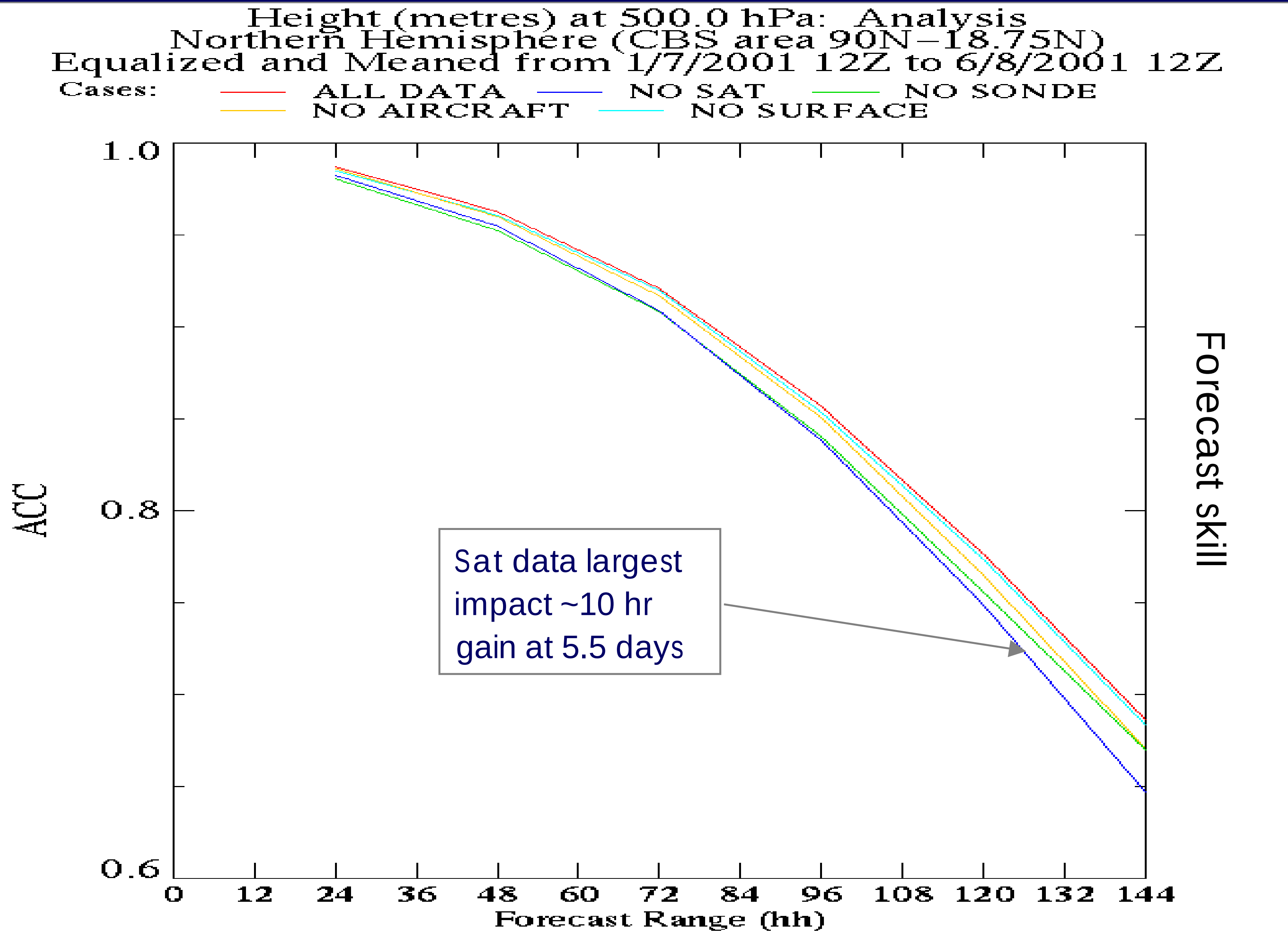
We can run experiments where satellite data are not used and observe the consequent degradation in the forecast skill relative to a system which has used all data (observing system experiment or OSE).

But.

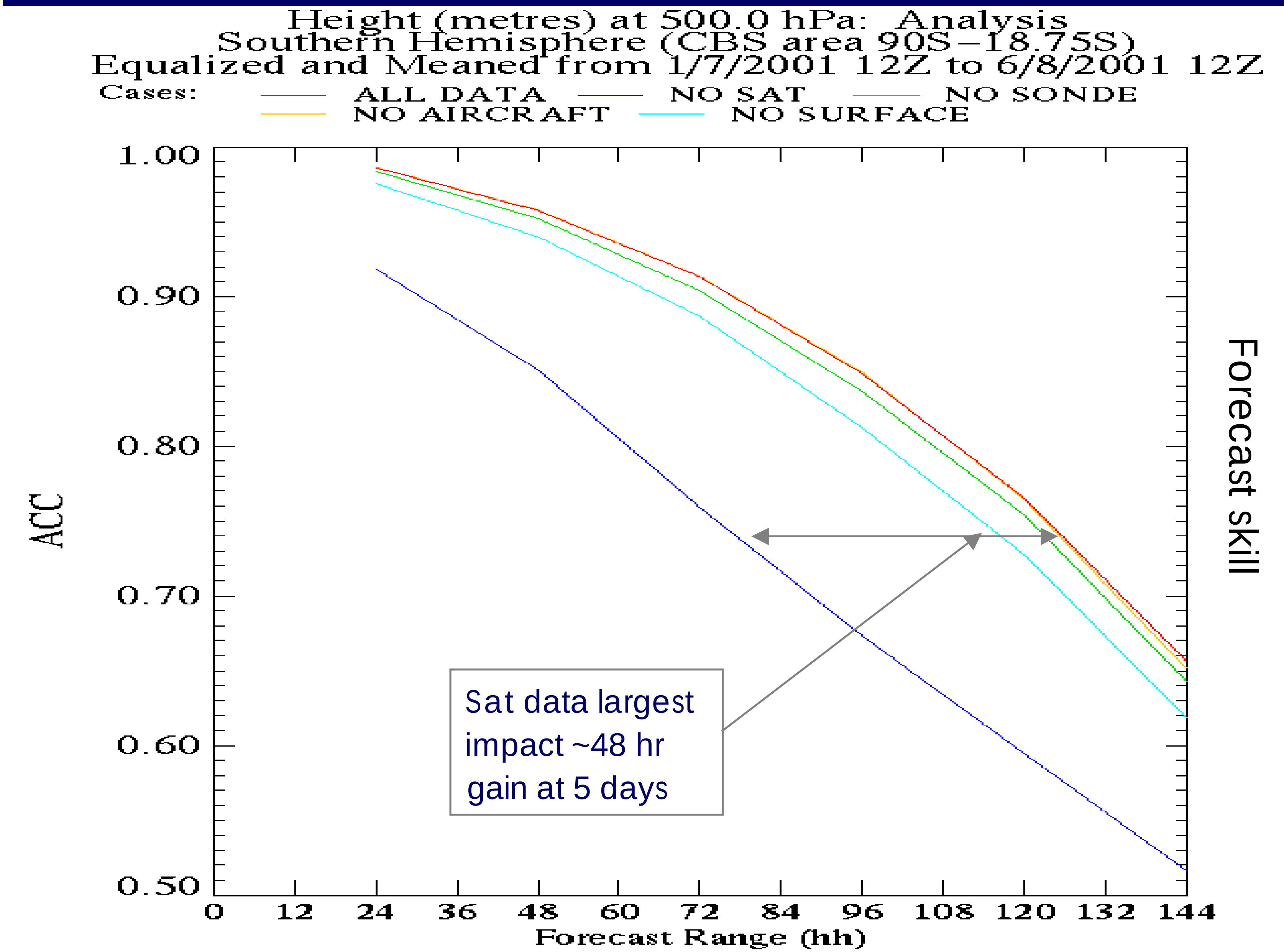
Can only do this using today's satellite data + processing and current data assimilation + forecast model systems.

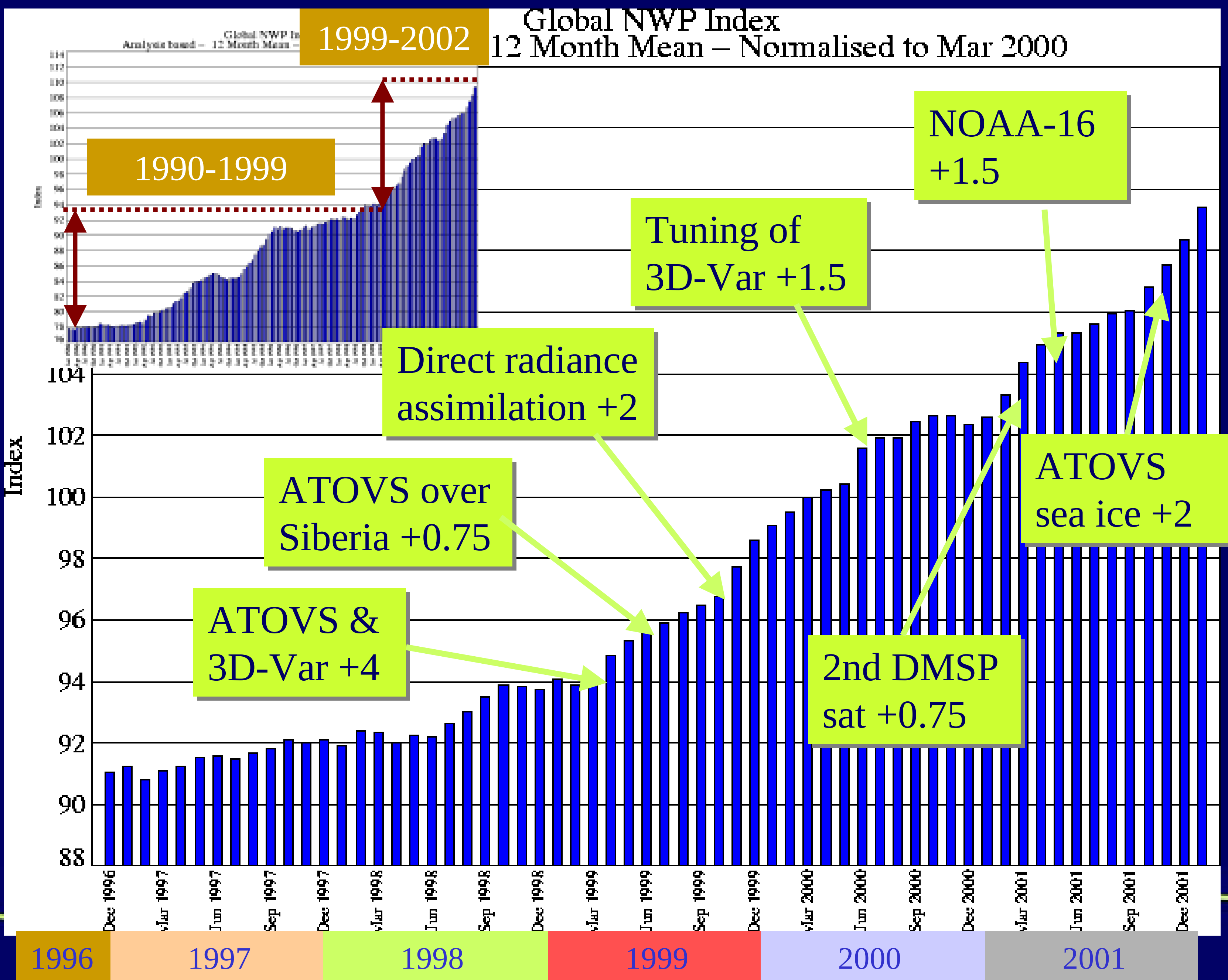
N.B. In 1995 OSE's suggested satellite data had a negative impact on forecast skill.

Satellite Vs Conventional: NH Height



Conventional Vs Satellite: SH Height





Global NWP Index
12 Month Mean – Normalised to Mar 2000
1999-2002
1990-1999
NOAA-16 +1.5
Tuning of 3D-Var +1.5
Direct radiance assimilation +2
ATOVS over Siberia +0.75
ATOVS & 3D-Var +4
2nd DMSP sat +0.75
ATOVS sea ice +2
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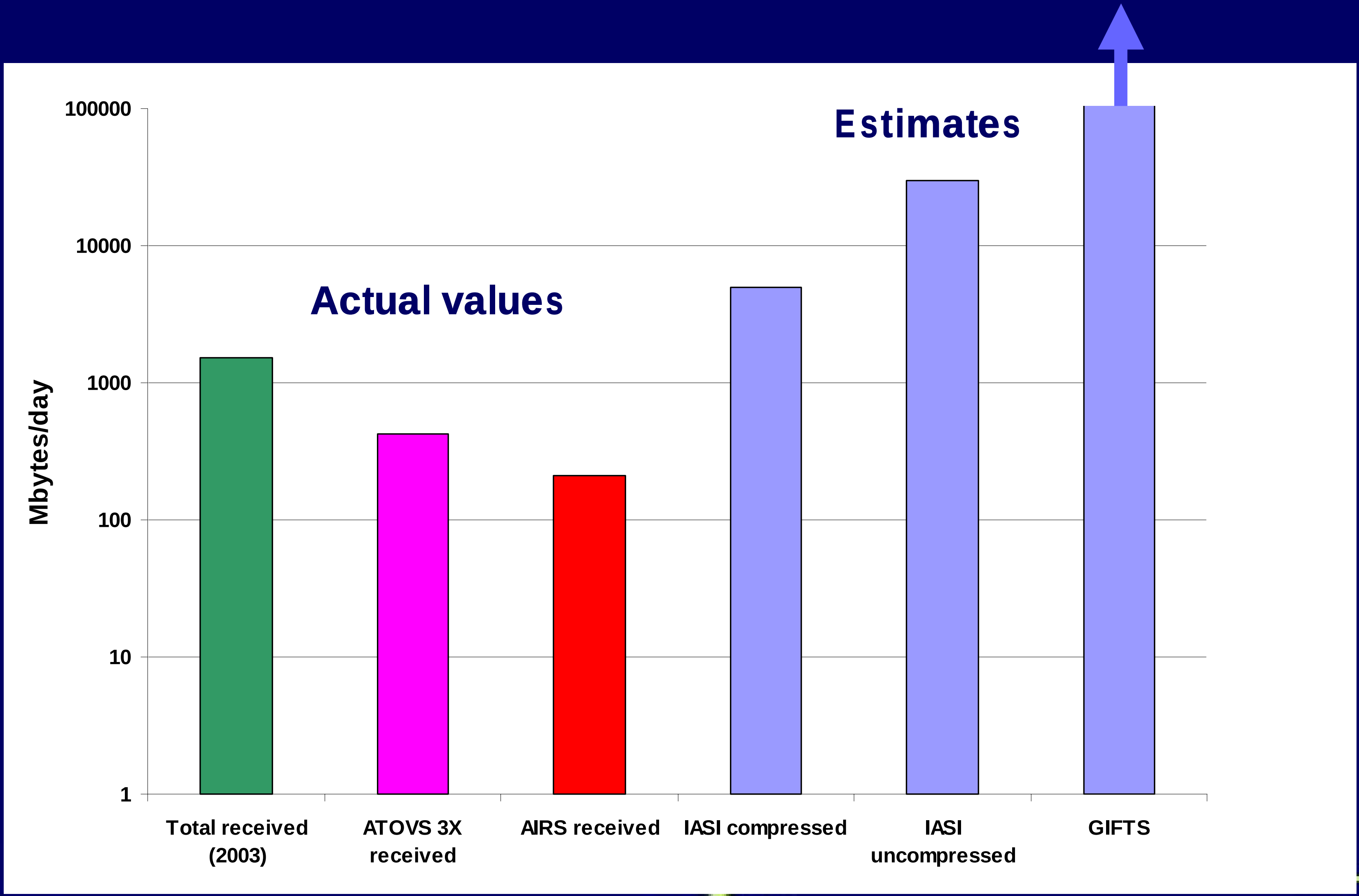
Advanced sounder data volumes



Summary of Current Status(1)

- The ATOVS sounder data has led to a significant improvement in forecast skill over the last 4 years
- Satellite data now have a larger impact than radiosondes in N. Hemisphere.
- New variational data assimilation techniques allowing direct use of satellite radiances has contributed enabling better use to be made of satellite data.
- Advanced IR sounder data show promise to improve the temperature, water vapour and ozone fields in the model.

Met Office

Summary of Current Status(2)

- Cloud and surface parameters should also be updated by using these data.
- AIRS is providing an excellent test bed for use of advanced IR sounder data.
- Data volumes will remain a challenge for NWP centres (e.g. only 324 channels used from AIRS).
- More research on using compressed forms of data and cloud affected data.

That's all!