Assimilation of clouds and precipitation

General issues and prospects from future sensors

Stephen J. English

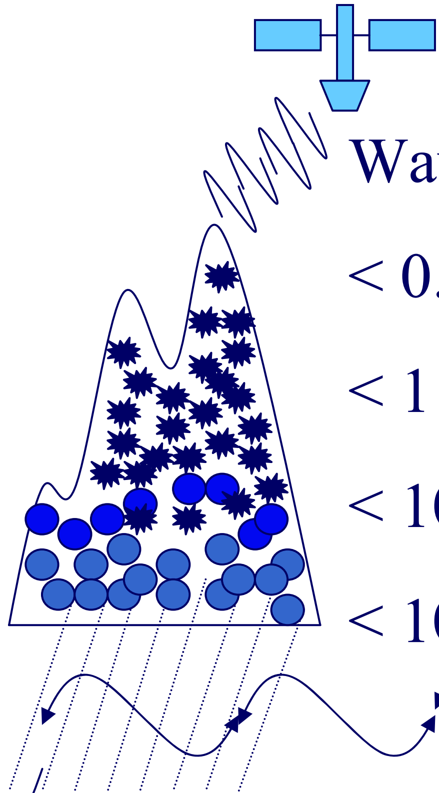
Met Office

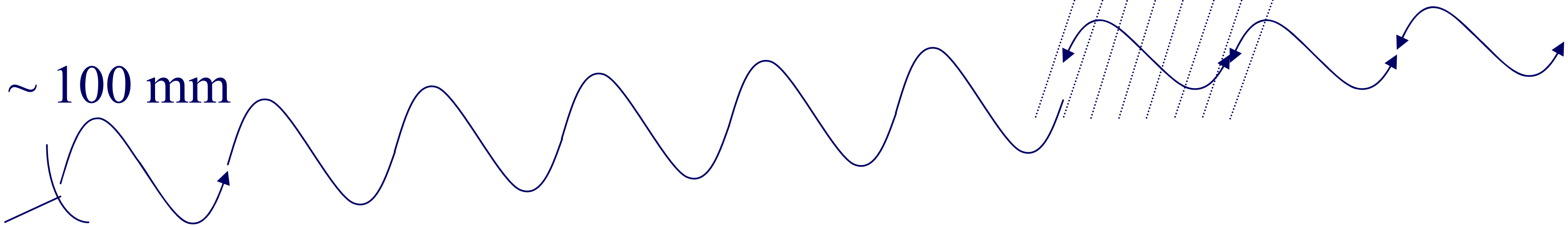
Outline

- Cloudy radiances – the basics
  - Existing sensors
- Applications of existing sensors
  - 1D-var analysis of cloud from AIRS
  - Assimilation of cloudy AMSU-A microwave radiances
  - The impact of ice cloud on MHS and AMSU-B
  - Assimilation of cloudy geostationary IR radiances (SEVIRI)
- Future sensors
  - Sub-mm sensors
  - Geostationary MW
  - Polametric radiometers (including wind vector potential)

Cloudy radiances - basics

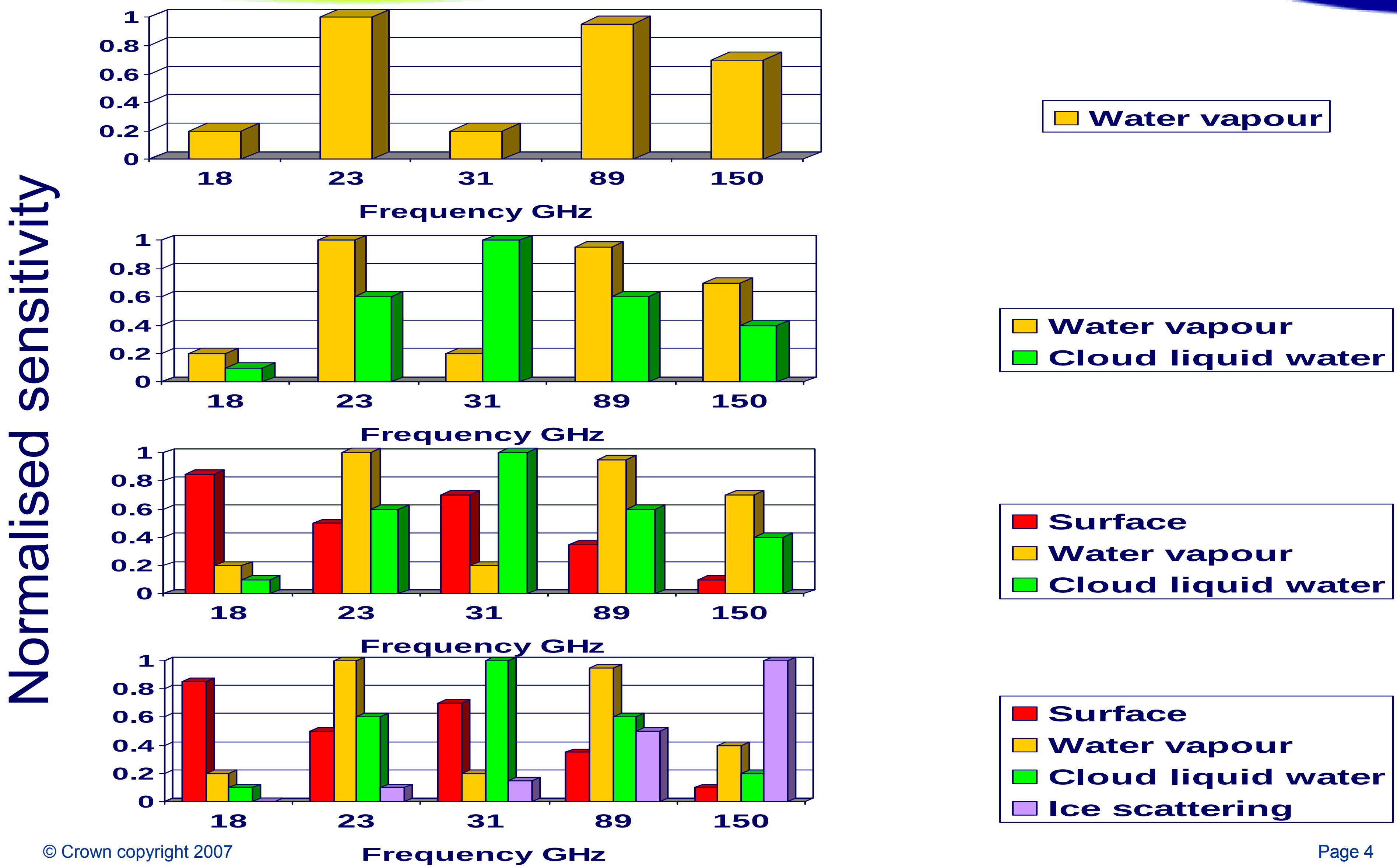
		Polar Orbit 830 km FOV size	Wavelength
MODIS	Infrared	< 1 km	< 0.1 mm
CIWSIR	Sub-mm	> 1 km	< 1 mm
MHS	Microwave	> 10 km	< 10 mm
AMSR	Radiowave	> 100 km	< 100 mm





Visible channels (e.g. 0.6 μm) ignored in this presentation though as clouds are non-absorbing in Vis bulk quantities e.g. LWP can be analysed.

Microwave “window” channels: schematic

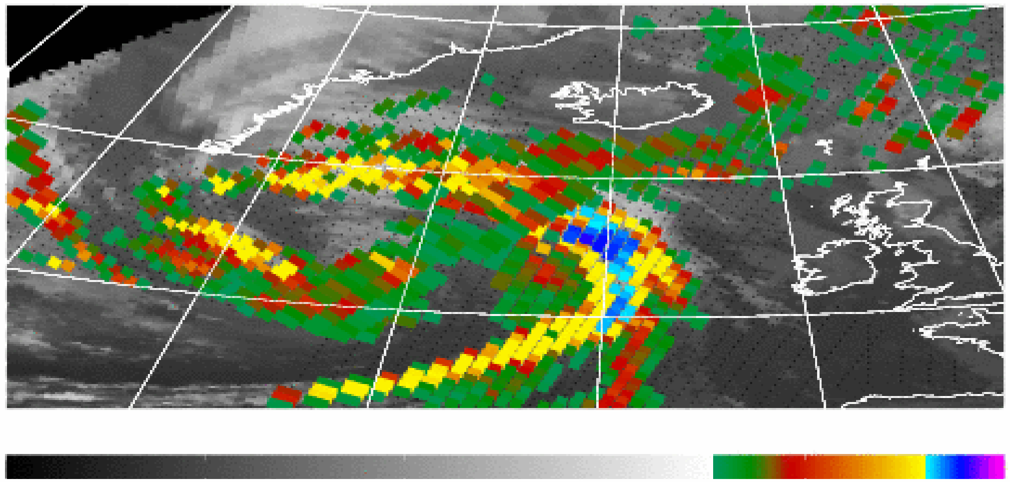


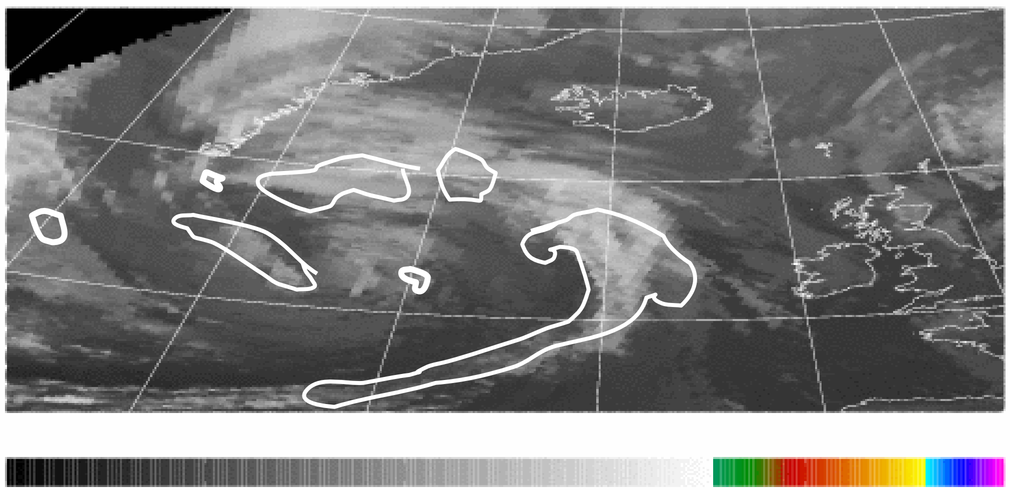
SEVIRI/AMSU-A/MHS composite image

Green to red to yellow
Cloud liquid water derived from 23/31 GHz

(AAPP)

White lines denote high cloud LWP.





Blue to purple
Heavy rain derived from 23/89 GHz or 89/150 GHz

(AAPP)

Gray scale = IR image.

Clouds and precipitation: issues

Sounding (**IASI**, **AIRS**, **AMSU**, **MHS**)

Surface (**ASCAT**, **QuikSCAT**, **WindSat**, **SSM/I**, **AVHRR**, **MODIS**)

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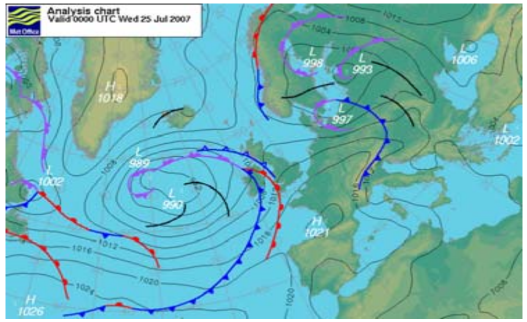
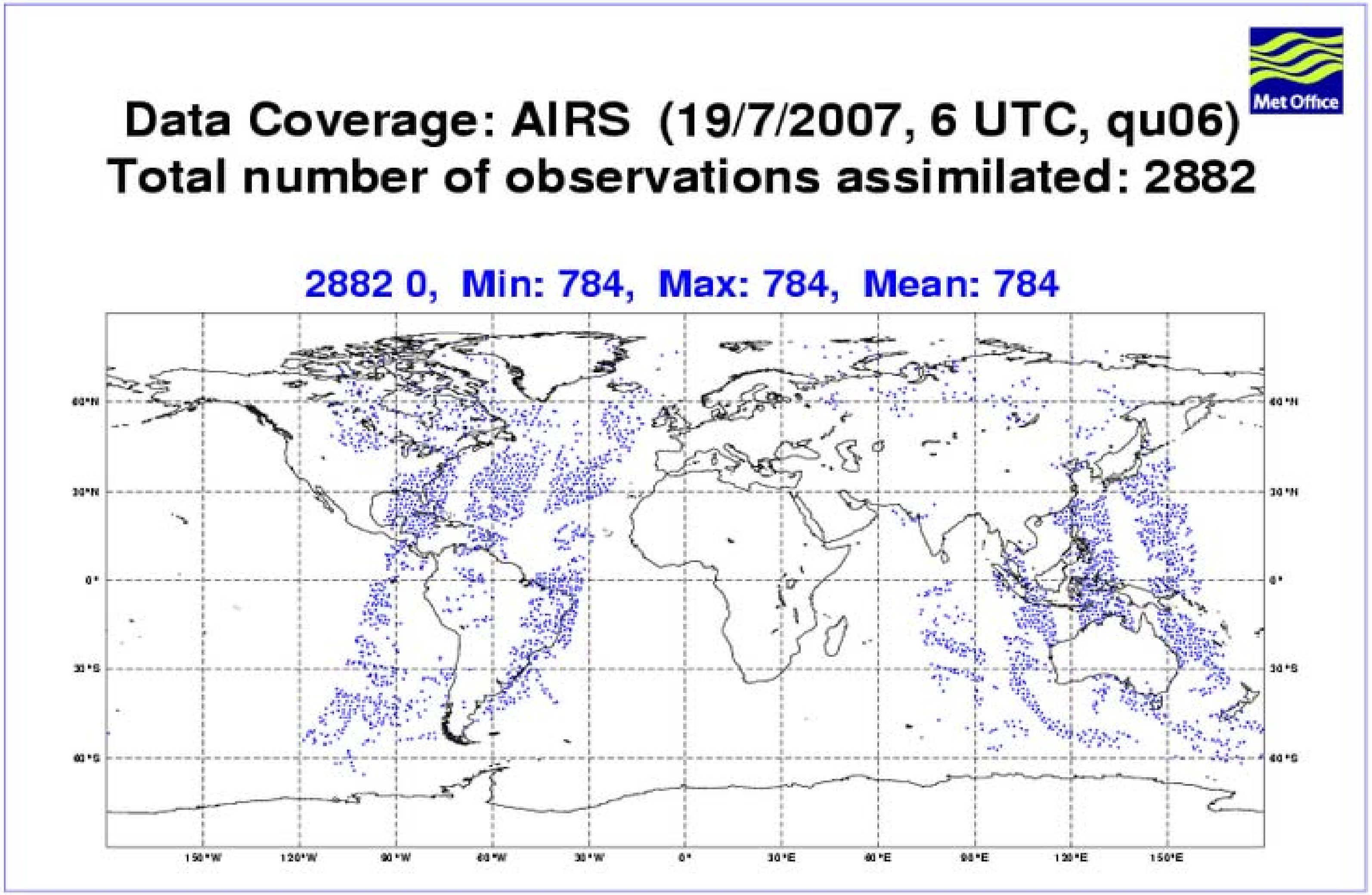
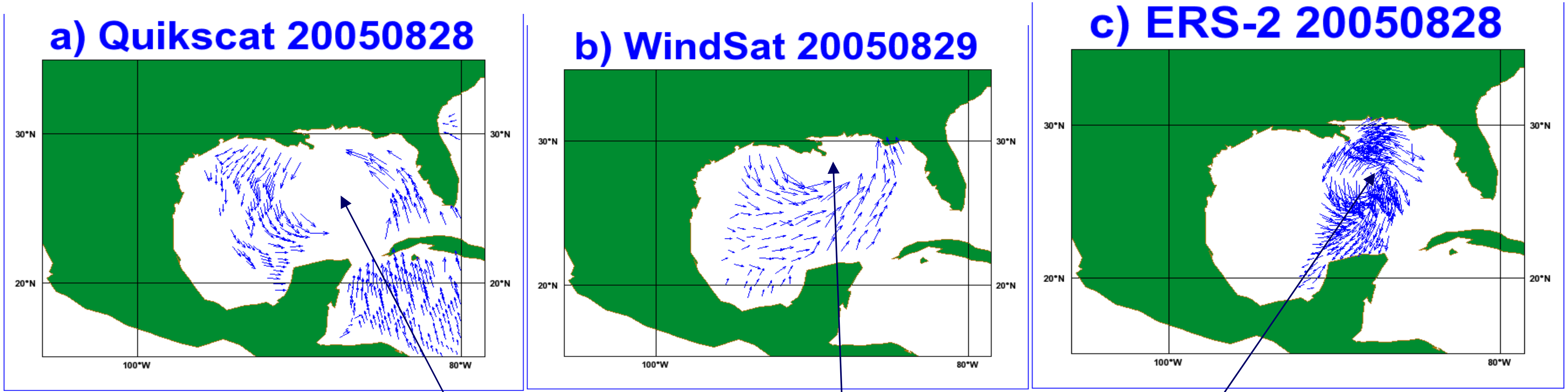


AIRS: cloud impact



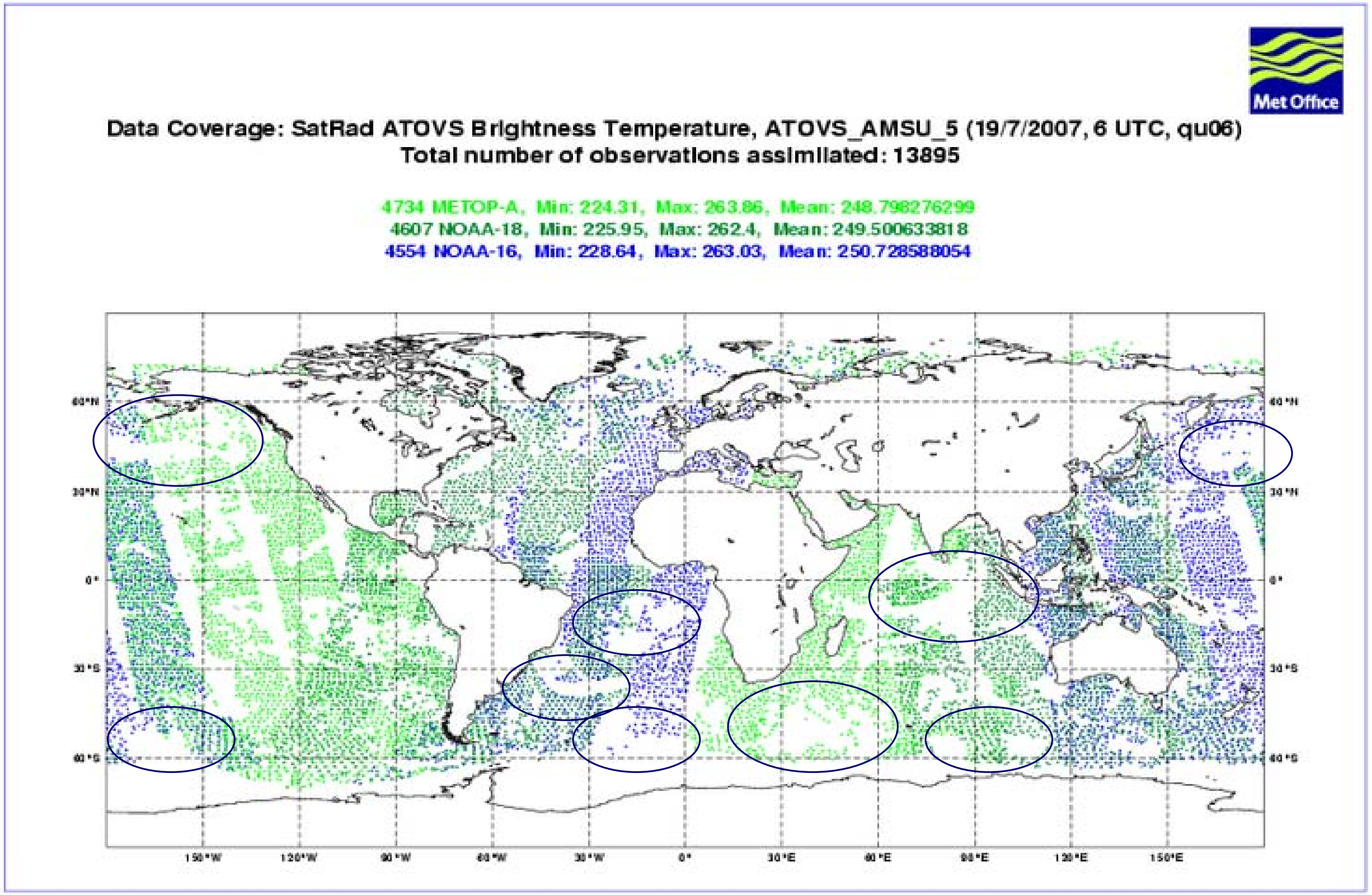
QuikScat, WindSat, ERS-2 over Hurricane Katrina



Both Ku-band (14 GHz) and WindSat (10 & 18 GHz) struggle near storm centre.

C-band (6 GHz) OK.

Low level microwave AMSU Ch.5, peak 750 hPa



There is a clear motivation to model cloud effects on satellite data not just to reject cloudy radiances

Approaches

Coping with presence of cloud and rain

- 1D-var analysis of cloud and pass cloud information to assimilation system with radiances (e.g. Pavelin).

- EOF regularisation e.g. NESDIS MIRS system (Boukabarra, Weng, Zhao & Ferraro).

Extracting cloud/rain information

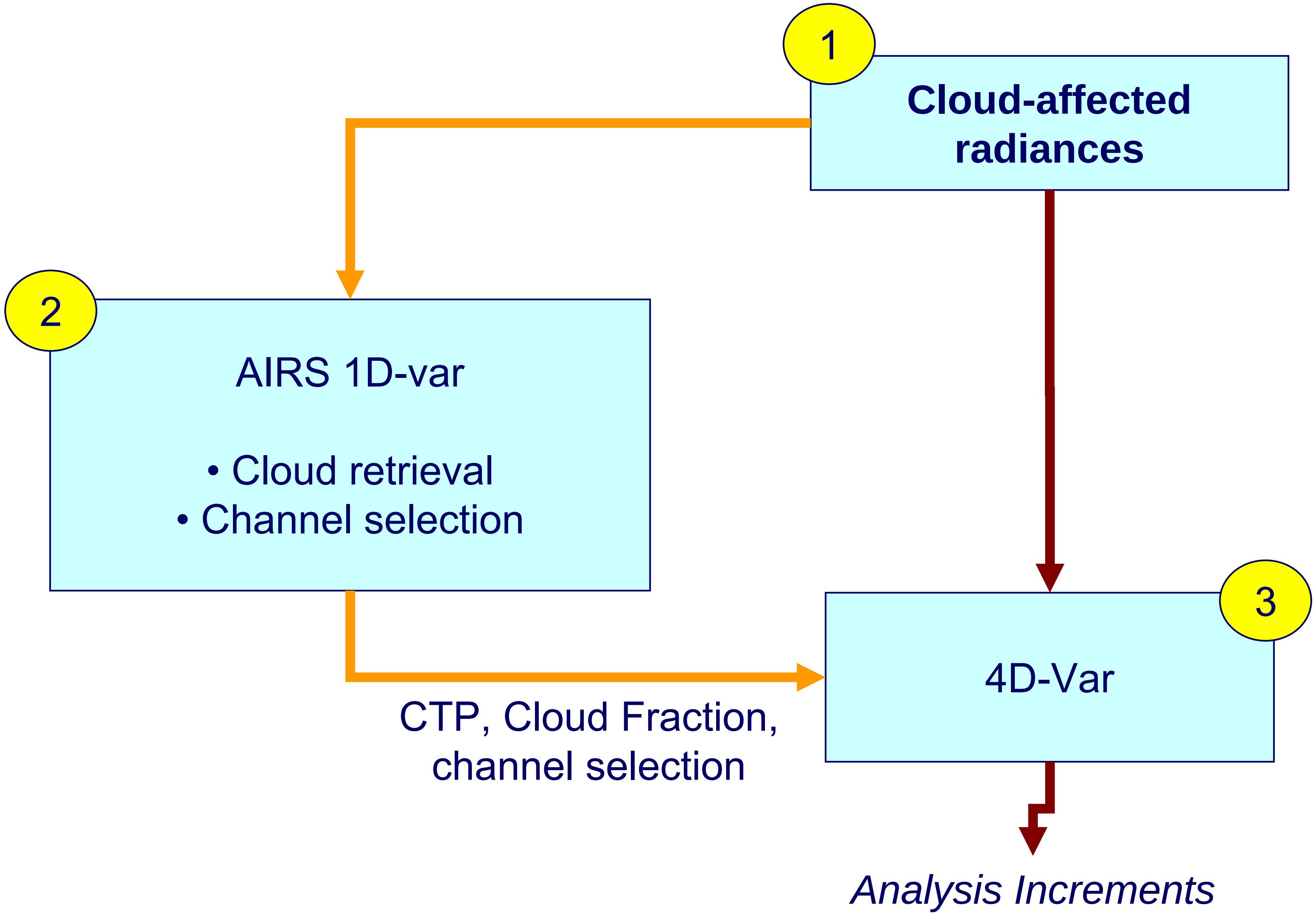
- Analyse cloudy radiances in 1D-var; assimilate 1D-var geophysical product. e.g. Deblonde and Mahfouf 2007, Peter Bauer, today!

- Incrementing cloud operator in 4D-var and direct assimilation of cloudy microwave radiances (e.g. Una O'Keeffe (MW), Dingmin Li (IR) at Met Office).

Assimilation of cloudy AIRS radiances

(Ed Pavelin)

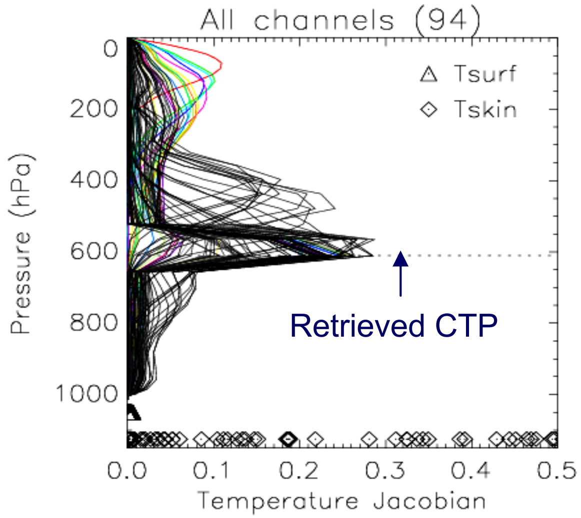
Simplified processing flowchart

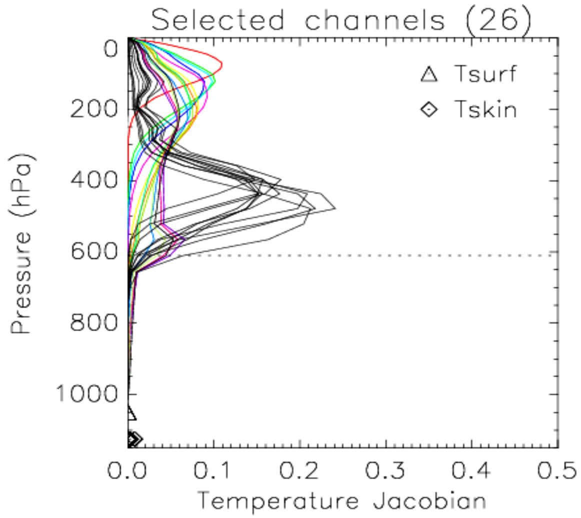


Example cloudy weighting functions ($\partial B_i / \partial T_j$)

Mid-level cloud

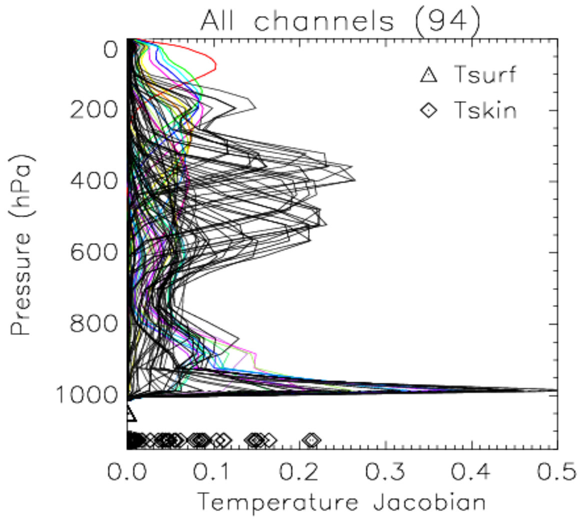
- Use 26 of 94 channels

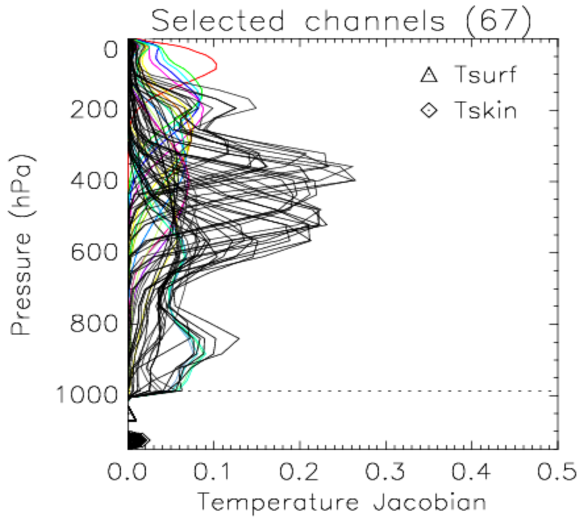




Low cloud

- Use 67 of 94 channels

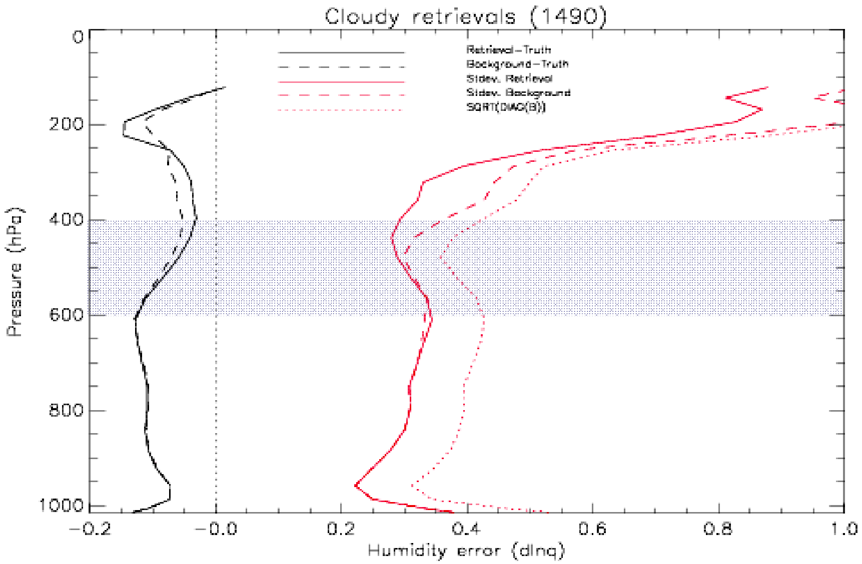


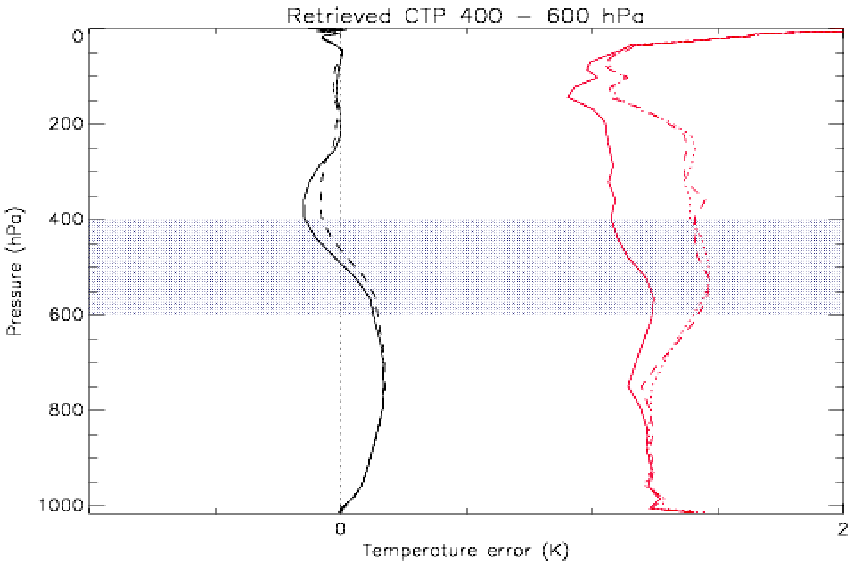


Example: Simulation for mid-level cloud

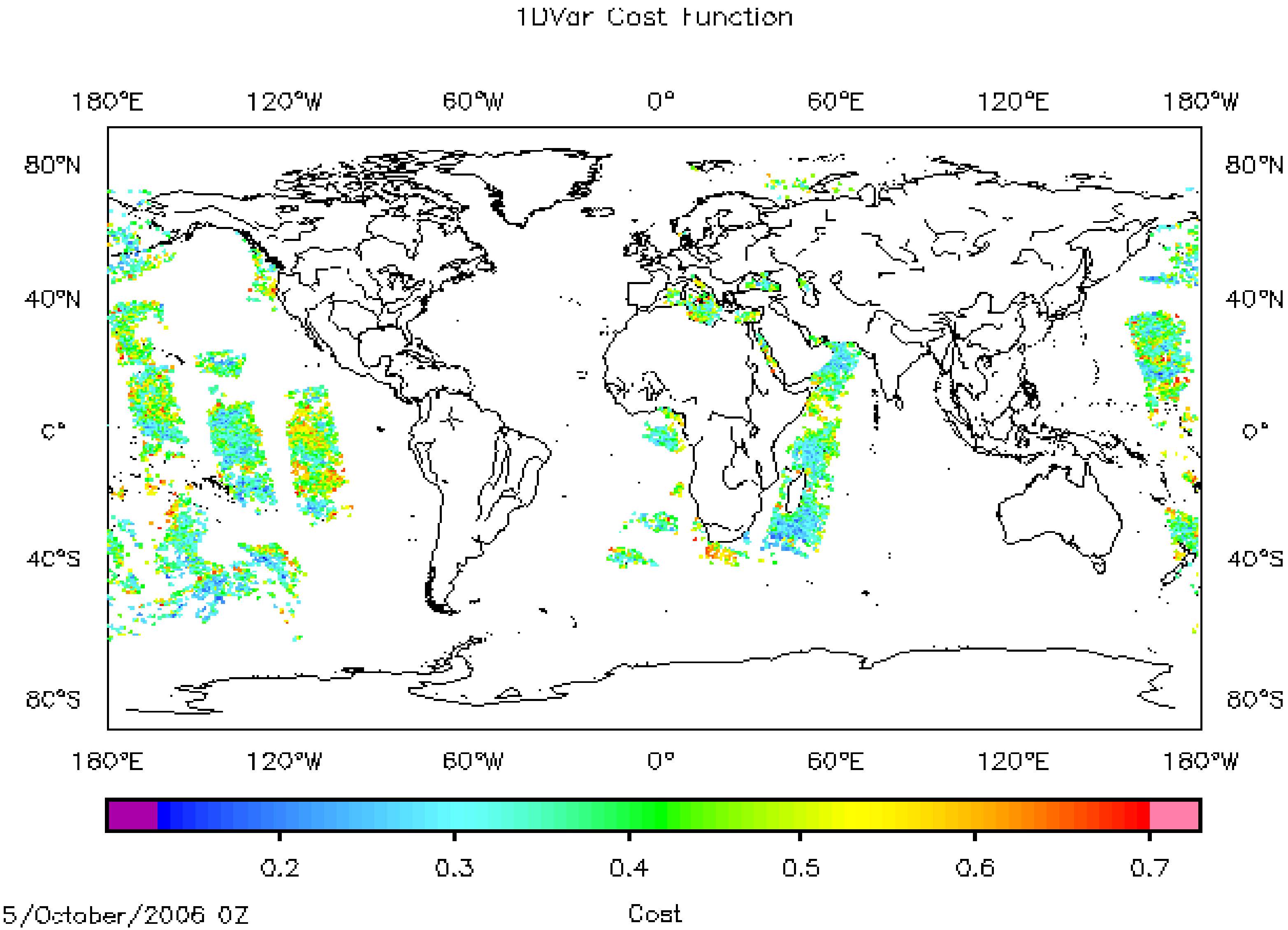
"Mid-level" cases: CTP 400-600 hPa

- 28% of 13495 cases
- Analysis improved above cloud
- Significant temperature information below cloud (from semi-transparent cloud + vertical correlations)
- Humidity analysis well-behaved below cloud (follows background)

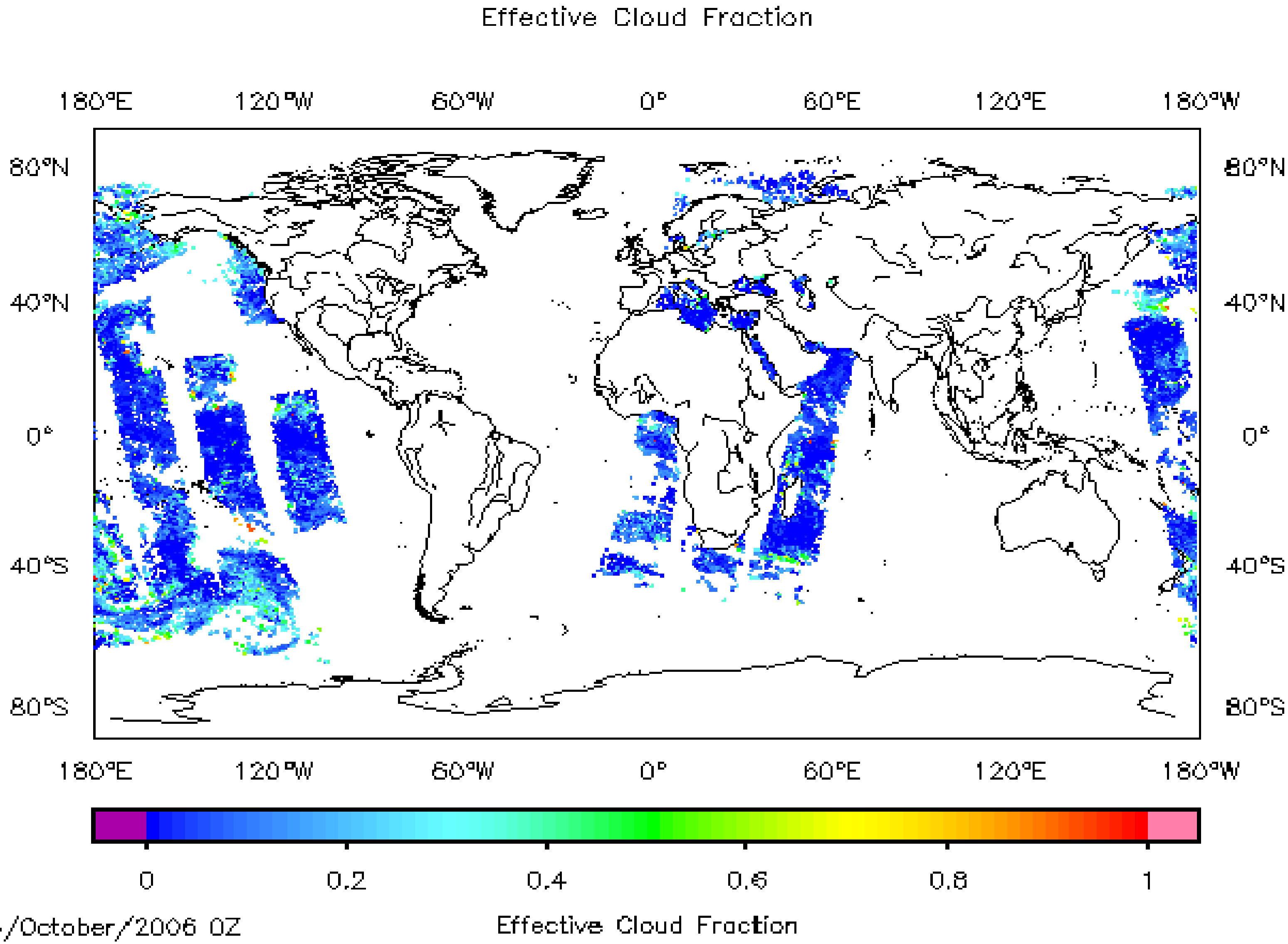




Coverage: Clear AIRS



Retrieved effective cloud fraction

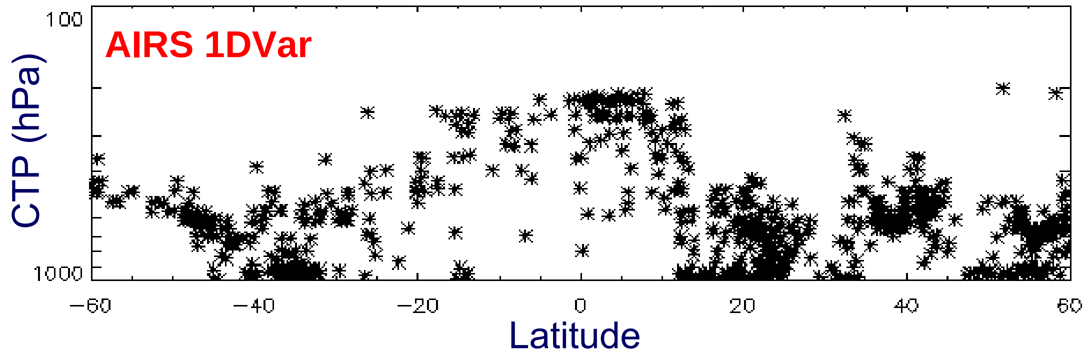


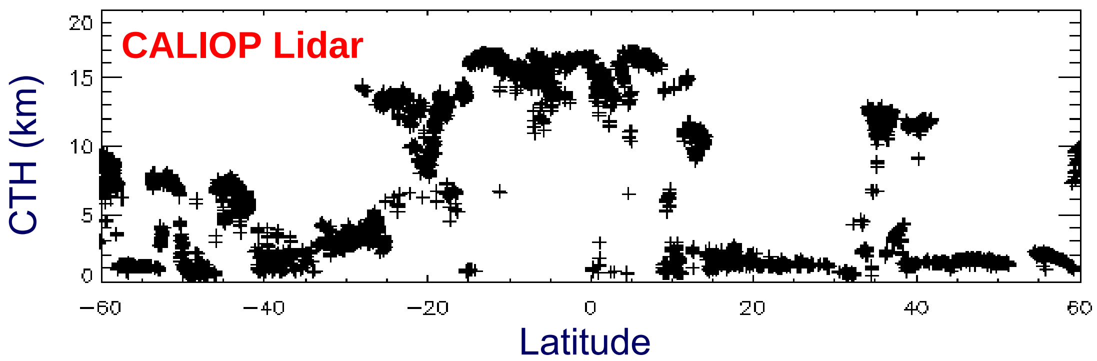
Aside: Validation of cloud retrievals

- **CALIPSO**: Spaceborne LIDAR (CALIOP)
  - Flies in A-Train close behind Aqua
  - Accurate cloud top height measurements

Qualitative comparison!

Section of one orbit

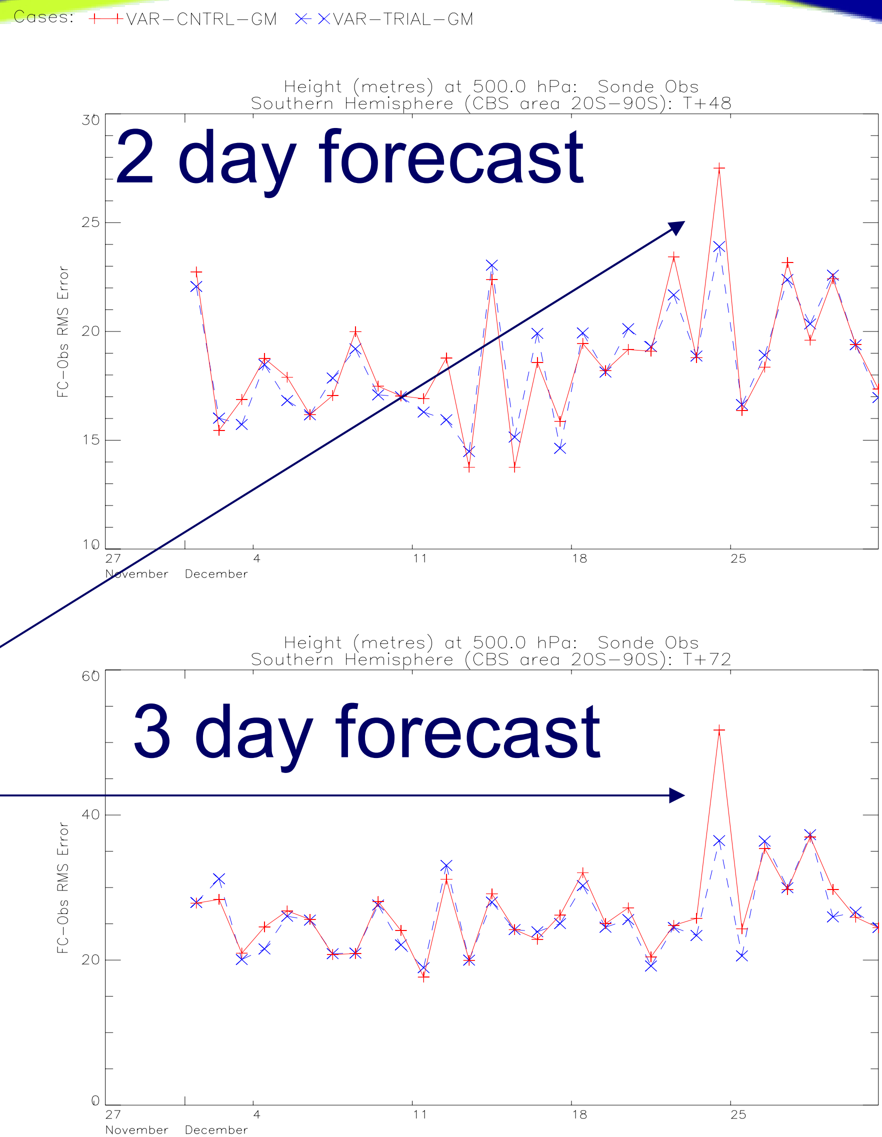




Cloudy AIRS radiances trial

Average impact ~ 2 x cloud-free AIRS.

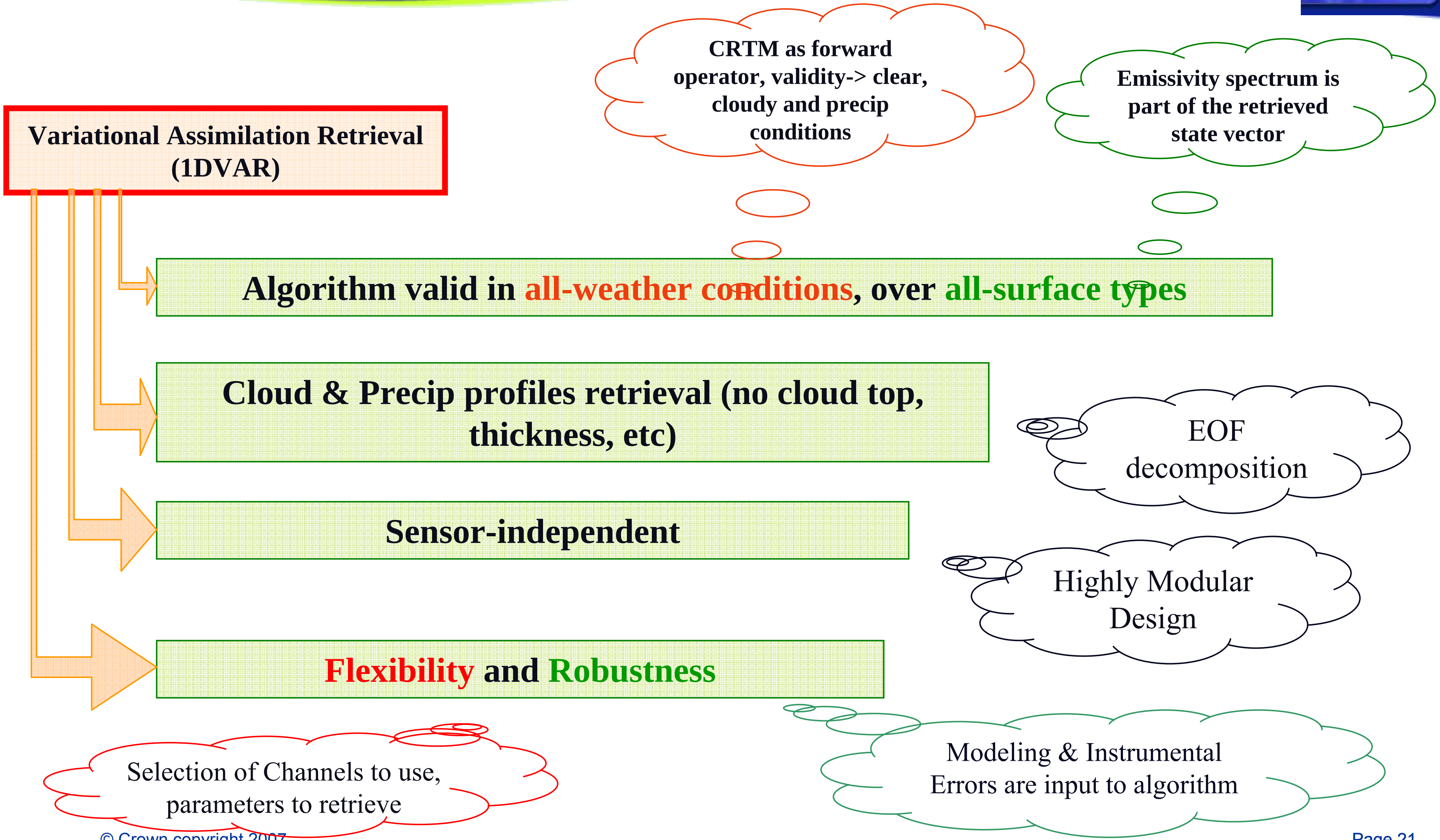
Some big impacts on forecast “busts” (as does clear AIRS) e.g. here z500 SH day 2 & 3



NOAA/NESDIS Microwave Integrated Retrieval System - MIRS

(Sid Boukabara, Fuzhong Weng, Limin Zhao, Ralph Ferraro)

Introduction to MIRS Concept



MIRS: Retrieval in Reduced Space (EOF Decomposition)

- All retrieval is done in EOF space, which allows:
  - Retrieval of profiles (T,Q, RR, etc): using a limited number of EOFs
  - More stable inversion: smaller matrix but also quasi-diagonal
  - Time saving: smaller matrix to invert

- Mathematical Basis:
  - EOF decomposition *(or Eigenvalue Decomposition)*
    - By projecting back and forth Cov Matrx, Jacobians and X

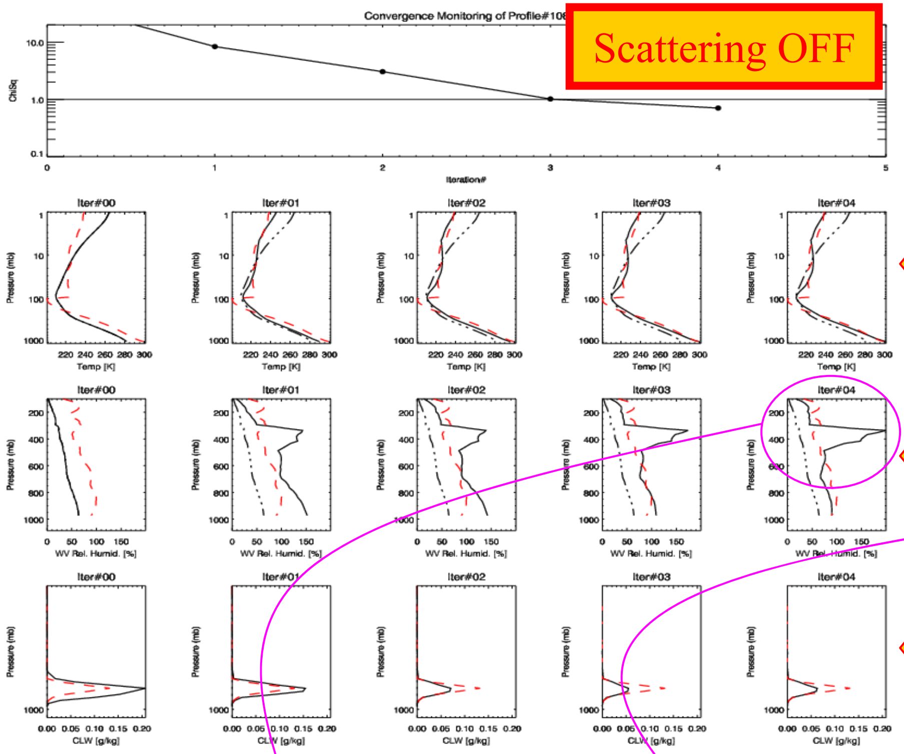
$$\Theta = L^T \times B \times L$$

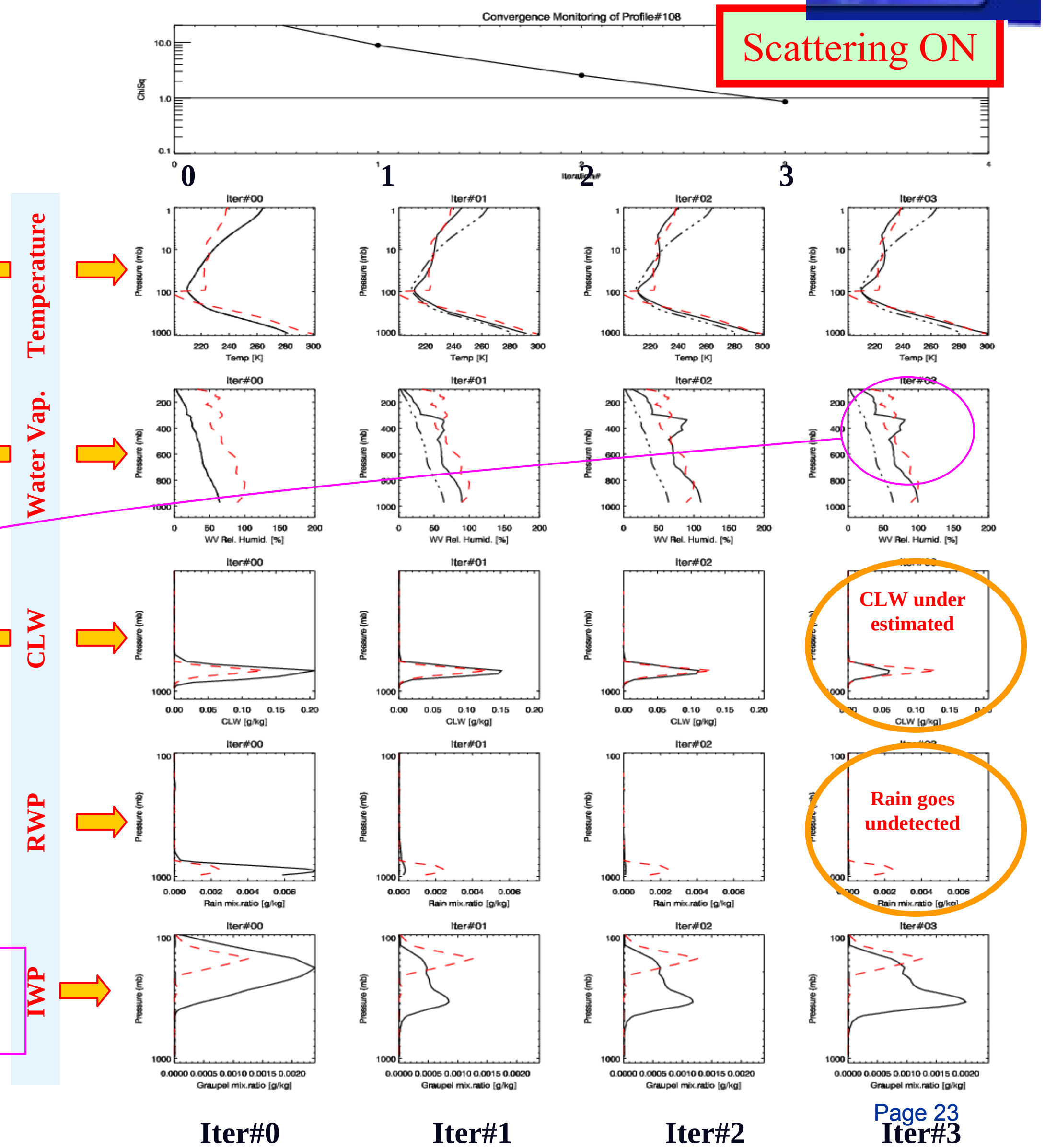
Diagonal Matrix (Θ)
(used in reduced space retrieval)

Transf. Matrx (L)
(computed offline)

Covariance matrix (B)
(geophysical space)

MIRS: Assessment in a Precipitating Case

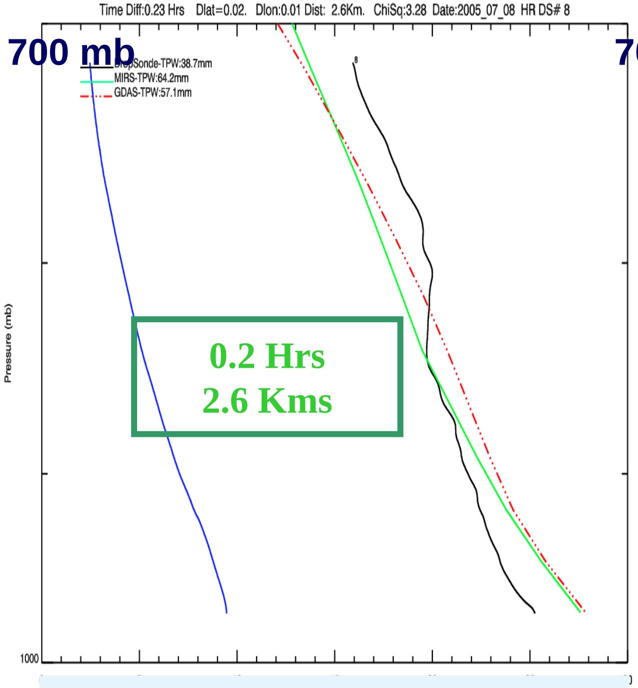


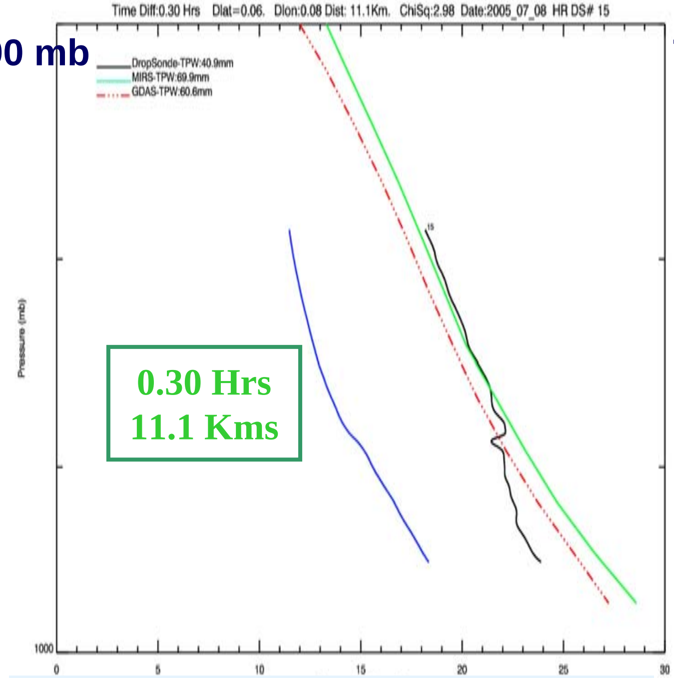


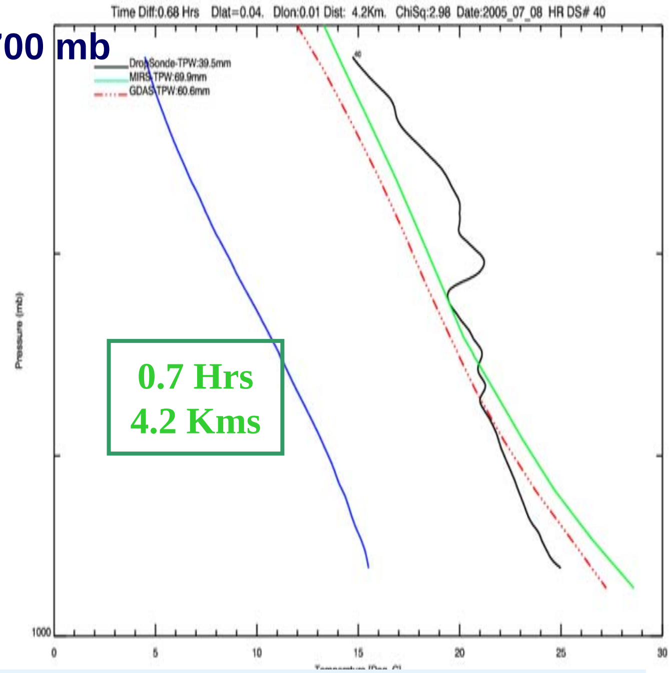
When scattering is OFF, Water vapor performance is hit.
When ON, '**precip-clearing**' takes place

In precipitation, cross-compensation is affecting retrieval
Radiometric solution reached but is not the geophysical one

MIRS: N-18 Profiling In Active Areas

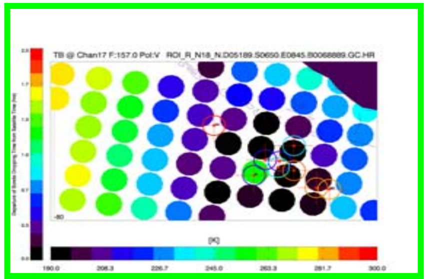






0 15 30 | 0 15 30 | 0 15 30

[Deg. C]
[Kms]



Retrieval

GDAS

DropSonde

Profile of DS Distance Departure

Assimilation of cloudy radiances in 4D-var using a total water control variable and a cloud incrementing operator

(Una O’Keeffe, Dingmin Li and Martin Sharpe)

Assimilating cloudy microwave radiances in 4D-var (Martin Sharpe/Una O'Keeffe)

Total moisture analysis variable used in 4D-Var

Need cloud incrementing operator that relates liquid water and specific humidity to the total water control variable

$$\boldsymbol{C_x^+ = C_x + KC_w'}$$

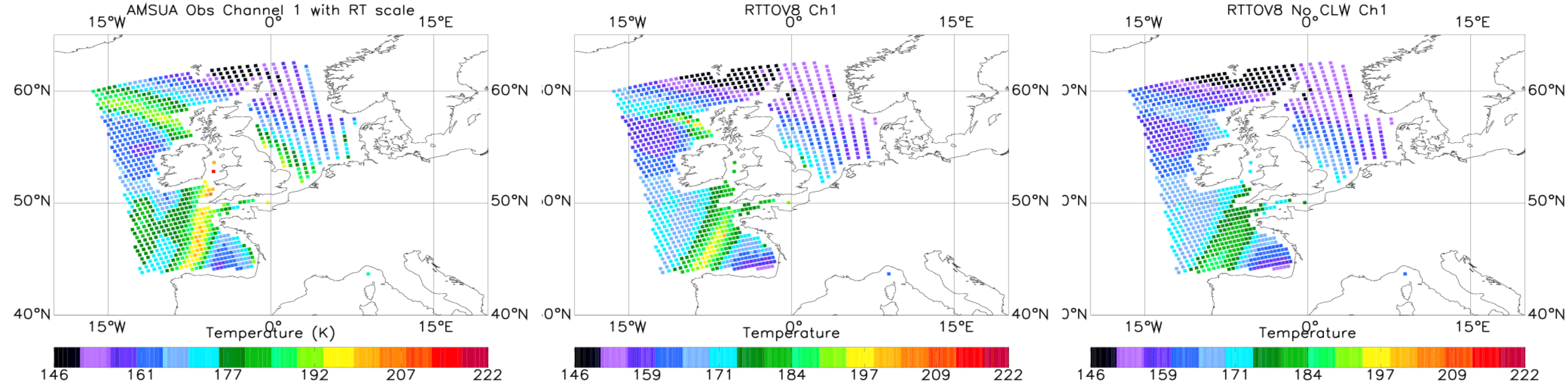
$\boldsymbol{C_x}$ = model state $(T,p,q,q_{cl},q_{ci},c_f)$
$\boldsymbol{C_w'}$ = analysis increment (T',p',q_T')
$\boldsymbol{K}$ = incremental transform variable between control variable space and model parameter space (uses linearised physics).

Information on cloud liquid water (Una O'Keeffe)

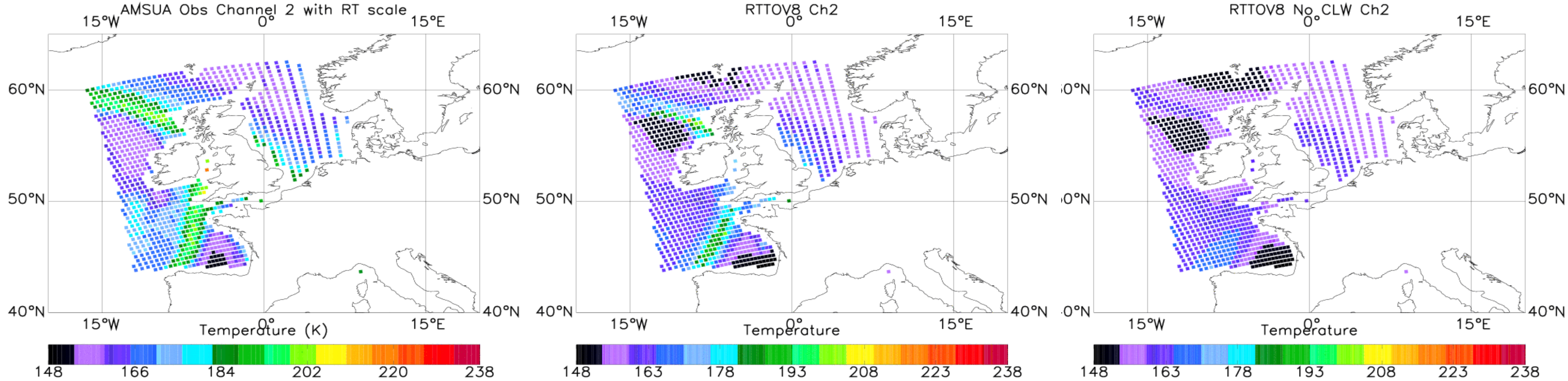
Met Office

	NOAA-16 Obs	RTTOV8 with clw emission	RTTOV8 without clw emission

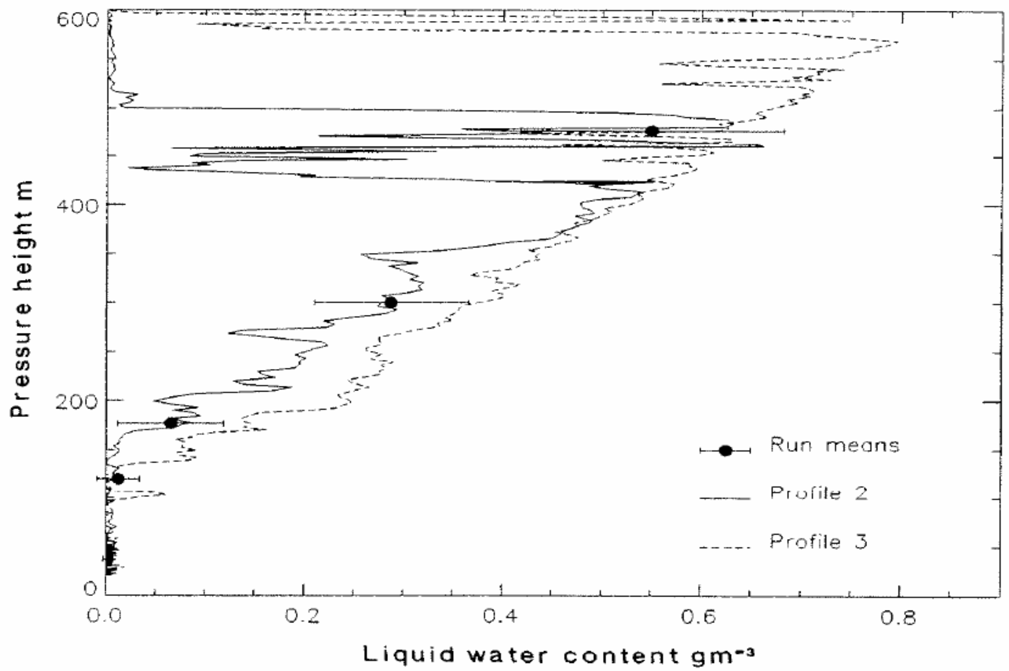
23GHz

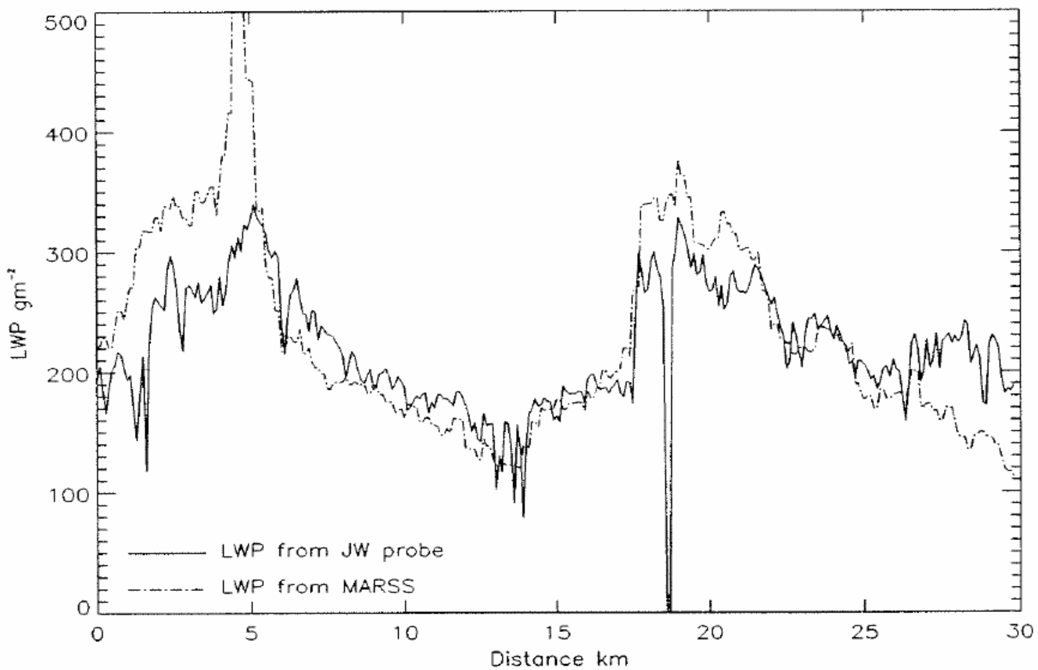


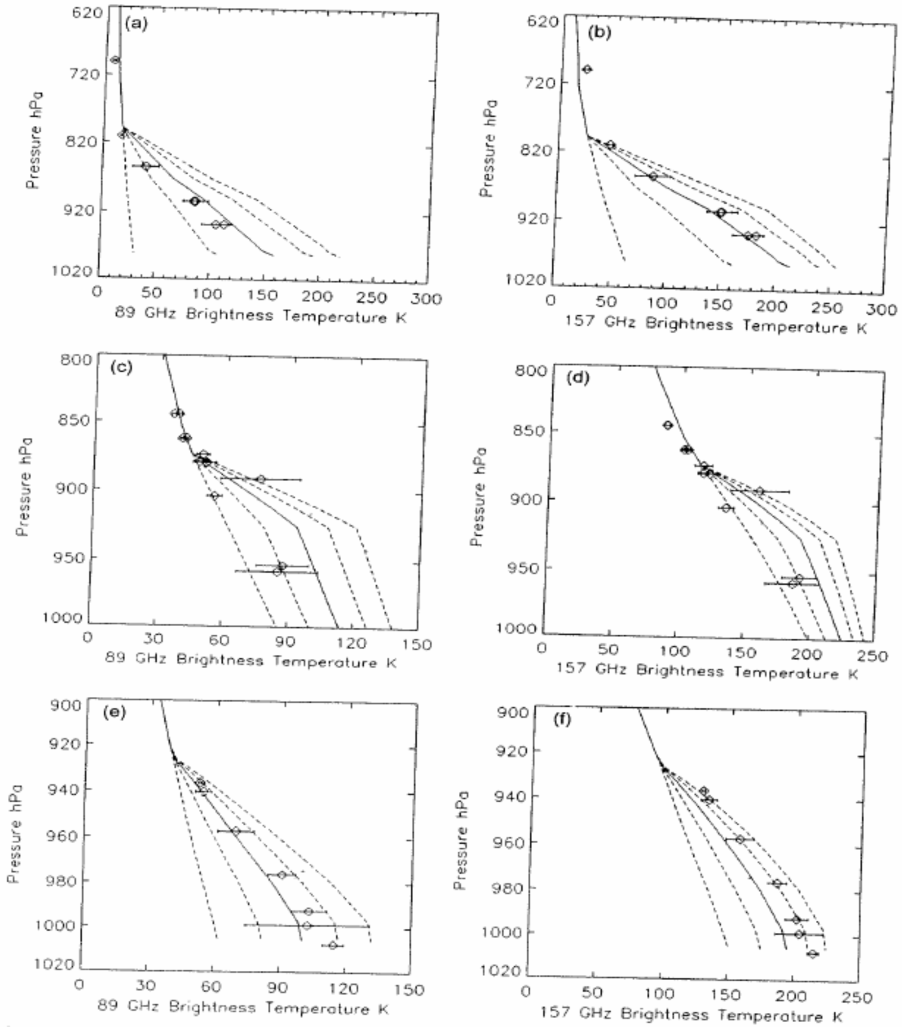
31GHz



Aircraft validation







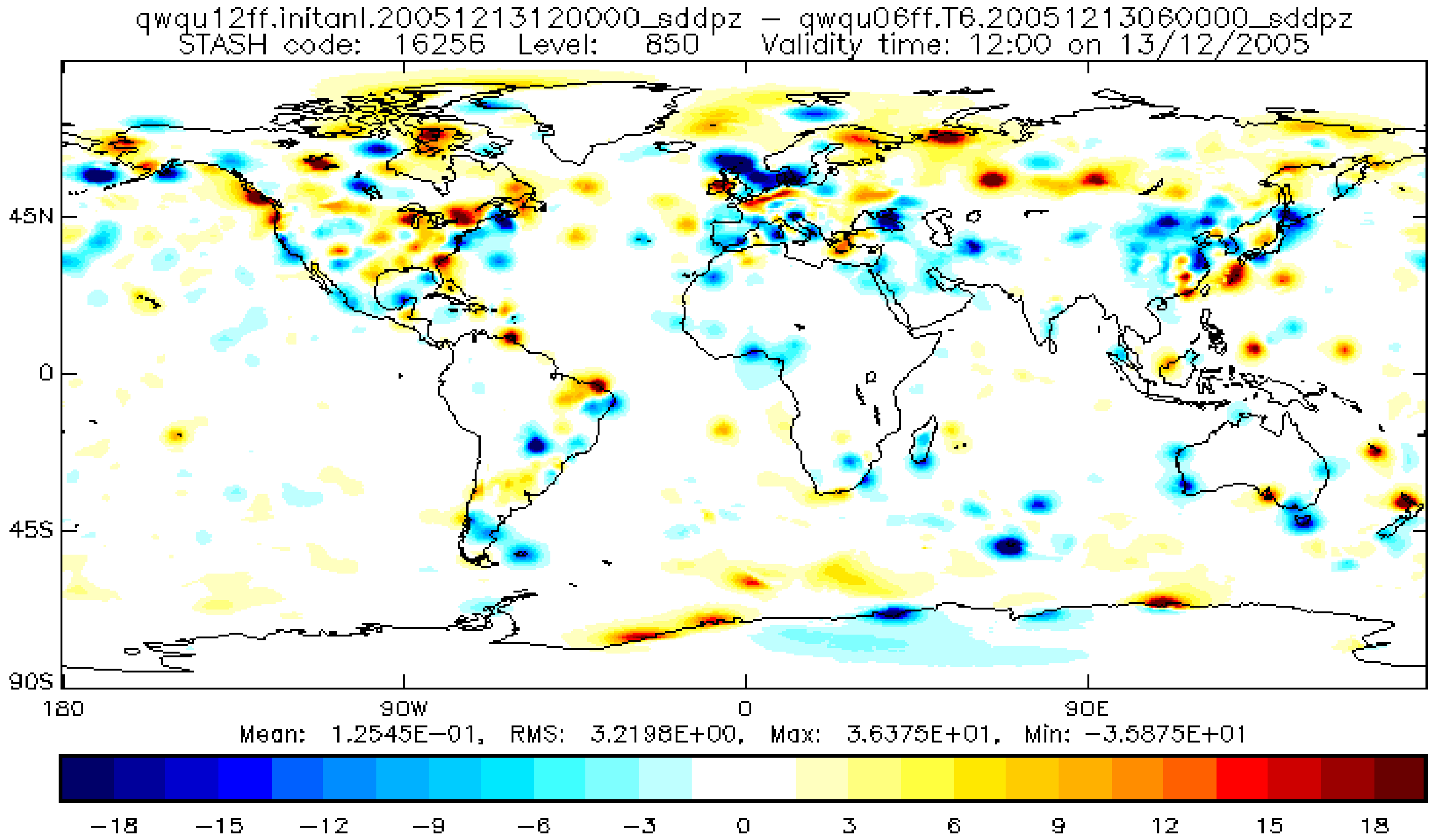
Approach

1. Test liquid cloud part only with microwave 23 and 31 GHz observations.

- Validate radiative transfer.
- Compare increments and check impact on fit to observations in next cycle.
- Run simplified assimilation experiment (NOAA-16 only).

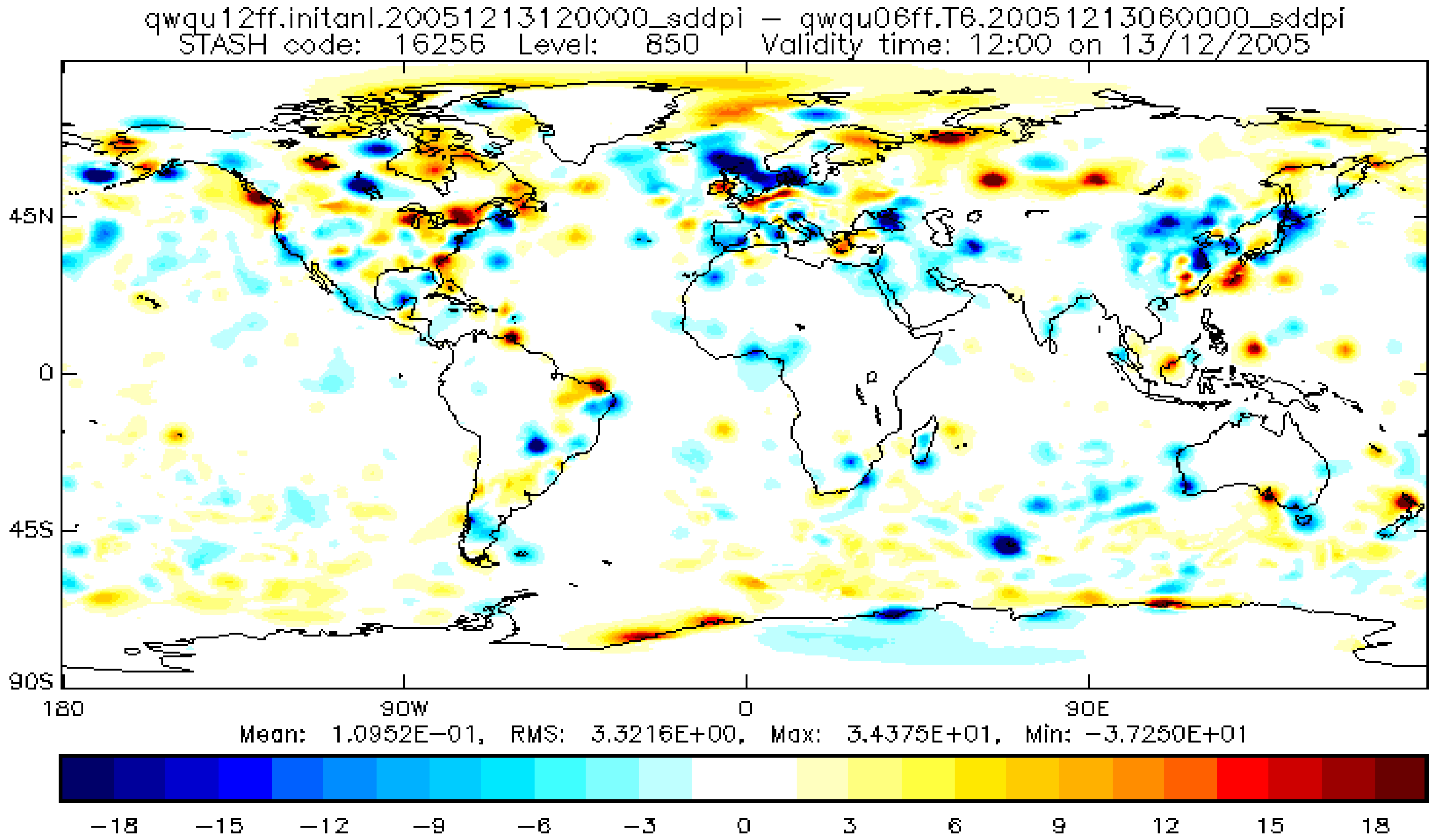
2. Extend to GeoIR cloudy radiances using ice cloud and cloud fraction in incrementing operator.

Cloudy 23 & 31 GHz Analysis Increments



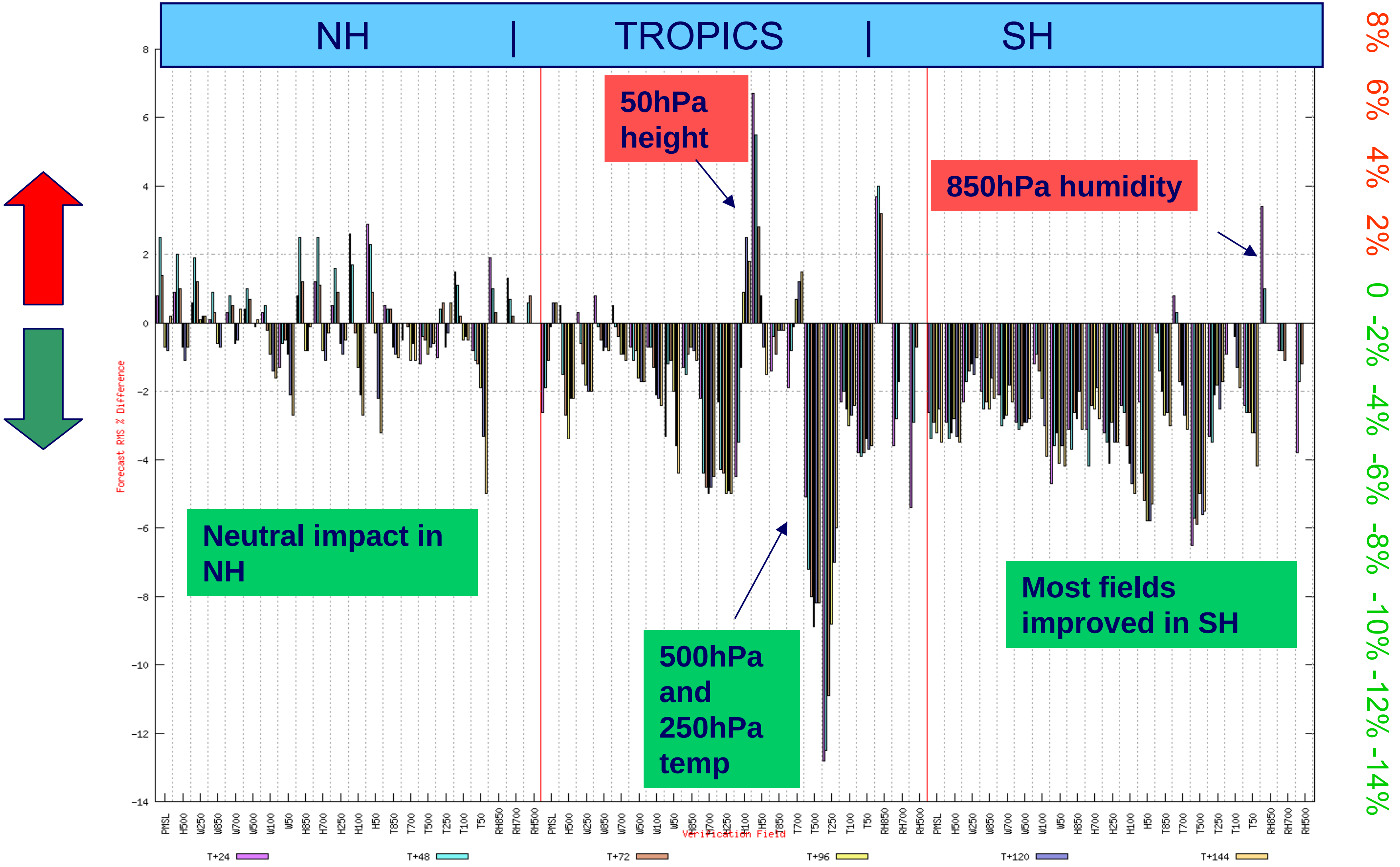
Specific humidity at 850 hPa.

Cloudy 23 & 31 GHz Analysis Increments

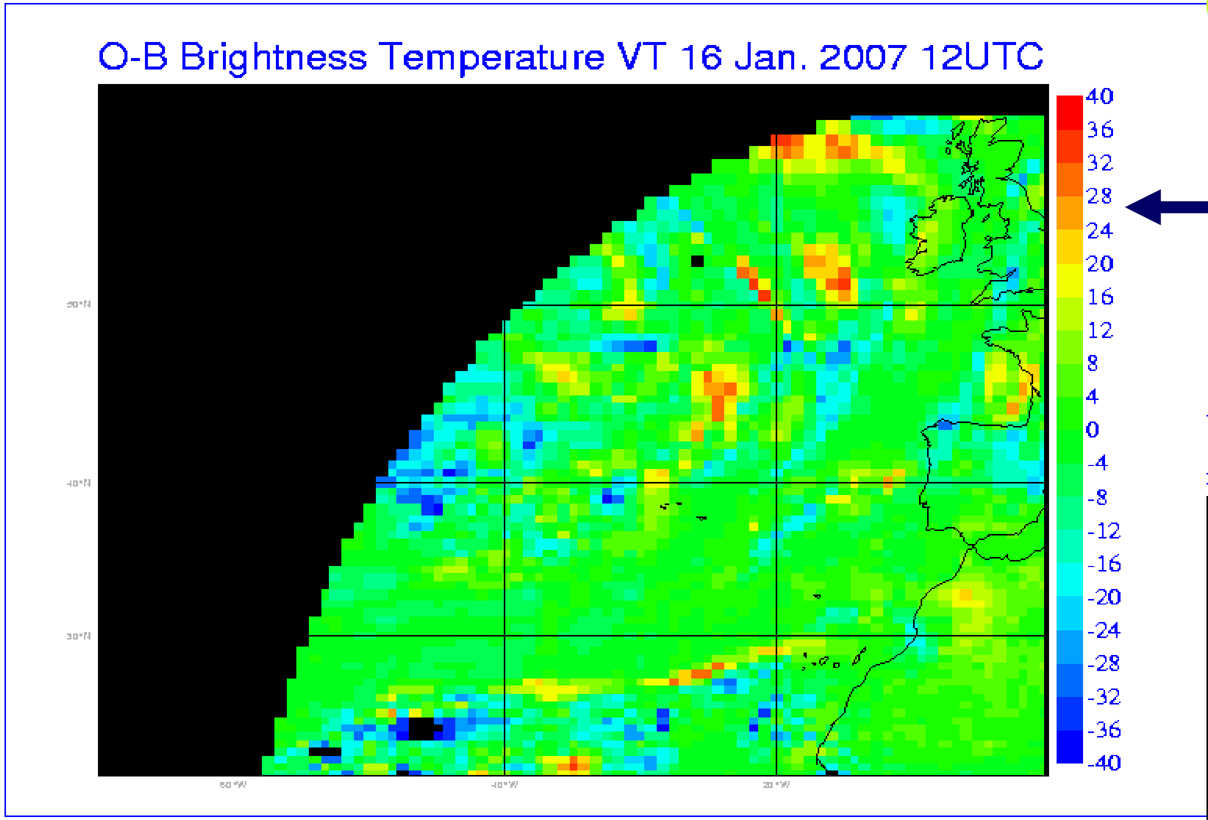


Specific humidity at 850 hPa.

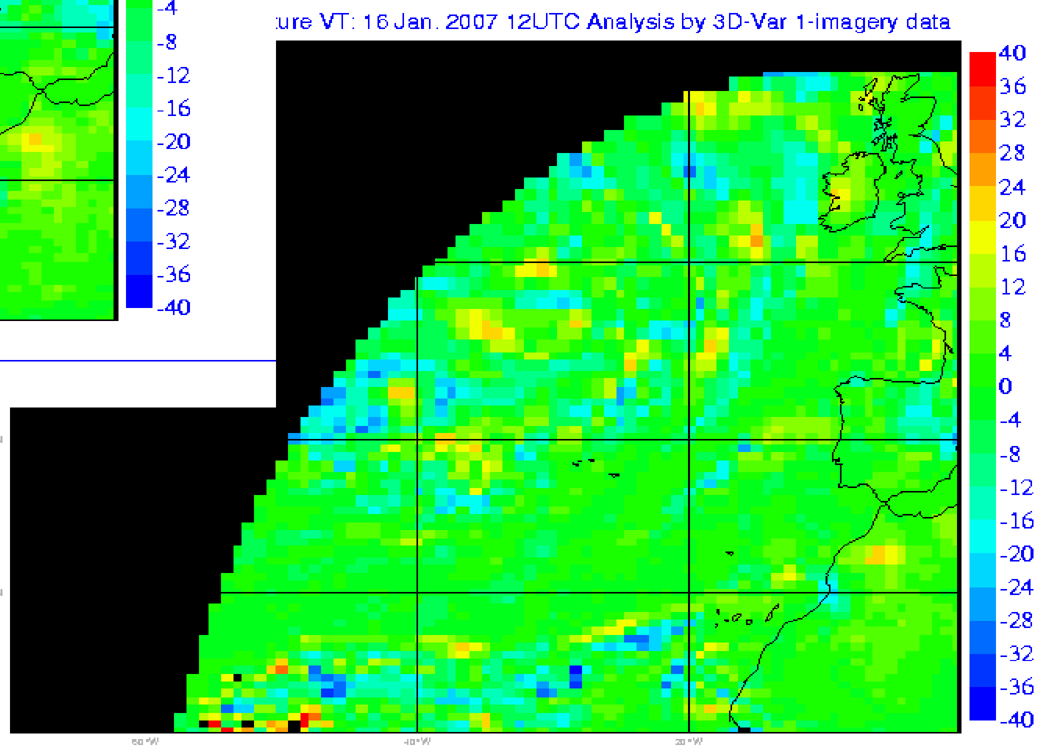
Impact on large scale fields fit to analysis



Ice incrementing operator: GeoIR assimilation



Observation minus background



Observation minus analysis

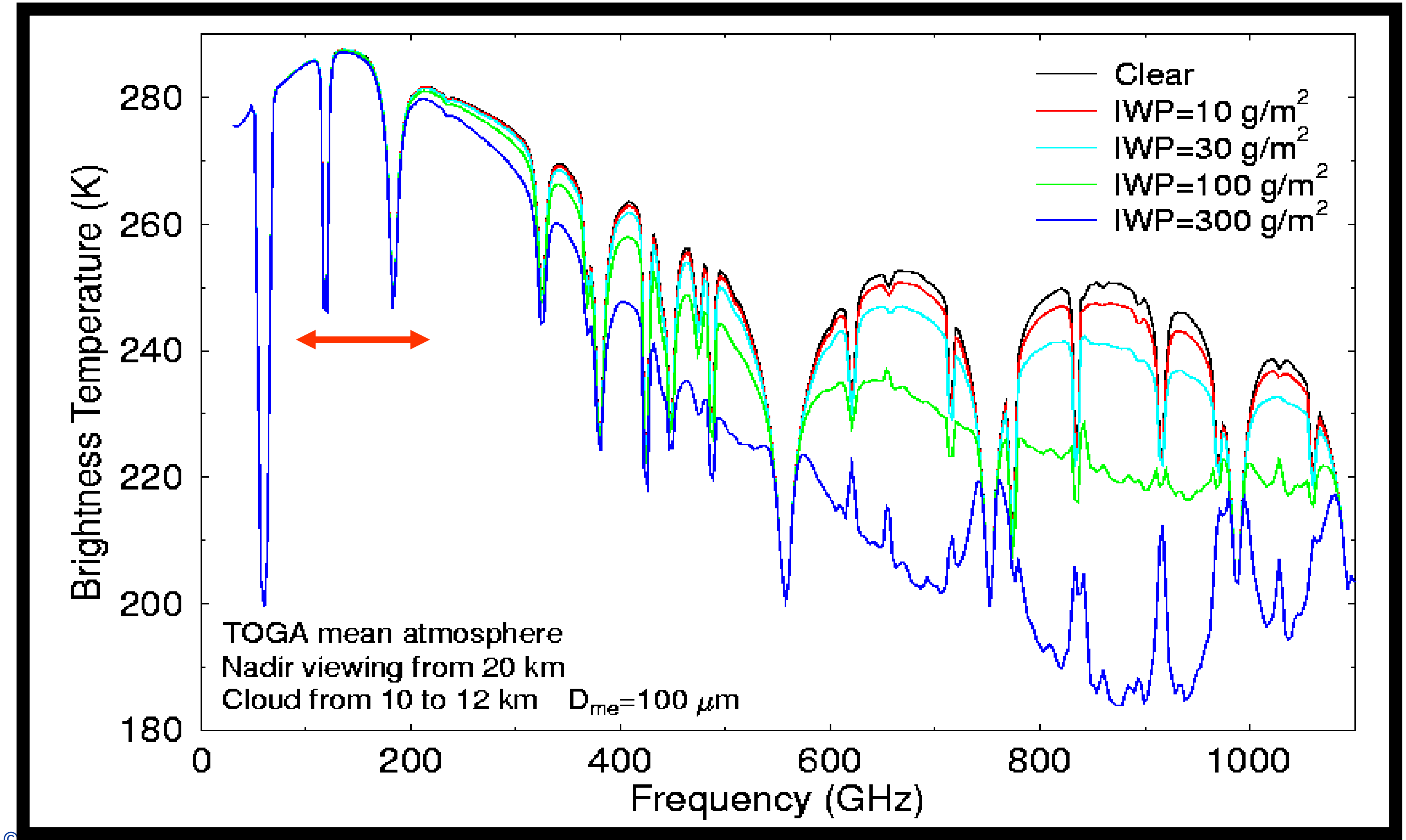
Met Office

Use of AMSU-B and MHS data in the presence of ice cloud and precipitation

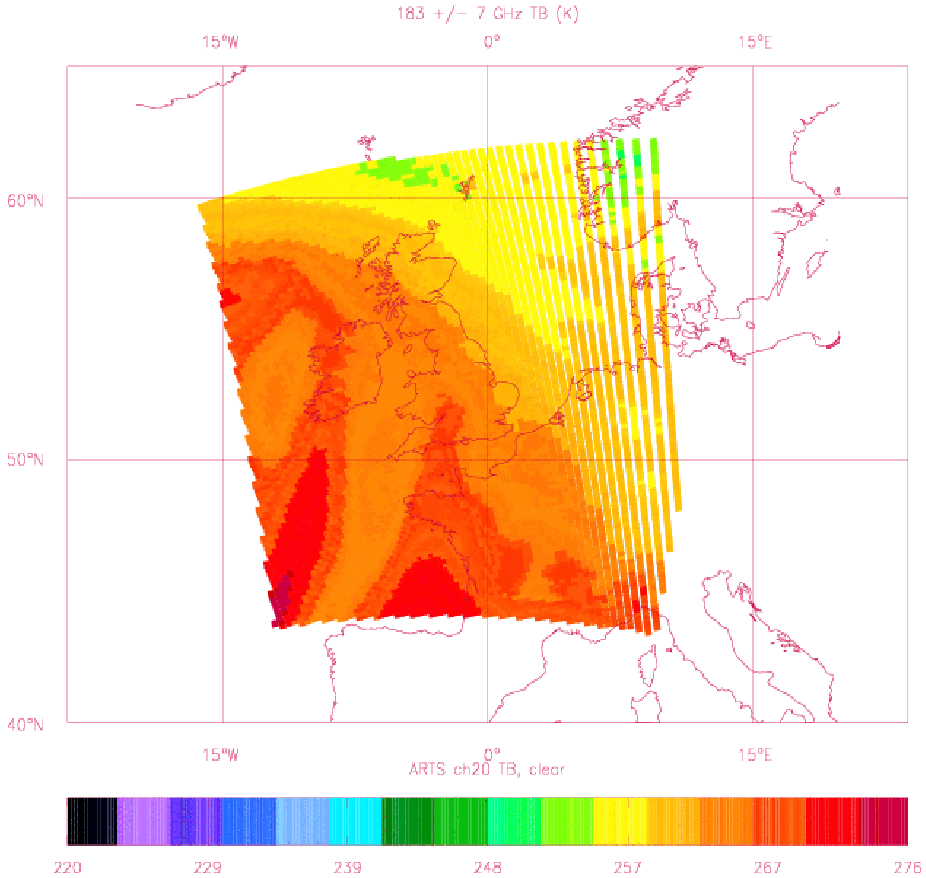
(Amy Doherty)

Effect of ice at microwave frequencies

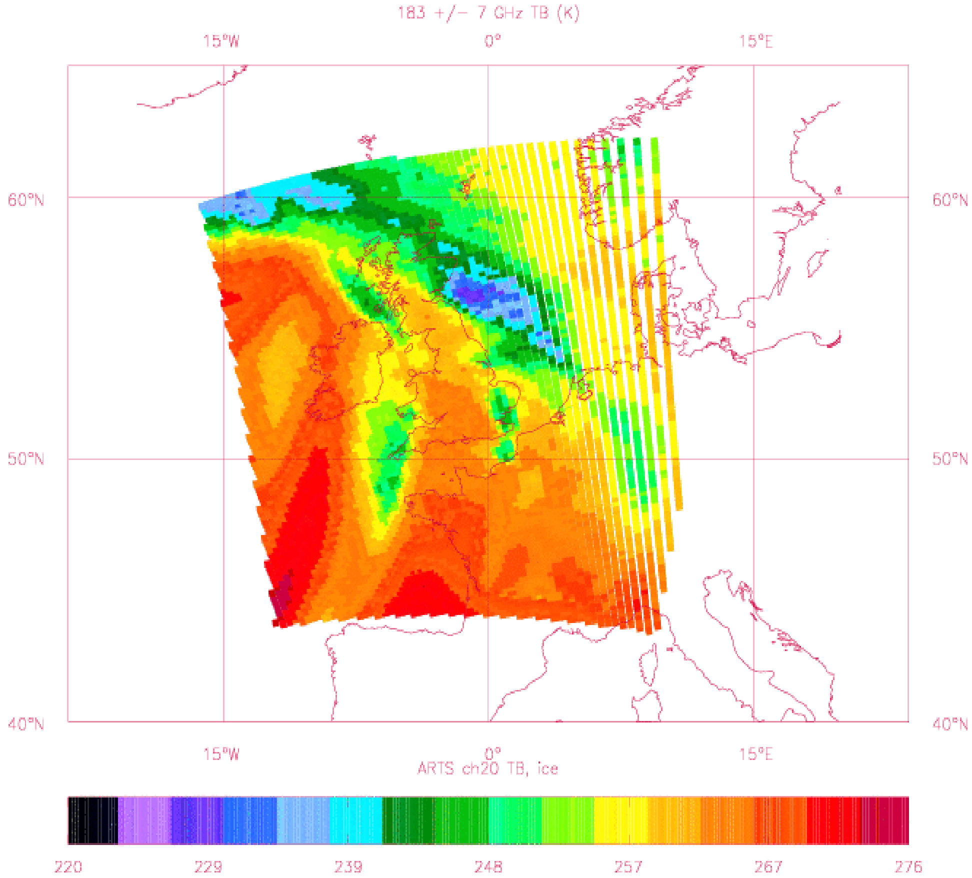
Courtesy of Frank Evans



Ice signal in AMSU-B channel 20 Brightness Temperatures: 10s of Kelvin.



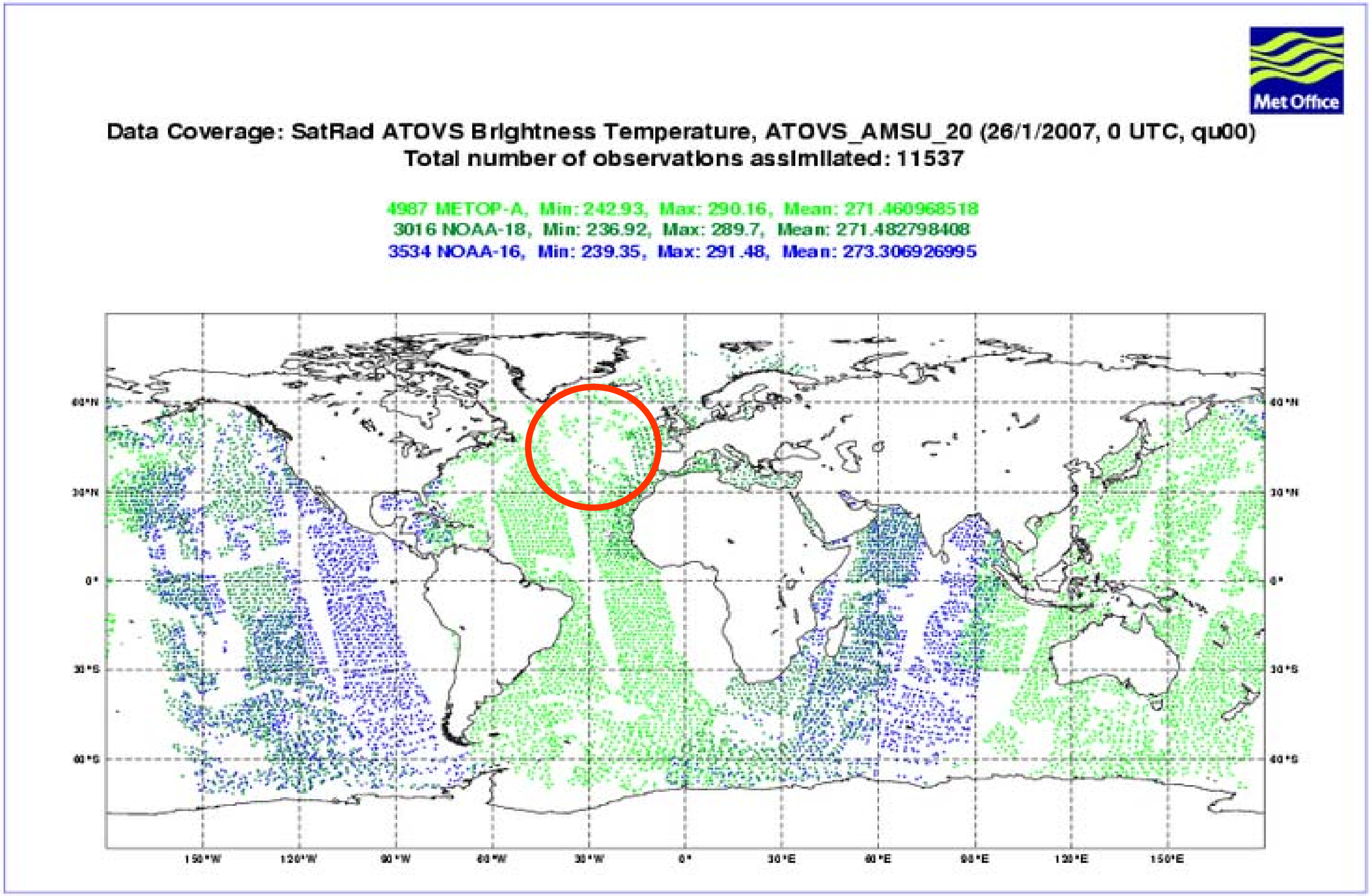
Simulation without ice



Simulation with ice

183 ± 7 GHz

Data actually assimilated from one AMSU-B channel

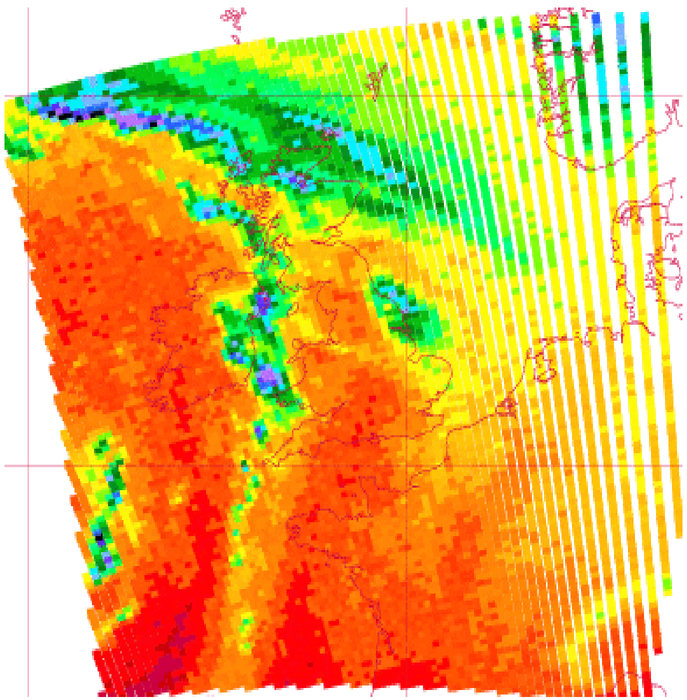


Interface between forecast model and RTM

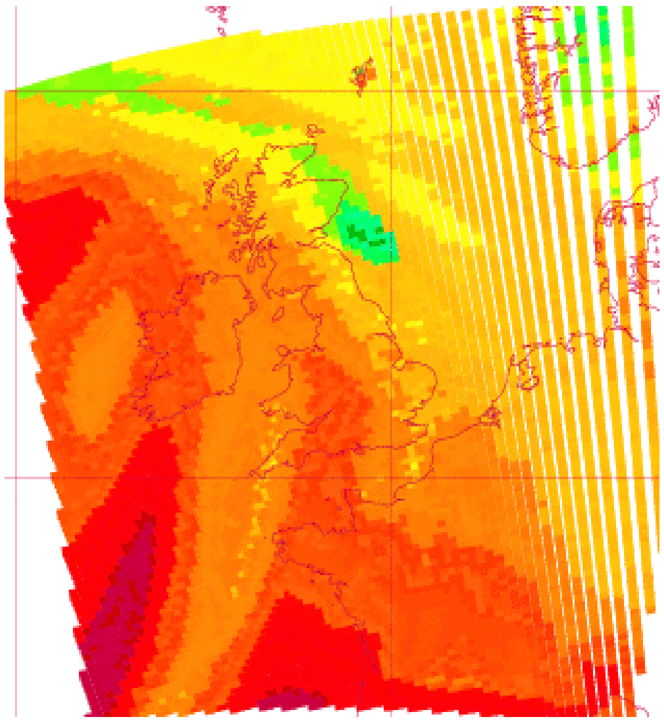
- Definition of snow and ice different in forecast model and RTTOV
- Ice hydrometeor density assumptions do not match
- Size distributions do not match
- Fall speed assumptions do not match
- Deblonde et al. (MWR 2007) noted that moist physics schemes are very different between NWP centres and this significantly affects results.
- Do we need to go back to more fundamental model quantities e.g. moisture fluxes and make RTM do more to ensure consistency?
  - Peter Clark said a recent intercomparison of NWP systems showed moisture fluxes are consistent but derived quantities e.g. ice water content are not.

Given IWC, RTM tuned DSD (ARTS) compared to fixed DSD (RTTOV)

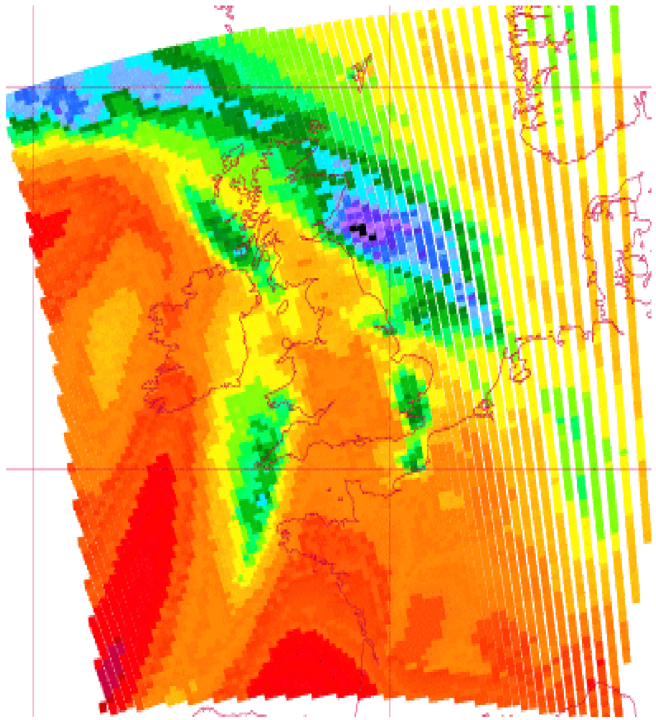
AMSU Channel 20 (183 ± 7 GHz)



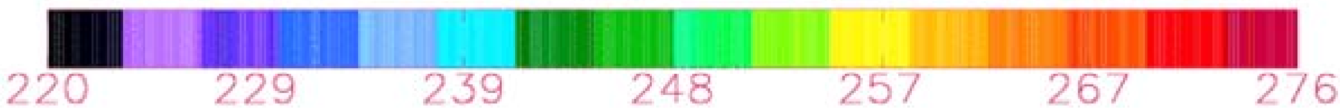
Observation



RTTOV-8 simulation



ARTS simulation



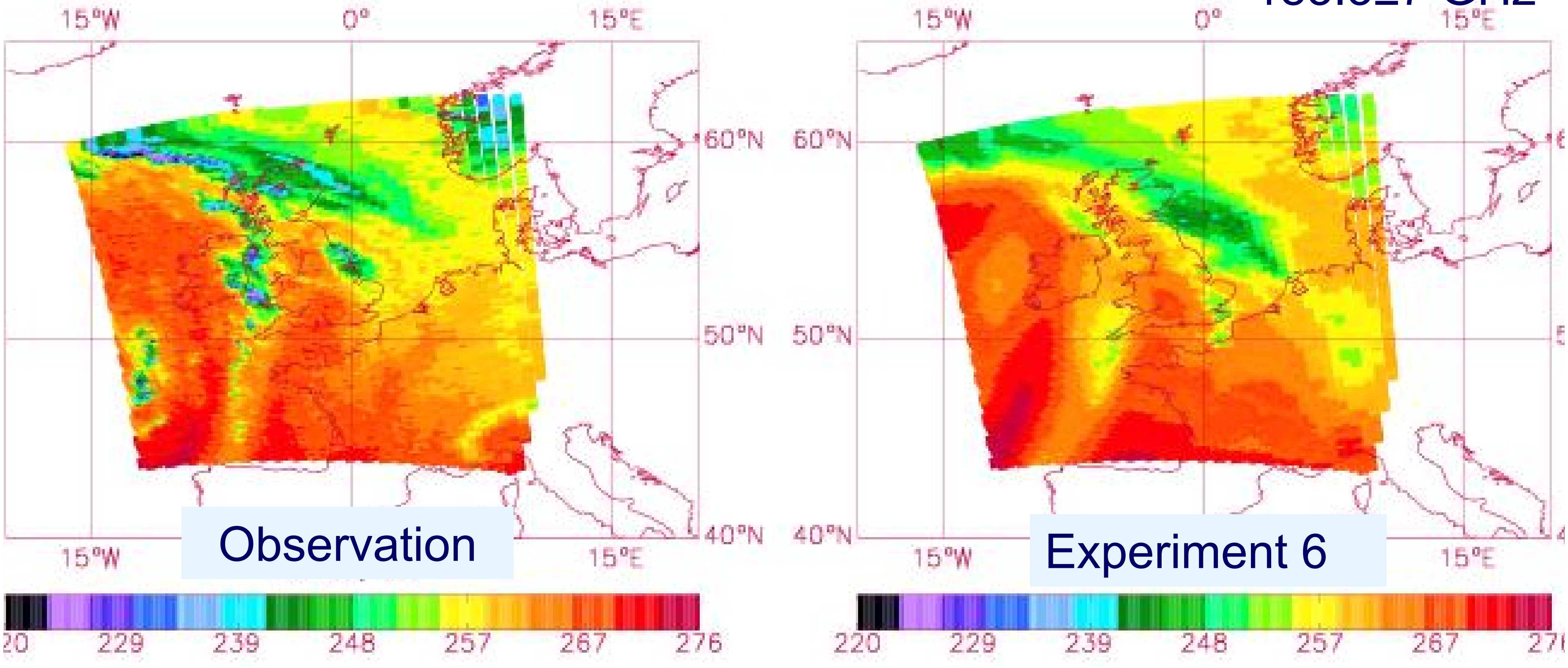
Brightness Temperature (K)

Results for Experiment 6

PSD = Function of T and IWC (Field *et al.*,2005)

Density = 0.132 D^{-1} (Wilson and Ballard, 1999)

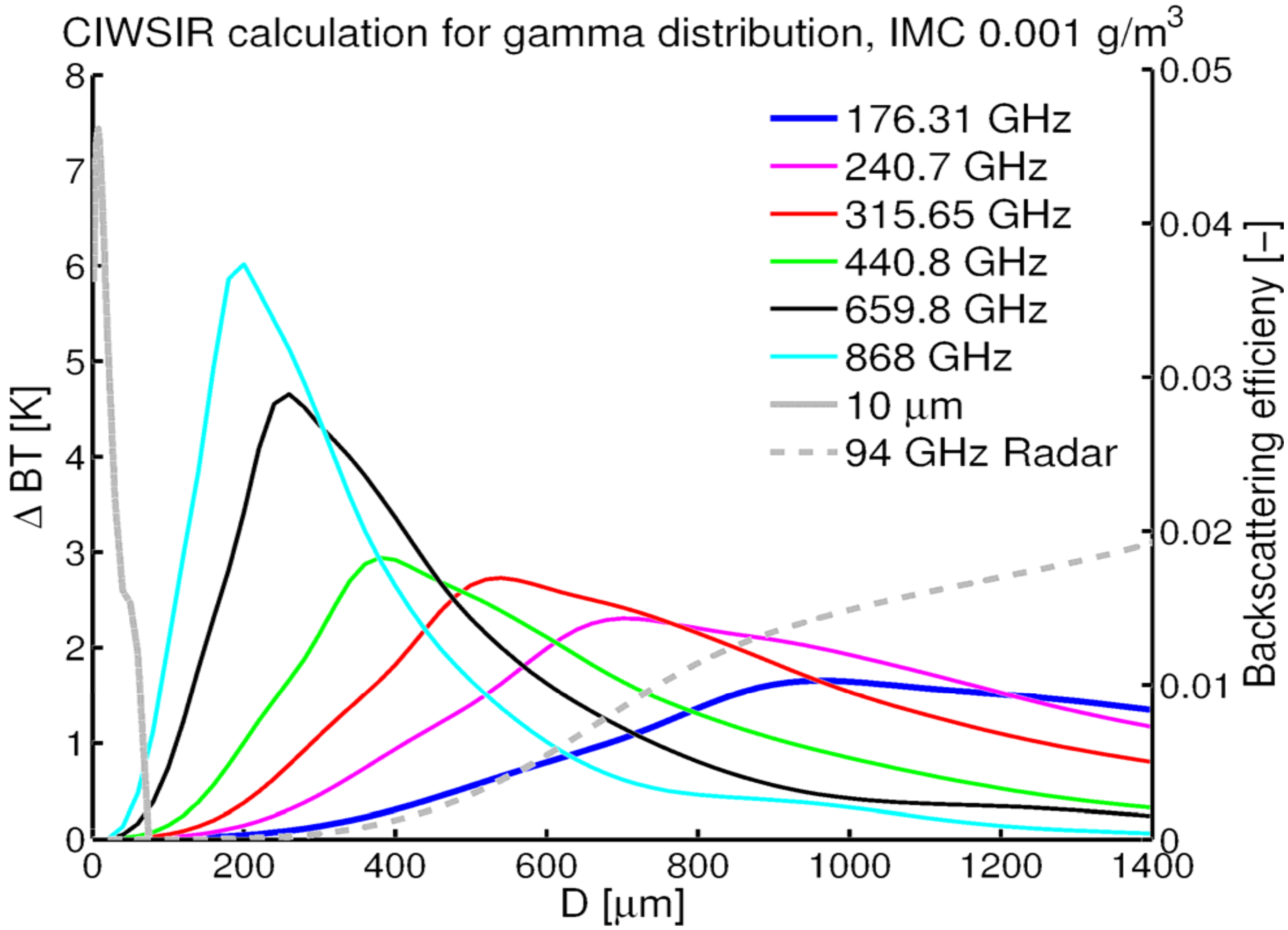
183.3±7 GHz



Use of sub-mm for ice cloud

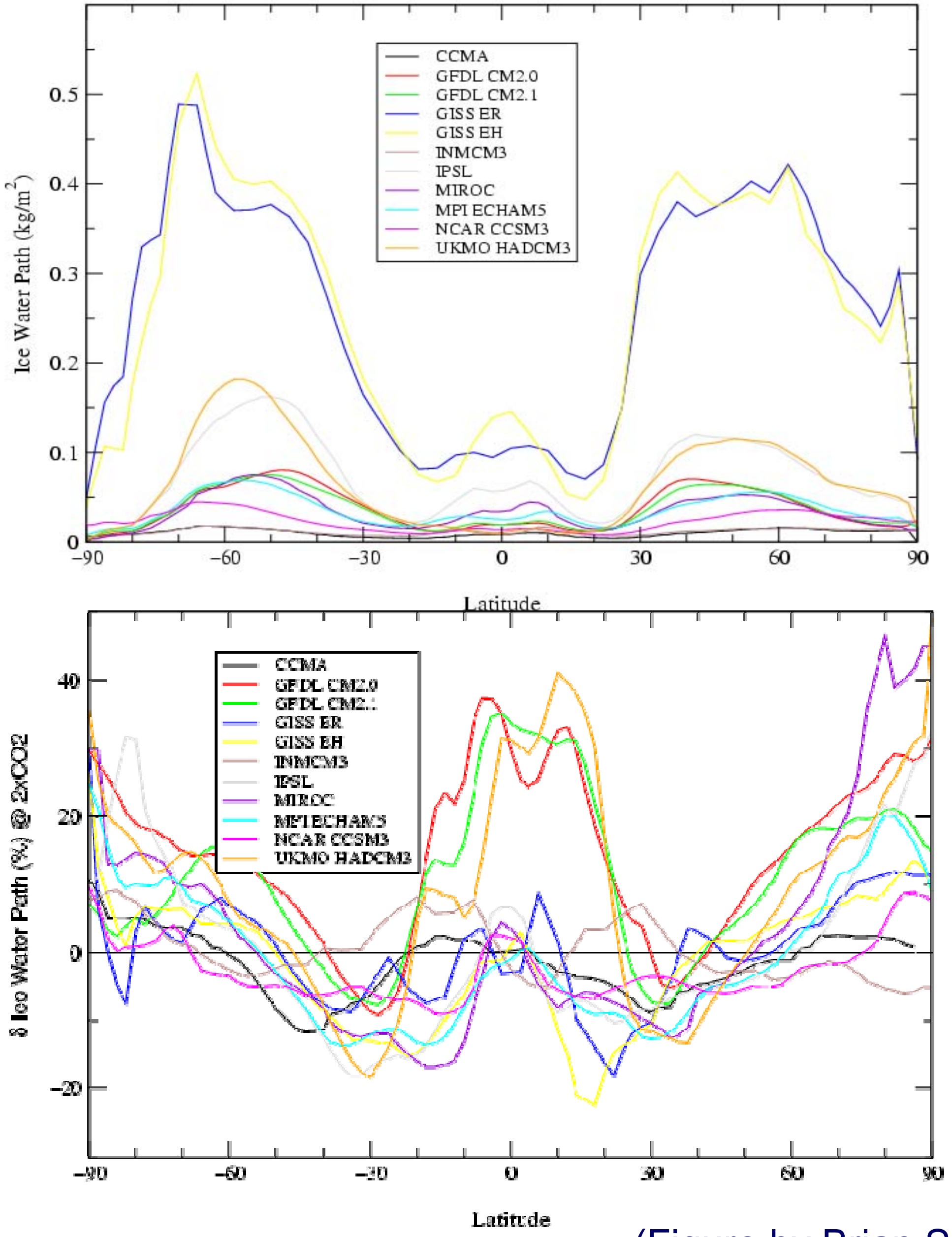
(Stefan Buehler, Clare Lee etc.)

Sub-mm (from Stefan Buehler, Kiruna Univ.)



IR sees only smallest particles, radar only largest particles

Ice Clouds in Climate Models



- Climatology of zonal, annual mean IWP from various models in the IPCC AR4 data archive shows difference up to an order of magnitude.
- Delta-IWP after a CO2 doubling shows also vast differences.
- IWP observations are needed to resolve model differences.

(Figure by Brian Soden, University of Miami)

Possible future instruments to exploit sub-mm…

- CIWSIR: multi-channel sub-mm instrument matching WV sensitivity with difference ice cloud sensitivity. LEO, resolution ~ 15 kms.

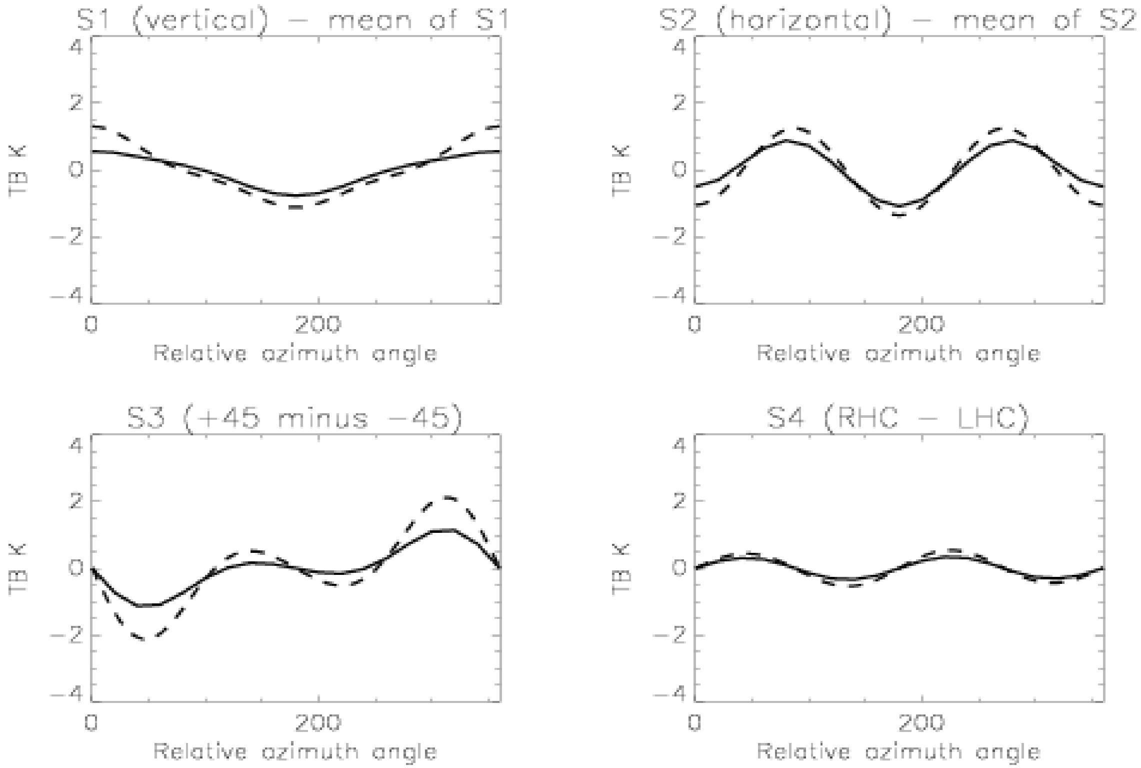
- GOMAS: Geostationary MW and sub-mm imager/sounder. From 81 km spatial resolution at 54 GHz to 10 km at 425 GHz. An IGeoLab concept.

- Geostar: similar to GOMAS with synthetic aperture. JPL proposal.

(but GOMAS & Geostar really precipitation missions)

Polarimetric radiometry

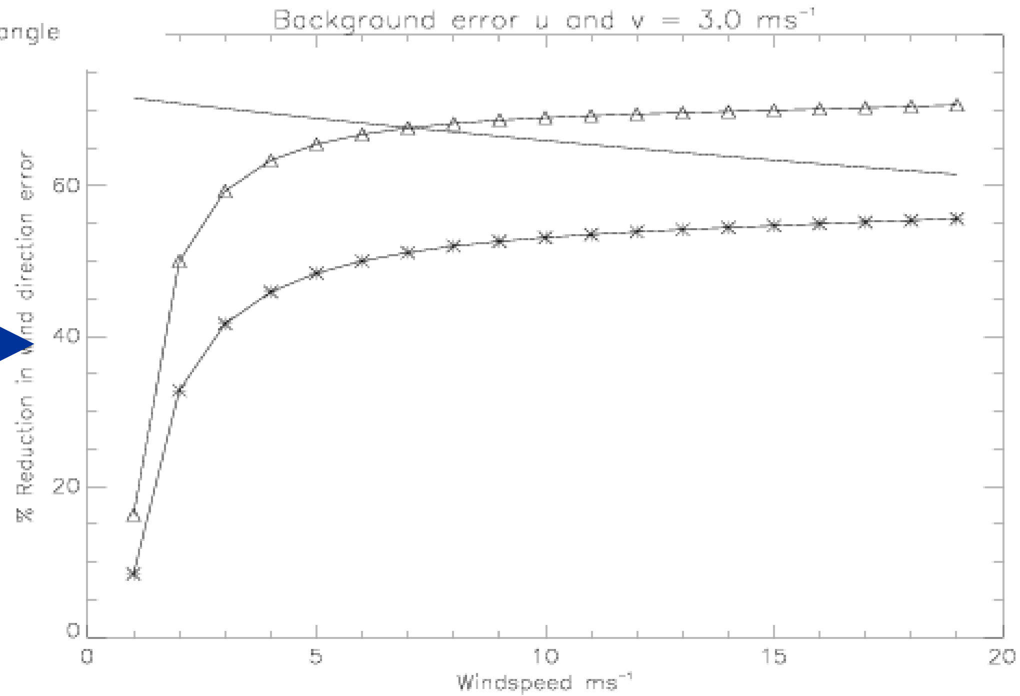
(Brett Candy)



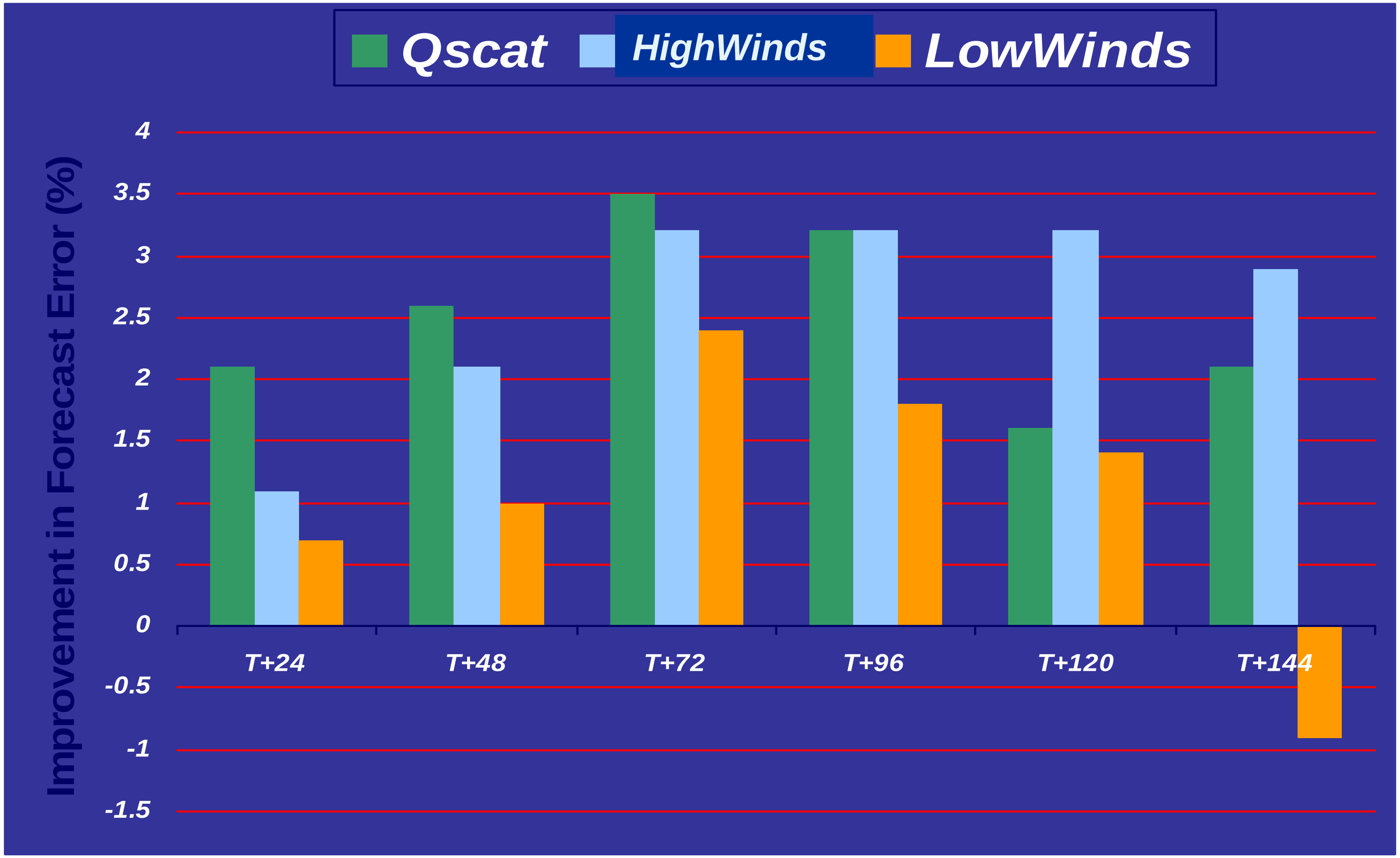
Amplitude and linear polarisation SSM/I etc. => wind speed

3rd/4th elements of Stokes vector WindSat => wind direction

Error analysis based on model fit to actual WindSat and QuikSCAT suggests WindSat comparable to QuikSCAT > 5 ms^{-1}



Extra-tropical pmsl impact of QuikSCAT high and low windspeed wind vectors



Ambiguities: QuikSCAT and WindSat

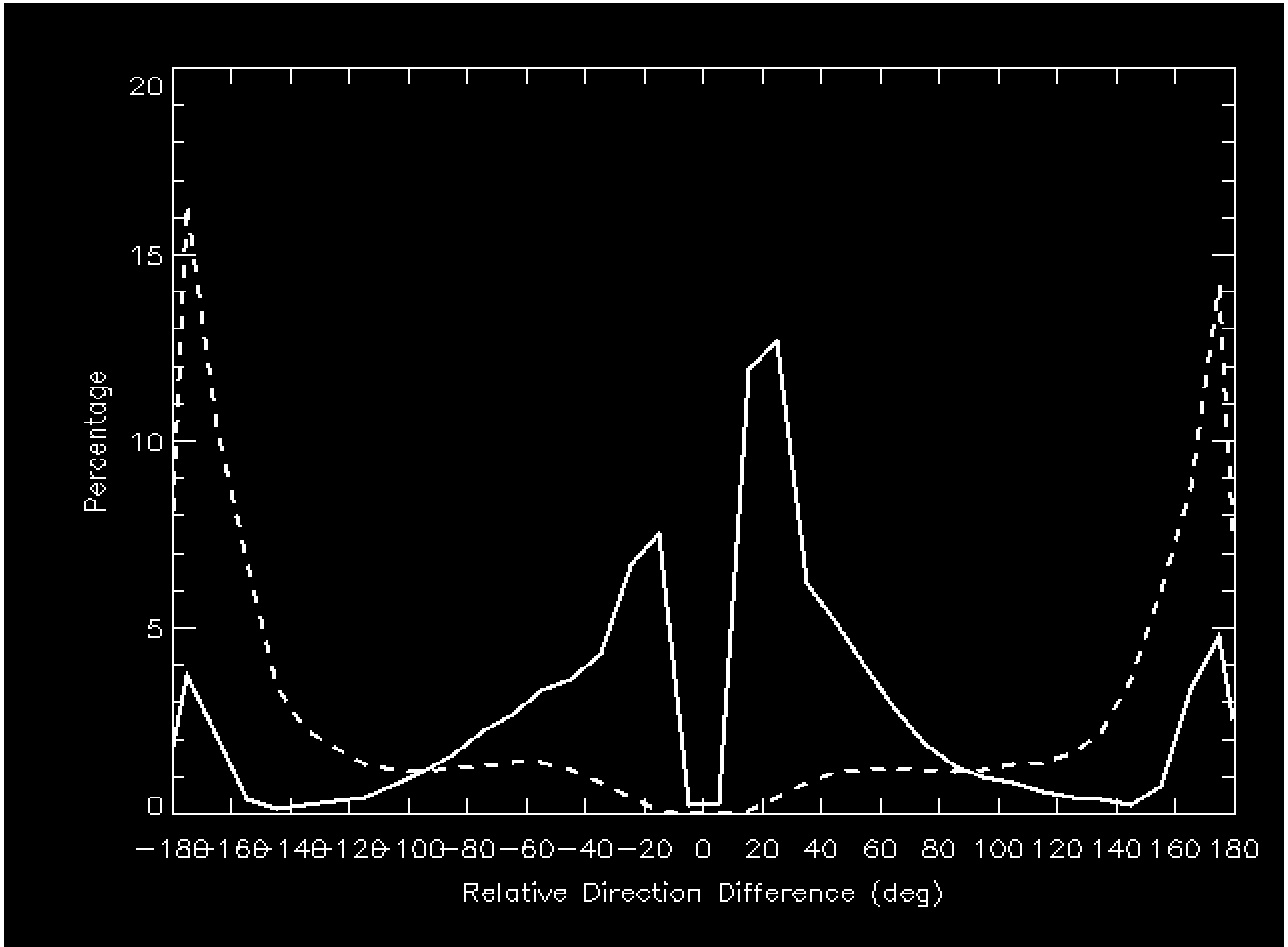
QuikScat

2% 1 wind

43% 2 winds

33% 3 winds

22% 4 winds



WindSat

<0.01% 1 wind

<0.01% 2 winds

28% 3 winds

72% 4 winds

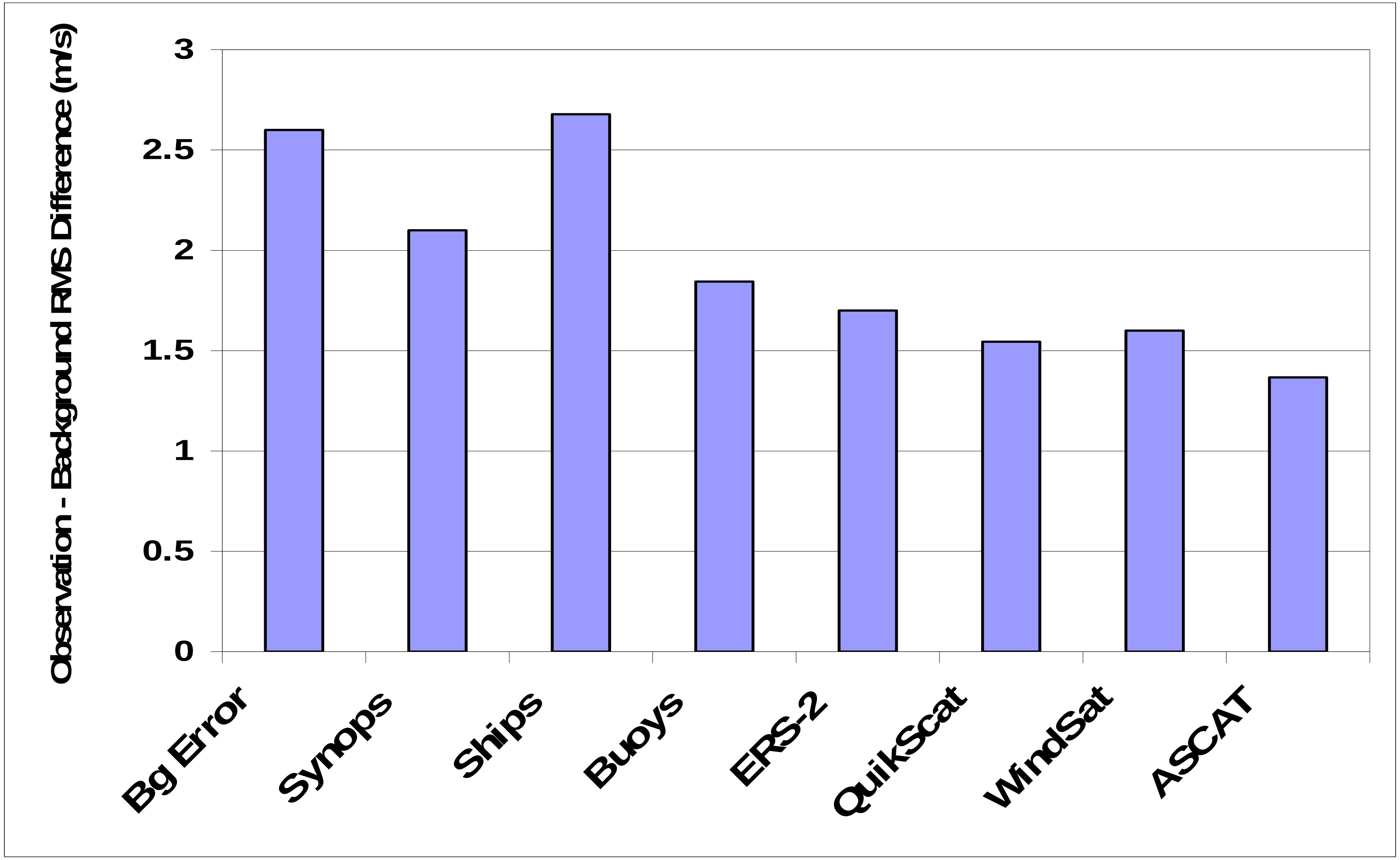
Wind Speed and Direction

WindSat Mission Requirements: 2m/s 20deg

Phase 1 suggested useful retrievals down to around 8m/s

Wind Speed Range (m/s)	**Standard Deviation of Observation – Background**	
	Wind speed (m/s)	**Wind Direction (°)**
5-6	1.26 *1.29* **B**	21.0 *17.2*
6-7	1.20 *1.26* **B**	16.8 *14.2*
7-8	1.19 *1.24* **B**	13.9 *12.1*
9-10	1.34 *1.33*	10.5 *9.8*
10+	1.42 *1.49* **B**	8.6 *9.0* **B**

How does this compare to other observing systems?



WindSat assimilation experiments

- As Met Office operations in mid-2005 except control had Scat, SSM/I, TC bogus withdrawn.

- Model Resolution N216 ~60km in mid-latitiudes, model top at 40km.

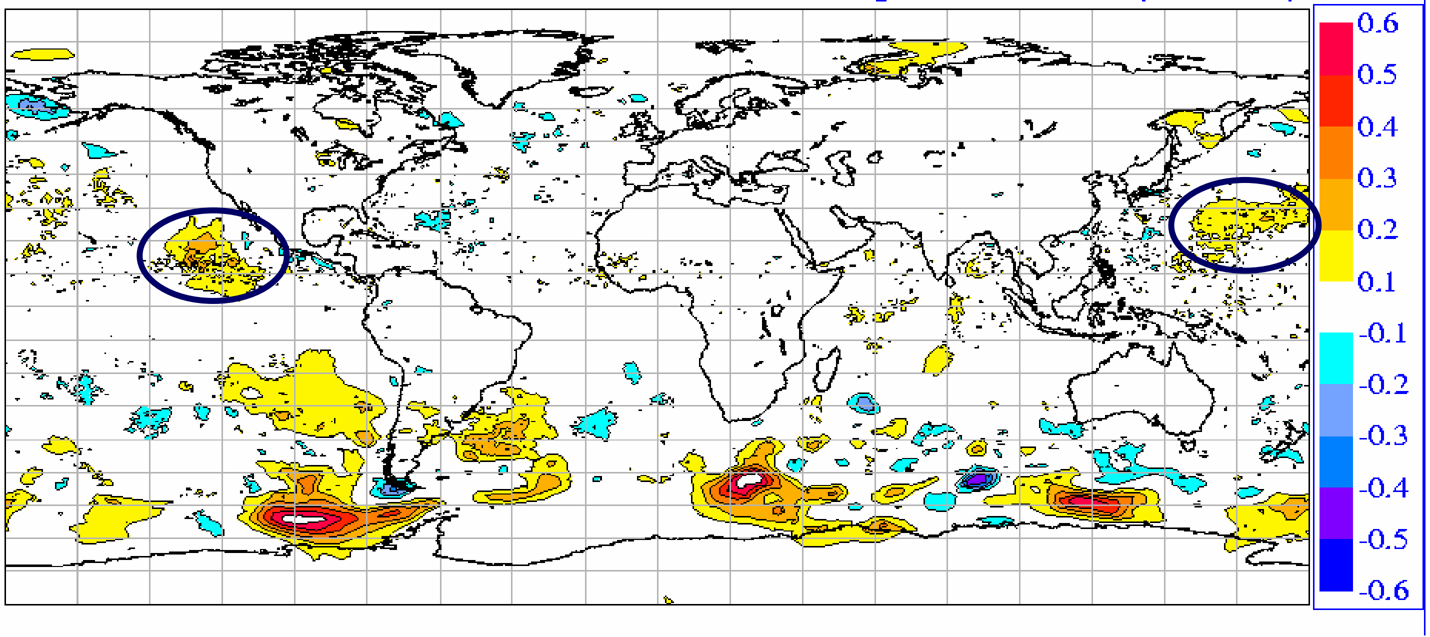
- 4D-Var Analysis scheme, four analyses per day with data windows of 6 hours.

- Period August-September 2005 (active TS season – over 20 different storms in 34 days!)

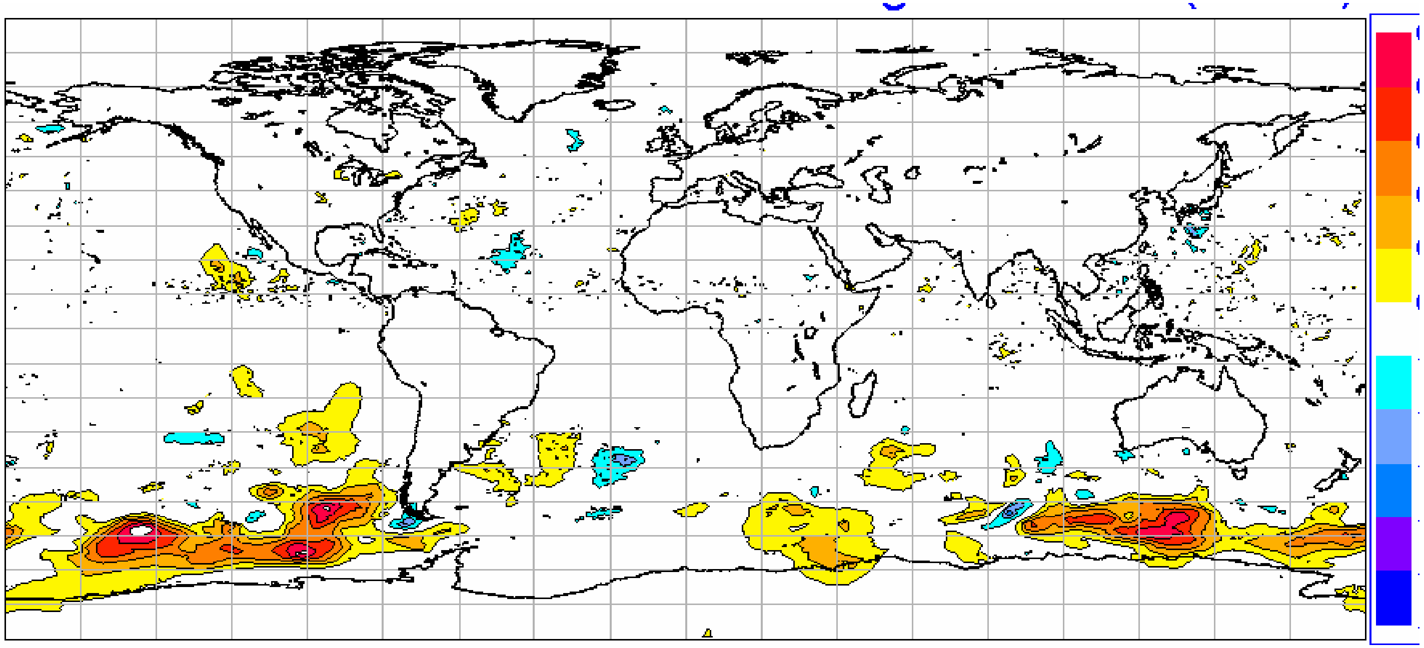
- WindSat treated identically to QuikSCAT (e.g. same ambiguity removal, thinning etc.)

Analysis Increments

QuikScat

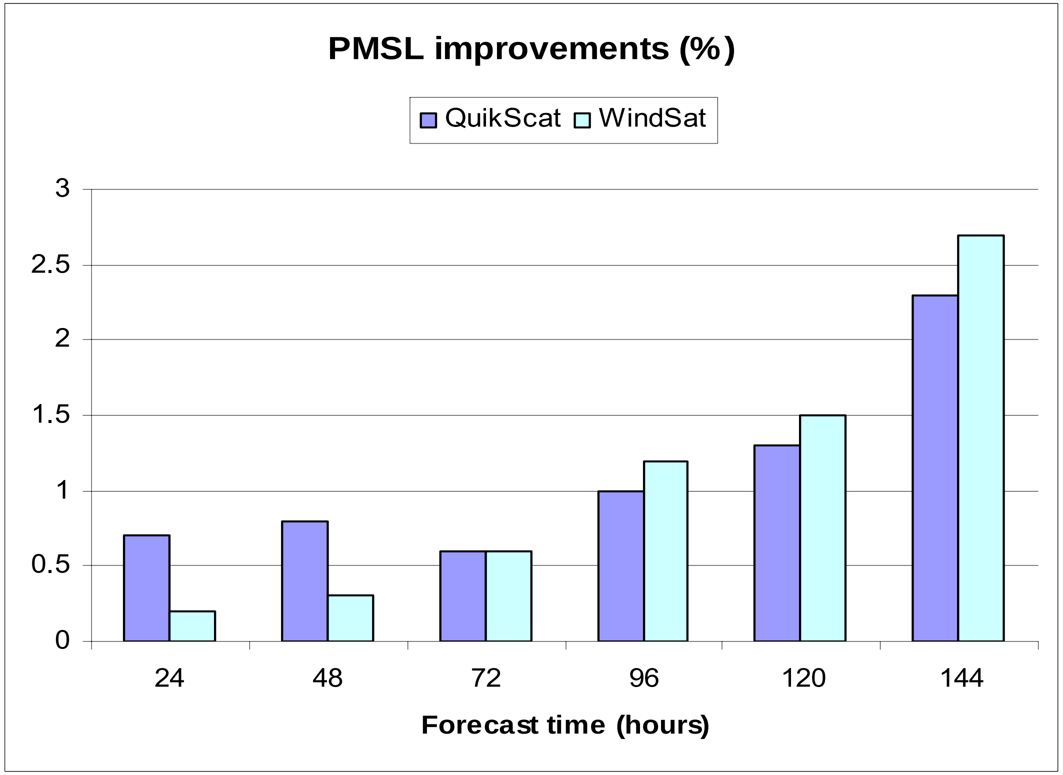


WindSat

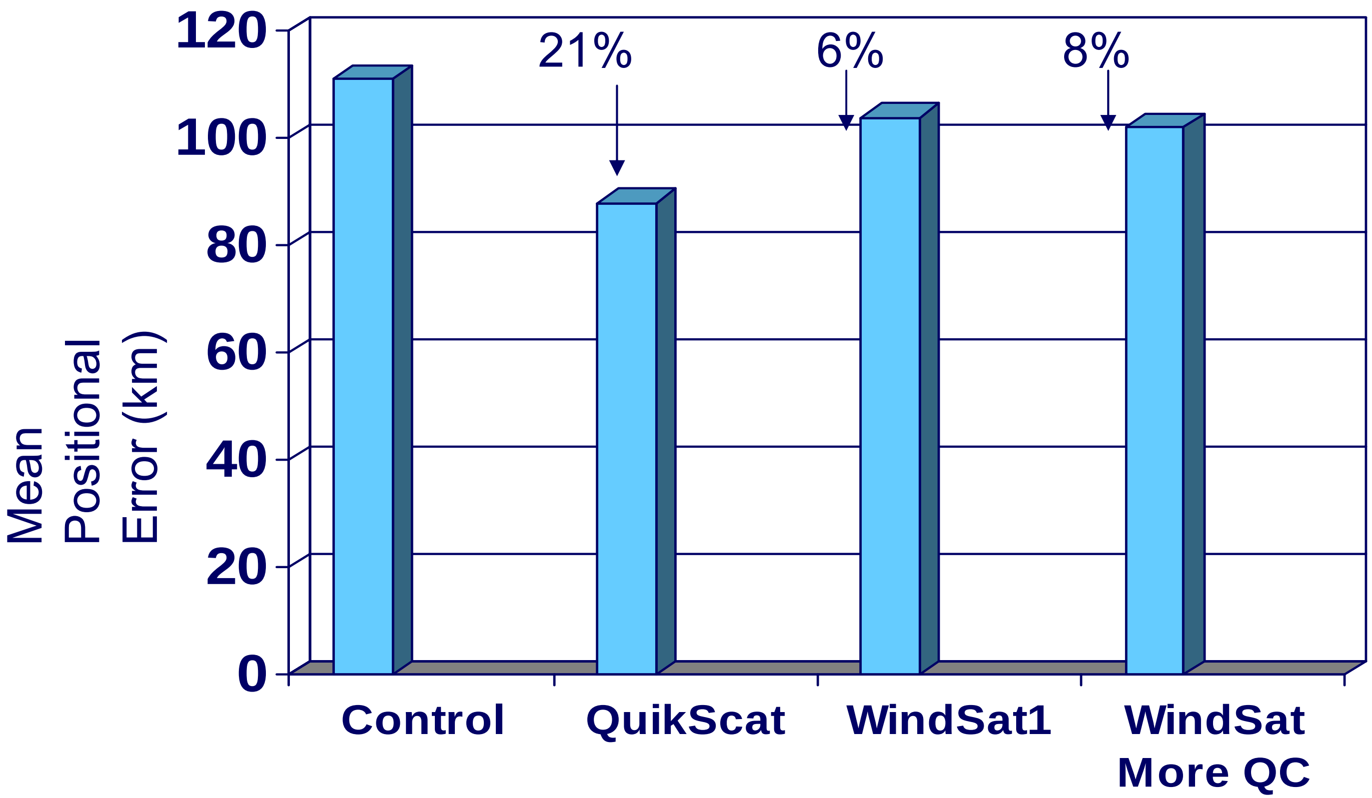


WindSat 1 Impact

5% of parameters improved, <0.5% degraded



Tropical Cyclone Errors in Analysis Results from 19 cyclones – 206 "events"



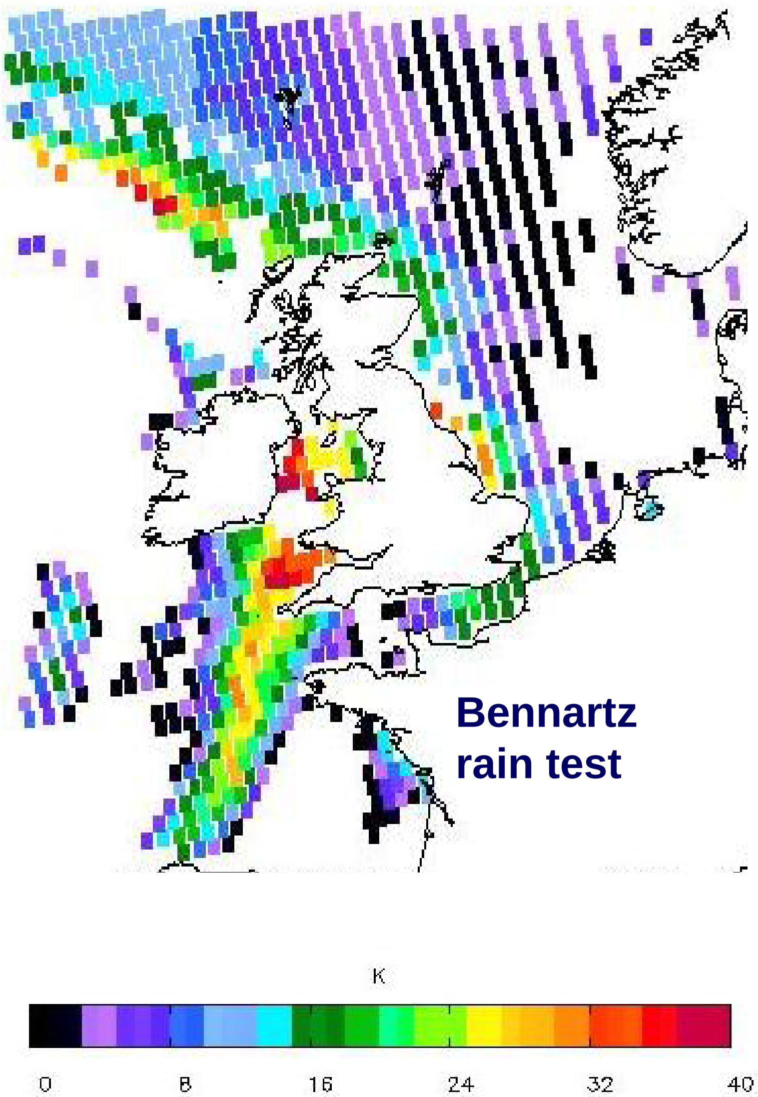
Much smaller study for ERS-2 in 2001 suggested improvement ~10%

Summary

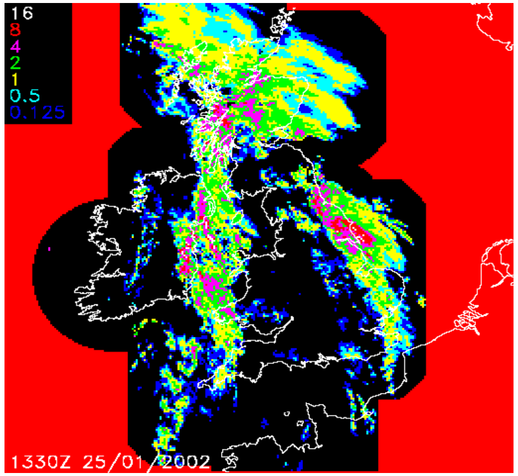
- Cloud and rain limit the use of sounding and surface observations.
- More sophisticated analysis can partly mitigate this loss.
- Analysing cloud prior to assimilation has worked with AIRS.
- Considerable progress has been achieved with direct assimilation of cloudy radiances: both MW and IR.
- Sub-mm sensors could provide new information on bulk ice cloud properties from polar or geo orbit.
- Polarimetric radiometry can replicate much of the information from scatterometers but scatterometers remain the best source of near surface wind vector information, especially for tropical storms.

Questions?

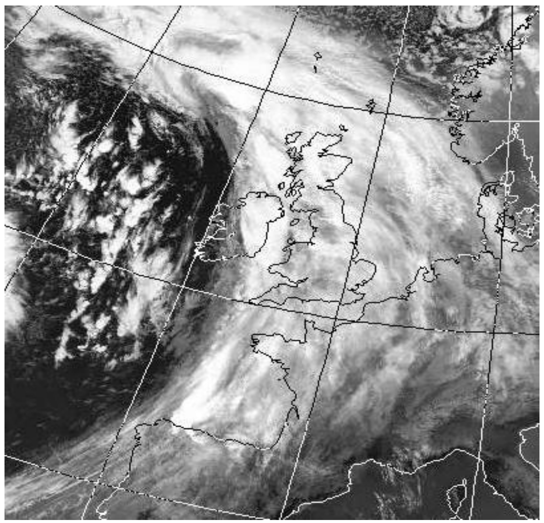
Cloud tests: rain and thick cirrus tests

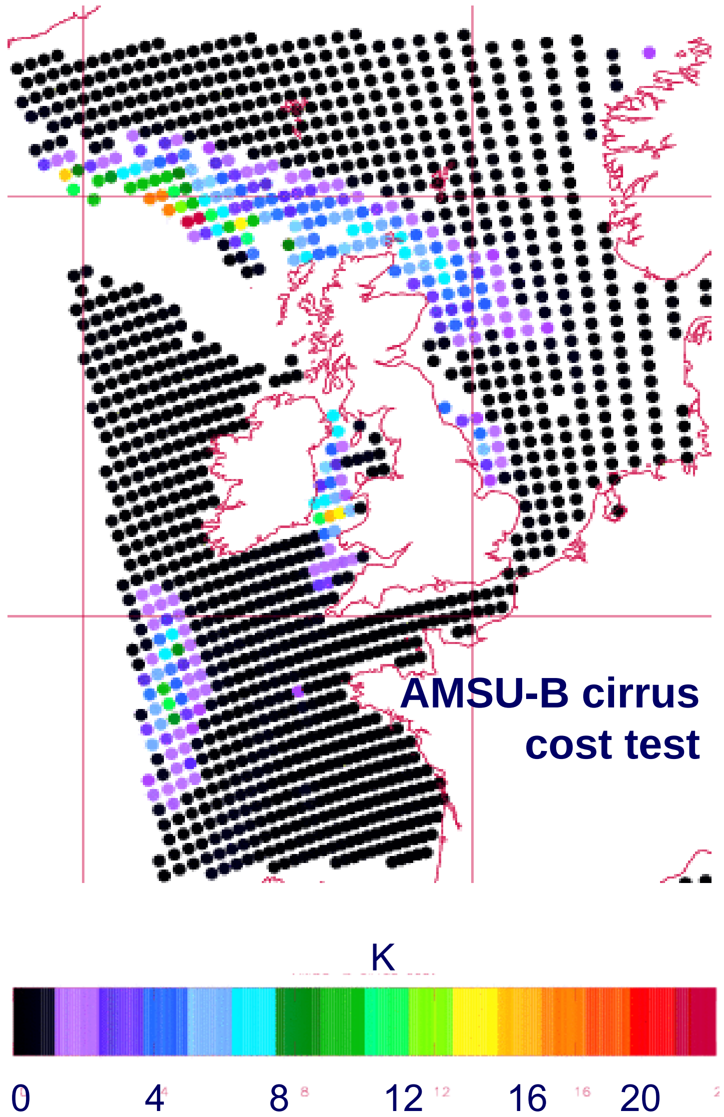


Radar

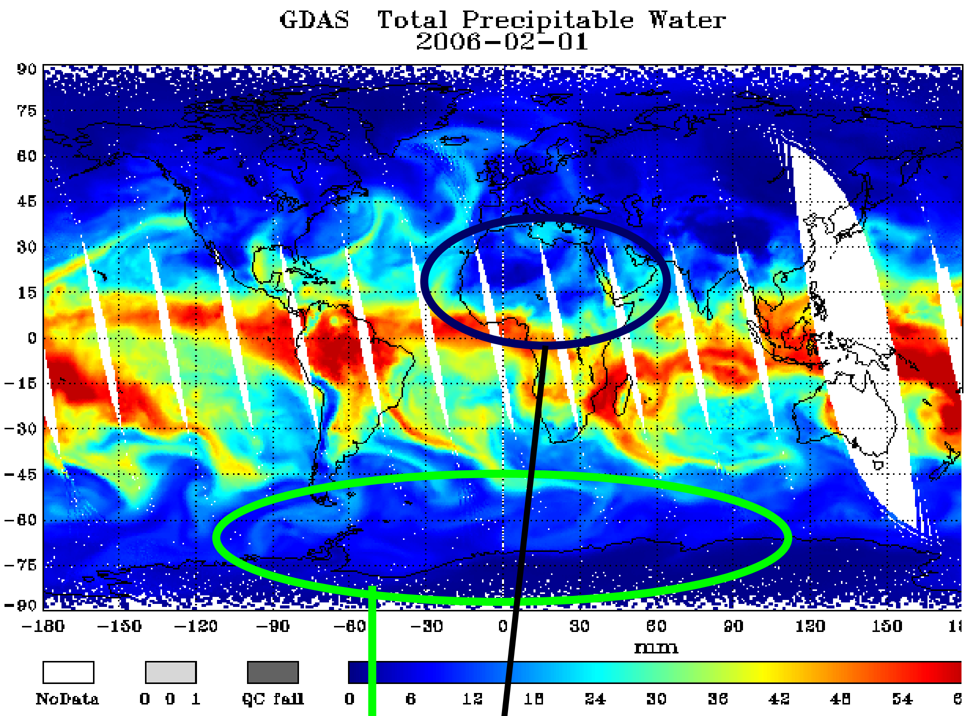


AVHRR IR image

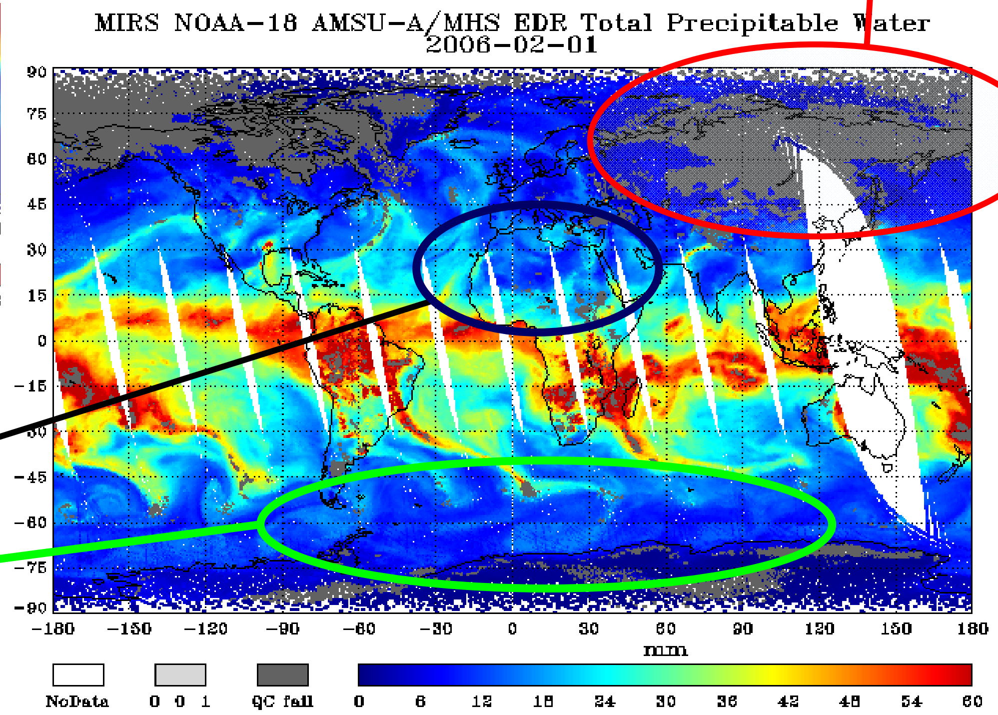




MIRS: Microwave TPW Extended over Land



GDAS Analysis



MIRS Retrieval

snow-covered surfaces need better handling

Retrieval over sea-ice and most land areas capturing same features as GDAS

Met Office

Assimilation of cloudy imagery products

(Ruth Taylor)