Precipitation assimilation at ECMWF

Alan Geer

Summarising the work of very many people, particularly:

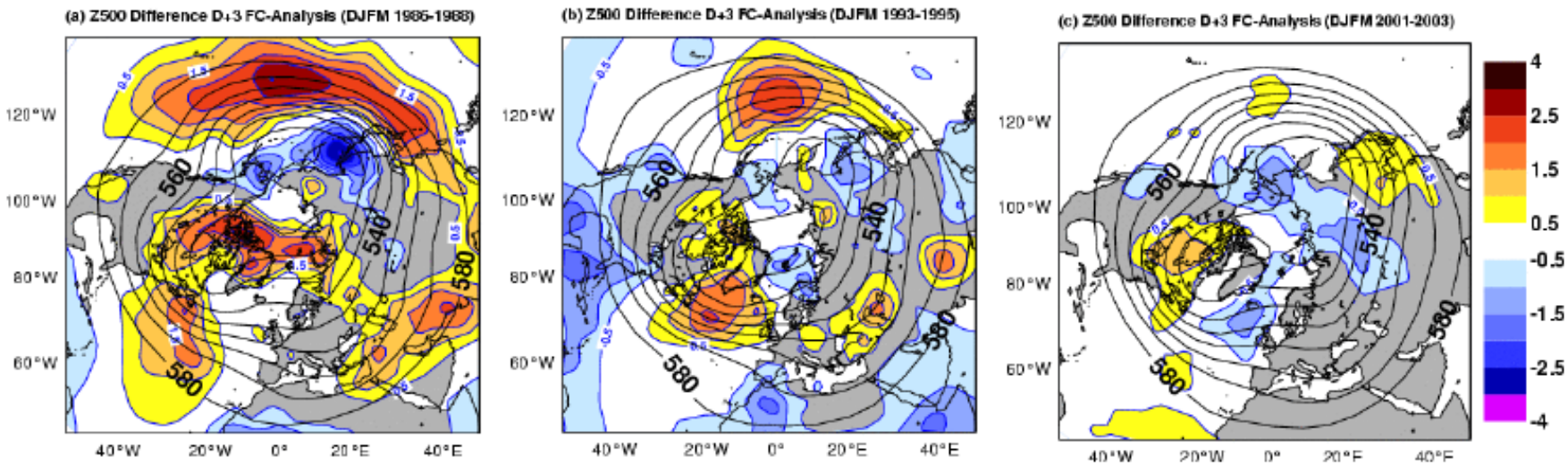
Peter Bauer
Sabatino Di Michele
Chris O'Dell
Philippe Lopez

Snowfall workshop, Montreal, 26-28th June, 2007

Validation

Geopotential at 500hPa: mean forecast errors at day 3

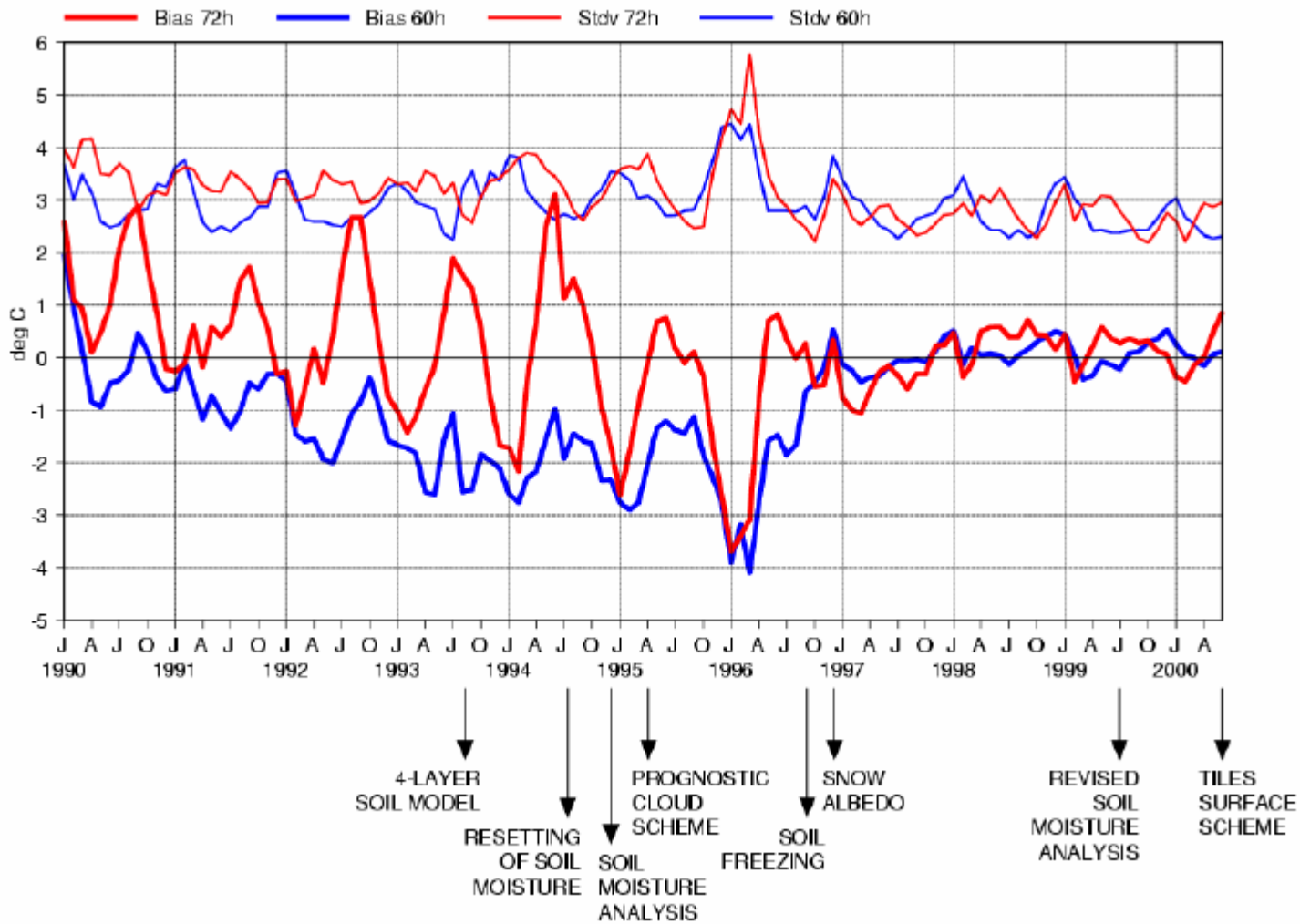
1986-1988 **1993-1995** **2001-2003**



Jung et al. 2005

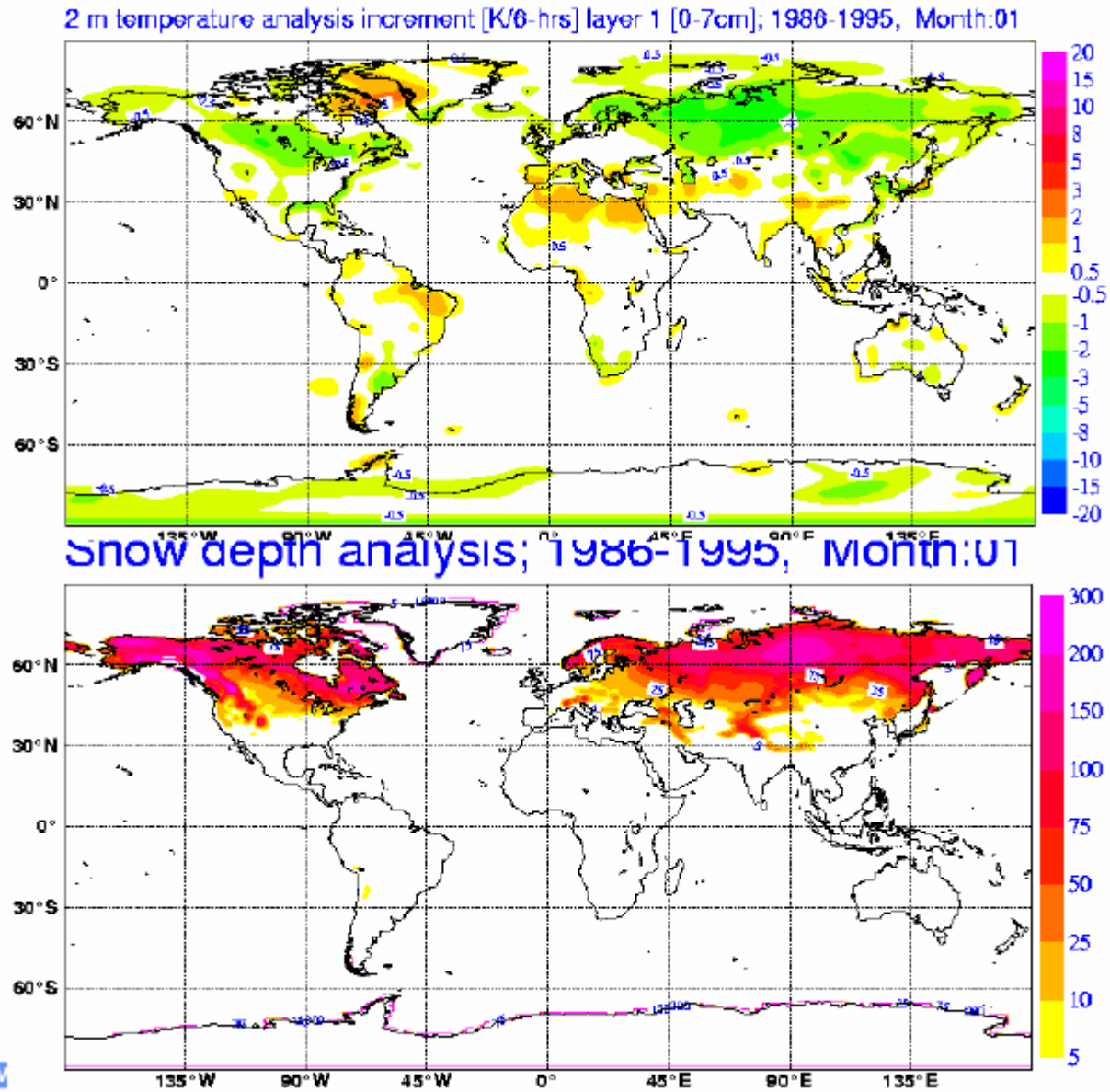
- Jung et al. 2005 (QJ) show an underestimation of synoptic activity in high latitudes
- Jung et al. 2006 (QJ) show high latitude cyclones are well analysed, but that high horizontal resolution is important for correctly forecasting them, particularly in North Pacific and Arctic.

2m temperature forecast mean errors around day 3



- Land surface modelling is important. There were large wintertime biases over continental areas before improvements to soil freezing and snow albedo.
- See Beljaars' paper from ECMWF polar meteorology seminar, 2006

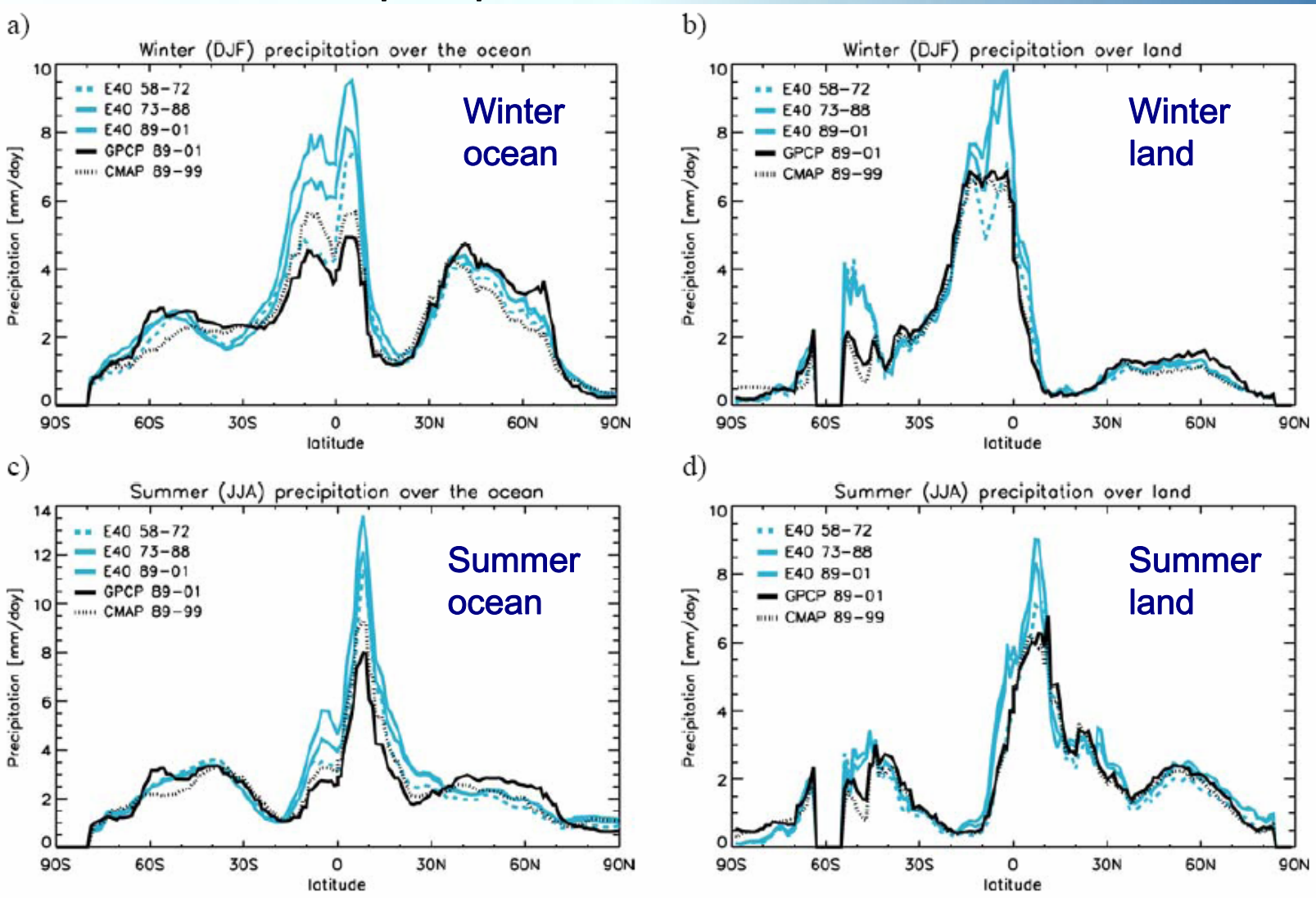
January, 1986-1995, in ERA-40: 2m temperature increments and snow depth



- 2m temperature analysis increments in ERA-40 reveal model biases in winter. Model is too warm.
- Thought to be linked to parametrized vertical diffusion in the stable air above snow-covered areas.

Beljaars, polar meteorology seminar 2006

ERA-40 precipitation vs. GPCP and CMAP



- Hageman et al. 2005 (ERA 40 project report) – an extensive validation of the ERA-40 hydrological cycle
- Most obvious problems are in tropics, not high latitudes
- Climatologies disagree in some areas – e.g. NH winter

ERA-40 Hydrological Cycle Validation

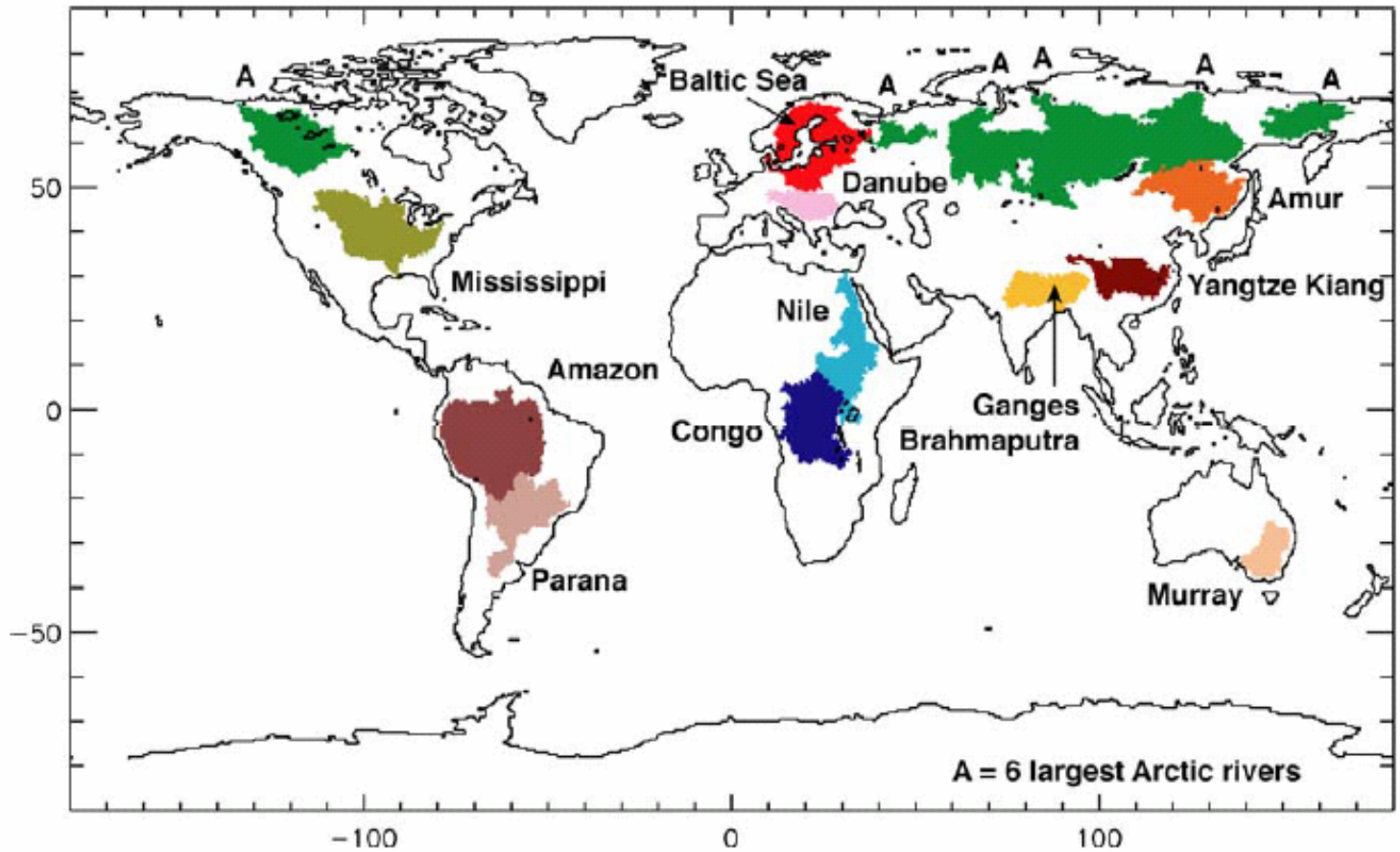


Figure 10. Several large catchments of the globe. The 6 largest Arctic rivers comprise (from west to east) Mackenzie, Northern Dvina, Ob, Yenisey, Lena, Kolyma.

(Hagemann et al. 2005)

ERA-40 Hydrological Cycle Validation

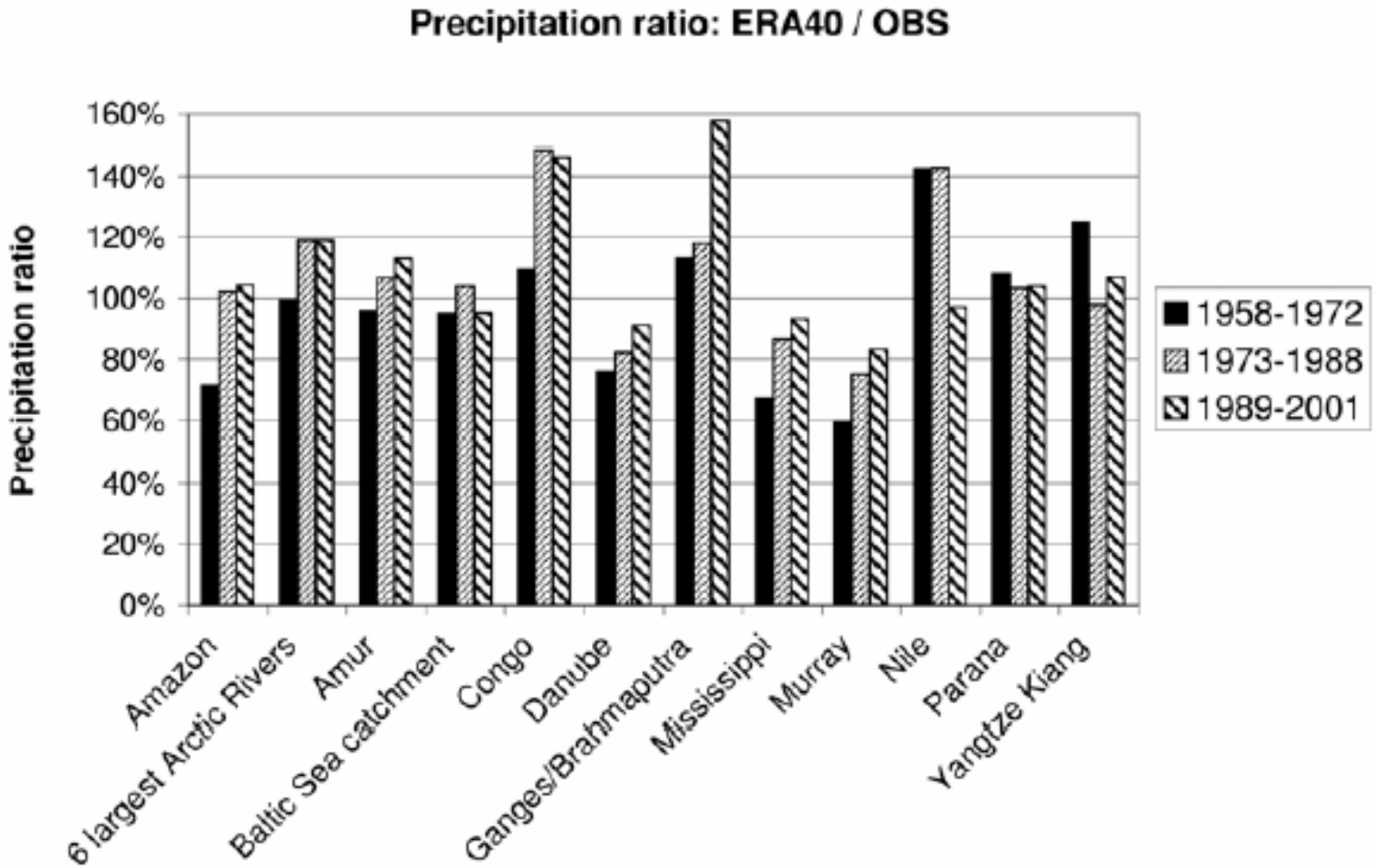


Figure 11. Precipitation ratio of ERA40 to observations for large river catchments. Observations comprise GPCC data for 1989-2001 and CRU data for the two earlier periods.

Difference between individual ERA-40 periods due to different data sets in data assimilation system

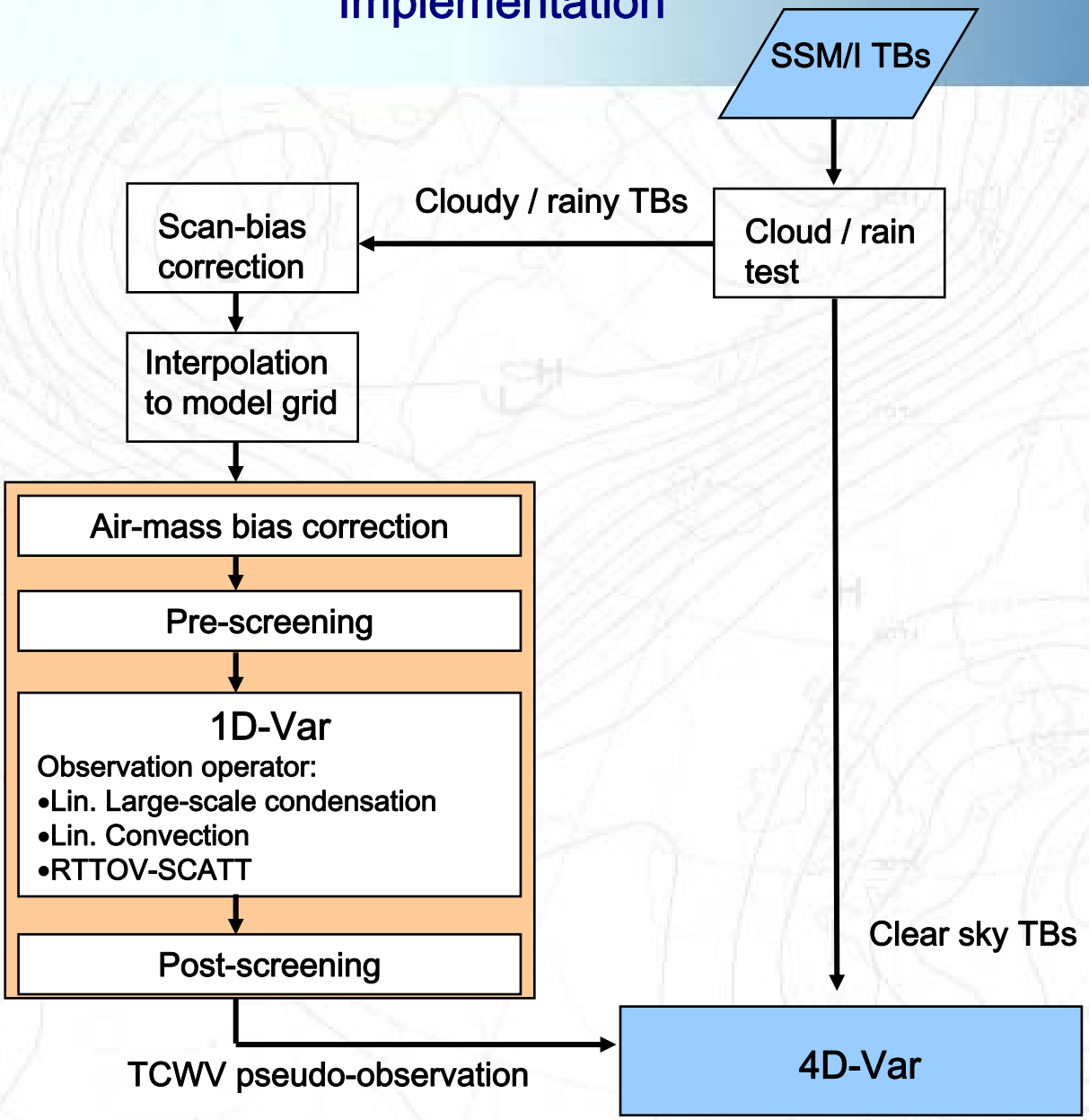
(Hagemann et al. 2005)

Operational assimilation of rain and cloud affected SSM/I observations

Overview

- Clear sky SSM/I radiances are directly assimilated in 4D-Var
- Cloudy and rainy SSM/I radiances have been assimilated operationally at ECMWF since 28th June 2005, over sea only, using a 1D+4D-Var method:
    - 1D-Var minimises T,q profiles and surface windspeed
    - 1D-Var observation operator includes:
        - simplified large-scale and convective cloud schemes
        - Microwave radiative transfer
    - TCWV retrievals are assimilated in 4D-Var

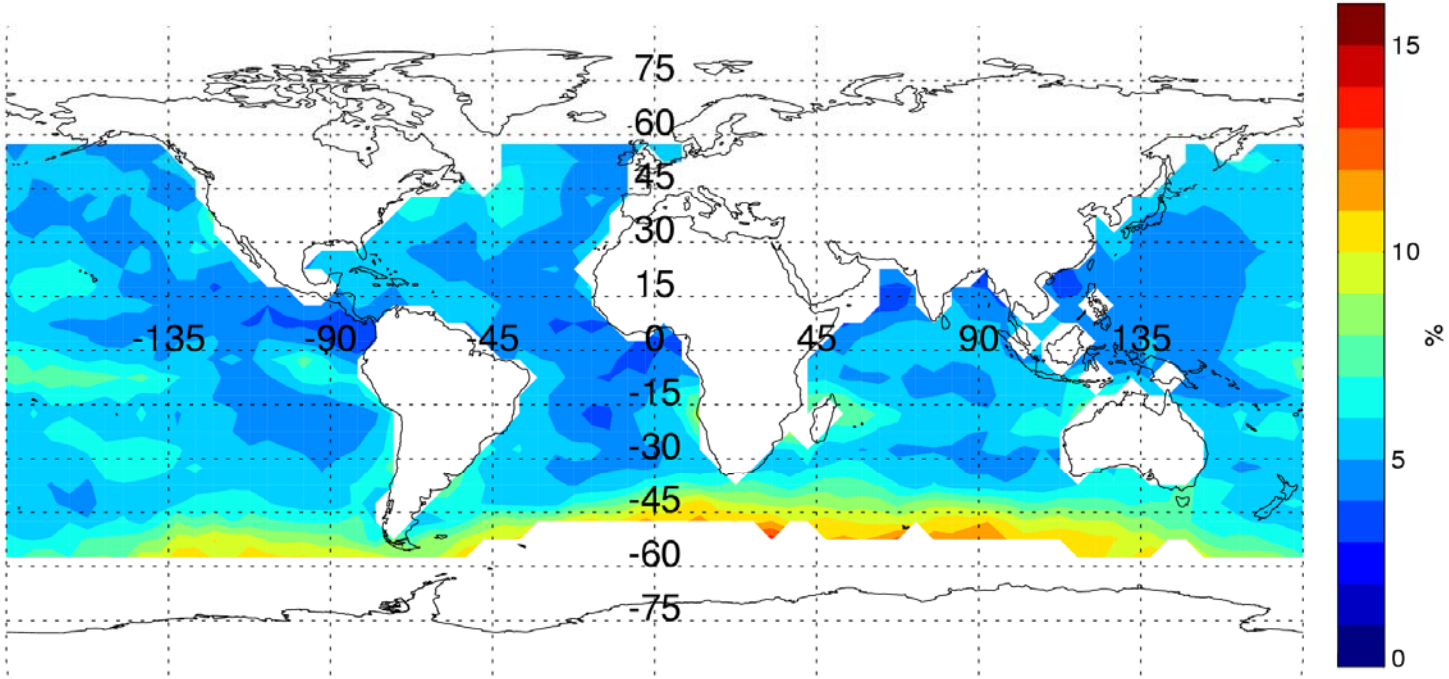
Implementation



Problems in winter in the Southern ocean

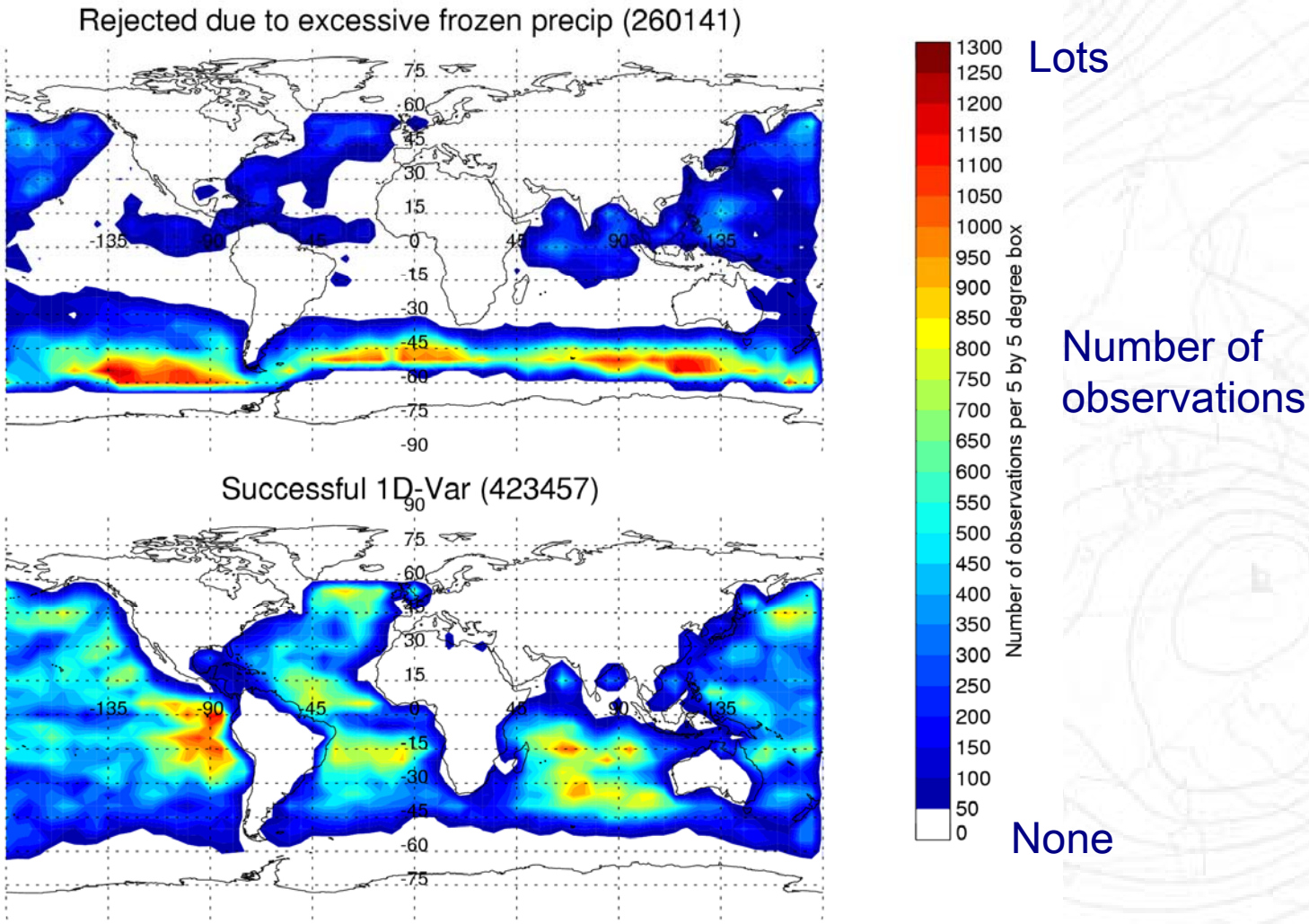
- Rain assimilation was causing deterioration in RMS forecast scores (RH, T and Z) in southern hemisphere
- Large first guess departures in rainy TCWV pseudo-observations at high latitudes in SH:

TCWV FG departures as percentage of FG: RMS, August 2005



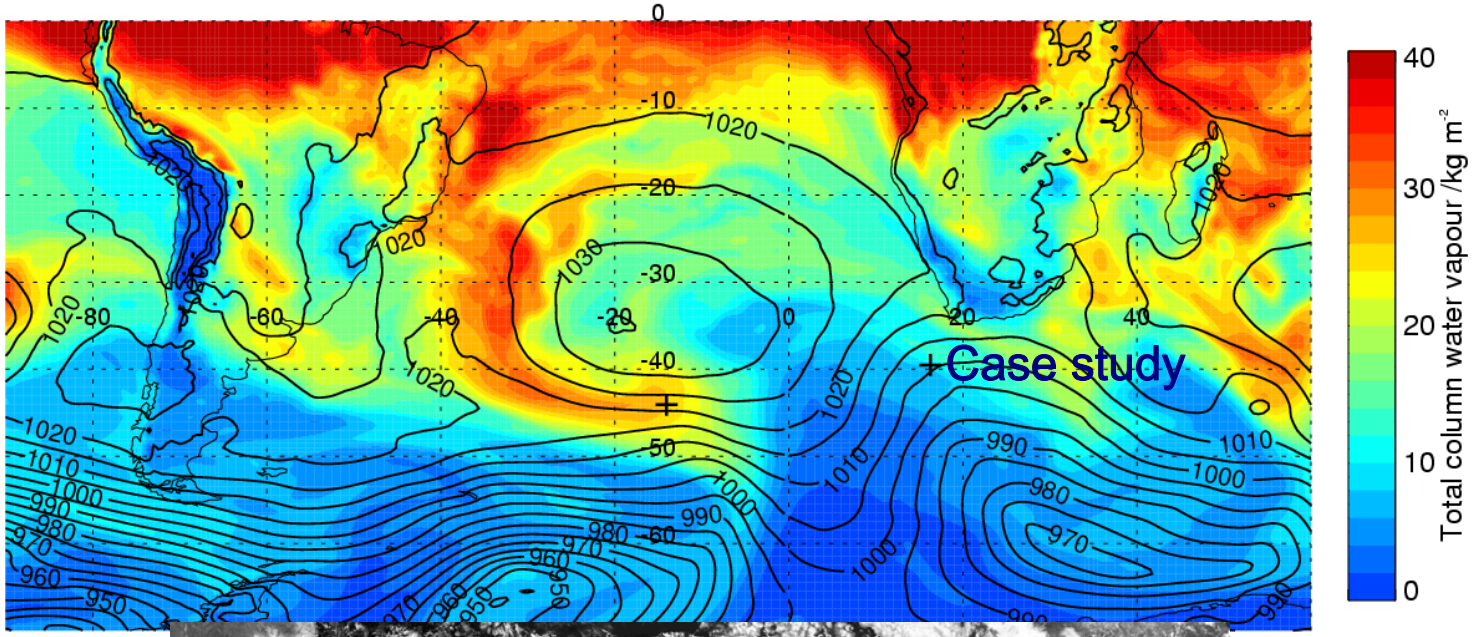
Solution

- Eliminate retrievals with too much snow (compared to rain) in the first guess column

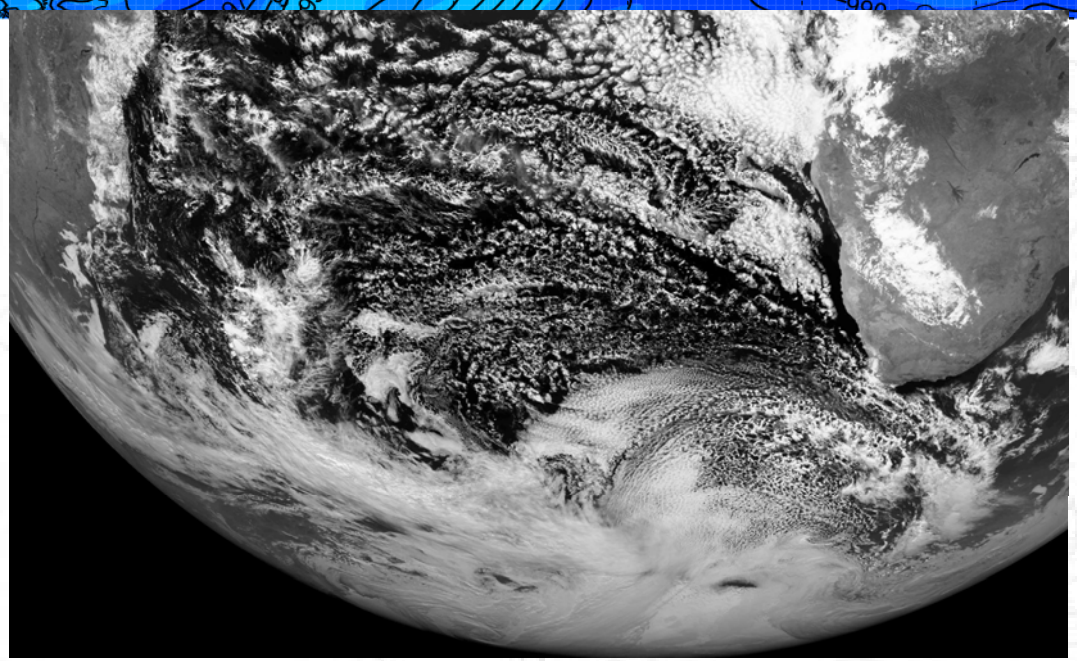


1D-Var case study: South Atlantic 12Z 14th August 2005

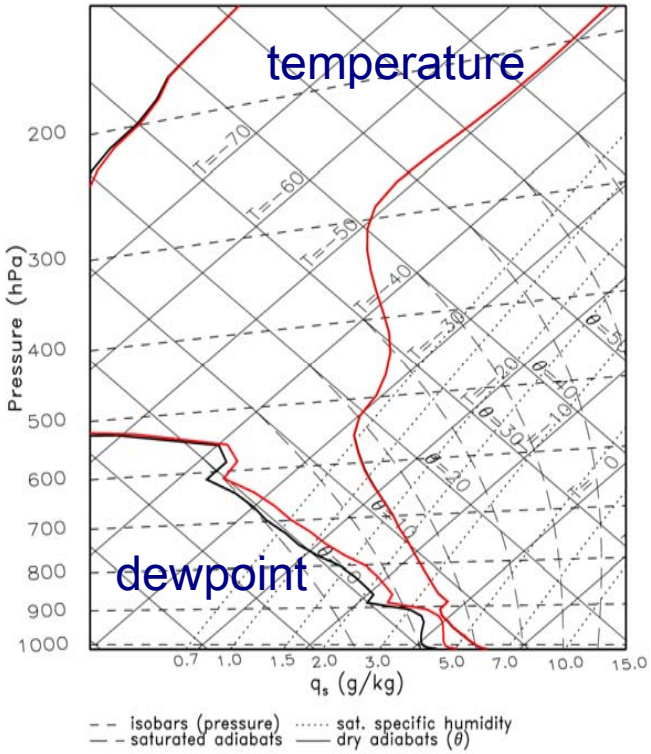
Pressure at MSL
TCWV

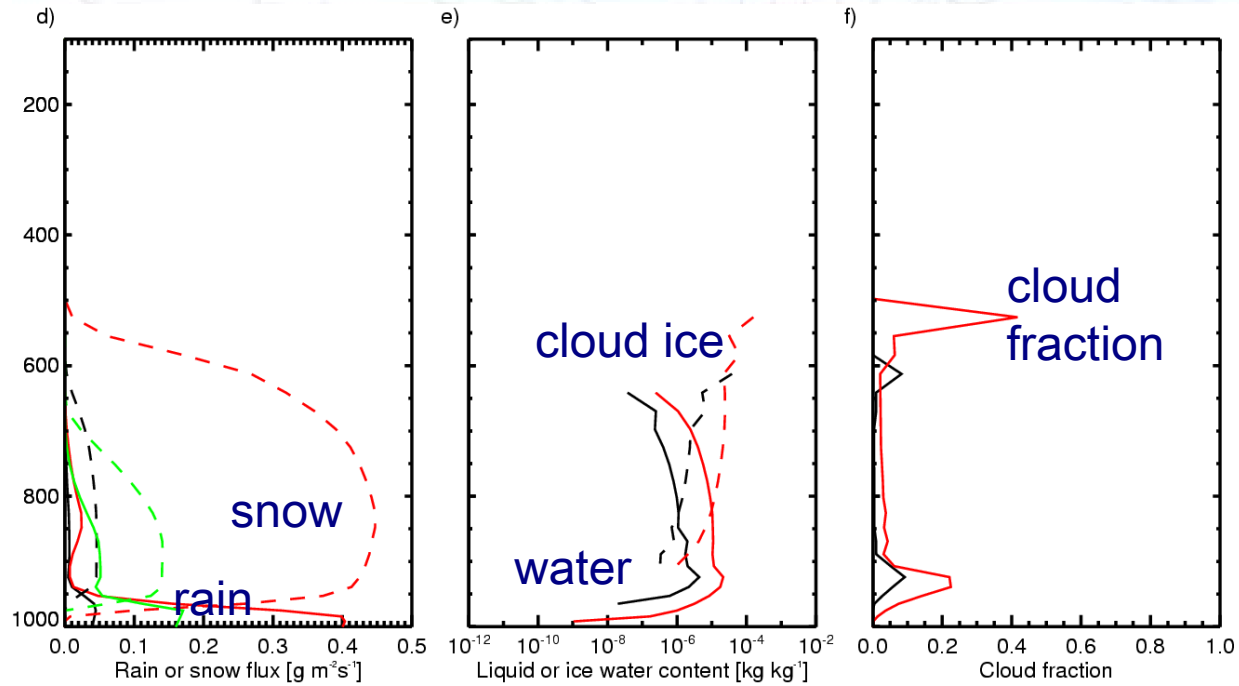


Meteosat visible



1D-Var case study – convective, low TCWV, low freezing level





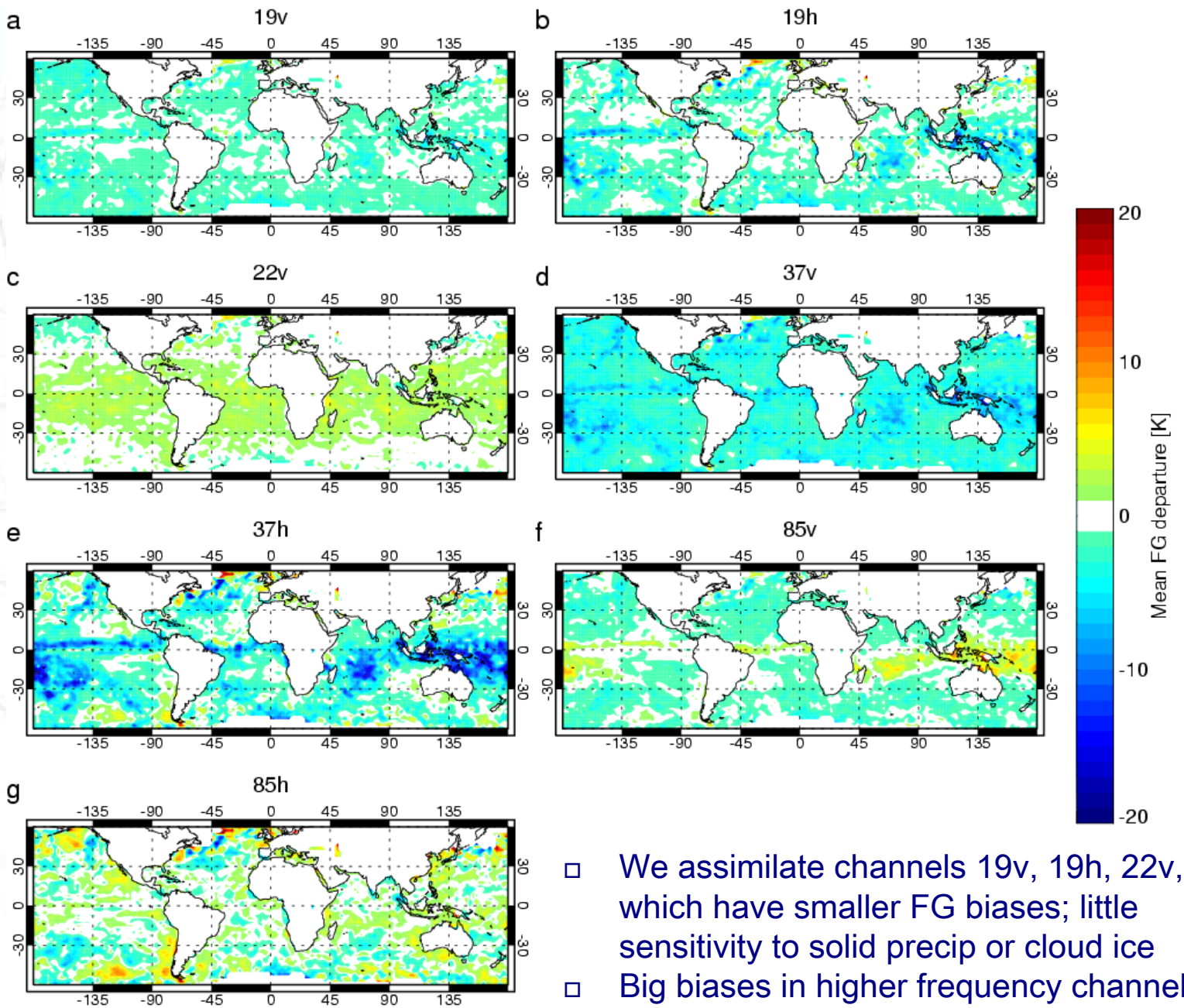
SSMI channel	TCWV /kgm-2	Tb departure /K 19v	19h	22v	37v	37h	85v	85h
FG	7.6	**4.5**	**7.9**	**2.0**	4.2	8.8	4.1	12.0
analysis	8.8	**2.0**	**1.3**	**-1.1**	3.4	-1.8	13.3	5.5

analysis

first guess

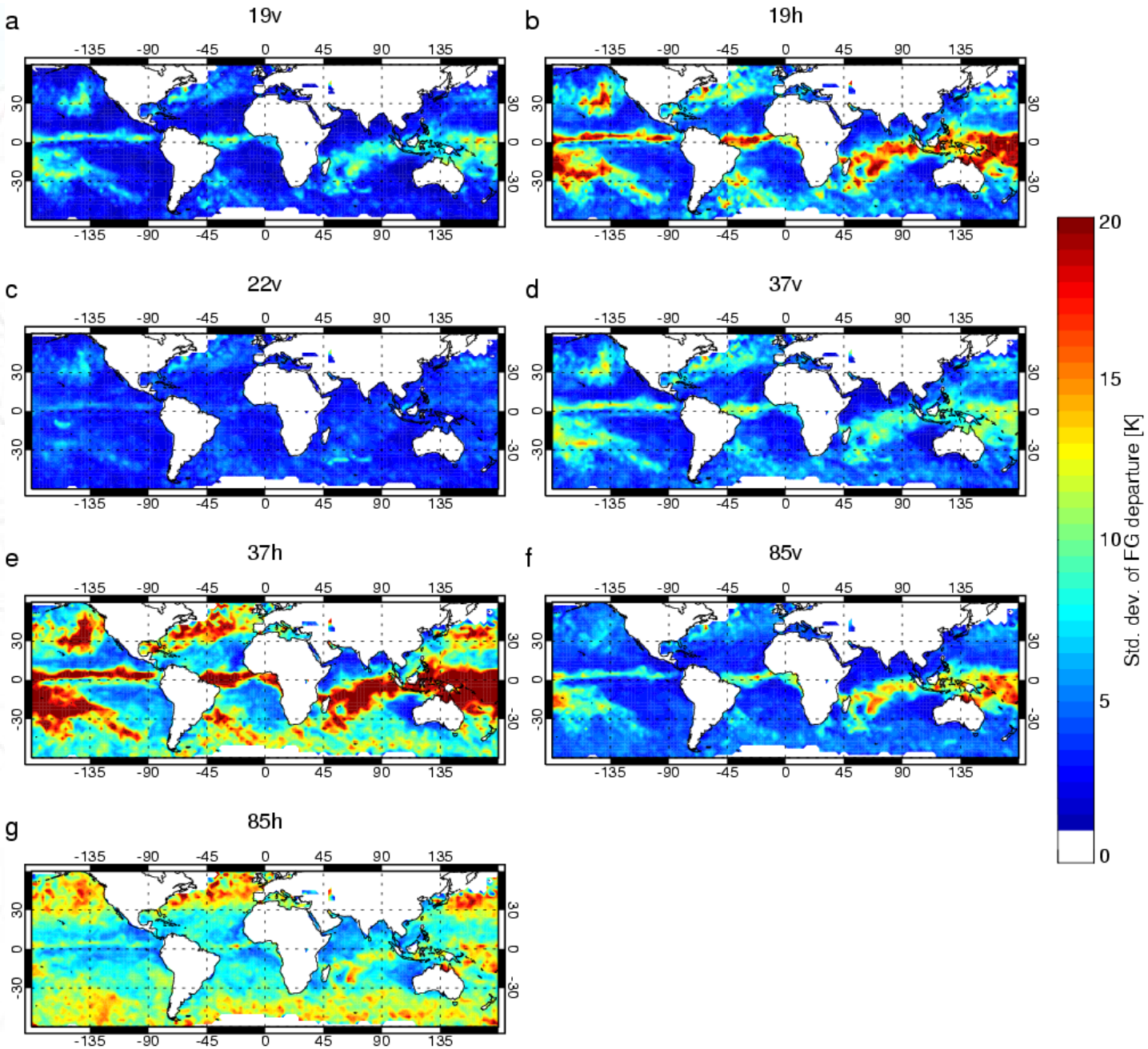
3D model

Mean SSM/I first guess departures (rainy and clear): 1st -10th February 2007



- We assimilate channels 19v, 19h, 22v, which have smaller FG biases; little sensitivity to solid precip or cloud ice
- Big biases in higher frequency channels

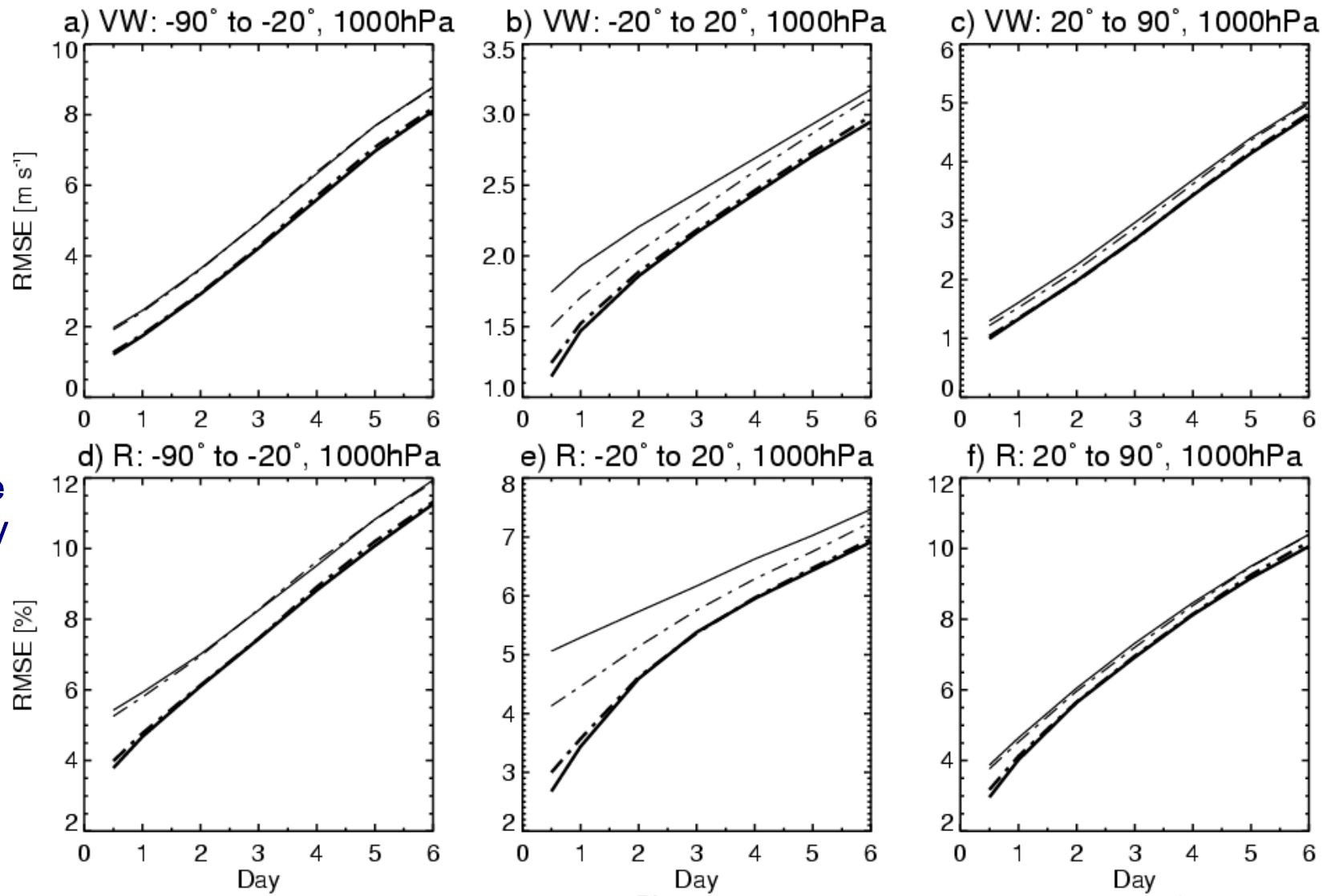
Std. dev. of SSM/I first guess departures (rainy and clear): 1st -10th February 2007



Forecast impact of rainy observations: June, July, August 2006

Vector wind

Relative humidity



BL Baseline: conventional obs plus one AMSU-A

BL + RAIN

CTRL - RAIN

CTRL Full observing system

Kelly et al., to be submitted

Lessons from assimilation of rainy SSM/I radiances over ocean

- FG biases and standard deviations are much larger in the higher frequency channels:
  - Increased sensitivity to precipitation and cloud reveals moist physics model biases
  - Ice and snow scattering radiative transfer less good
  - Possible surface emissivity biases

- Profiles with more than 30% precipitation in the form of snow are rejected. Low frequency channels give little sensitivity to snow.

- Forecast impact of rainy observations within the full observing system is very small. This is true for most observation types: there is redundancy in the system.

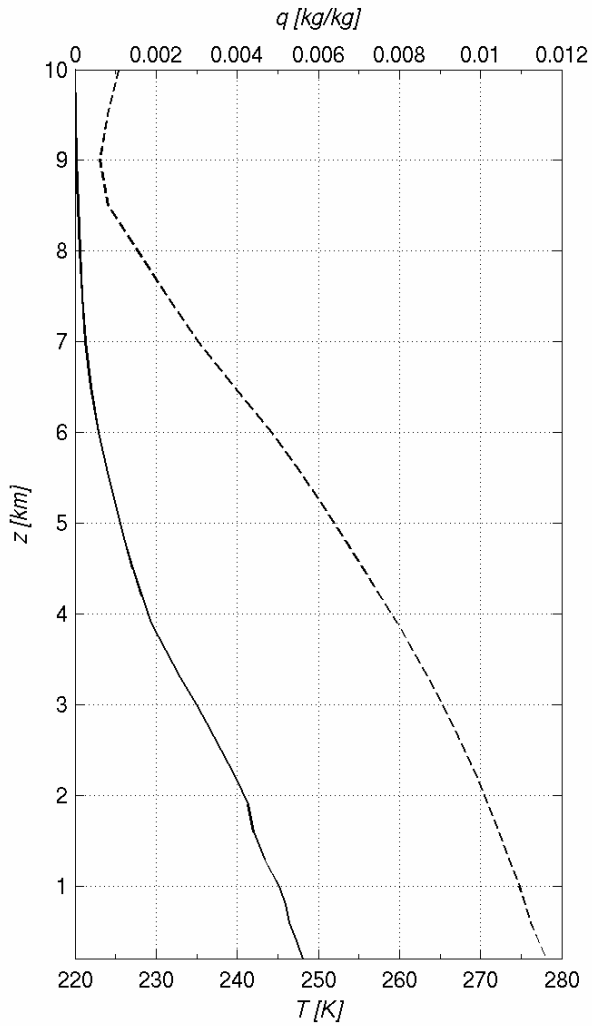
- Forecast impact of moisture, rain, and cloud observations in a low baseline system is large, but principally found in the tropics. Here, wind forecasts are substantially improved, not just moisture.

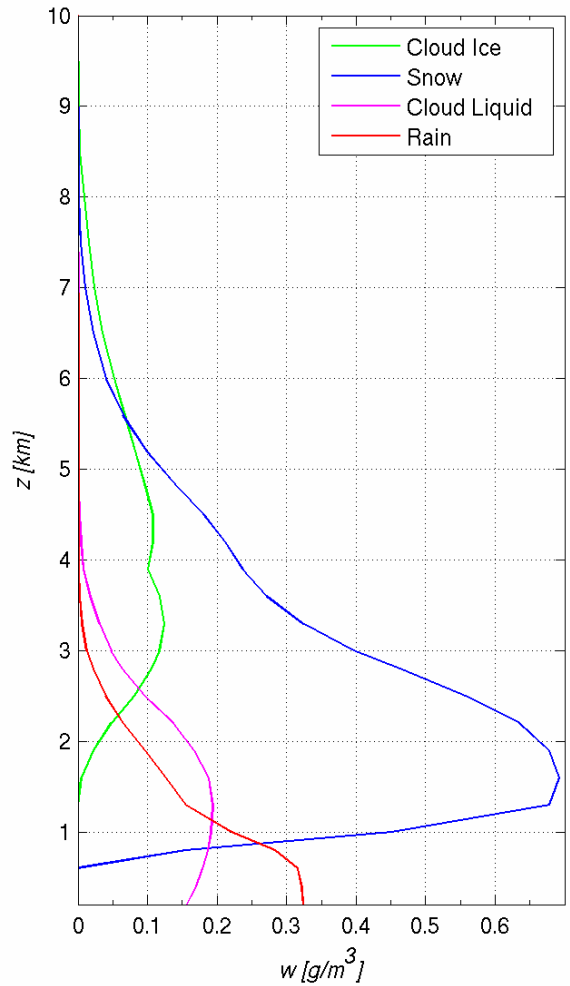
- Many areas (e.g. moist physics in the model, moisture control variable, background errors, assimilation technique) require improvement before rain- and cloud-affected observations can be used to their full potential.

Precipitation and cloud information content in the microwave spectrum

WP 3110/3120: Information content

Reference profile: 02 Jan 2004, 12:00 UTC 52.50°N - 41.66°W





Observation operator: Hydrometeor Jacobians

Ocean surface

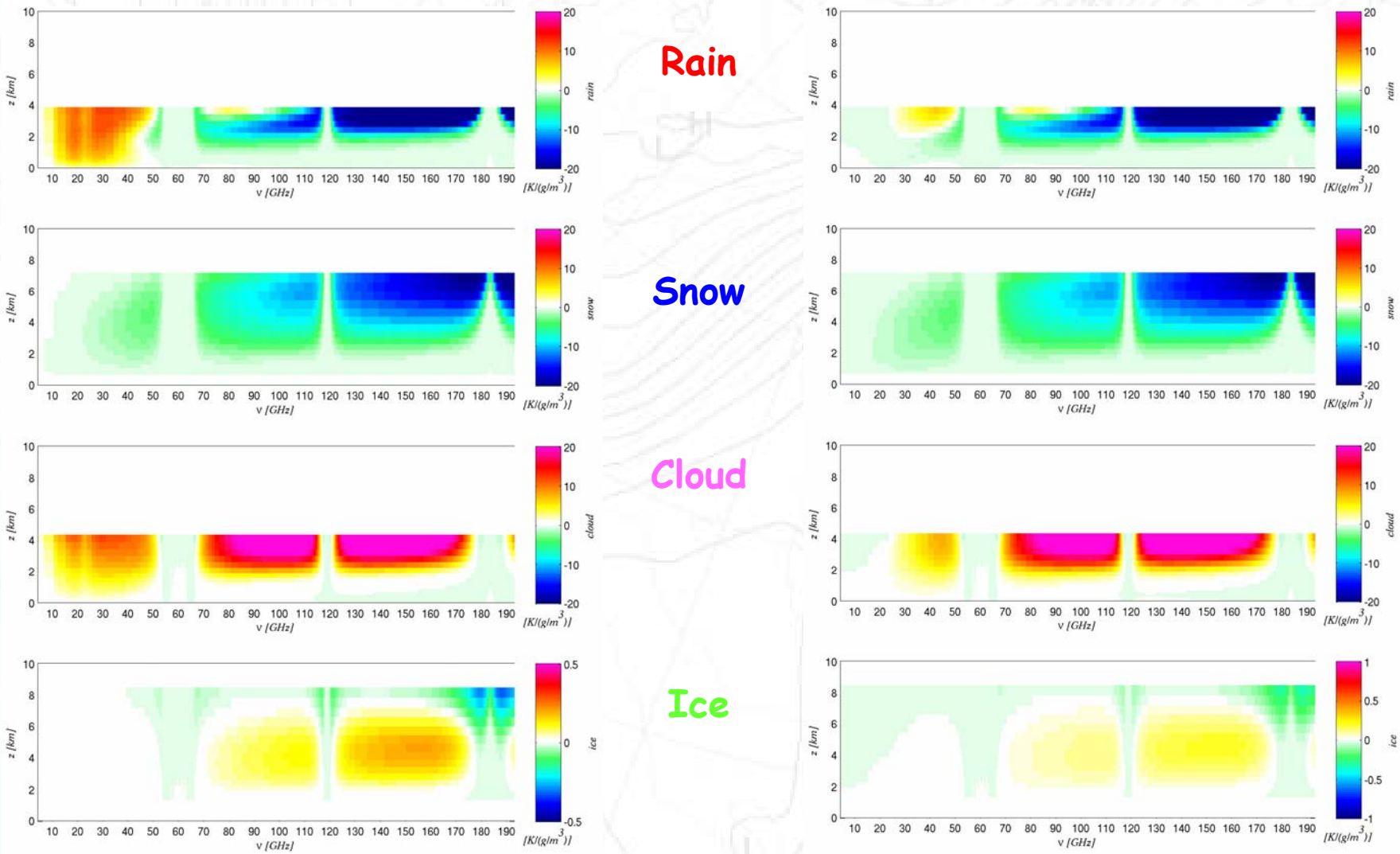
Land surface

Rain

Snow

Cloud

Ice



Observation operator: Profile and surface Jacobians

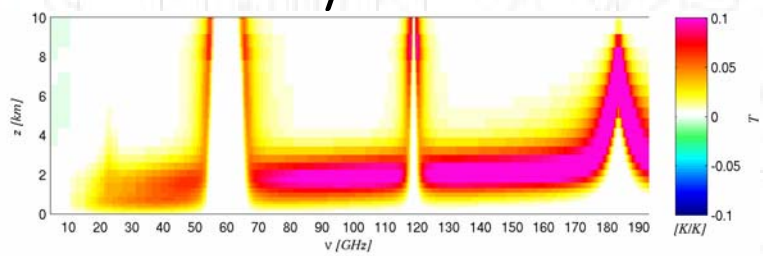
Ocean surface

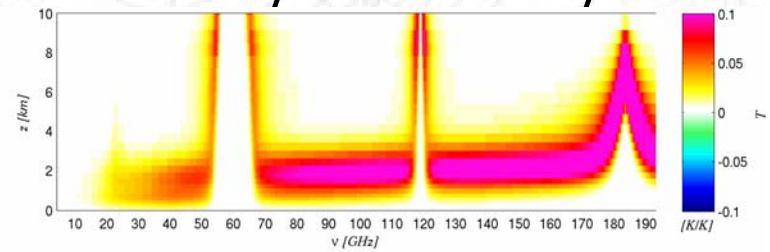
V pol.

Land surface

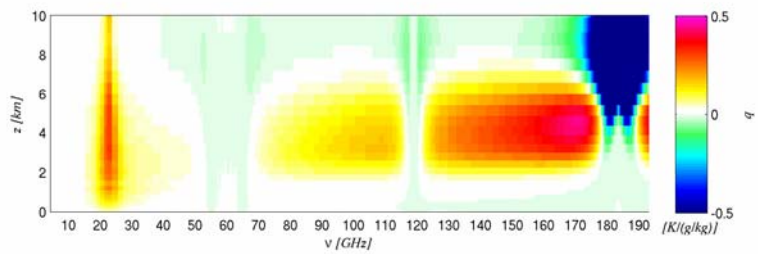
V pol. minus H pol.

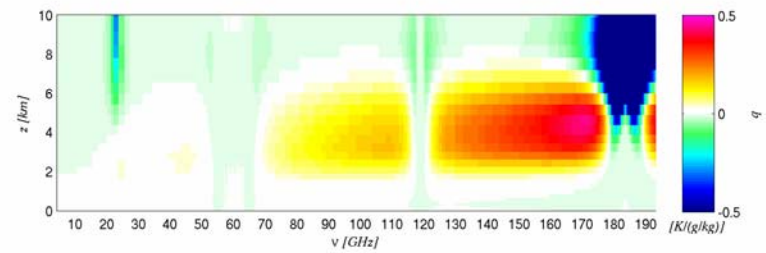
Temp



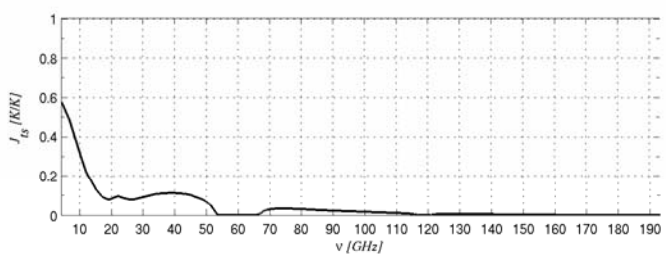


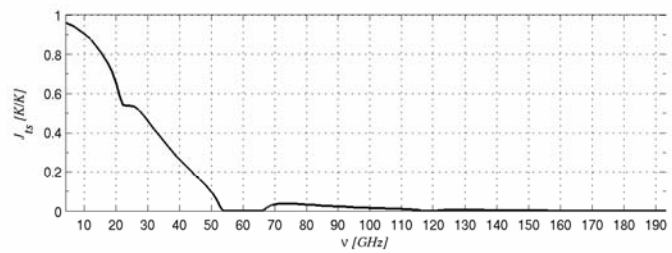
Hum



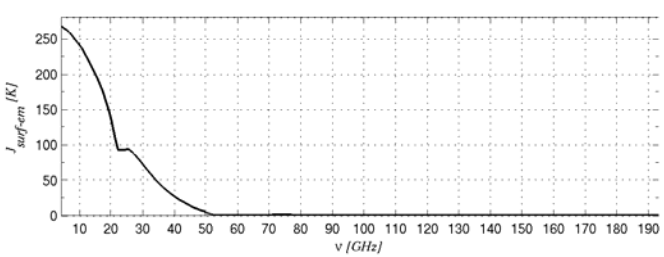


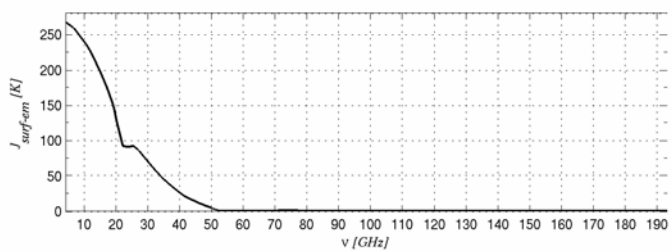
Surf Temp





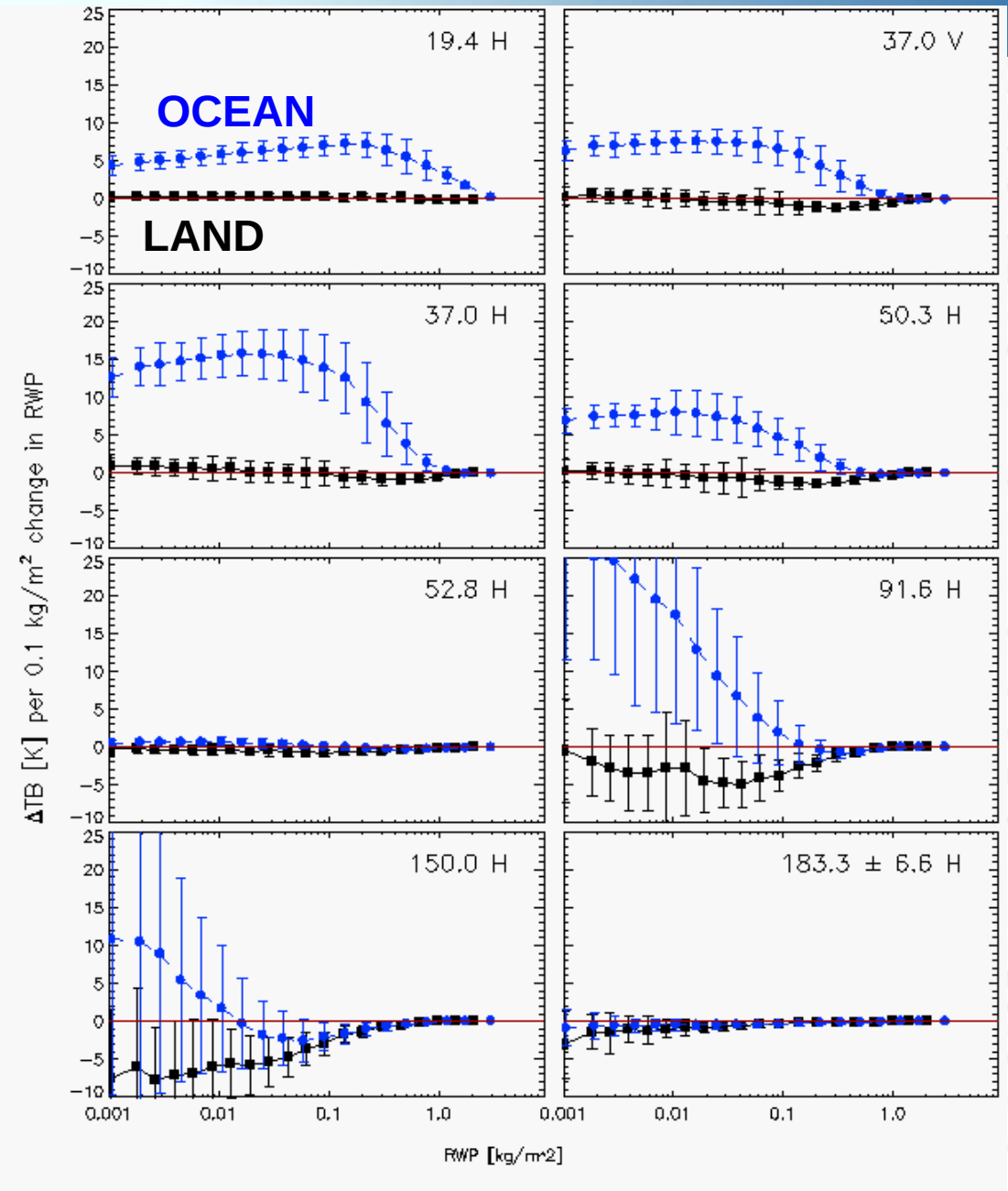
Surf Emis





SSMIS Channel Sensitivity Study - rain

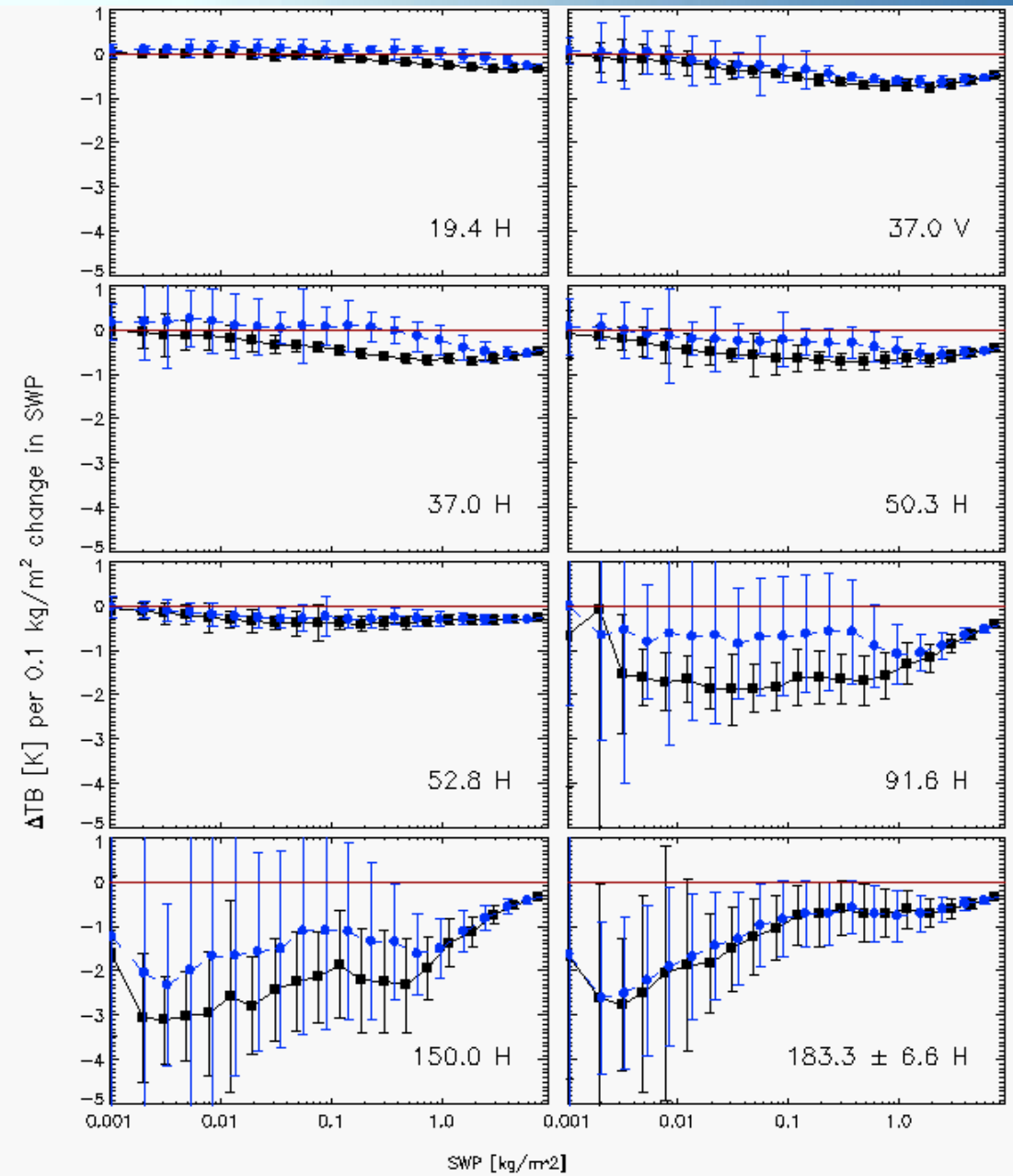
- Take 20,000 profiles
- Output profiles of T, q, cloud water, cloud ice, rain & snow content.
- Use RT model to calculate theoretical TB
- Increase rain (snow) contents by 1% for each profile; calculate TB changes.
- Scale change in TB to a 0.1 kg/m^2 change in integrated rain (snow) water path, assuming linearity.



Snowfall wo

SSMIS Channel Sensitivity Study - snow

- Take 20,000 profiles
- Output profiles of T, q, cloud water, cloud ice, rain & snow content.
- Use RT model to calculate theoretical TB
- Increase rain (snow) contents by 1% for each profile; calculate TB changes.
- Scale change in TB to a 0.1 kg/m^2 change in integrated rain (snow) water path, assuming linearity.

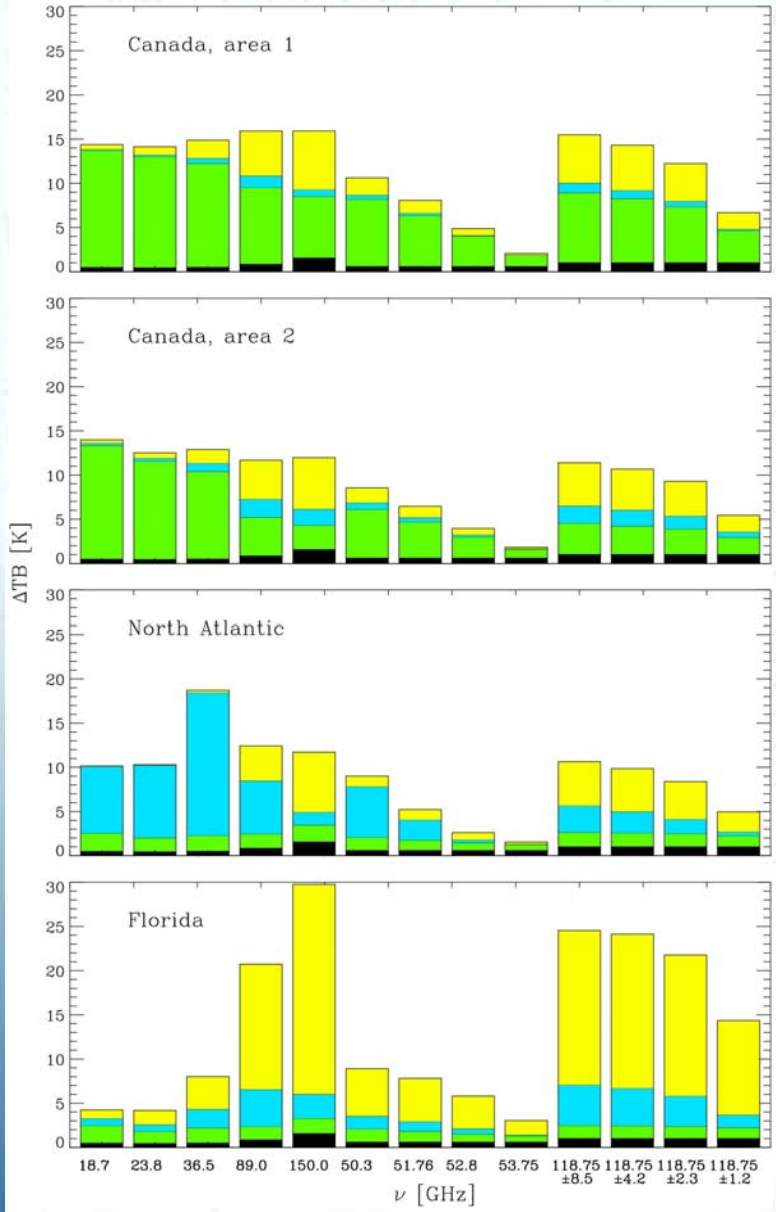


Snowfall works

OCEAN

LAND

Signal vs. Noise



Canadian snowstorm, Area 1:
Heavy frozen precipitation
Little liquid precipitation

Canadian snowstorm, Area 2:
Moderate frozen precipitation
Moderate liquid precipitation

North Atlantic frontal system:
Moderate frozen precipitation (above surface)
Moderate liquid precipitation

Florida convection:
Heavy frozen precipitation (above surface)
Moderate liquid precipitation

Contributions:
NEΔT ■, surface emissivity ■, liquid precipitation ■, solid precipitation ■

(Bauer et al. 2005)

Mission Requirements for a Post-EPS Microwave Radiometer

Peter Bauer, Sabatino Di Michele, Jean Noël Thépaut

European Centre for Medium-range Weather Forecasts (ECMWF)

Snowfall workshop, Montreal, 26-28th June, 2007

Objectives

"Derive mission requirements related to the observation of clouds and precipitation with a polar microwave radiometer"

Project:

- Identify those microwave frequencies between 5-200 GHz that are optimally suited for cloud and precipitation remote sensing (and that are protected by International Telecommunication Union, ITU, regulations).
- Consider ocean/land surfaces and all weather conditions.
- Develop framework for the estimation of potential hydrometeor retrieval accuracies given the identified channel selection.
- Assess retrieval accuracy based on user requirements defined for post-EPS.

Information Content

Signal to noise can be characterized as x/σ or σ_x/σ with:

x	atmospheric/surface variable
σ_x	standard deviation of x's variability
σ	noise

Information content of a measurement = factor of x-knowledge improvement when making observation(s) [often as *log (factor)*]

Linear Gaussian case:

$H_s = \mathbf{S}\,[P(\mathbf{x})] - \mathbf{S}\,[P(\mathbf{x}|\mathbf{y})]$ *Entropy reduction*

A = Analysis error covariance matrix

P = (joint) pdf of **x**(**y**)

Iterative method for channel optimization:

$\mathbf{A}^{-1} = \mathbf{B}^{-1} + \mathbf{h}\mathbf{h}^T$ Improvement of **A** over **B** with **H**

B = Background error covariance matrix

H = Jacobian matrix with columns **h**, normalized with **R**

R = Observation+Modelling error covariance matrix

1. calculate H_s for all channels and select highest
2. update **B** with **A**
3. calculate H_s for remaining channels and select highest

Observational Method: R

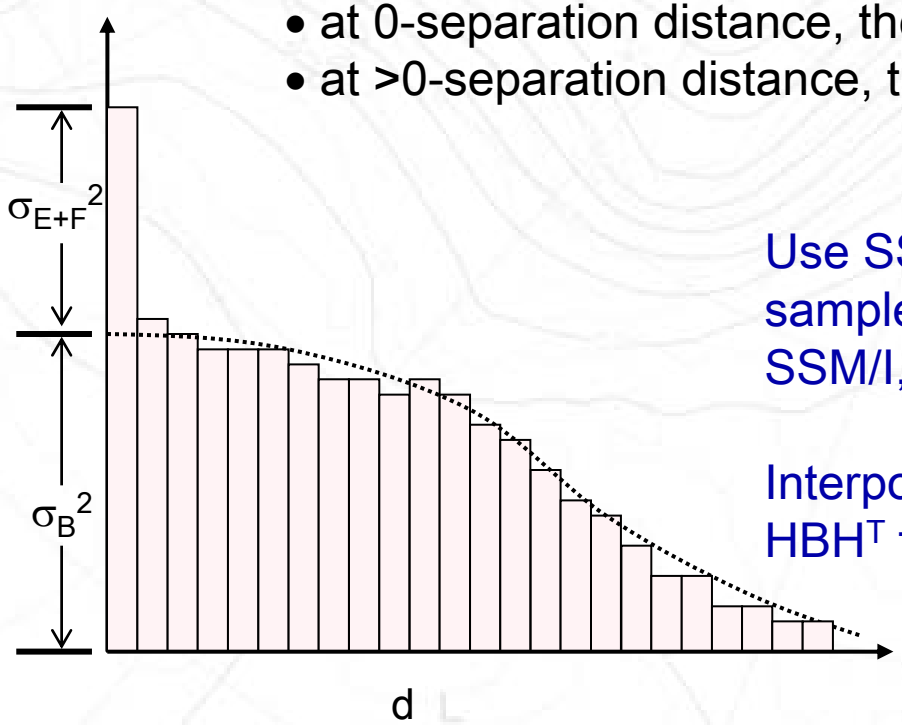
Estimation of σ_B vs. σ_{E+F} from spatial covariance structure of first-guess departures

Assumptions:

- observation network is rather dense
- observations are spatially uncorrelated (and discrete)

Conclusions:

- at 0-separation distance, the variance is $\sigma_B^2 + \sigma_{E+F}^2$
- at >0-separation distance, the variance is covariance σ_B^2 (d)

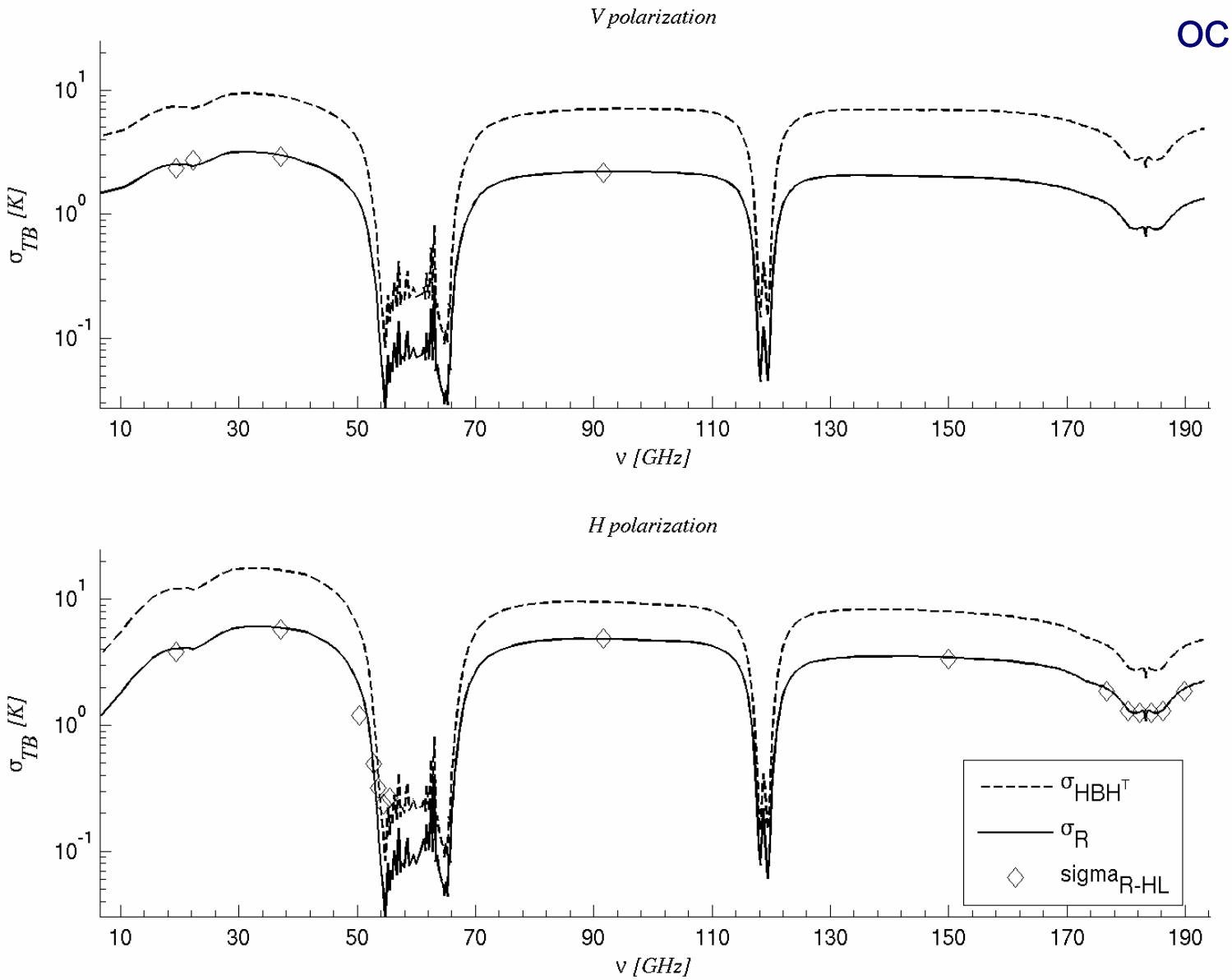


Use SSMIS data over ocean to sample spectrum at SSM/I, AMSU-A, AMSU-B frequencies!

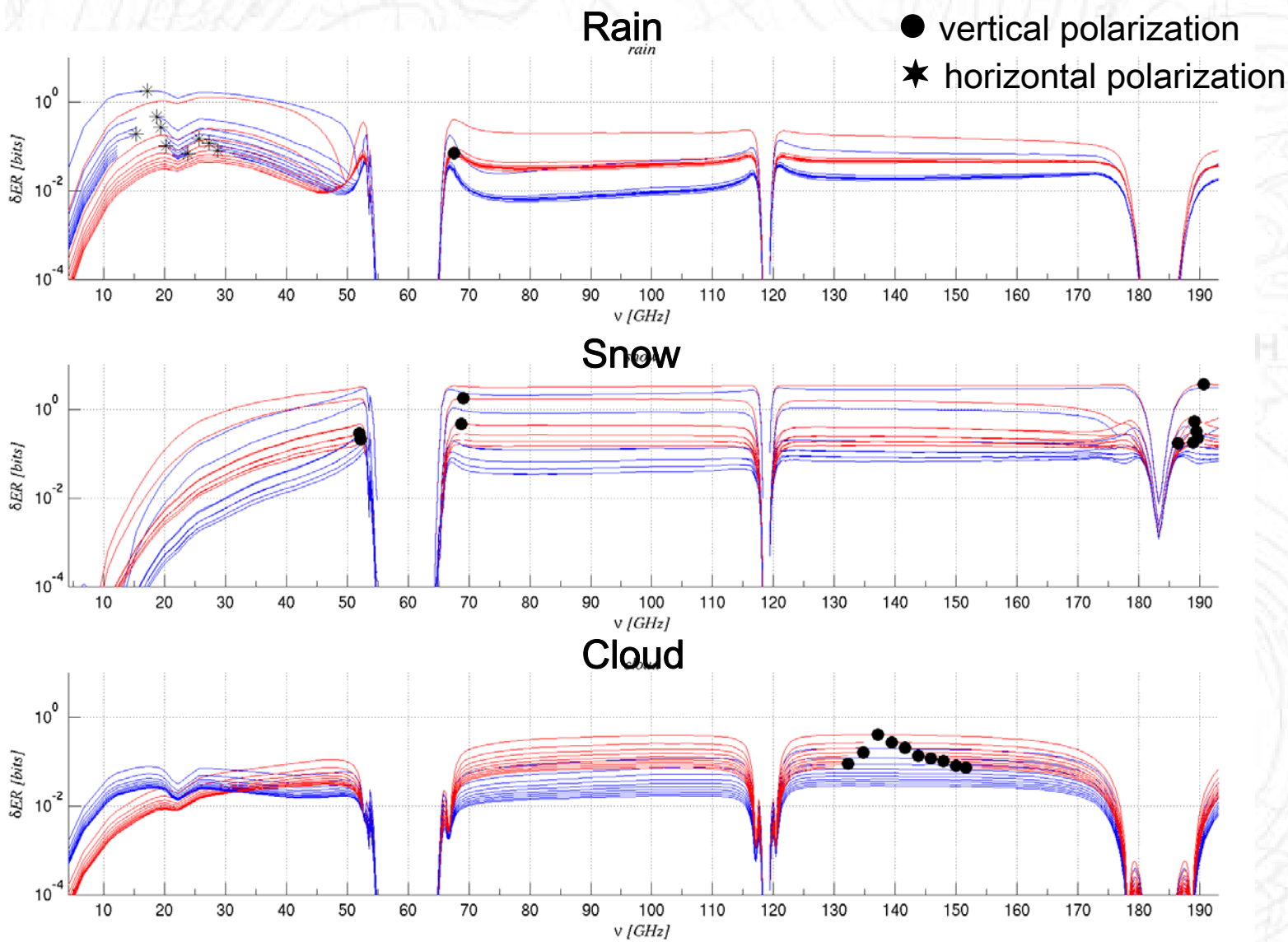
Interpolate between frequencies with HBH^T from simulations

Resulting σ_R Spectrum

OCEAN



Information Content Reduction 1st 10 Iterations



Information Content: Impact of R

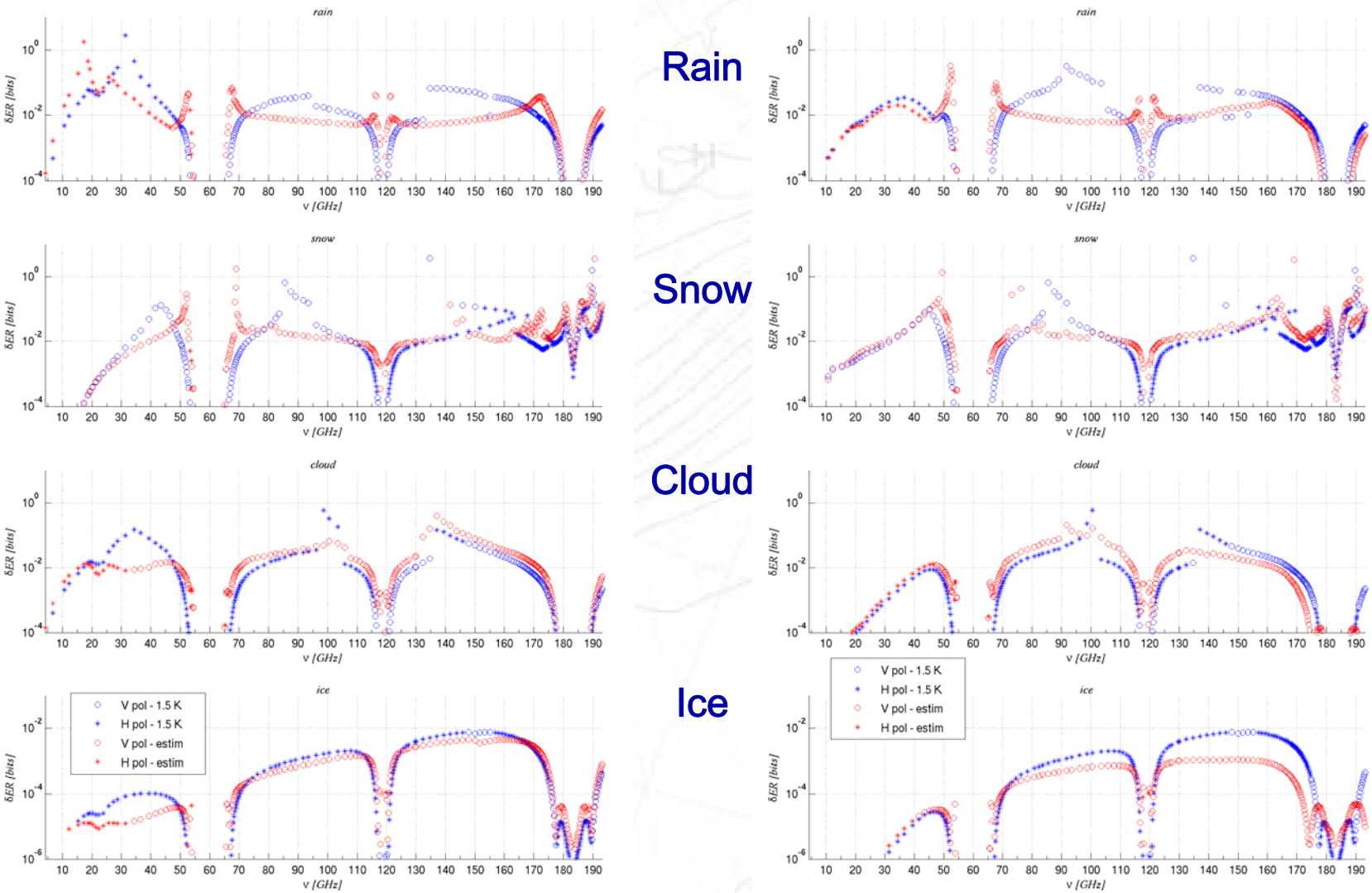
Ocean | Land

Rain

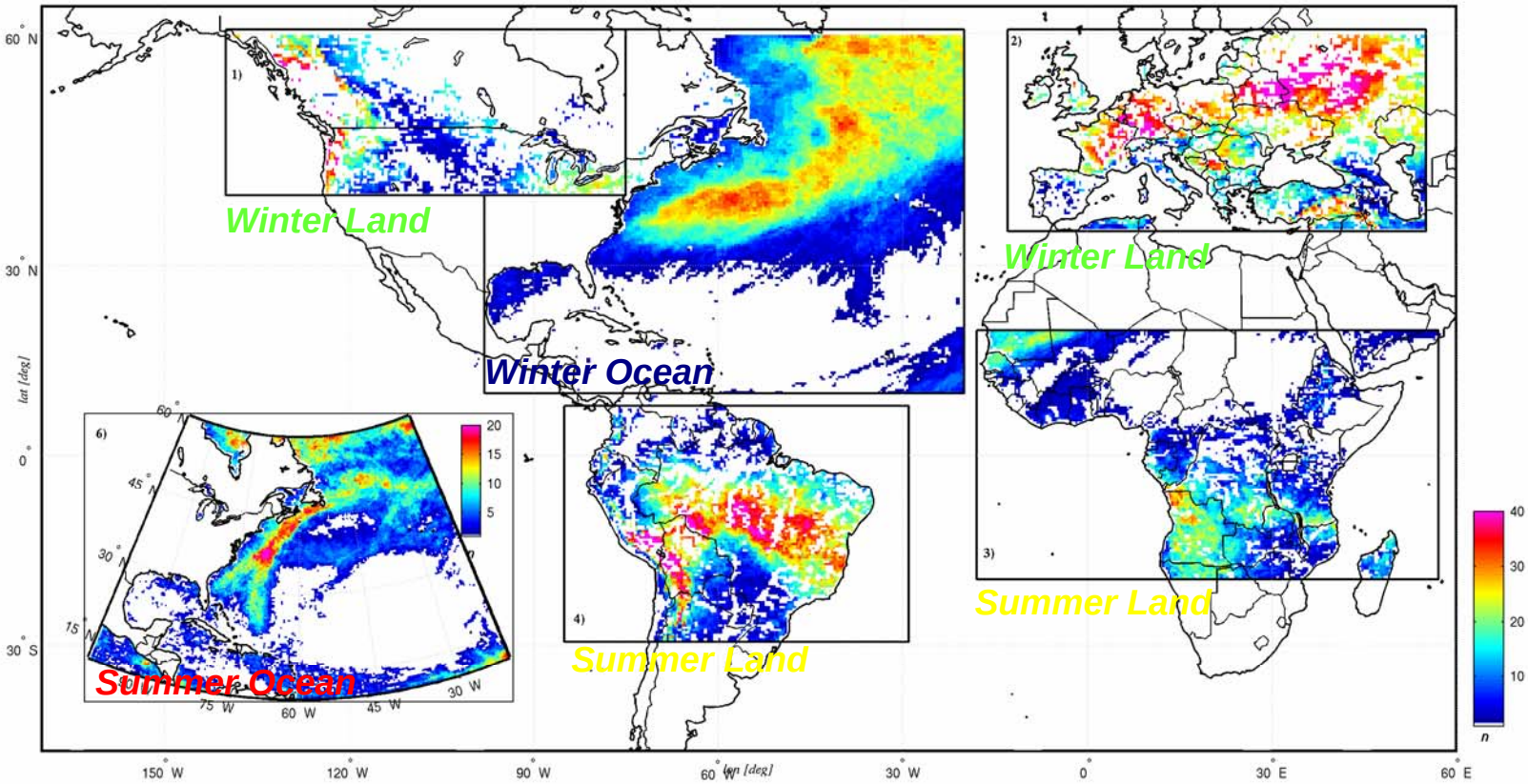
Snow

Cloud

Ice

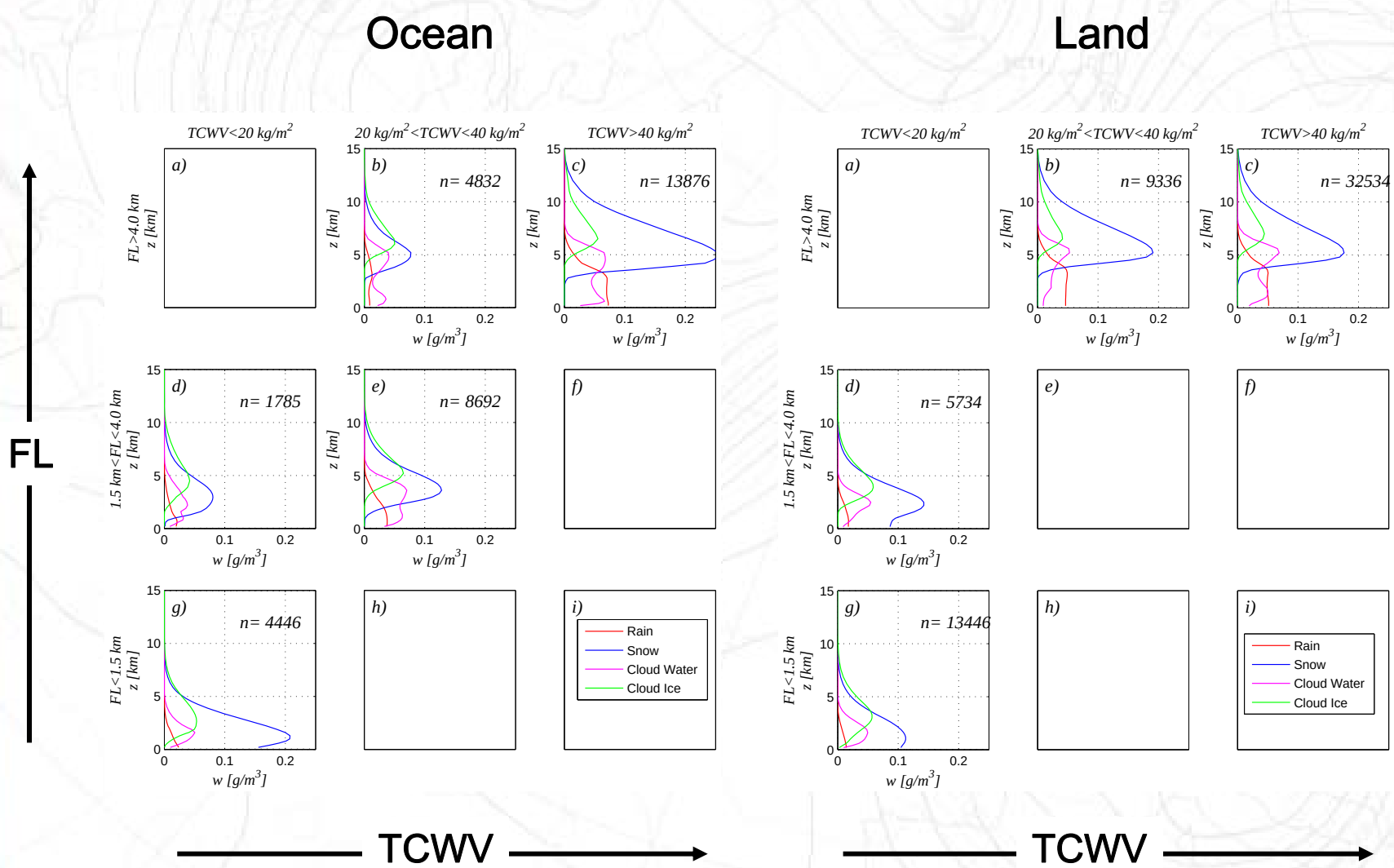


Global Profile Dataset



	Type	Zone	Period	Original	Normalized	Representative
1	Ocean Winter	Atlantic O.	January, 2004	133829	46766	10000
2	Ocean Summer	Atlantic O.	July, 2004	72992	31420	25000
3	Land Winter	N. America, Europe	January, 2004	85888	25317	20000
4	Land Summer	Africa, Amazons	January, 2004	156412	63367	45000

Global Profile Characteristics



Channel Selection

Channel Number	Centre $[GHz]$	Bandwidth [MHz]	Polarization	$NE\Delta TB$ [K]
1	6.925	350	v	0.34
2	6.925	350	h	0.34
3	10.65	100	v	0.7
4	10.65	100	h	0.7
5	18.7	200	v	0.7
6	18.7	200	h	0.7
7	23.8	400	v	0.6
8	23.8	400	h	0.6
9	31.4	1000	v	0.7
10	31.4	1000	h	0.7
11	89.0	3000	v	1.2
12	89.0	3000	h	1.2

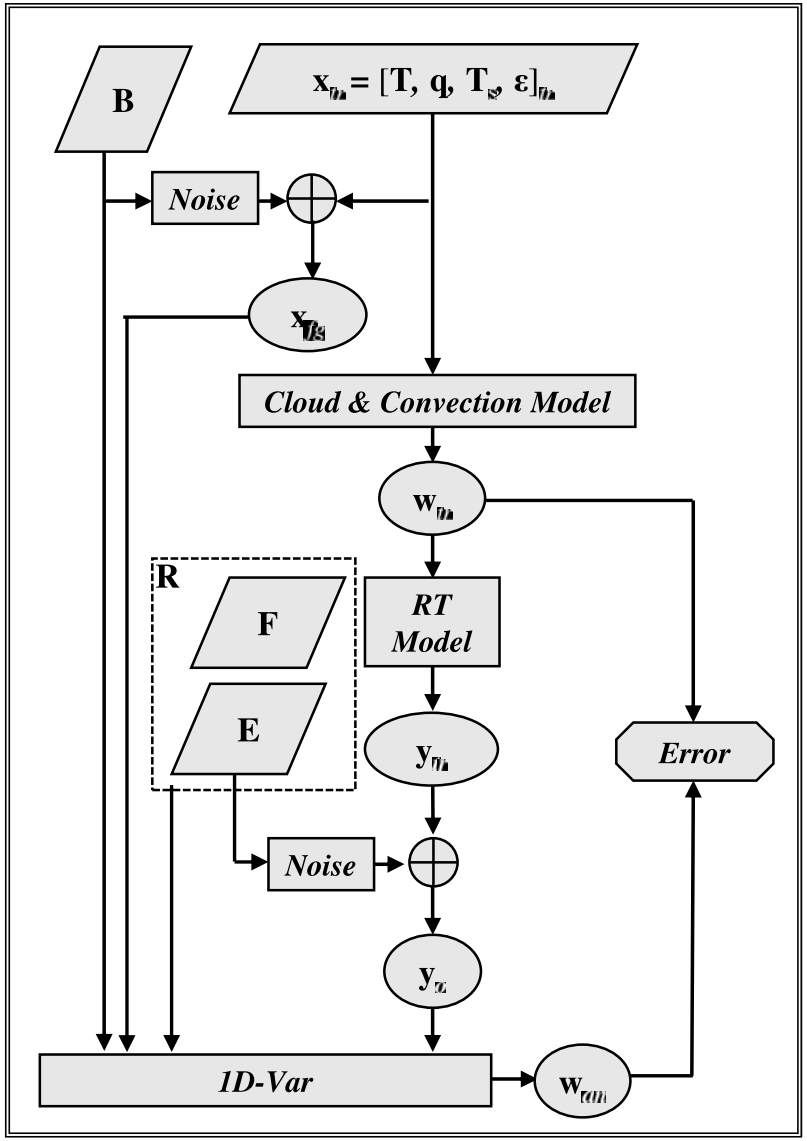
AMSR-E*

Upgrade

Priority	**Ocean** ν $[GHz]$	**Land** ν $[GHz]$
1	50.30 (rain, cloud water)	52.61 (rain)
2	52.61 (rain, snow)	53.24 (rain)
3	53.24 (rain)	53.75 (rain, snow, cloud water)
4	100.49 (rain, cloud water)	117.55 (snow)
5	120.16 (snow)	120.16 (cloud water)
6	191.70 (snow)	120.91 (snow)
7		186.67 (snow)
8		188.17 (snow)
9		189.42 (snow)

*unprotected 36.5 GHz channels replaced with fully protected 31.4 GHz channels

1D-Var Retrieval Logic



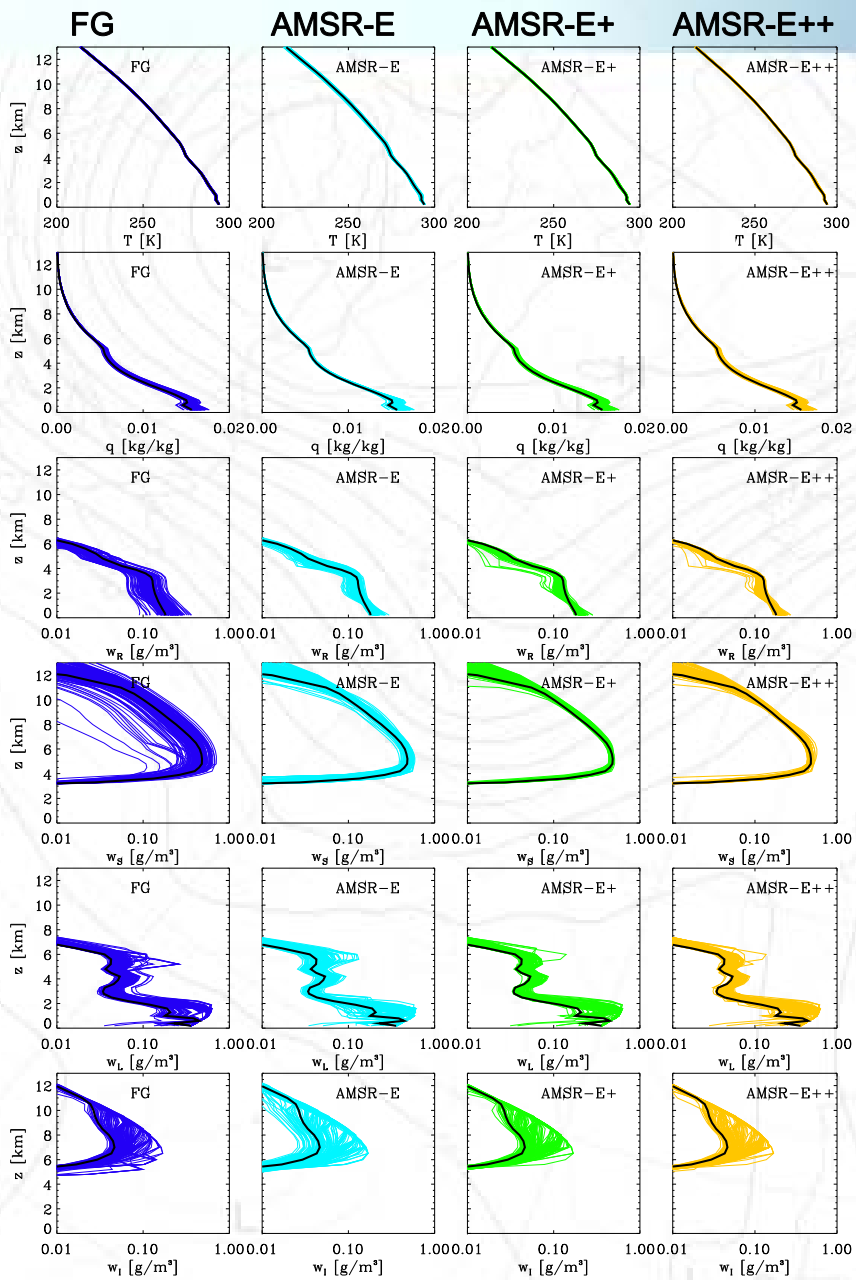
Applied to:

- 4 test profiles with respect to channels optimized for rain/snow retrieval.
- Bulk of global datasets.

For radiometer options:

- AMSR-E baseline.
- AMSR-E+ upgrade according to IC per profile.
- AMSR-E++ upgrade according to IC from global datasets.

1D-Var Example



Temperature [K]

Specific humidity [kg/kg]

Rain water content [g/m^3]

Snow content [g/m^3]

Cloud water content [g/m^3]

Cloud ice content [g/m^3]

1D-Var Test: Rain over ocean

Hydrometeor Profiles

Temperature/ moisture profiles

Relative error:

Temperature

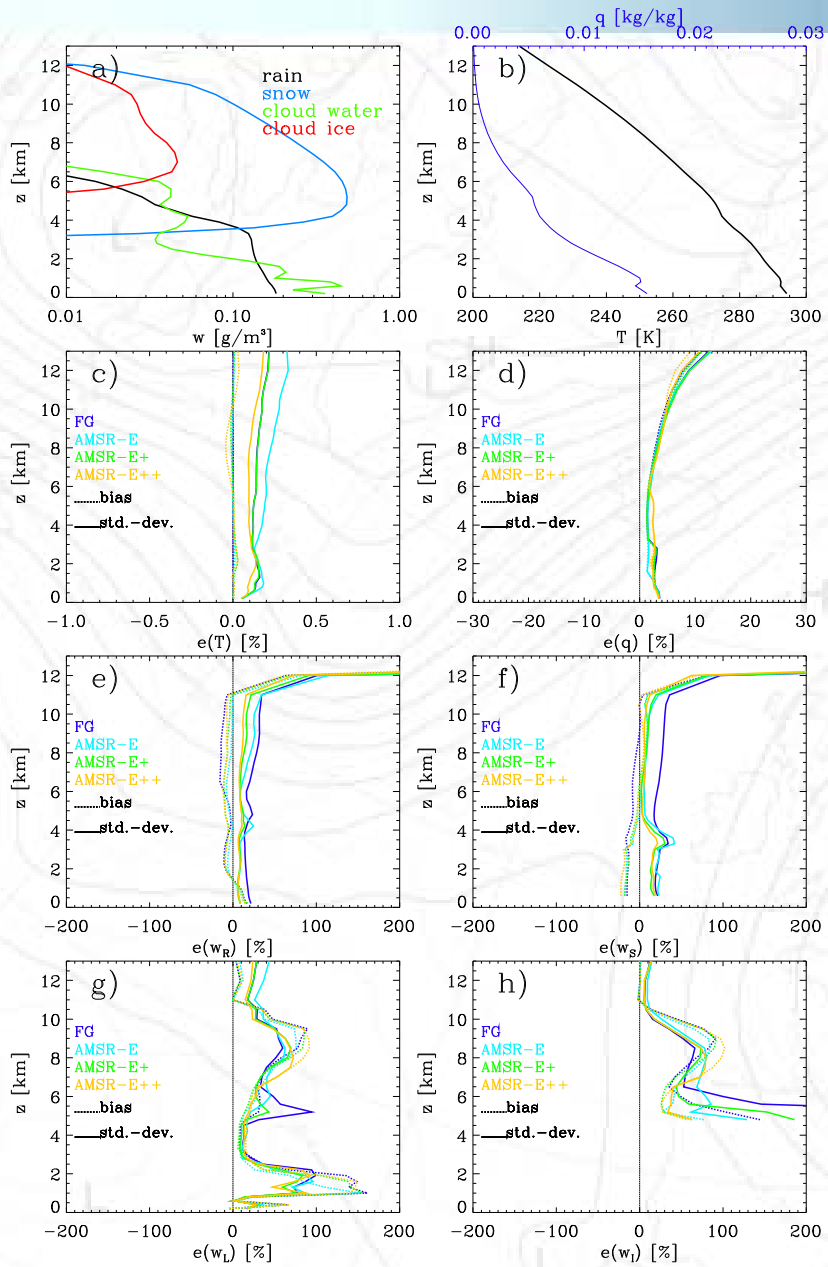
Specific humidity

Rain water

Snow

Cloud water

Cloud ice



1D-Var Test: Snow over land

Hydrometeor Profiles

Temperature/ moisture profiles

Relative error:

Temperature

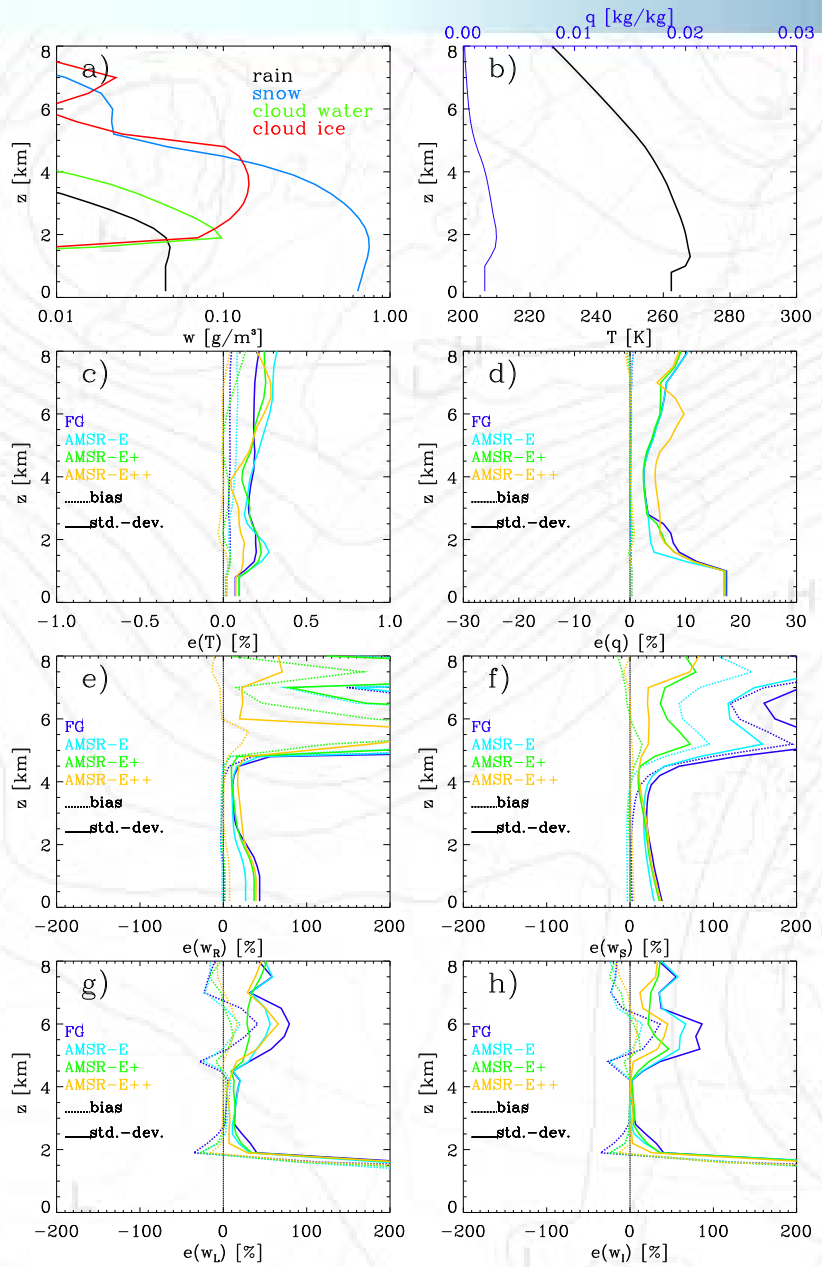
Specific humidity

Rain water

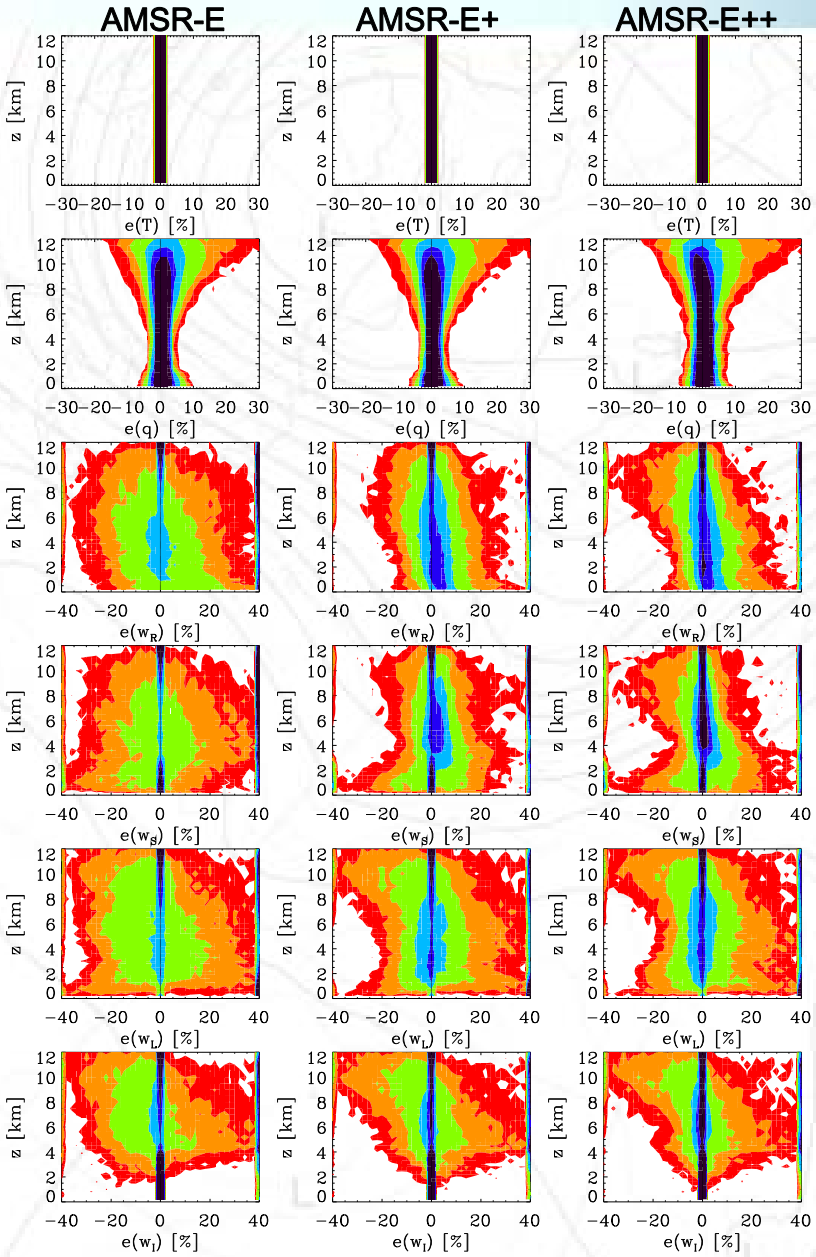
Snow

Cloud water

Cloud ice



1D-Var: Retrieval biases over oceans



Temperature [%]

Specific humidity [%]

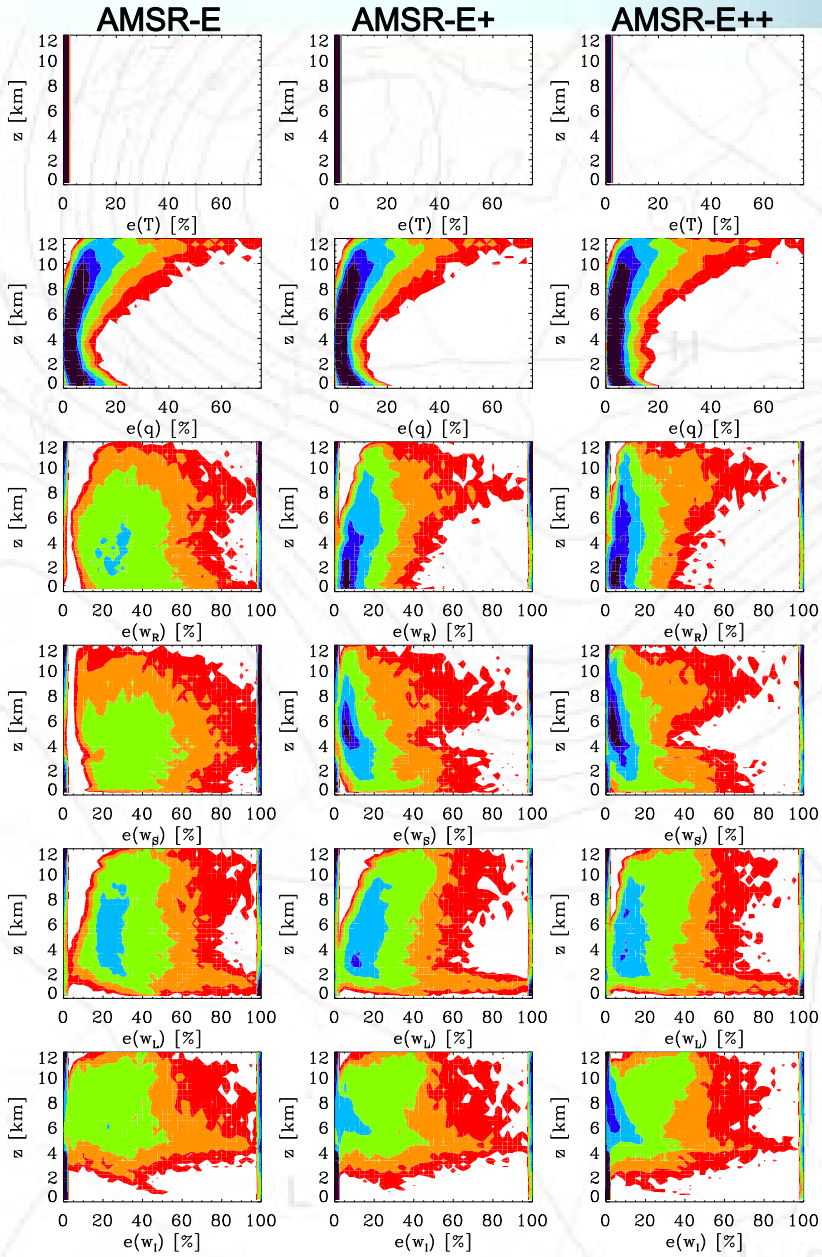
Rain water content [%]

Snow content [%]

Cloud water content [%]

Cloud ice content [%]

1D-Var: Retrieval error standard deviations over oceans



Temperature [%]

Specific humidity [%]

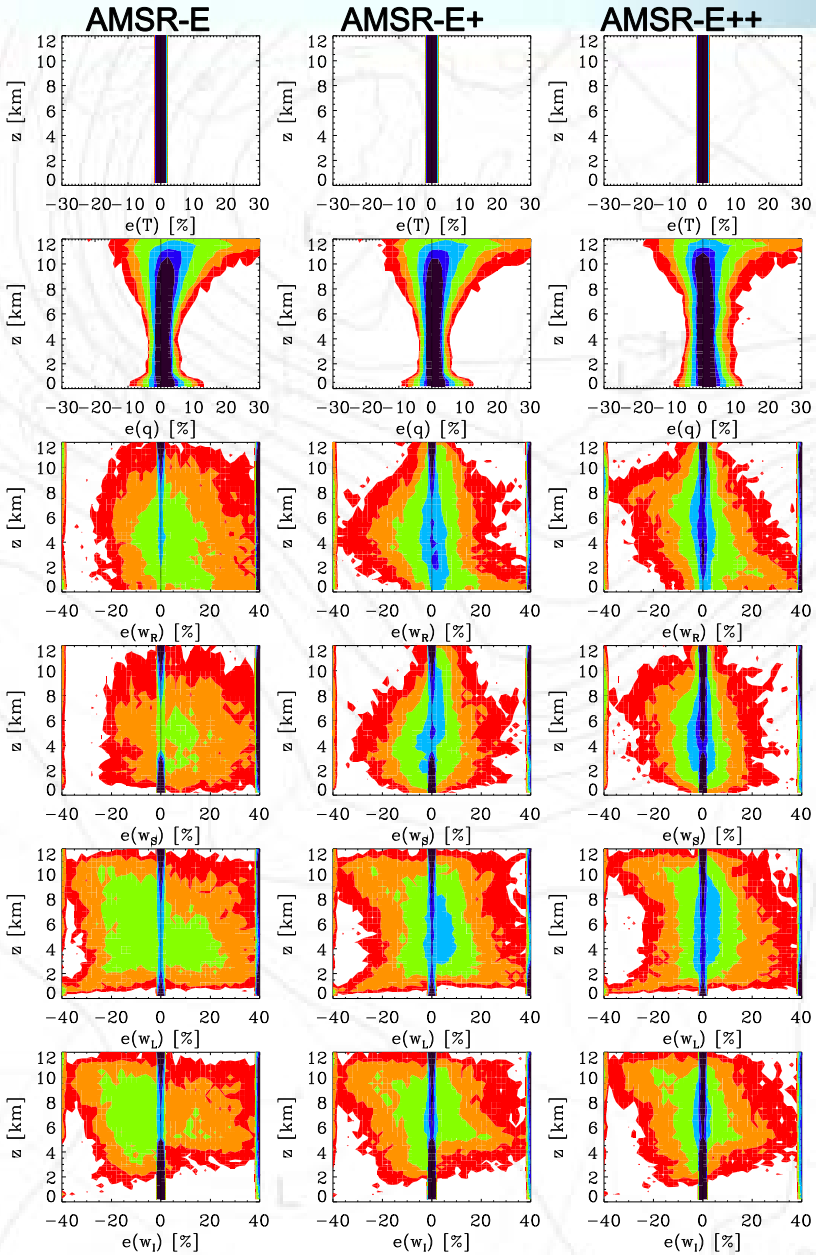
Rain water content [%]

Snow content [%]

Cloud water content [%]

Cloud ice content [%]

1D-Var: Retrieval biases over land



Temperature [%]

Specific humidity [%]

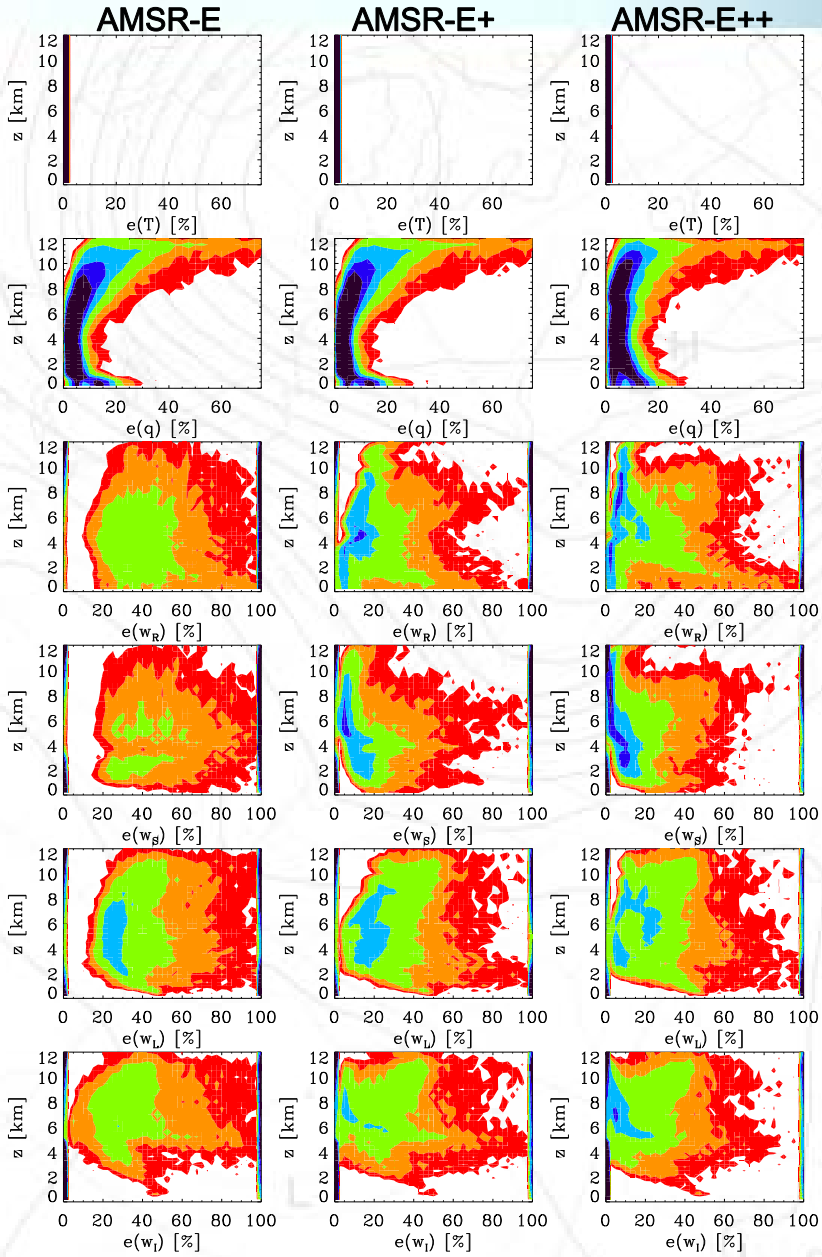
Rain water content [%]

Snow content [%]

Cloud water content [%]

Cloud ice content [%]

1D-Var: Retrieval error standard deviations over land



Temperature [%]

Specific humidity [%]

Rain water content [%]

Snow content [%]

Cloud water content [%]

Cloud ice content [%]

Conclusions

Information Content Analysis:

- Channel selection rather sensitive to definition of modelling+observation errors.
- Analysis based on assumption that operator (radiative transfer model) is linear.
- ECMWF model profiles, error statistics, emissivity data, observation operator provide most consistent framework that is available.
- AMSR-E radiometer represents good baseline; significant upgrades possible with AMSU-A – type sounding channels wrt rain and AMSU-B – type sounding channels wrt snow. 118-GHz channels are strong for both rain and snow.
- Recommended radiometer (AMSR-E++) similar to SSMIS with trade-off for sea-surface, snow and ice observation; clear-sky data assimilation in NWP.

1D-Var Retrieval Analysis:

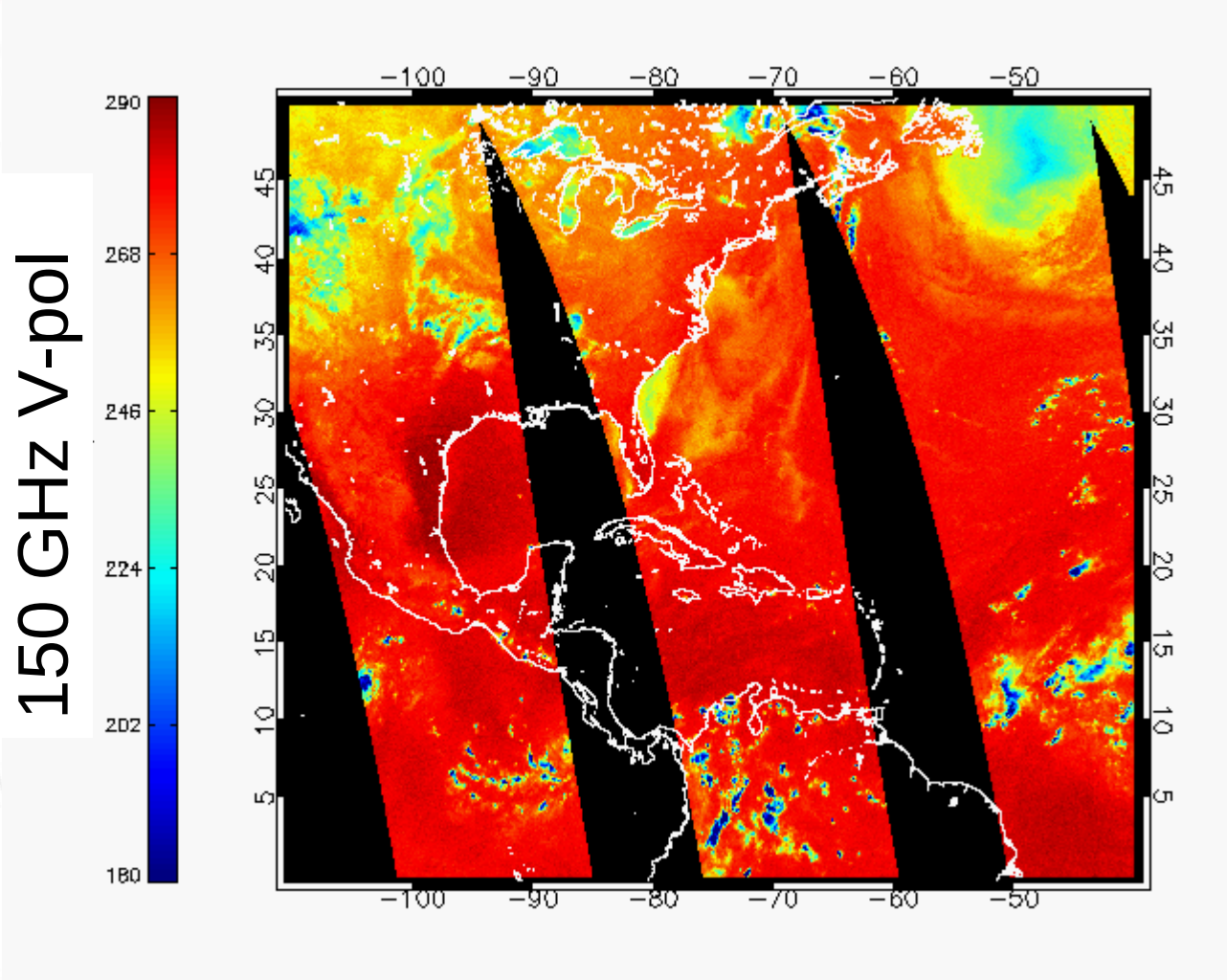
- 1D-Var is more complicated because observation operator also contains moist physics parameterizations; but produces results most comparable to data assimilation framework.
- Error estimates rely on FG-constraint and may be too good wrt off-line retrievals.
- AMSR-E++ significantly better than AMSR-E wrt all variables, in particular for mid-to-upper cloud levels.
- Relative errors (wrt state) well within user requirements.

Assimilation of SSMIS over land

Rain assimilation over land

- Looks like it might be possible, using SSMIS 50.3, 52.8, 91, 150, 183 GHz channels.
- Consistent with findings of di Michele & Bauer (2006) channel selection study for future sensors. However, no 120 GHz on SSMIS.
- Trade-off between sensitivity to clouds/rain and sensitivity to surface.
- SSMIS data available at ECMWF since 2003.

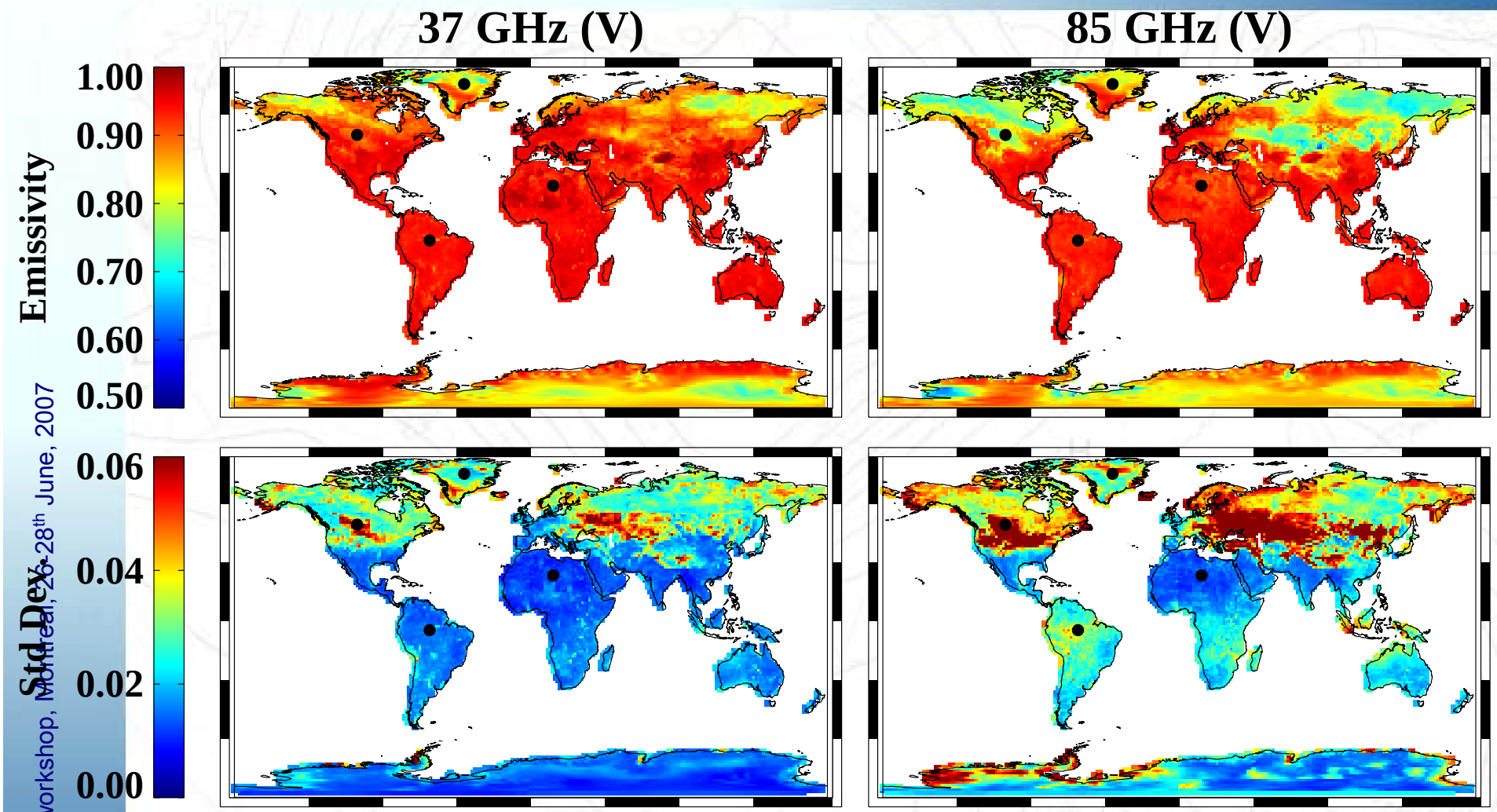
"Raw" SSMIS data stream



Surface Emissivity Atlas

- Prigent et al., 2006: Land Surface microwave emissivities over the globe for a decade. *Bull. Am. Meteor. Soc.*, **87**, 1573-1584.
- Uses SSM/I observations from 1992-2001
- ISCCP co-located observations to screen for only clear obs
- Surface temperature from ISCCP IR
- Temperature/humidity profiles from NCEP-NCAR reanalysis
- One emissivity for each of the 7 SSM/I channels, monthly at 0.25°

Surface emissivity climatology: January mean



- Prigent et al., 2006: Land Surface microwave emissivities over the globe for a decade. *Bull. Am. Meteor. Soc.*, **87**, 1573-1584.

Extension to Other Frequencies

1) Fit each monthly averaged, 0.25° grid box observation to Grody (1988) formula. P = {V, H} → 6 parameters.

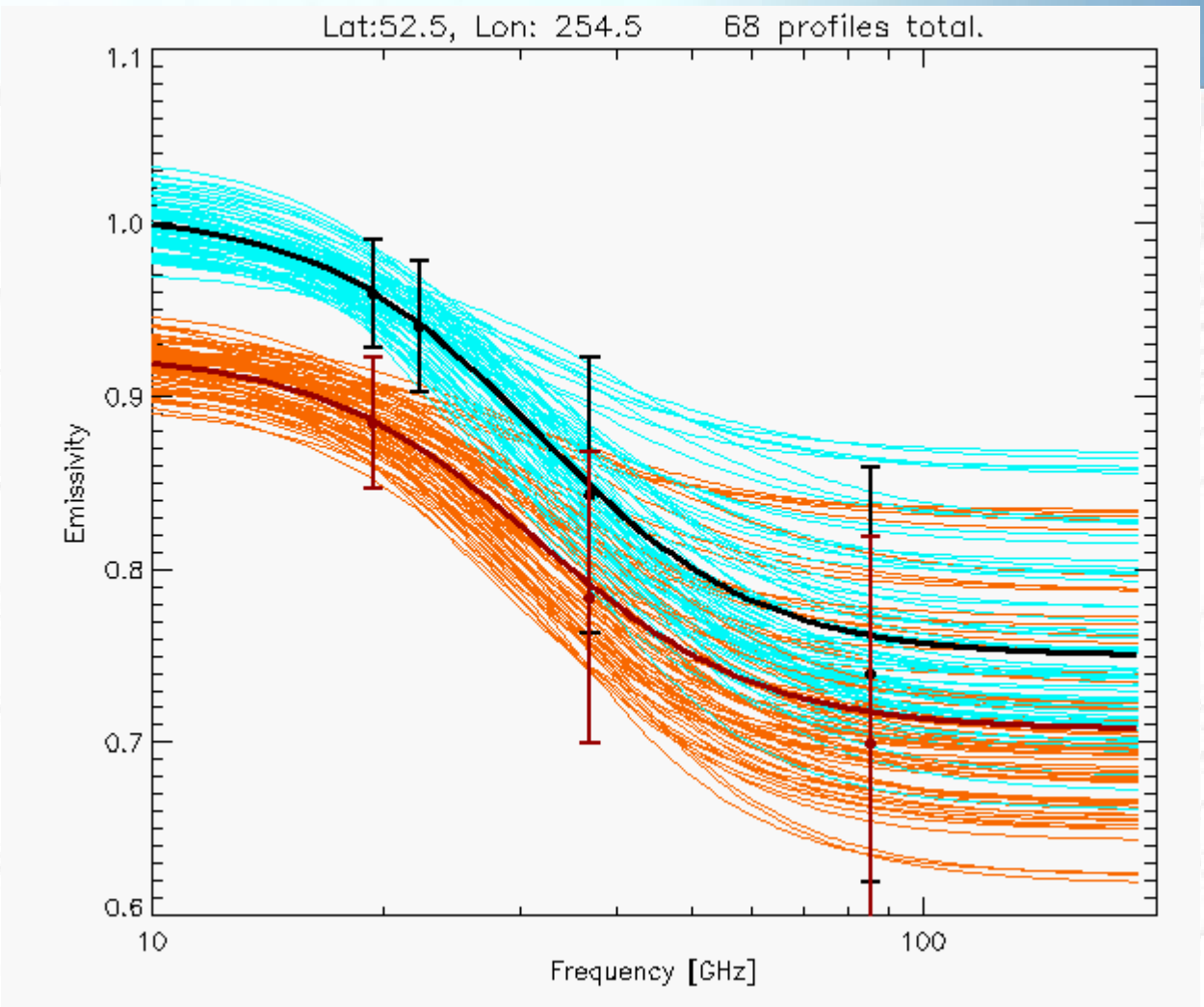
2) Average fits to 1° grid boxes and over all 10 years. Typically 50-100 contributing fits.

3) Obtain error covariance matrix

$$\varepsilon_p(\nu) = \frac{\varepsilon_{0,p} + \varepsilon_{\infty,p}\left(\frac{\nu}{\nu_0}\right)^k}{1 + \left(\frac{\nu}{\nu_0}\right)^k}$$

$$S_p(j,k) = \frac{1}{N-1}\sum_{i=1}^{N}\left(p_j(i) - \langle \vec{p}_j \rangle\right)\left(p_k(i) - \langle \vec{p}_k \rangle\right)$$

j,k = 1..6



Central Canada, March

1D-Var Methodology Changes over land

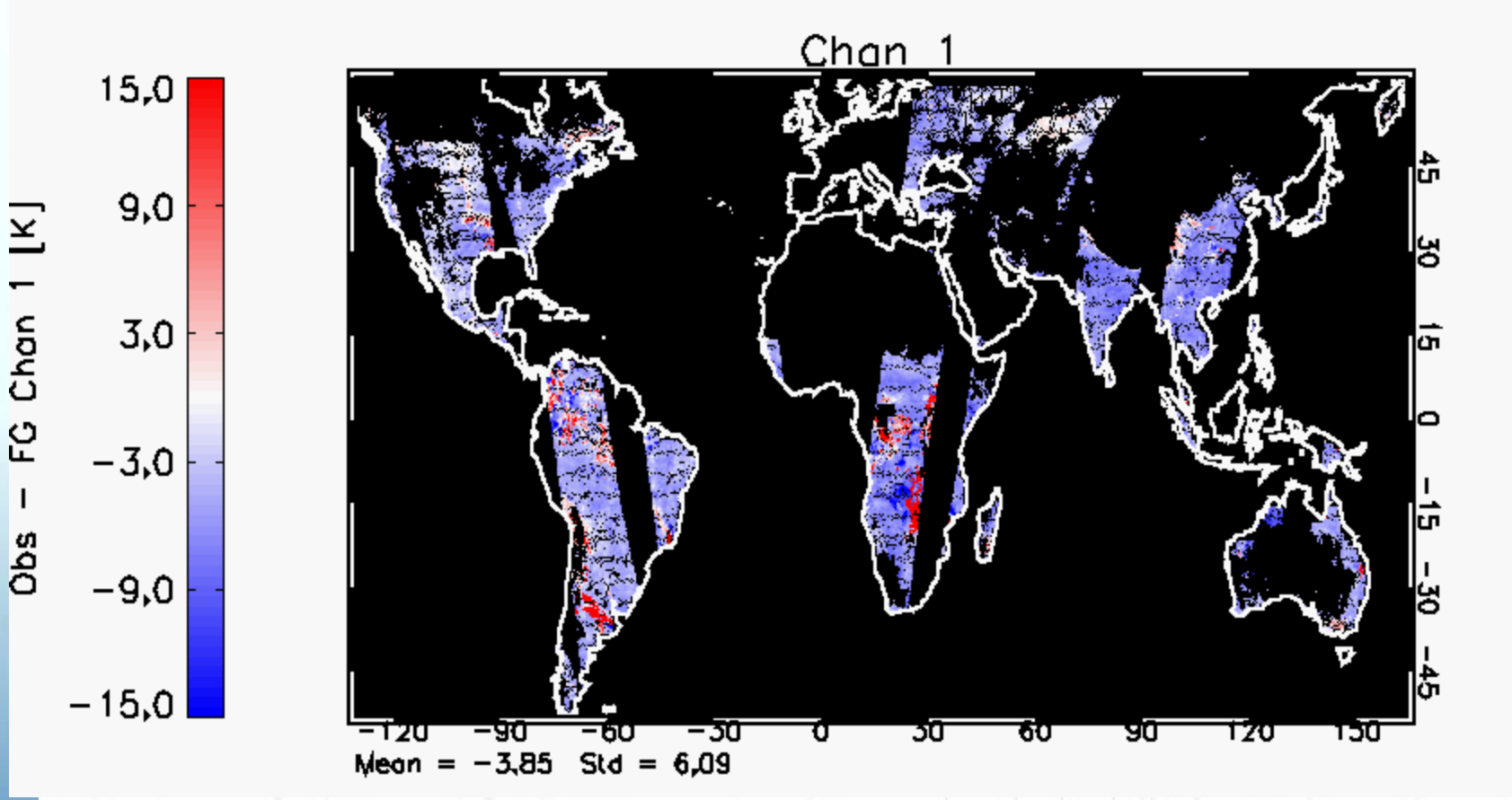
Ocean → ***Land***

$$\vec{x} = \begin{pmatrix} \vec{t} \\ \vec{q} \\ u_{10} \\ v_{10} \end{pmatrix}$$

$$\vec{x} = \begin{pmatrix} \vec{t} \\ \vec{q} \\ T_{skin} \\ \vec{\varepsilon} \end{pmatrix}$$

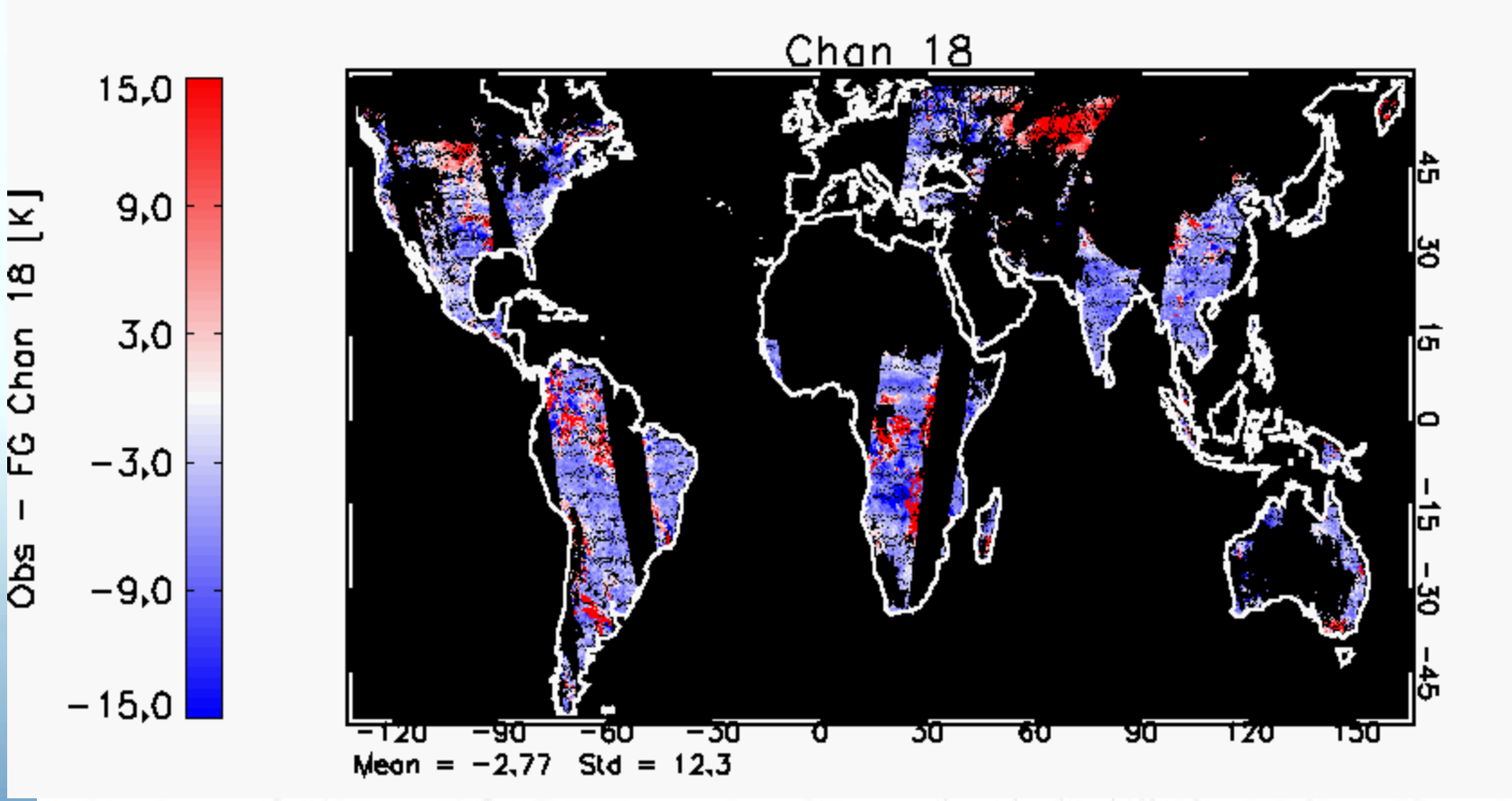
May be actual emissivities or Grody formula parameters

First-Guess Statistics, Map-View



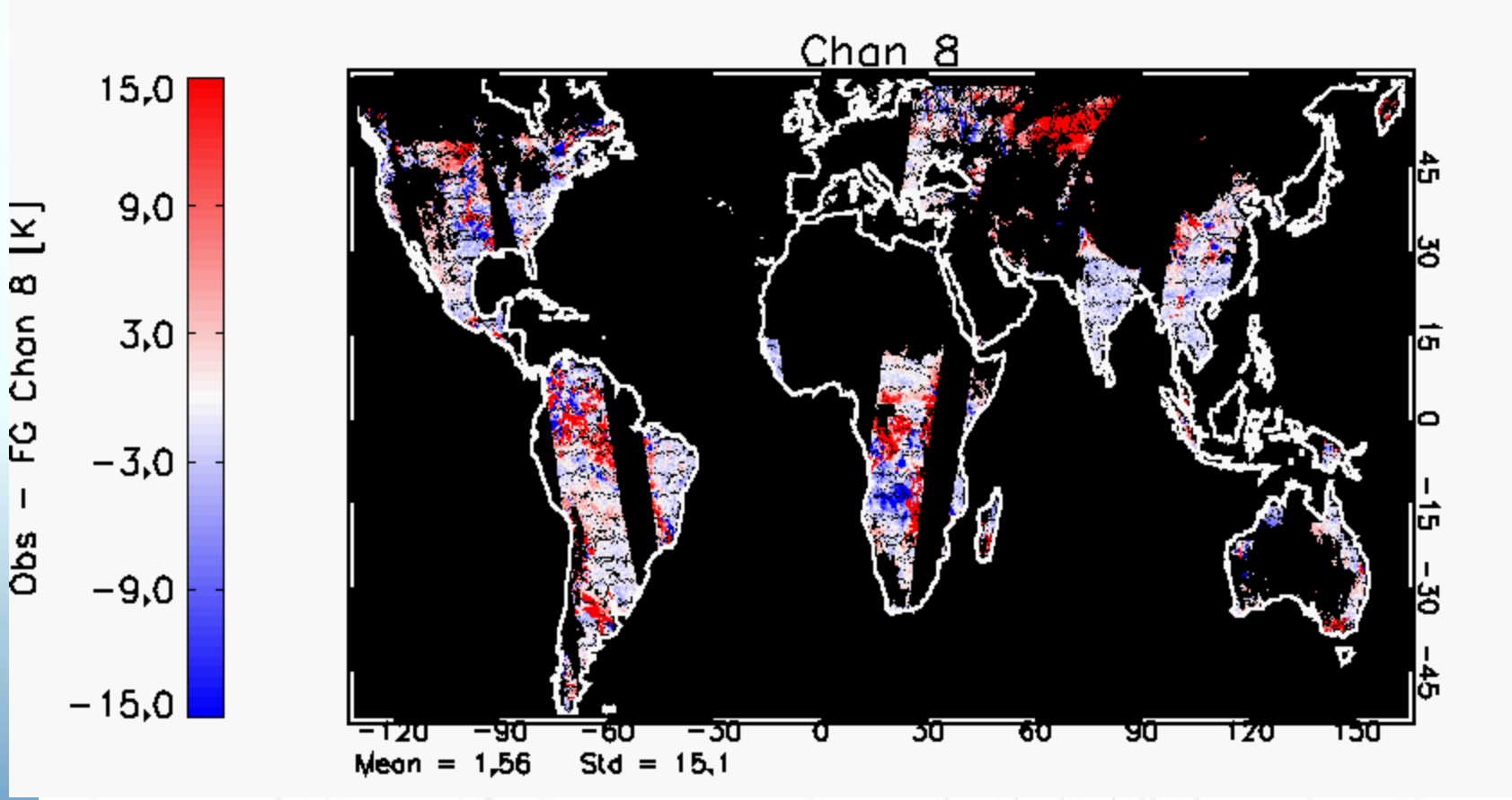
50.3 GHz V-pol

First-Guess Statistics, Map-View



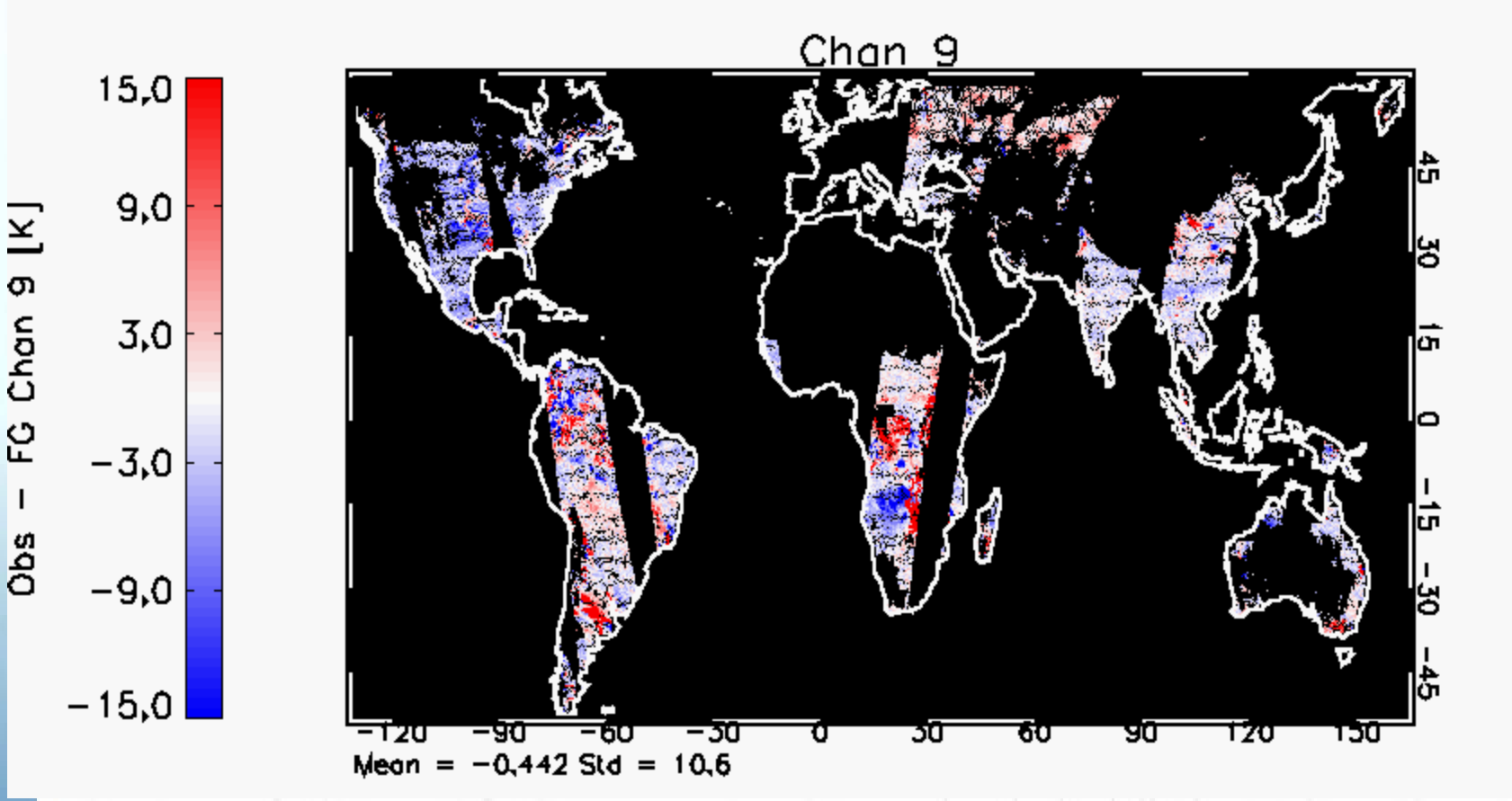
91 GHz H-pol

First-Guess Statistics, Map-View



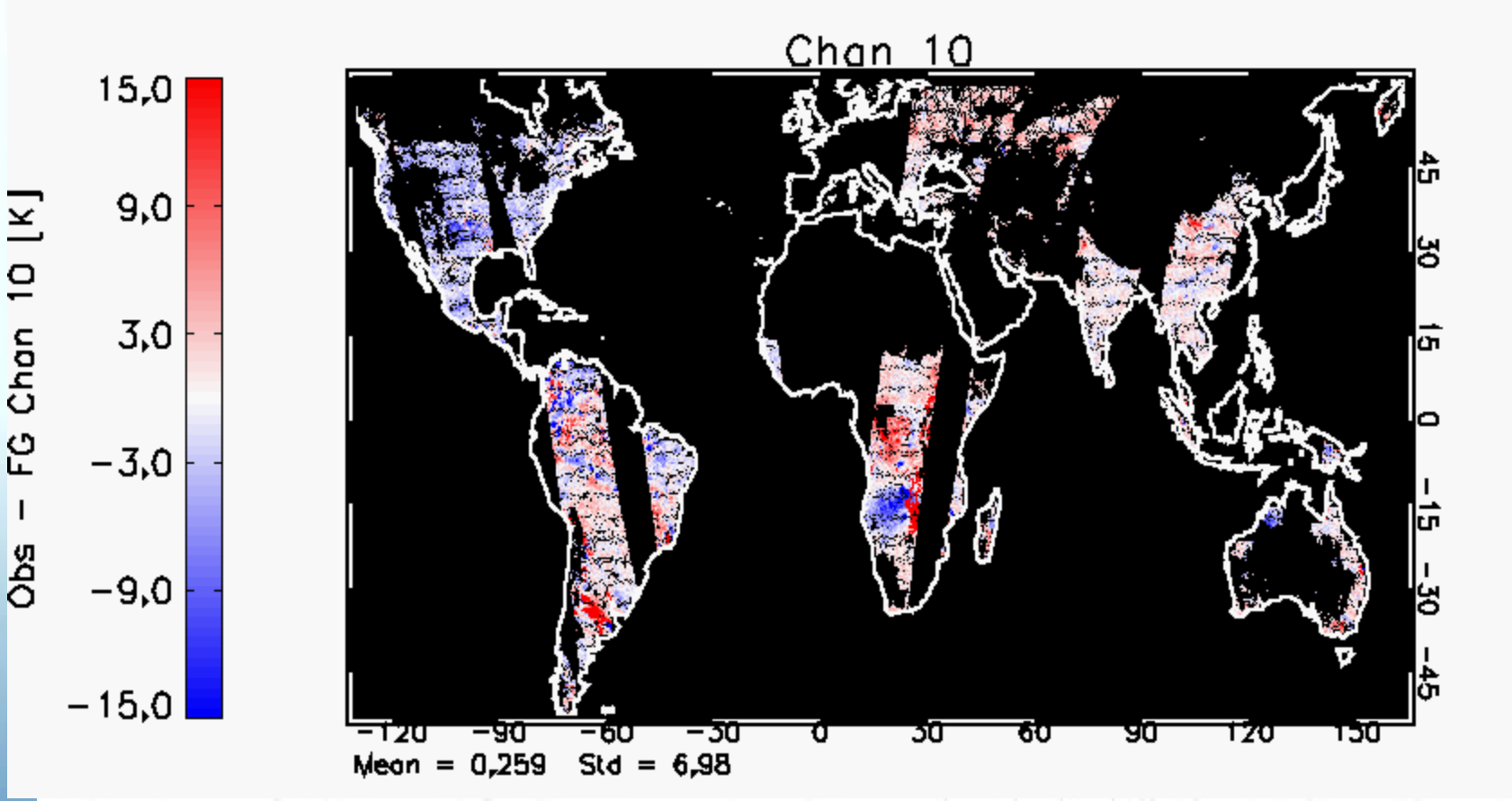
150 GHz H-pol

First-Guess Statistics, Map-View



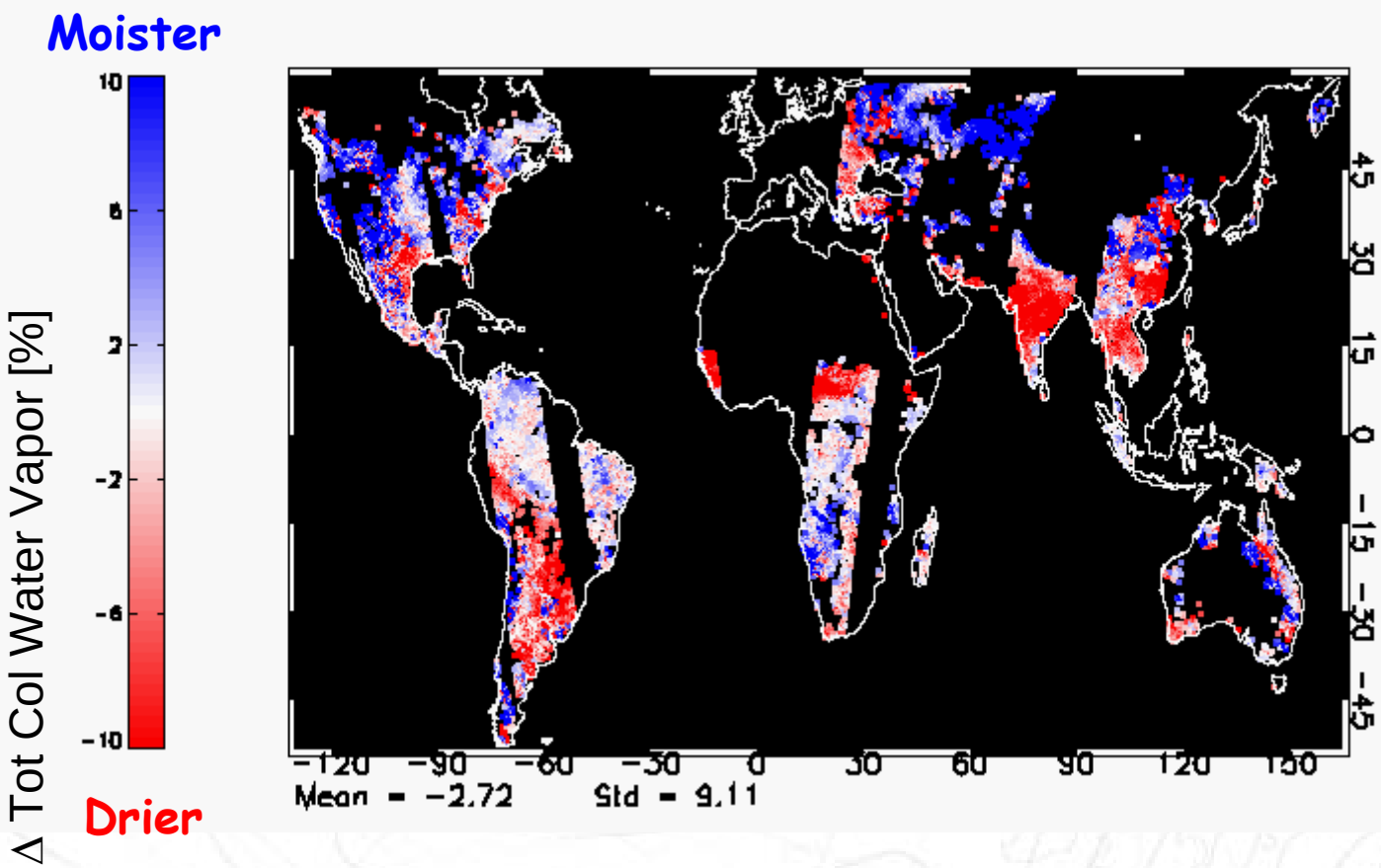
183±7 GHz H-pol

First-Guess Statistics, Map-View



183±3 GHz H-pol

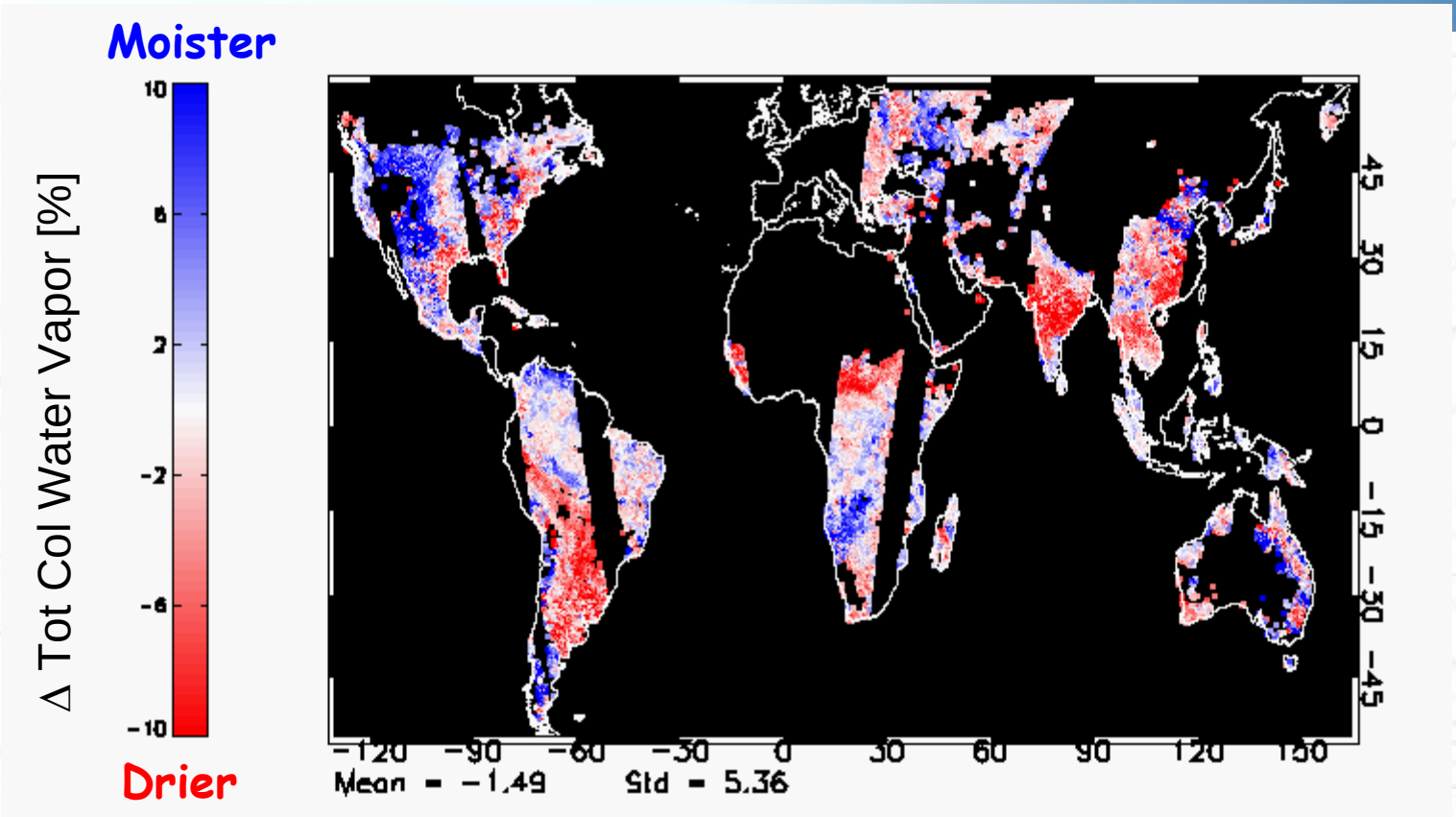
1D-Var TCWV Increments



Experiment: OLDEMIS:

- surface emissivity retrieved individually for each channel
- 50, 52, 150±1, 183±3,6, 91 Ghz channels used

1D-Var TCWV Increments



Experiment: ALL:

- retrieve the parameters of the surface emissivity model
- much larger errors assigned to the first guess of these parameters
- 19, 37, 50, 52, 150±1, 183±1,3,6, 91 Ghz channels used

Conclusions after first tests over land

- Basic assimilation seems to be working as desired for precipitating regions.
- TCWV error reduction much less than that of over-ocean SSM/I assimilation
- Can still have a significant impact on the 4D-Var analysis
- Land emissivity can have spurious effects and is likely leading to the general drying trends seen in clear-sky areas.

Summary

- Channel selection studies:
  - For snow: 118+/- (around the oxygen line) and 183+/- (around the water vapour line) on top of a baseline ASMR-E configuration
  - NWP gives very large database of profiles, so good statistics
- From operational rain assimilation:
  - Biases and standard deviations are higher in higher frequency window channels – many things become more difficult
  - Current rain assimilation system has mainly tropical impact
  - Much work still to be done to get the best out of this kind of observation.
  - Direct 4D-Var in testing and should make significant improvements
- Experiments with assimilation of rainy SSMIS over land:
  - For snow retrievals, would prefer 183GHz channels to 90 or 150GHz, as less/no surface contribution, and more linear radiative transfer due to the sensitivity to atmospheric humidity
  - Rainy microwave assimilation is more difficult over land, but certainly possible. Crucially, must retrieve surface emissivity model parameters and skin temperature.
- Gaps:
  - For a focused snow mission may need focused study of microwave information content over snow and sea ice.
  - Surface emissivity models over land, snow and ice
  - Validation of model rain, snow, and cloud at high latitudes

References

- Information content:
  - Bauer, Moreau and DiMichele: Hydrometeor retrieval accuracy using microwave window and sounding channel observations, J. App. Met., 2005.
  - DiMichele and Bauer: Passive microwave radiometer channel selection based on cloud and precipitation information content, Q. J. R. Meteorol. Soc., 2006
  - Bauer and DiMichele: Study on definition of mission requirements for a post-EPS microwave radiometer for cloud and precipitation observation, EUMETSAT contract report EUM/CO/06/1510/PS, 2007. Need permission from EUMETSAT to release this, but should be fine.
- Operational rain assimilation:
  - Bauer et al.: Implementation of 1D+4D-Var assimilation of precipitation-affected microwave radiances at ECMWF, parts I and II, Q. J. R. Meteorol. Soc., 2006
  - Geer, Bauer and Lopez: Lessons learnt from the 1D+4D-Var assimilation of rain and cloud affected SSM/I radiances at ECMWF, ECMWF tech. memo, in preparation
  - Kelly, Bauer, Geer, Lopez, and Thépaut: Impact of SSM/I observations related to moisture, clouds and precipitation on global NWP forecast skill, to be submitted, 2007
  - O'Dell and Bauer: Assimilation of precipitation affected SSMIS radiances over land in the ECMWF data assimilation system. Report for EUMETSAT hydrology SAF, 2007

Microwave Spectrum: Sampled/Protected Frequencies