Sources of Biases in Microwave Radiative Transfer Modelling

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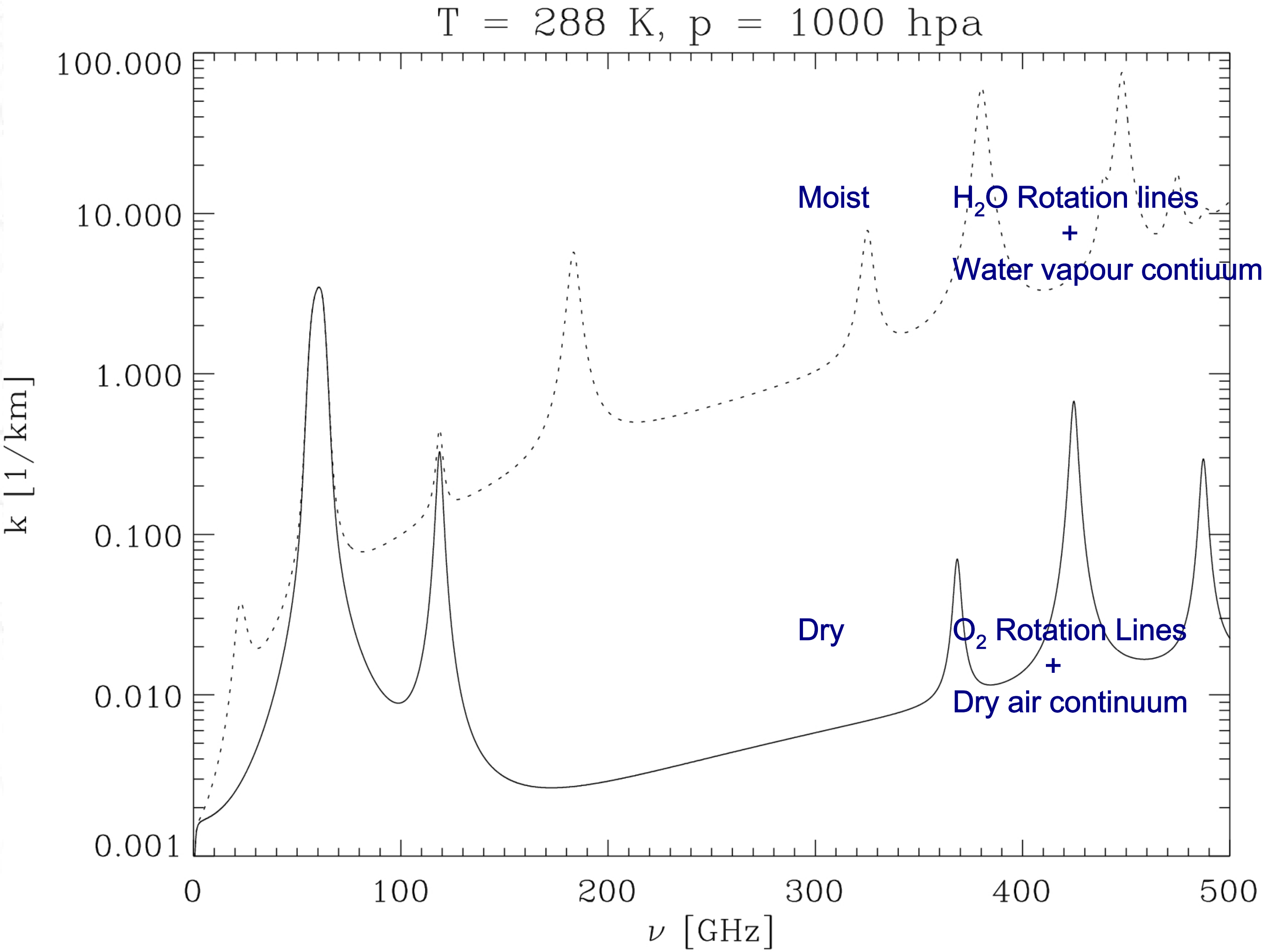
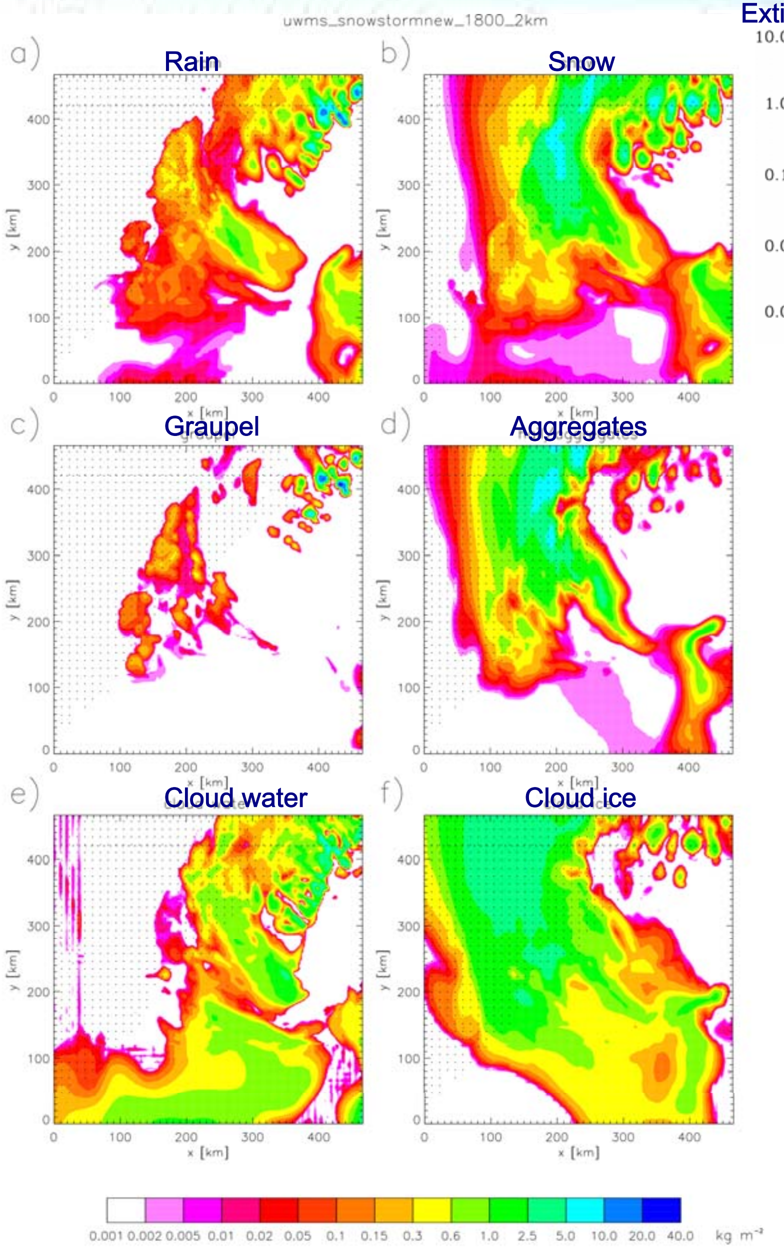
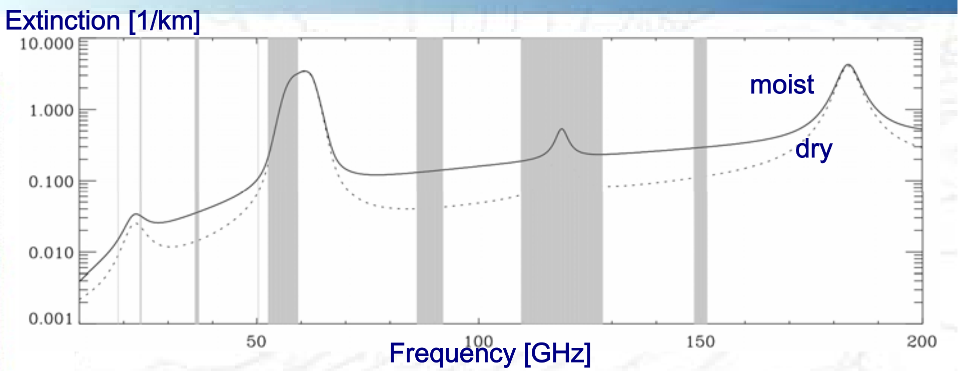
ECMWF/NWP-SAF Workshop on bias estimation and correction in data assimilation
8-11 November 2005, Reading, UK

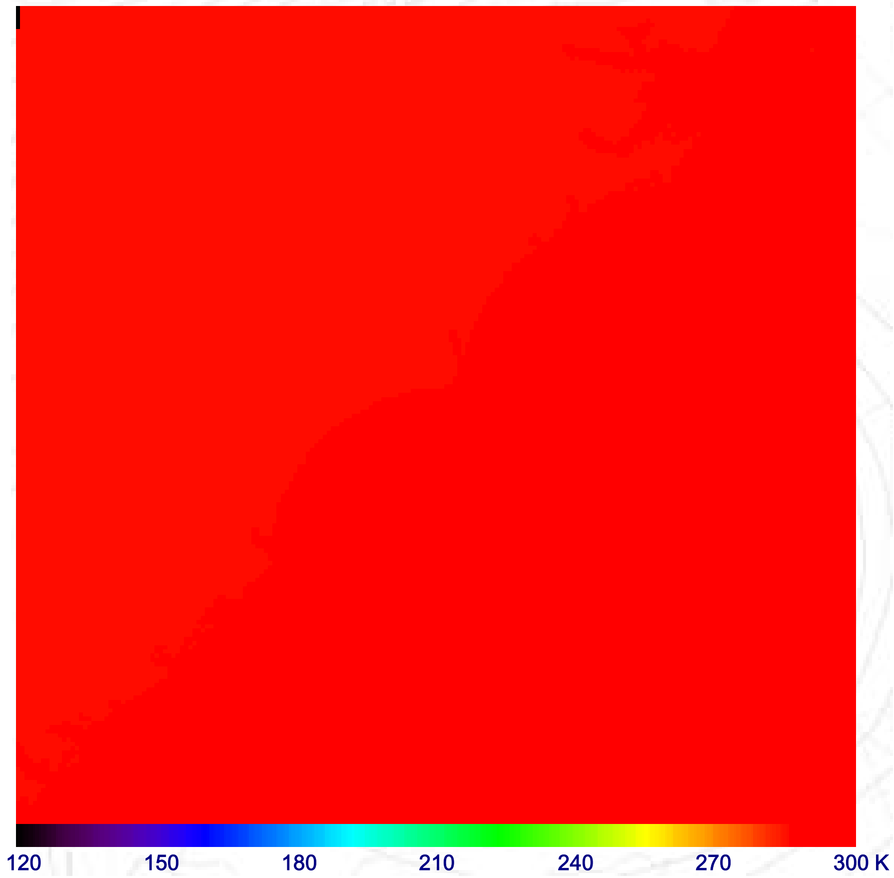
μ~ Spectrum


T = 288 K, p = 1000 hpa
100.000
10.000
1.000
0.100
0.010
0.001
k [1/km]
0
100
200
300
400
500
ν [GHz]
Moist
H2O Rotation lines
+
Water vapour contiuum
Dry
O2 Rotation Lines
+
Dry air continuum

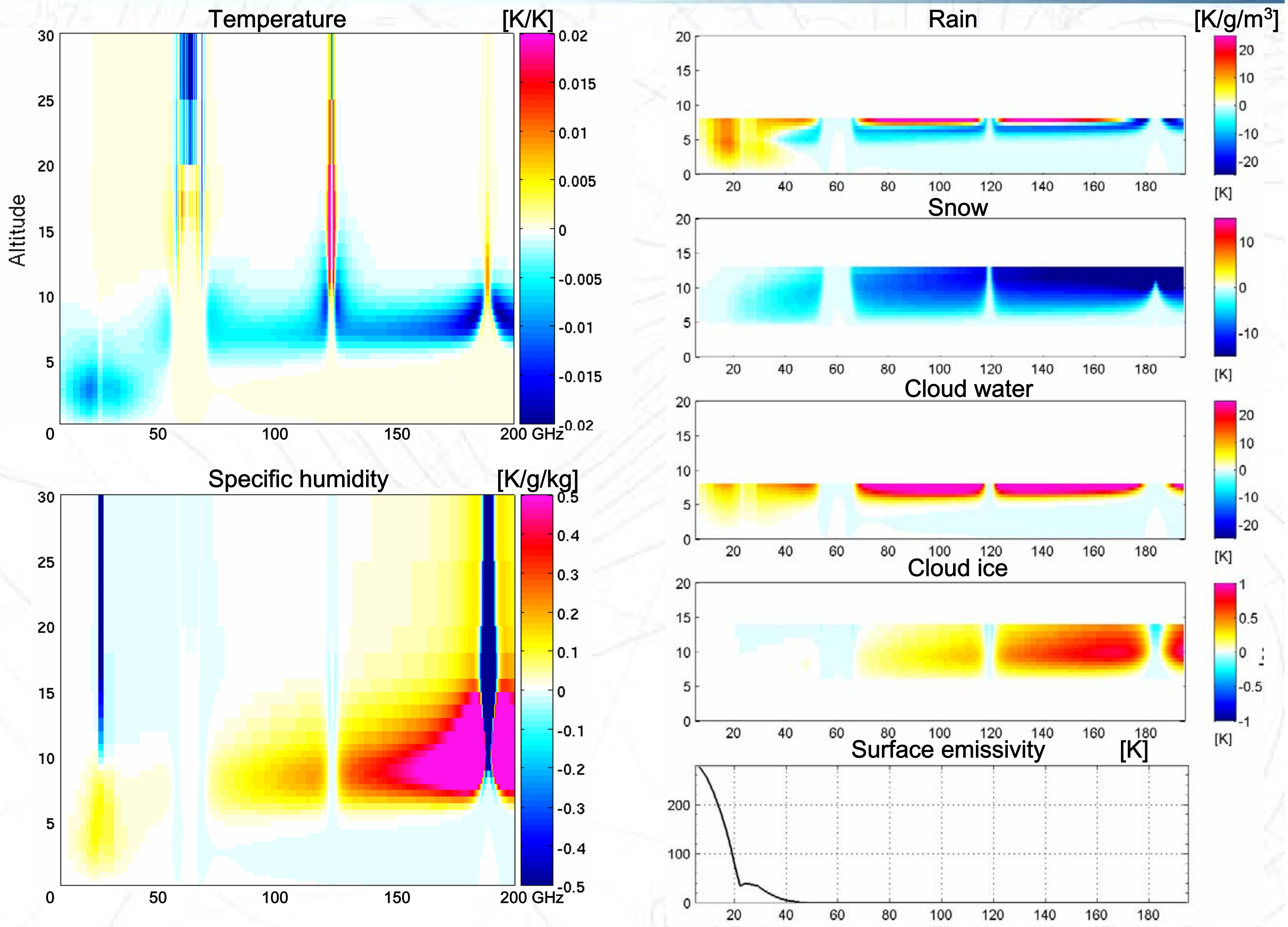
Combined cloud-radiative transfer modelling







Microwave H_{TB}: Single profile over ocean



Microwave H_{TB}: Single profile over land

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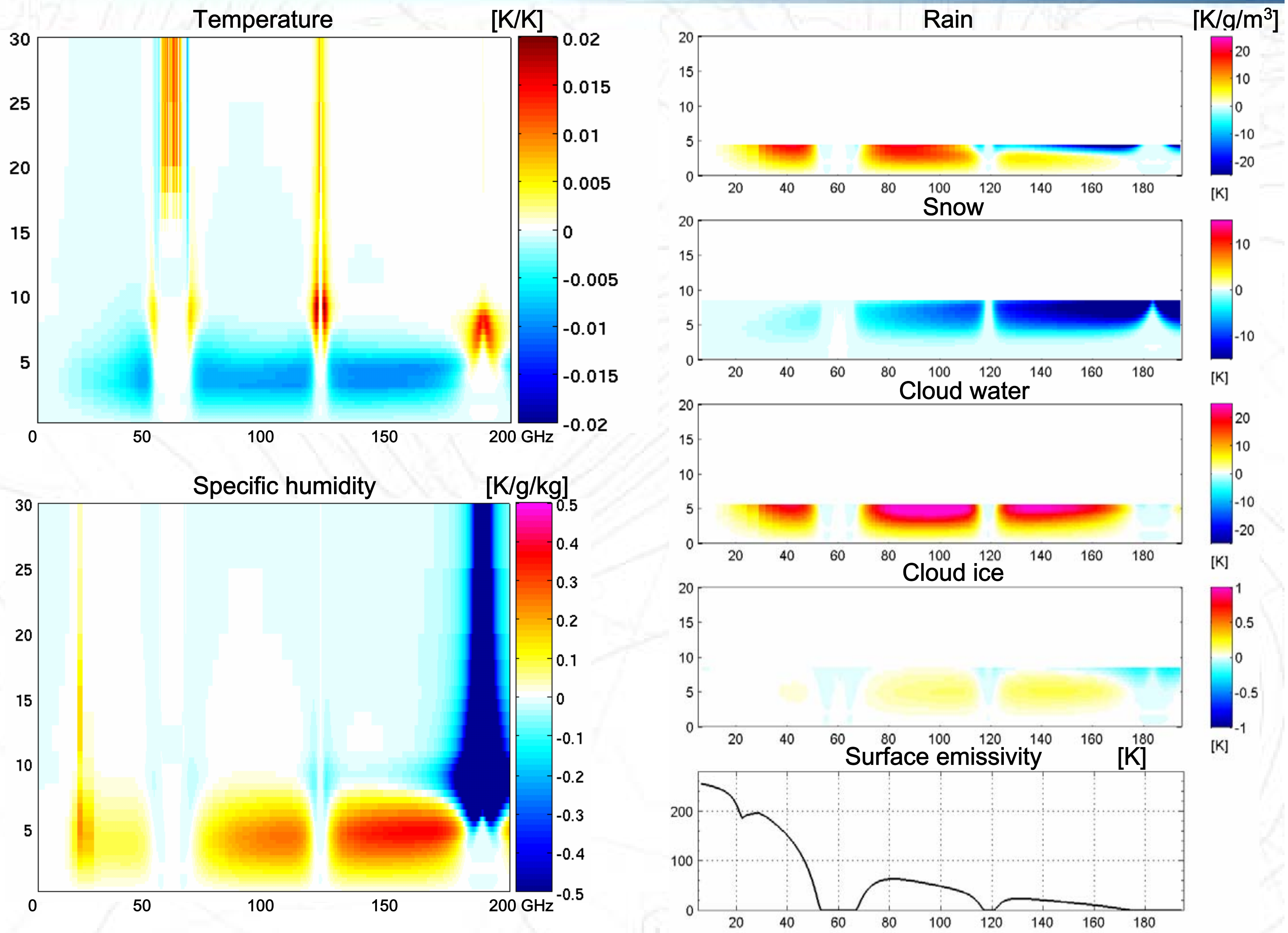
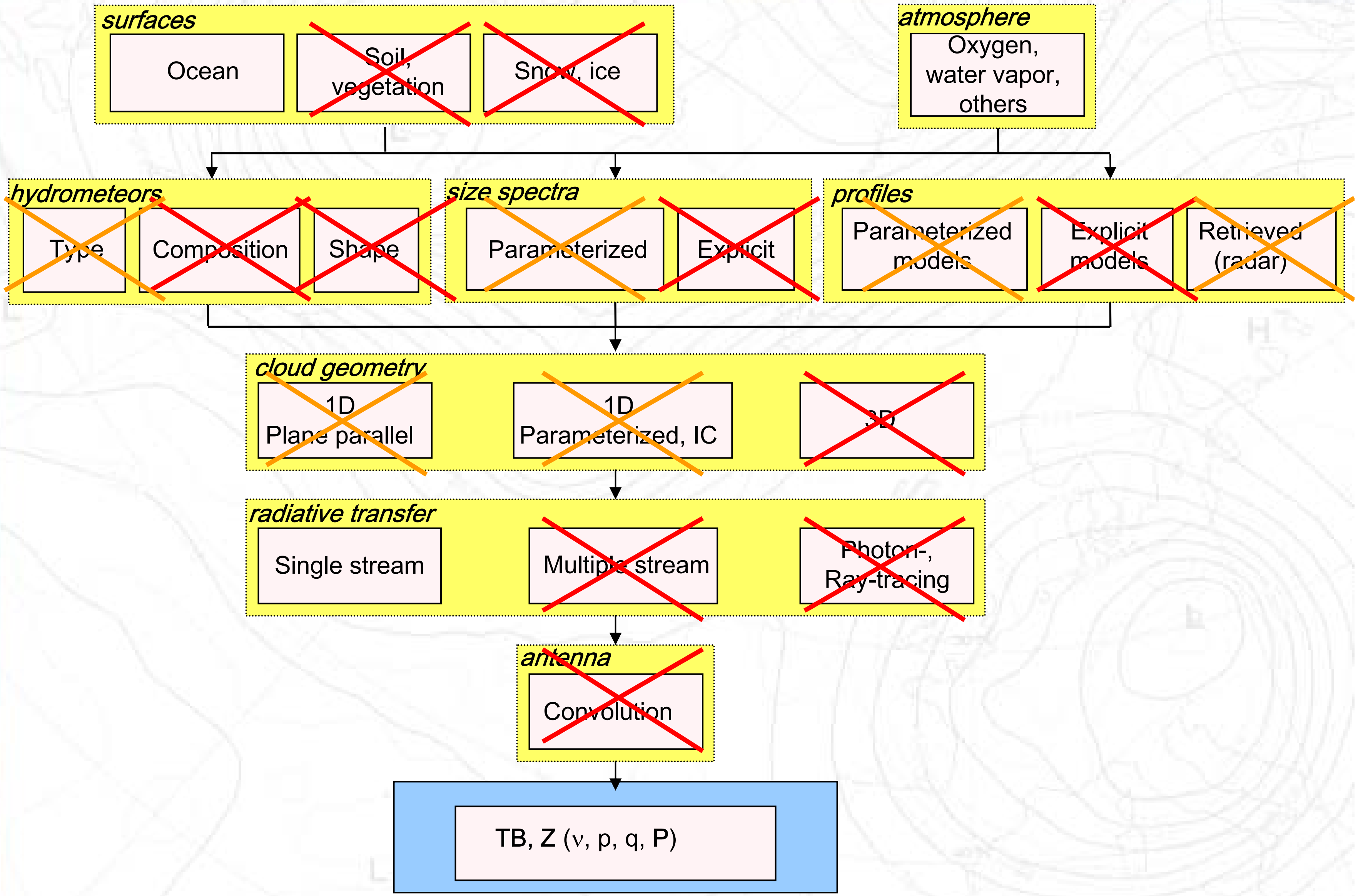
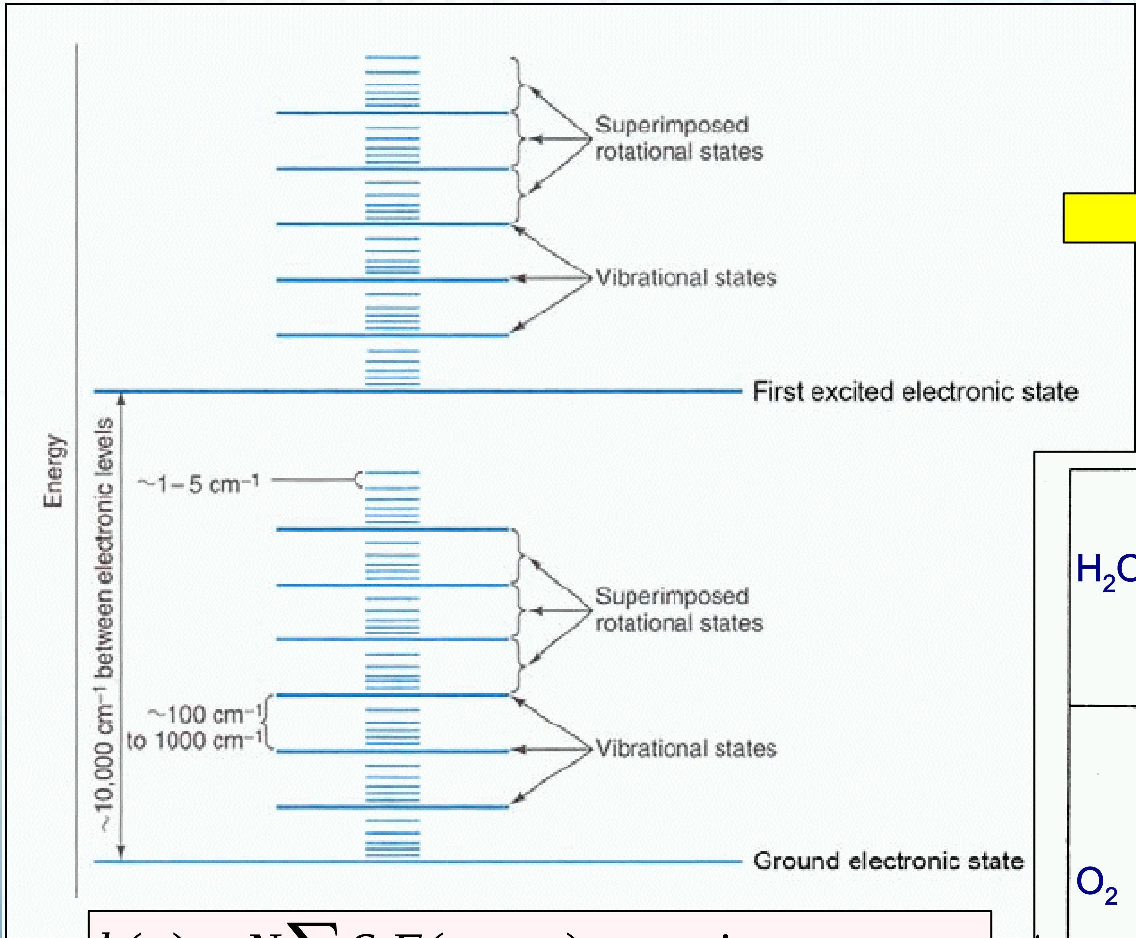
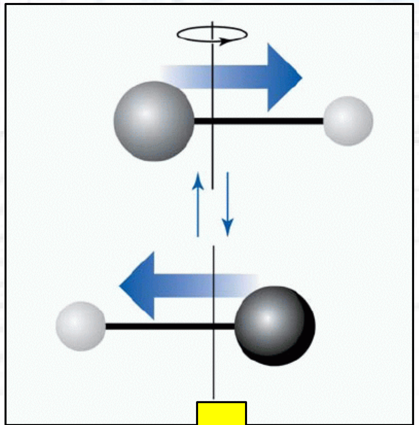


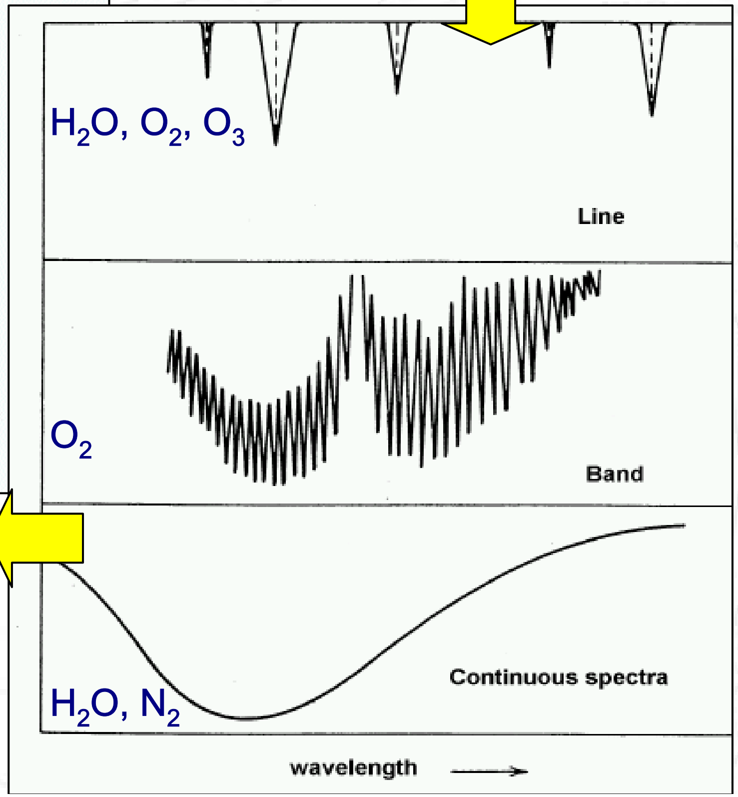
Components of μ~ RT Modelling



Atmospheric absorption







$$k(\nu) = N \sum_i S_i F(\nu - \nu_o) + \text{continuum terms}$$

Absorption Coefficient

Gas abundance

Line strength

Shape factor

Frequency

Center frequency

Inter-model evaluation

ECMWF

117 Profiles, RTTOV vs. LBL model

AMSU-A		RTTOV-8 117 independent set		
Channel #	NeDT degK	Mean bias degK	St. dev. degK	Max diff degK
1	0.20	0.00	0.01	0.04
2	0.24	-0.01	0.02	0.12
3	0.19	-0.02	0.03	0.18
4	0.13	0.01	0.01	0.07
5	0.13	0.02	0.01	0.08
6	0.11	0.01	0.01	0.06
7	0.12	0.00	0.01	0.03
8	0.13	0.00	0.00	0.01
9	0.15	-0.01	0.01	0.07
10	0.19	0.19	0.16	0.39
11	0.20	0.00	0.04	0.27
12	0.31	-0.02	0.07	0.44
13	0.42	-0.05	0.09	0.58
14	0.70	-0.04	0.06	0.41
15	0.10	0.07	0.10	0.34

117 Profiles, RTTOV vs. LBL model

AMSU-B		RTTOV-8 117 independent set		
Channel #	NeDT degK	Mean bias degK	St. dev. degK	Max diff degK
1	0.32	0.07	0.10	0.33
2	0.71	-0.02	0.08	0.73
3	1.05	-0.01	0.07	0.74
4	0.69	-0.01	0.04	0.44
5	0.57	0.00	0.05	0.40

Inter-model model differences >> LBL-parameterized model differences

All vs.CIMSS MWLBL model

Model	AMSU-06		AMSU-10		AMSU-14		AMSU-18	
	std	bias	std	bias	std	bias	std	bias
RTTOV-7/8	0.04	-0.06	0.15	0.25	**1.36**	0.90	**0.35**	-0.39
OPTRAN	0.09	0.00	0.05	-0.04	**0.73**	-1.97	0.10	0.00
AER_OSS	0.06	0.13	0.04	0.03	0.09	0.14	0.14	-0.16
MIT	0.01	0.00	0.04	-0.04	0.08	-0.09	0.19	-0.40
RAYTHEON	**0.42**	-0.57	0.17	0.24	0.20	0.60	**0.50**	-0.07
AER_LBL	0.06	0.13	0.05	0.03	0.09	0.16	0.14	-0.15
MSCMWLBL	0.03	0.05	0.03	0.04	0.20	0.51	**0.32**	-0.36
ATM	0.19	0.46	0.07	0.08	0.11	0.23	0.24	-0.28

(Saunders et al. 2005)

Evaluation with measurements

Table 2.8. Evolution of O_2 and H_2O line and continuum parameters in the Millimeter-wave Propagation Model of Liebe (1977-1993). The O_2 parameters include line-mixing coefficients.

Year of publ.	O_2 parameters	H_2O lines	H_2O continuum
1977	M	O	O
1978	M	-	-
1981	R	O	-
1984	-	O	M
1987	-	O	M
1989	R	O	-
1992	M	-	-
1993	R	O	O

key
M: new measurements by Liebe and co-workers
R: revised analysis of earlier measurements by Liebe and co-workers
O: revision based on measurements by others
- : no change from previous version

Table 2.10. Calculated minus measured brightness-temperature differences (K) at Wallops Island, VA from England *et al.* (1993).*

frequency, GHz	PWV	average T_B, K	MPM89	W76
20.7	low	14.1	+0.38	+0.80
20.7	high	30.0	+0.15	+1.00
22.2	low	18.8	+0.56	-0.49
22.2	high	45.0	-0.76	-4.30
31.4	low	13.5	-0.33	+0.31
31.4	high	20.0	-1.10	+0.22

low PWV: <1 cm; high PWV: 2.1 cm.

Table 2.11. Calculated minus measured brightness-temperature differences (K) at Nauru Island (tropical western Pacific) from Westwater *et al.* (2003). Average PWV = 4.7 cm. The values in parentheses are 99% confidence intervals for the final digit.

frequency, GHz	average T_B, K	MPM87	MPM93	R98
23.8	65	+0.80 (67)	+3.90 (70)	+0.69 (67)
31.4	32	-0.16 (32)	+3.37 (36)	+0.86 (33)

Table 2.12. Calculated minus measured 31.4-GHz brightness-temperature differences (K) at three sites, from Marchand *et al.* (2003).

location	average PWV, cm	MPM87	R98	MonoRTM
Nauru	4.0	-0.35	+0.65	-0.51
Oklahoma	1.0	-0.04	+0.42	+0.05
Alaska	0.7	-0.79	-0.34	-0.84

Ground-based intercomparison

Satellite data based intercomparisons

Meissner and Wentz (2003)
SSM/I: retrievals tuned with 19-37 GHz observations, verified against 85 GHz to within 1.2 K

Pumphrey and Bühler (2000)
MLS/MAS: 183 GHz line shift verified to within 0.2 MHz/torr

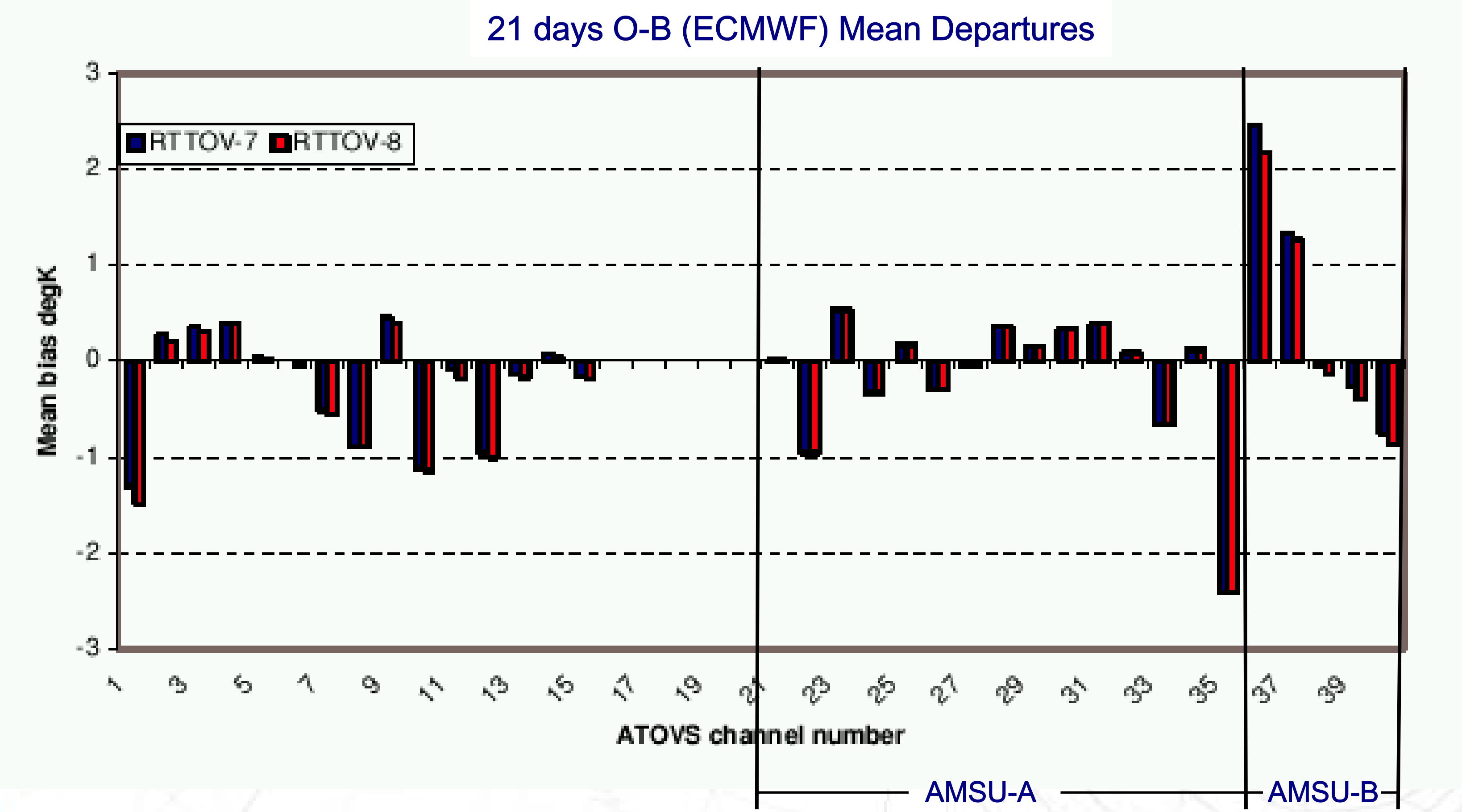
Bühler (2005)
ASUR: 626 GHz line shift verified to within 0.15 MHz/torr

Rosenkranz and Barnet (2005)
HSB: 0.2-0.8 K

Rosenkranz (2003)
AMSU-A: -0.23 – 0.42 K

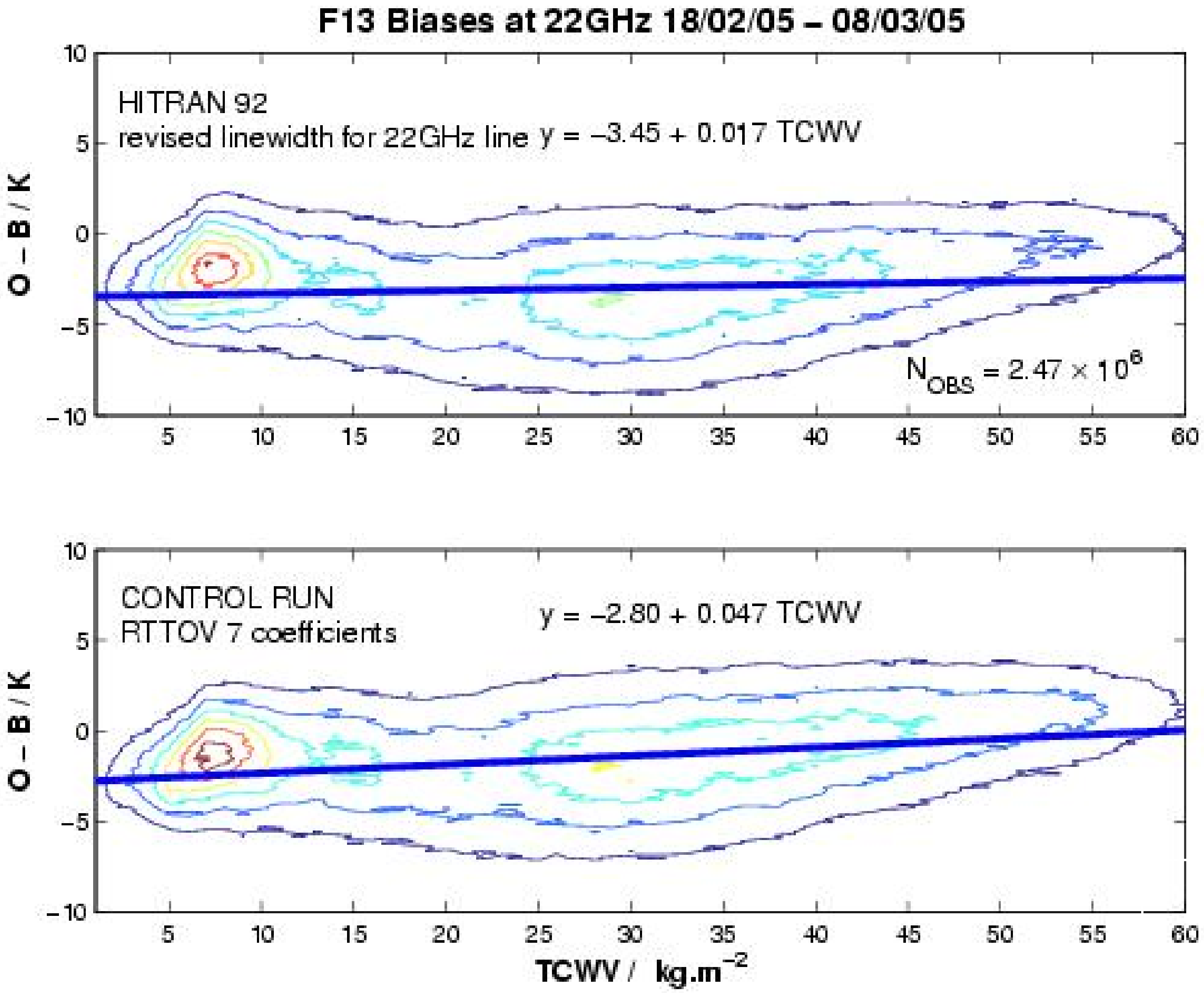
(Mätzler et al. 2005)

Evaluation inside NWP system



(Saunders et al. 2005)

22.235 GHz line-width



William Bell
Met Office

Issues

LBL

- Line inventory
  - HITRAN
  - MONORTM/LBLRTM
  - MPM89/92
  - Rosenkranz
  - ATM
  - STRANSAC
  - ARTS
- Pressure/temperature dependence
  - Natural broadening (small)
  - Pressure broadening
  - Doppler broadening (at low pressures)
- Continuum absorption (mainly H_2O)
  - Photoionization (IR)
  - Photodissociation (IR)
  - Far wings vs. H_2O clusters (MW windows)

- line intensities agree within 1%
- line frequencies accurate to within 0.1 kHz
- line widths/shifts modelling-measurements agree within a few %
- H_2O continuum controversial, modelling-measurements agree within 10-20 %

All the above is function of molecule and frequency!

Parameterizations

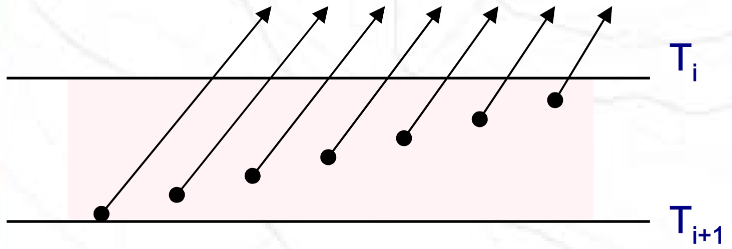
- Profile datasets
  - Representativeness
- Predictors
  - Temperature, pressure, gas concentration

Integrated layer emission

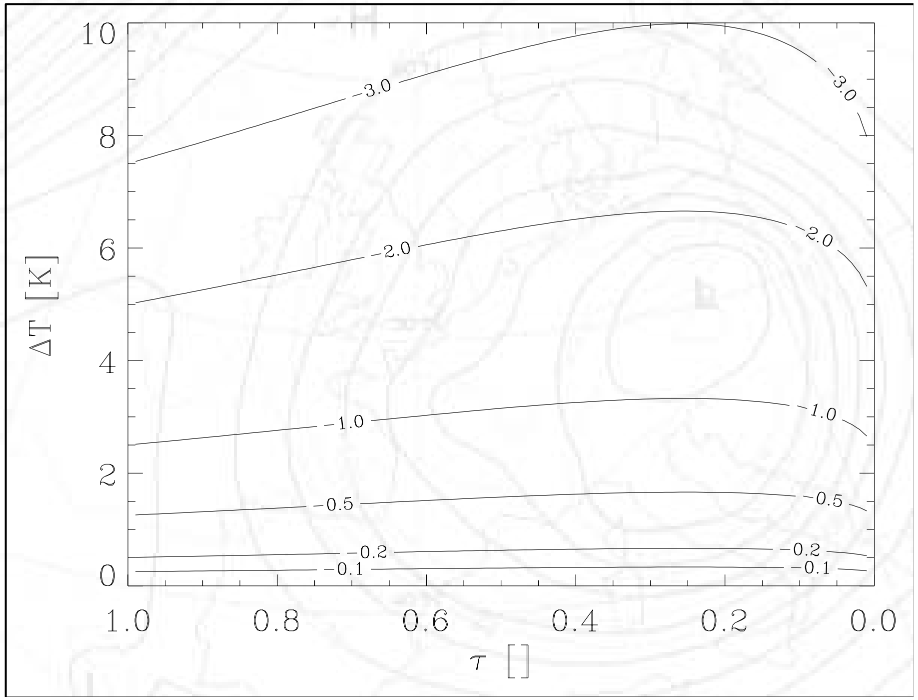
$$L_{\downarrow} = \int_{0}^{\Delta\delta} B\left[T(\delta)\right] \exp\left[-\left(\Delta\delta - \delta\right)/\mu\right] d\delta, \quad L_{\uparrow} = \int_{\Delta\delta}^{0} B\left[T(\delta)\right] \exp\left[-\delta/\mu\right] d\delta$$

RTTOV: $L_{\uparrow} = L_{\downarrow} = \frac{B(T_i) + B(T_{i+1})}{2}\left[1-\tau\right], \quad \tau = \exp\left(-\Delta\delta/\mu\right)$

Exact: $\begin{cases} L_{\uparrow} = B(T_i) - B(T_{i+1})\tau + B'\left[1-\tau\right], & B' = \frac{B(T_{i+1}) - B(T_i)}{\Delta\delta} \\ L_{\downarrow} = B(T_{i+1}) - B(T_i)\tau - B'\left[1-\tau\right] \end{cases}$



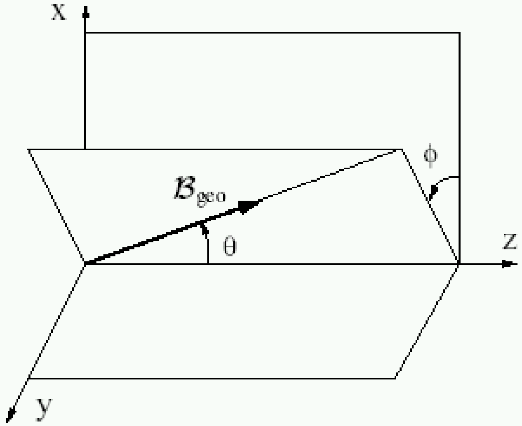
$L_{\uparrow,RTTOV} - L_{\uparrow,Exact}$



Zeeman splitting

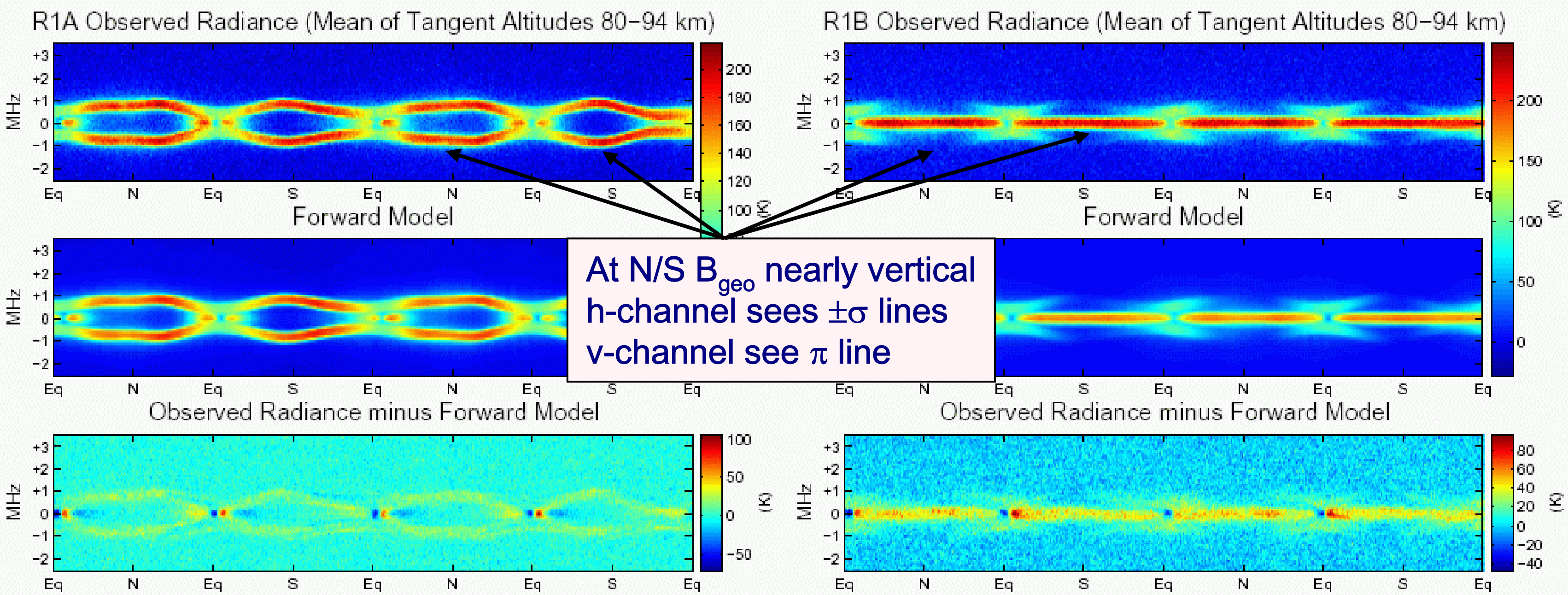
Splitting of O_2 lines in 60 GHz band and 118.75 GHz line through interaction of O_2 electronic spin (with magnetic dipole moment) with Earth's magnetic field:

- e.g. 118.75 GHz line has 3 components ($\Delta\nu$ ~ 1 MHz)
- RT becomes polarization dependent
- RT becomes dependent on magnetic field orientation
- SSMIS, MLS



MLS Channel H_h at tangent point

MLS Channel H_v at tangent point

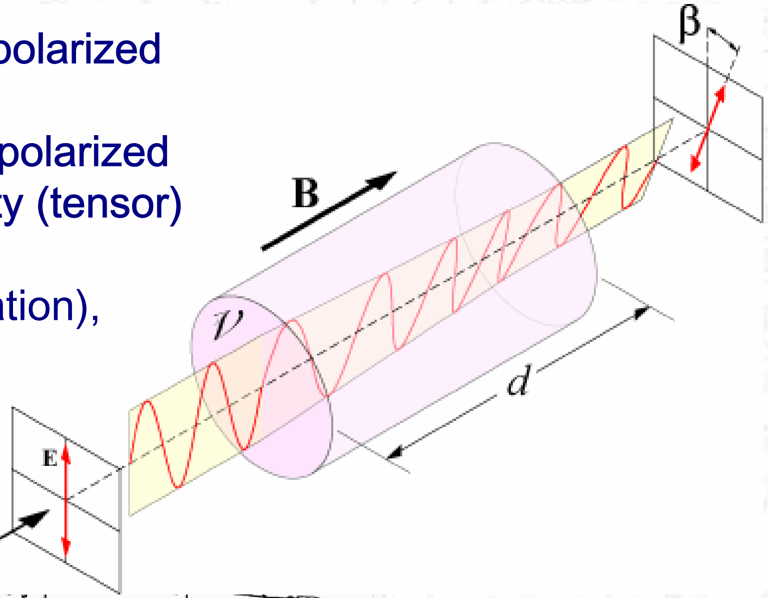


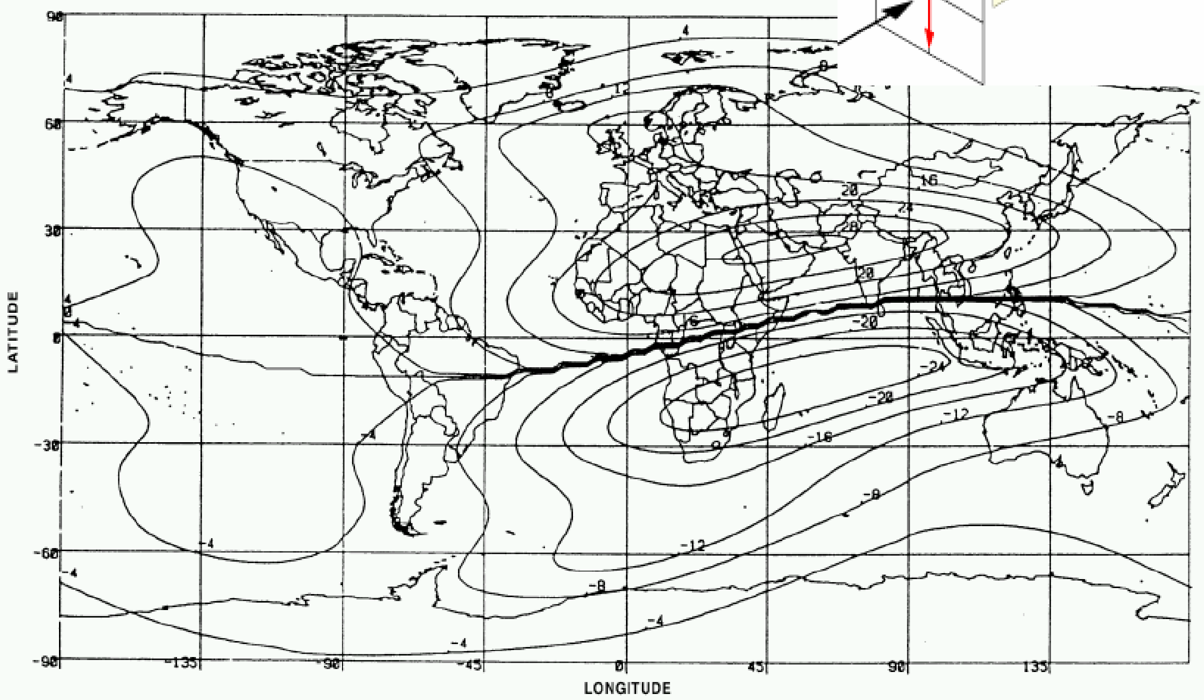
(Schwartz et al. 2005)

Faraday Rotation

Rotation of polarization through interaction of polarized light passing through strong magnetic field (in ionosphere). Splitting of wave into 2 circularly polarized rays due to polarization dependent permeability (tensor) causing phase delay.

- affects polarized light (surface sensitive radiation), also 3rd Stokes vector
- $\beta \approx 17 / \nu^2$ (β in degrees, ν in GHz)
- SMOS, AMSR, Windsat





Rotation angle simulation for 1.4 GHz
(Svedlend 1986)

Refractive index $n = \sqrt{\varepsilon\mu} = n' + in''$ = f(material, frequency, temperature)

Water permittivity models are based on Debye model + fits to observational datasets:

- 2 datasets (3-20, 30-100 GHz)
- no sea-water data above 105 GHz
- 1 dataset for 9.62 GHz for super-cooled water (-18^{o}C)
- fits required for T $\in$ [250-300 K] and $\nu \in$ [1, 1000 GHz]

Ice permittivity models are mainly based on empirical fits to observational data:

- Real part rather constant
- Imaginary part very uncertain

Snow/ice permittivity:

- From mixing formulae based on air/water/ice and inclusion shape/orientation

Vegetation permittivity:

- Mainly function of water content but complex organic structure limits applicability of conventional mixing theory
- Experimental (field) observations available but extrapolation to satellite scale and wide frequency range difficult

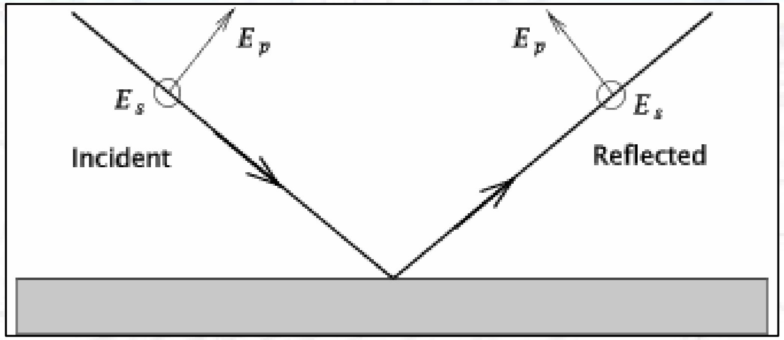
Soil permittivity:

- Function of frequency, temperature, and salinity, volumetric water content, volume fraction of bound and free water related to the specific soil surface area, soil bulk material, and shape of the water inclusions
- Experimental (field) observations available but extrapolation to satellite scale and wide frequency range difficult

(Mätzler et al. 2005)

Surface emissivity - Oceans

Plane surface:
- Sea-water permittivity
- Fresnel equations (I, Q)



Wind roughened surface:
- Sea-water permittivity
- Fresnel equations (I, Q)
- Large-scale waves
- Gravity-capillary, capillary waves (> 2m/s)
- Whitecaps (> 7 m/s)
- Foam (> 10-12 m/s)

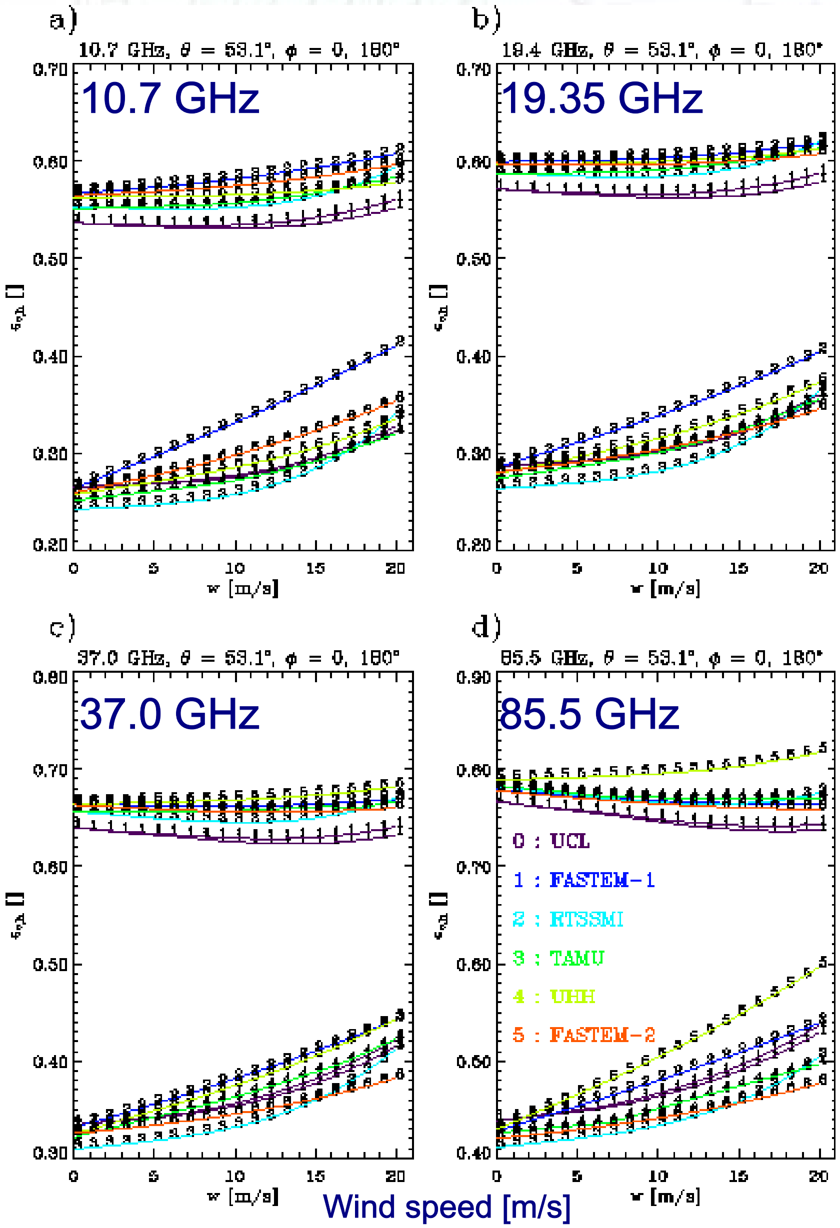
RTTOV FASTEM-2

Directional wind roughened surface:
- Sea-water permittivity
- Fresnel equations (I, Q, U, V)
- Large-scale waves
- Gravity-capillary, capillary waves (> 2m/s)
- Whitecaps (> 7 m/s)
- Foam (> 10-12 m/s)

RTTOV FASTEM-3

$$\mathbf{L} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \frac{1}{2\sqrt{\mu/\varepsilon}} \begin{pmatrix} \langle E_v E_v^* \rangle + \langle E_h E_h^* \rangle \\ \langle E_v E_v^* \rangle - \langle E_h E_h^* \rangle \\ 2\,\mathrm{Re}\langle E_v E_h^* \rangle \\ 2\,\mathrm{Im}\langle E_v E_h^* \rangle \end{pmatrix} \approx \begin{pmatrix} I_o + I_1 \cos\varphi + I_2 \cos 2\varphi + \ldots \\ Q_o + Q_1 \cos\varphi + Q_2 \cos 2\varphi + \ldots \\ U_1 \sin\varphi + U_2 \sin 2\varphi + \ldots \\ V_1 \sin\varphi + U_2 \sin 2\varphi + \ldots \end{pmatrix}$$

Modelled emissivity - Oceans



θ = 53.1°

φ = 0, 180°

v-pol.

h-pol.

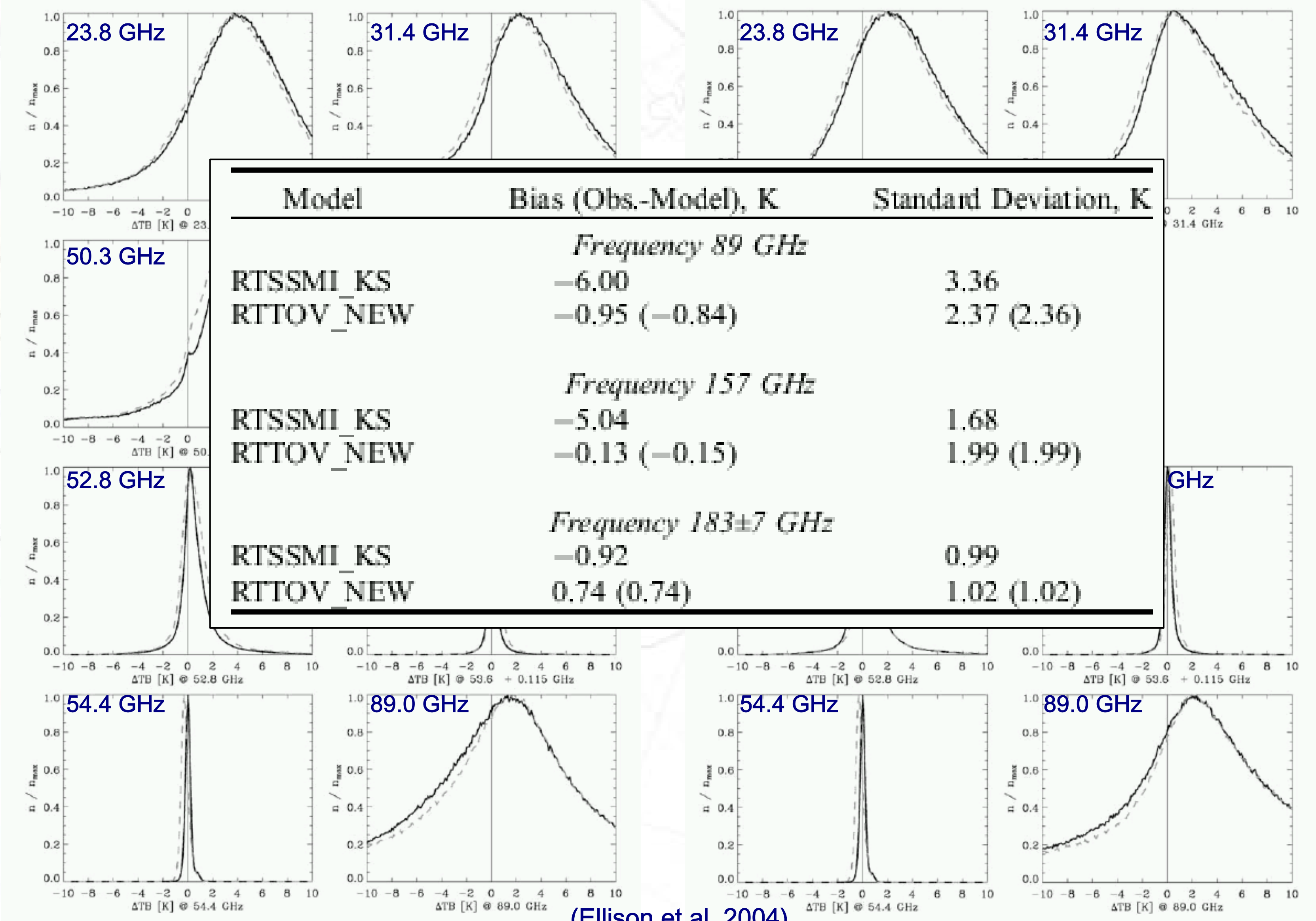
Sensitivity of surface emission ($E_o T_s$) to real and imaginary part of dielectric constant (Meissner and Wentz 2004)

$v\,[GHz]$	$\left.\frac{\Delta(E_0 T_S)}{\Delta \mathrm{Re}(\varepsilon)}\right\|_{T_s=273.15K}\,[K]$	$\left.\frac{\Delta(E_0 T_S)}{\Delta \mathrm{Im}(\varepsilon)}\right\|_{T_s=273.15K}\,[K]$
19.35	-0.056	+1.571
37.0	+0.300	-2.705
85.5	+0.082	+4.470

AMSU-A FG Departures - Oceans

NOAA-16 AMSU-A before FASTEM-2

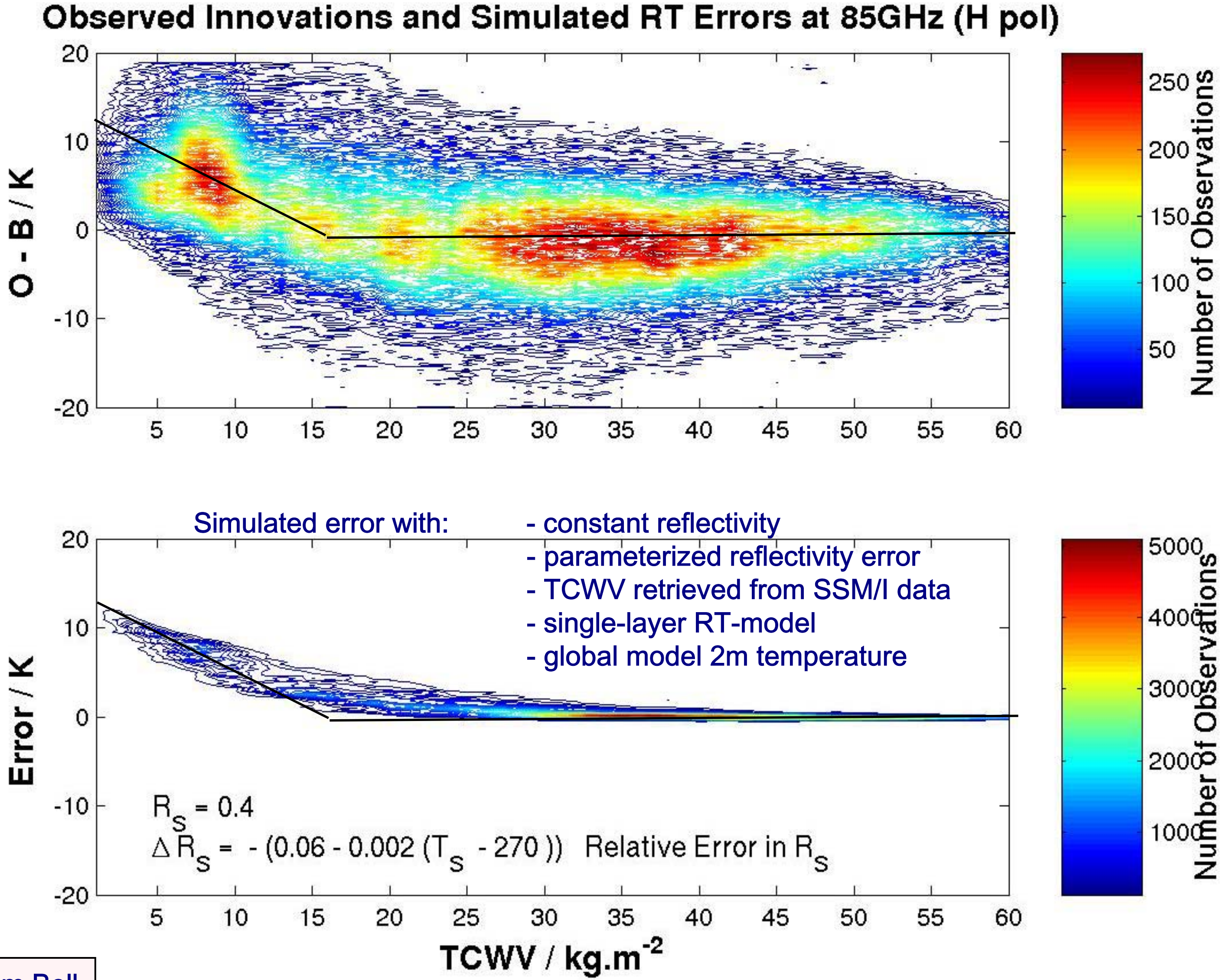
NOAA-16 AMSU-A after FASTEM-2



Model	Bias (Obs.-Model), K	Standard Deviation, K
	Frequency 89 GHz	
RTSSMI_KS	−6.00	3.36
RTTOV_NEW	−0.95 (−0.84)	2.37 (2.36)
	Frequency 157 GHz	
RTSSMI_KS	−5.04	1.68
RTTOV_NEW	−0.13 (−0.15)	1.99 (1.99)
	Frequency 183±7 GHz	
RTSSMI_KS	−0.92	0.99
RTTOV_NEW	0.74 (0.74)	1.02 (1.02)

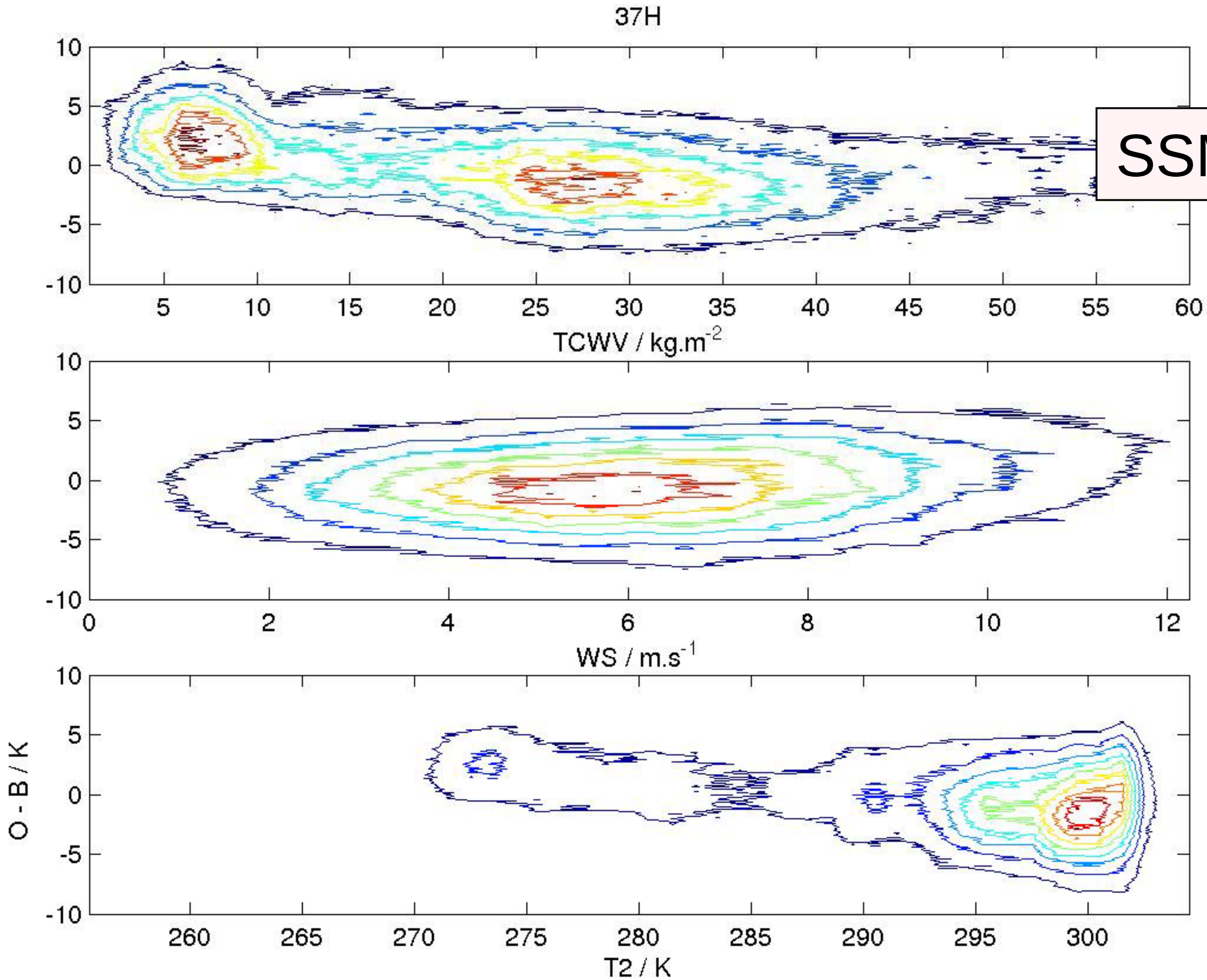
(Ellison et al. 2004)

SSM/I FG-Departure bias in dry/cold environments



William Bell
Met Office

Bias at low T: 37 GHz H pol



SSMI DATA

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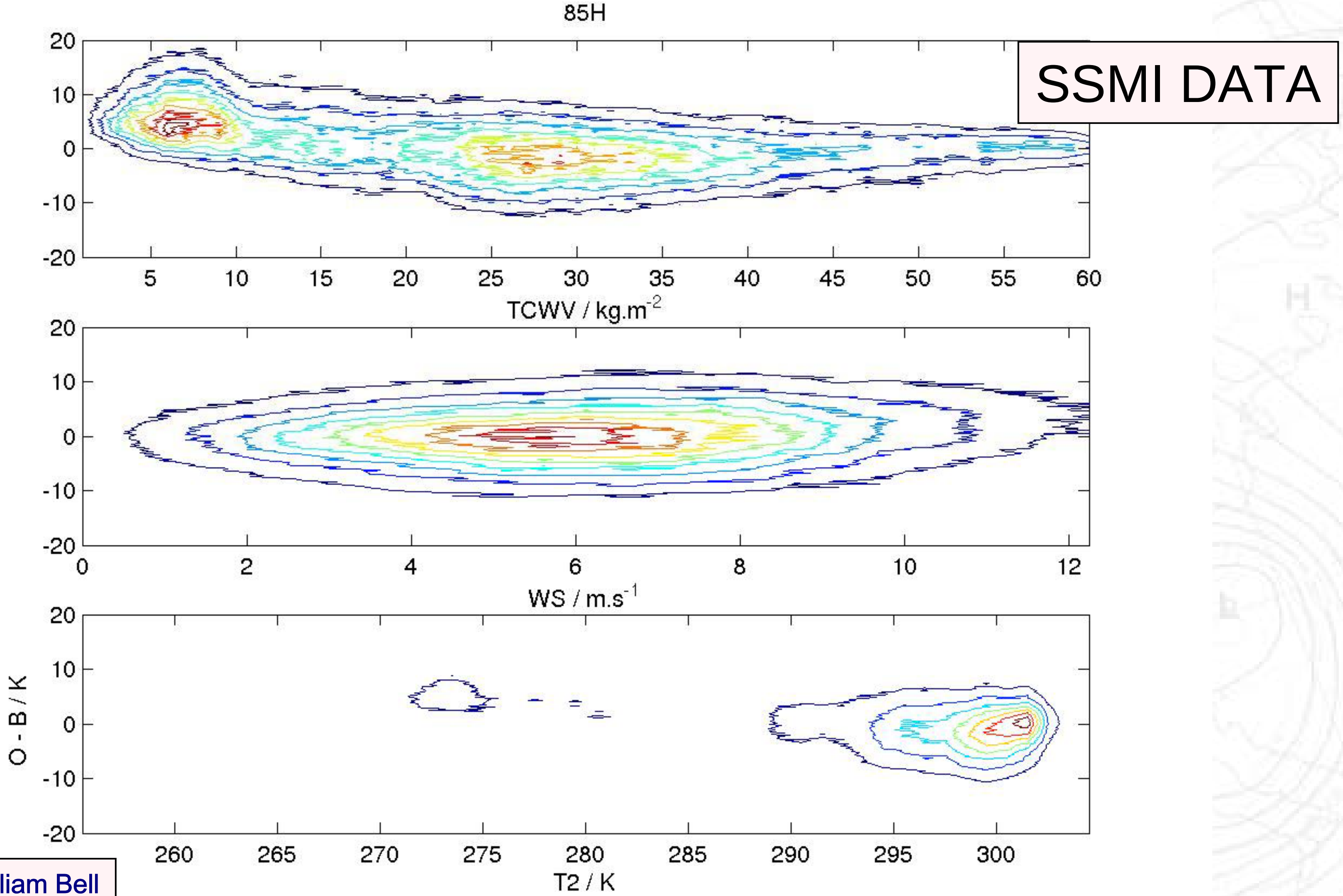
Bias at low T: 85 GHz H pol



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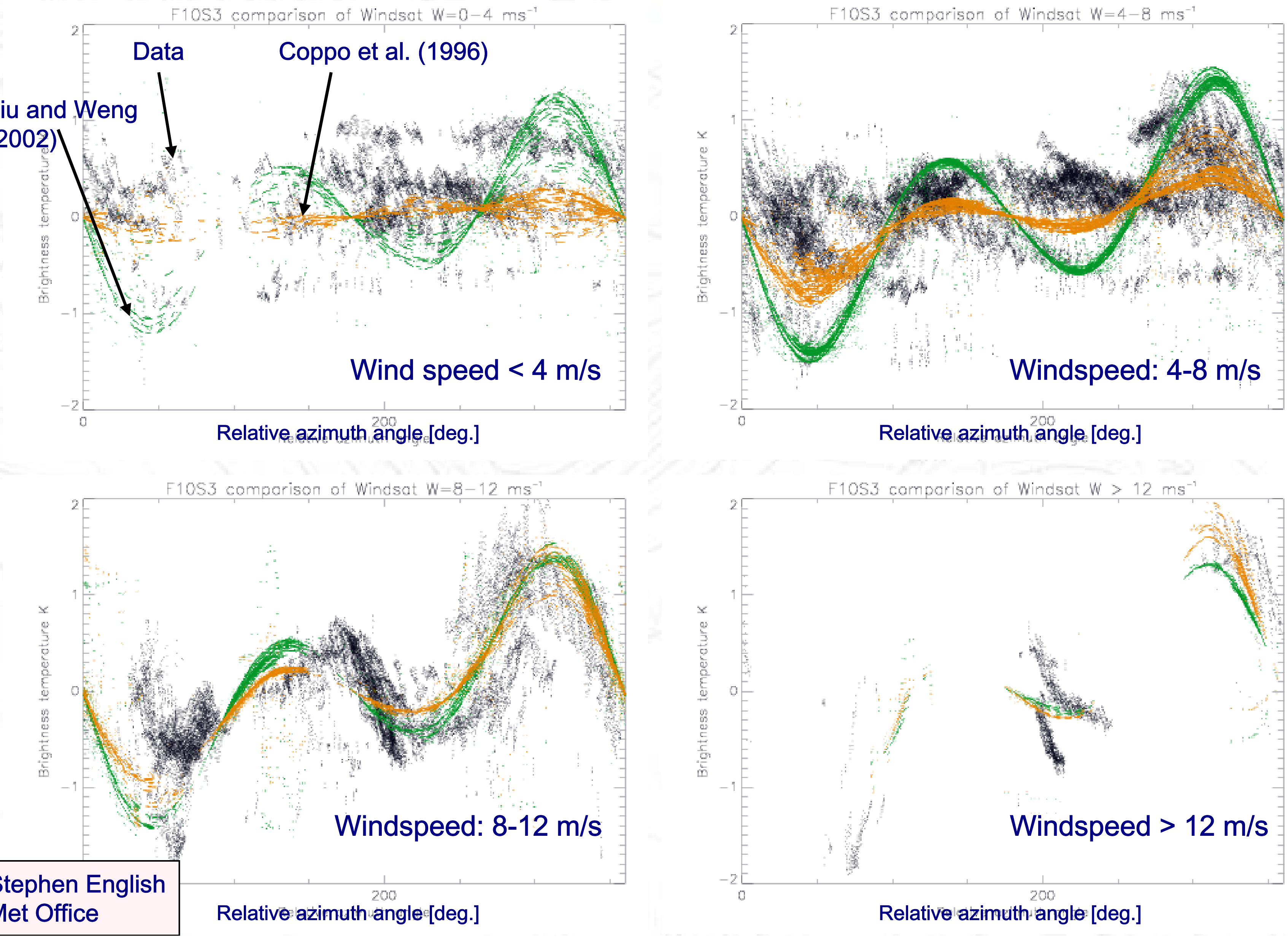
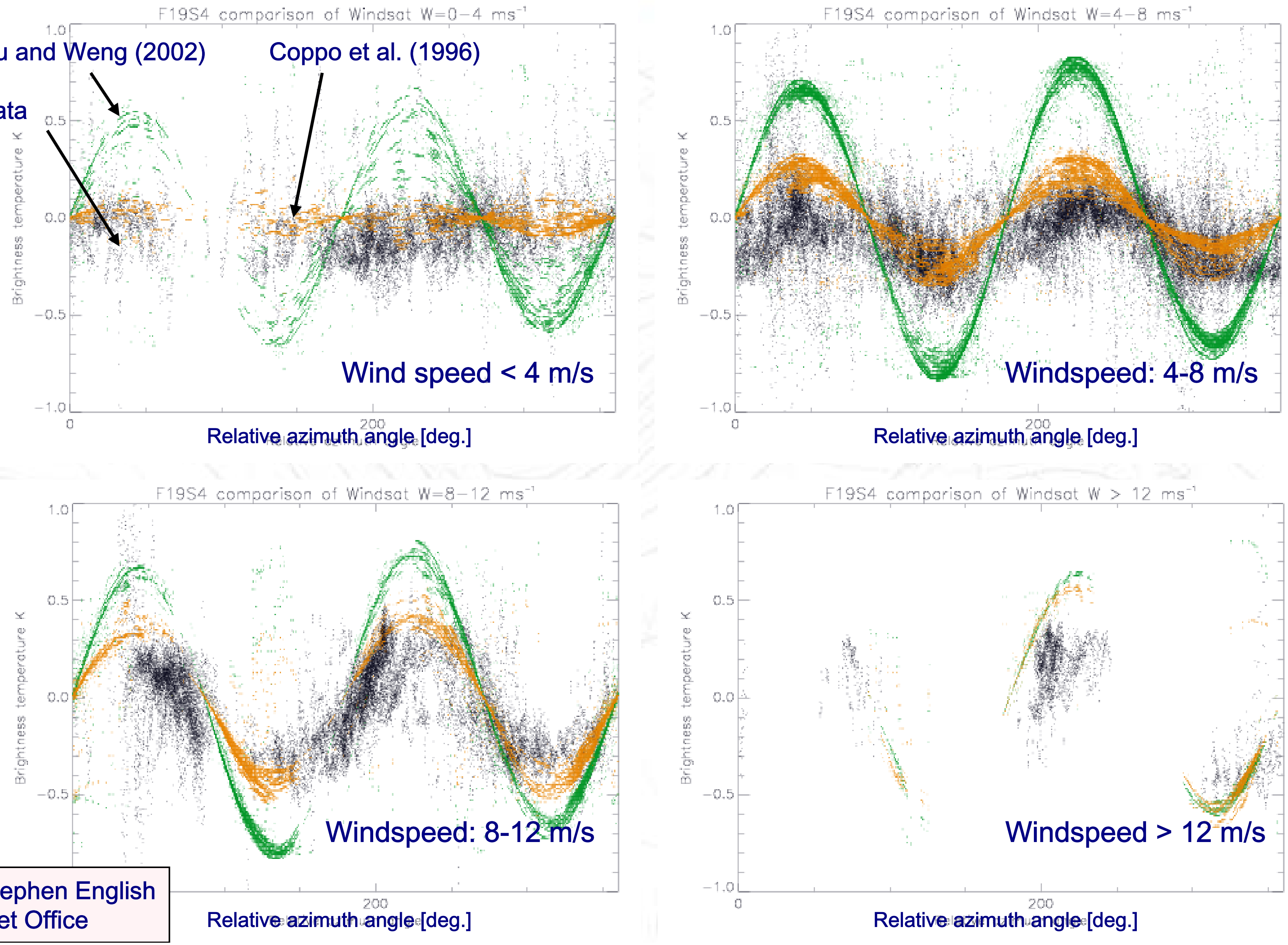
3rd Stokes Vector at 10.7 GHz: Models vs. Windsat Data



Stephen English
Met Office

4th Stokes Vector at 19.35 GHz: Models vs. Windsat Data



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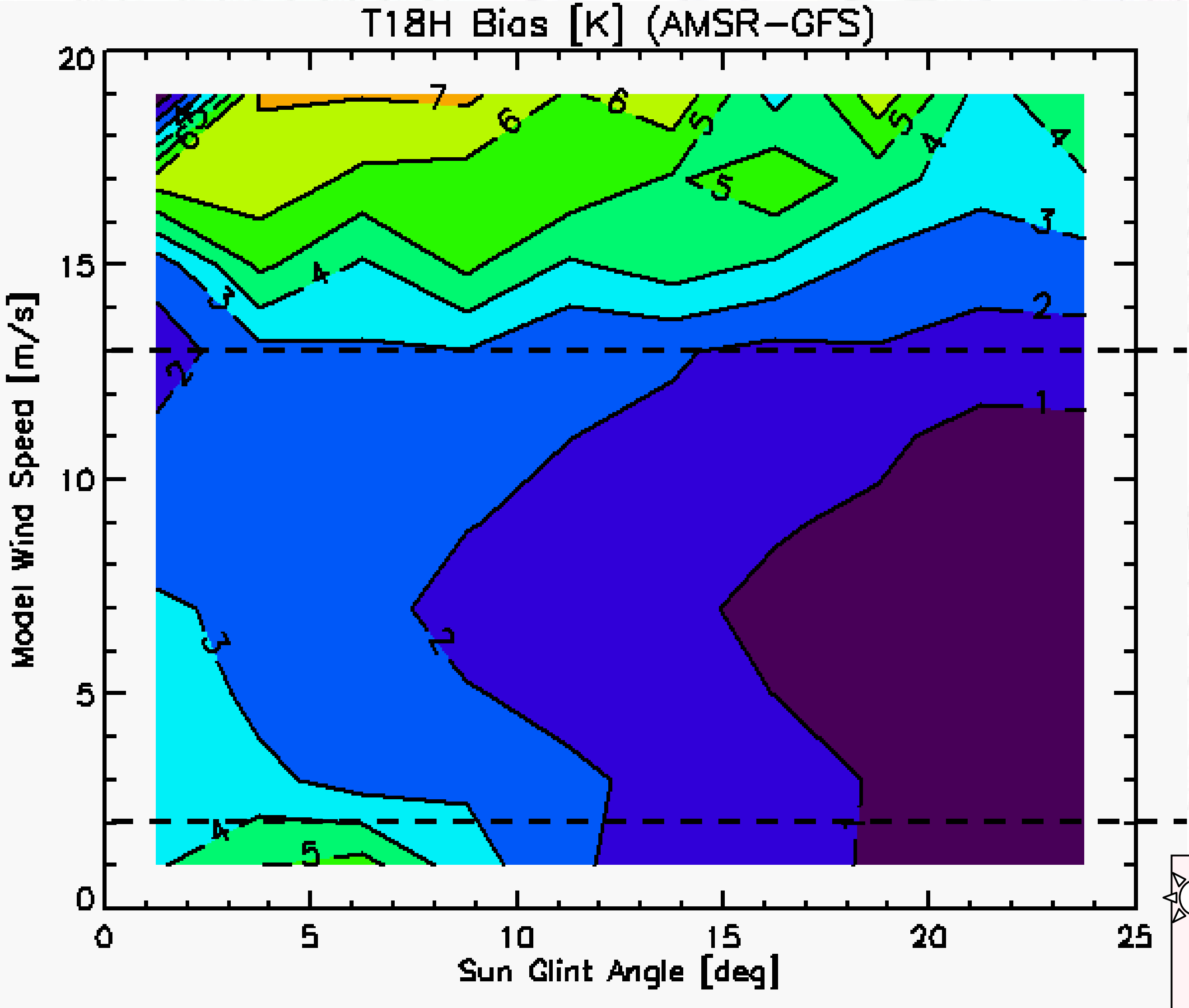
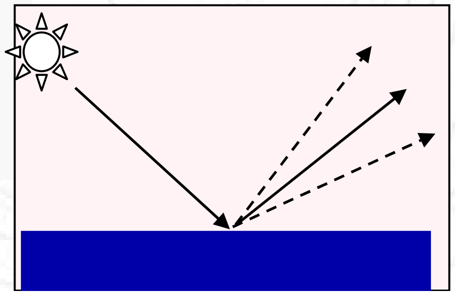
Sun-glint



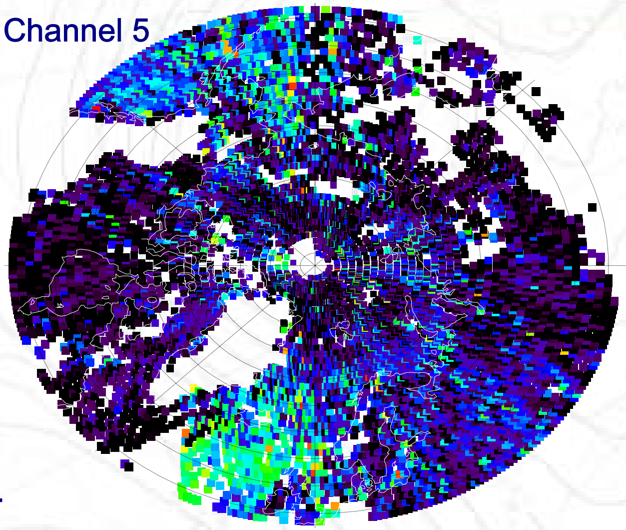
Sufficient
Data sample



Ralf Bennartz
University of Wisconsin

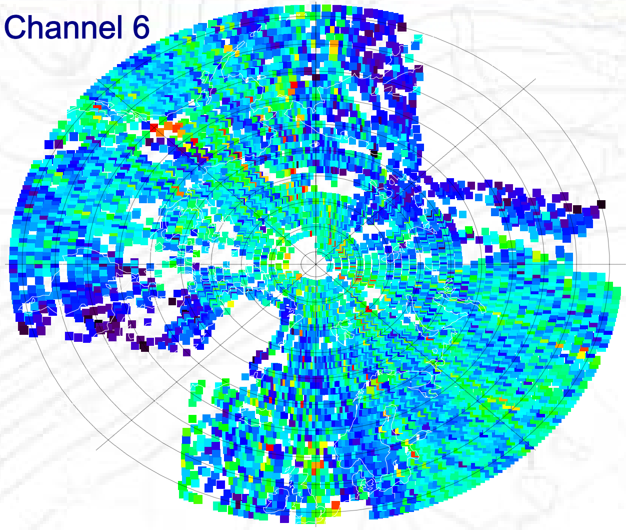
Surface emission - Land

AMSU-A Channel 5



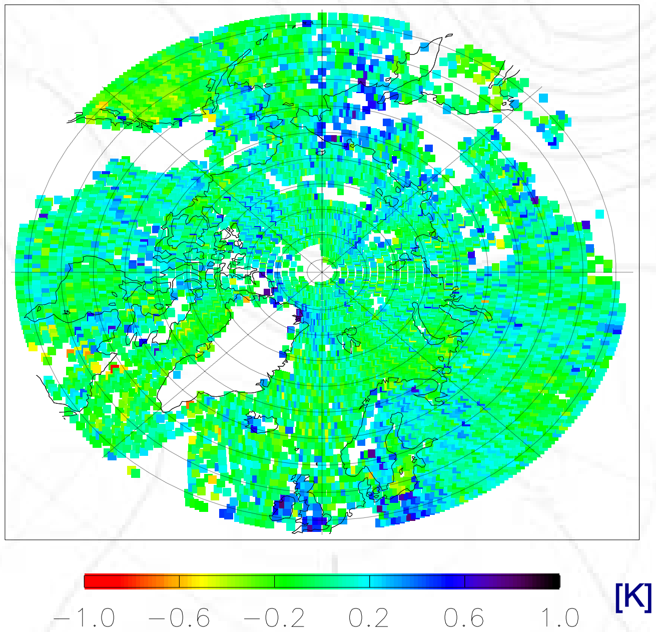
Before …

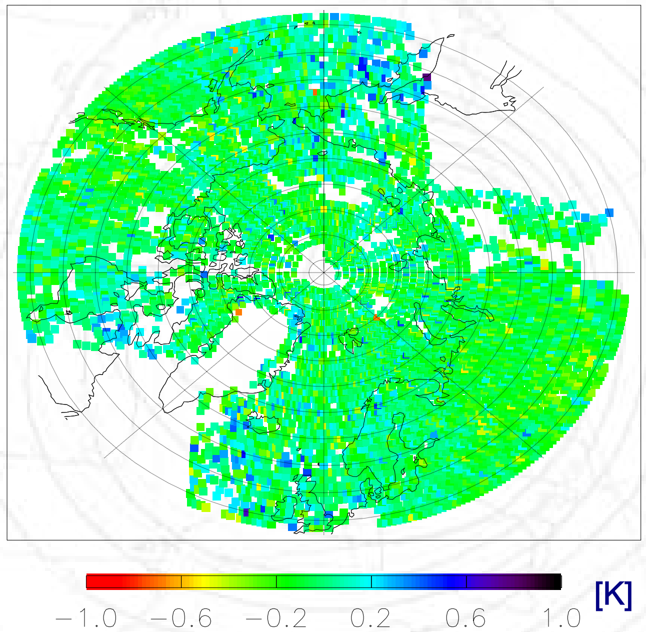
AMSU-A Channel 6



… after bias correction

Used data 20050801-03

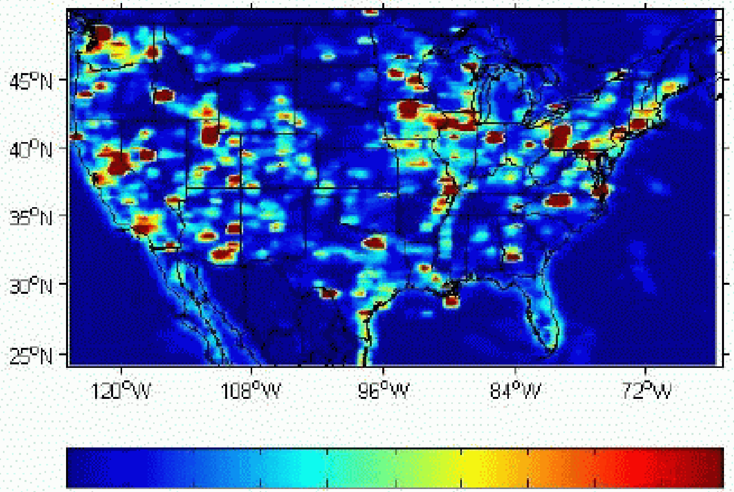




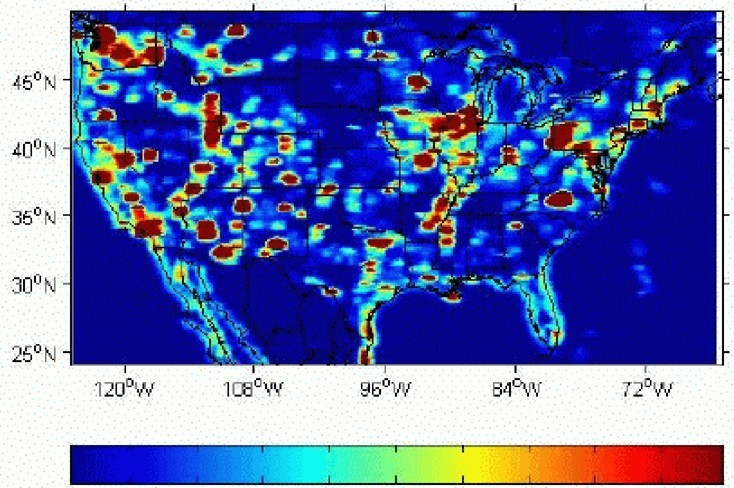
ECMWF

"Spectral Index" $T_{B,\ 6.8\ GHz} - T_{B,\ 10.7\ GHz}$

- **This index is nominally < 5 K (typically, negative) for the geophysical signal**
- **Values > 5K indicate RFI**
- **May be a more sensitive test for RFI than absolute T_B's**



V: $T_{B,\ 6.8\ GHz} - T_{B,\ 10.7\ GHz}$ [K]
Max Hold over 6 Months



H: $T_{B,\ 6.8\ GHz} - T_{B,\ 10.7\ GHz}$ [K]
Max Hold over 6 Months

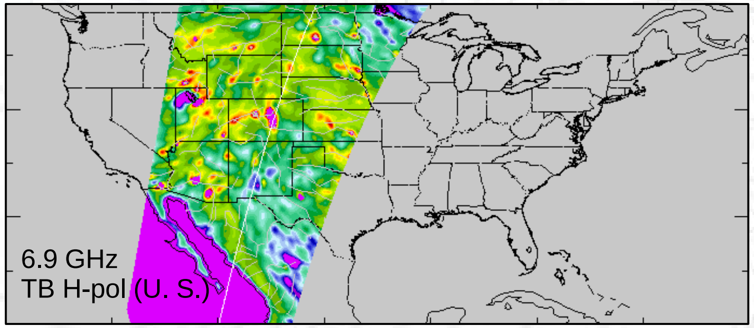
THE OHIO STATE UNIVERSITY
Virginia Tech

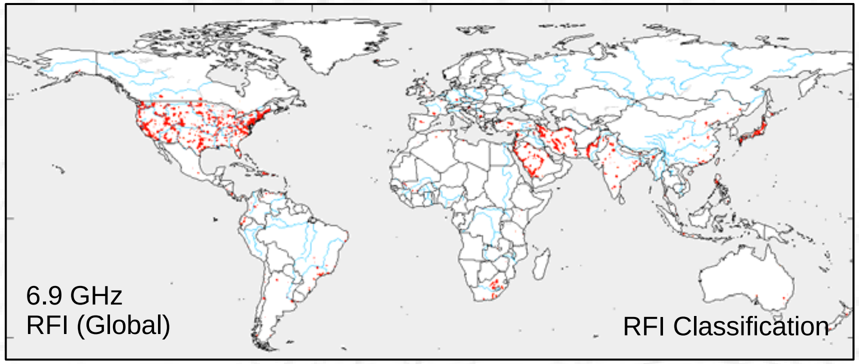
(Ellingson and Johnson 2004)

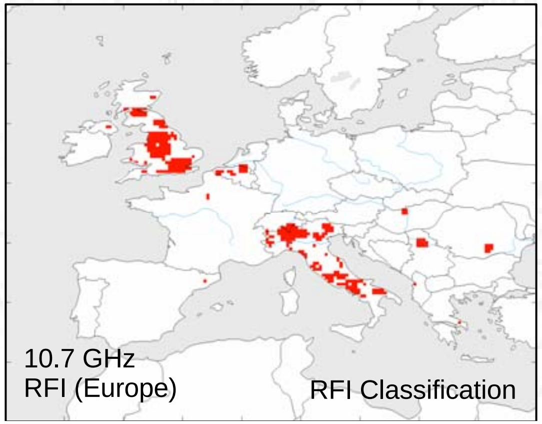
Surface emission - RFI

- RFI is observed in the AMSR C-band (6.75–7.1 GHz) and X-band (10.6–10.7 GHz) data
  - C-band is unprotected
  - X-band is protected from 10.68–10.7 GHz
- Classification algorithms can identify and filter strong RFI for AMSR-E geophysical algorithms
  - But, weak RFI cannot reliably be separated from geophysical signals
- C-band RFI mostly in the U. S., Japan, Middle East, some in Europe, Asia, S. America, Africa
- X-band RFI mostly in Japan, England, Italy, some in U. S.
- Situation at C-band has worsened considerably since Seasat and Nimbus-7 SMMR 1978-1987 (6.6 GHz)
- NPOESS/CMIS also operates at C- and X-bands
  - Re-assessment of radiometer design is in progress

(Njoku 2004)



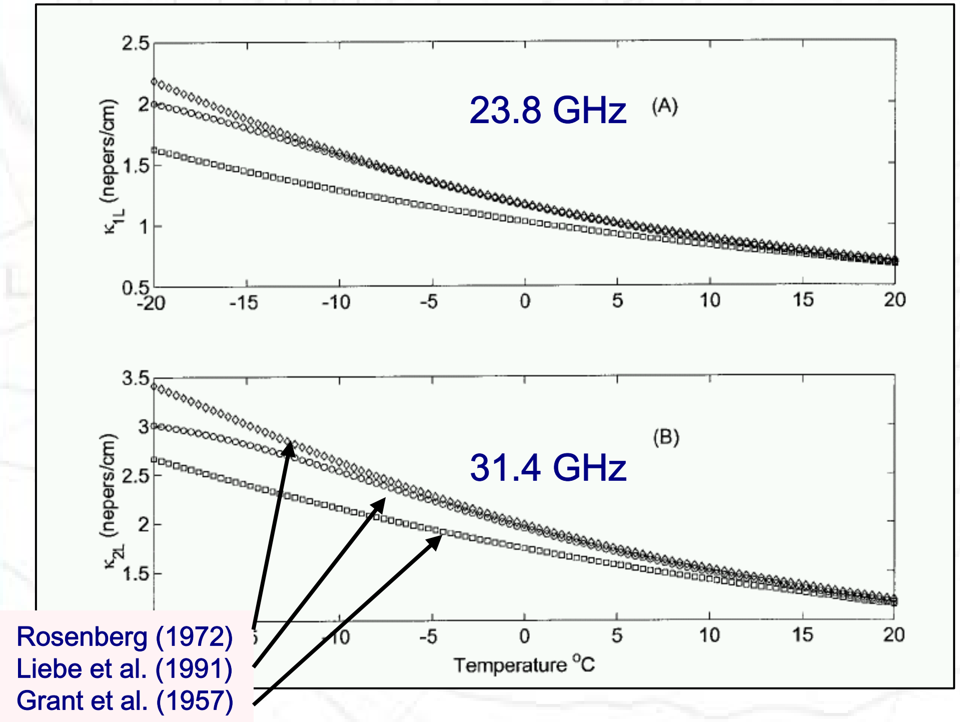


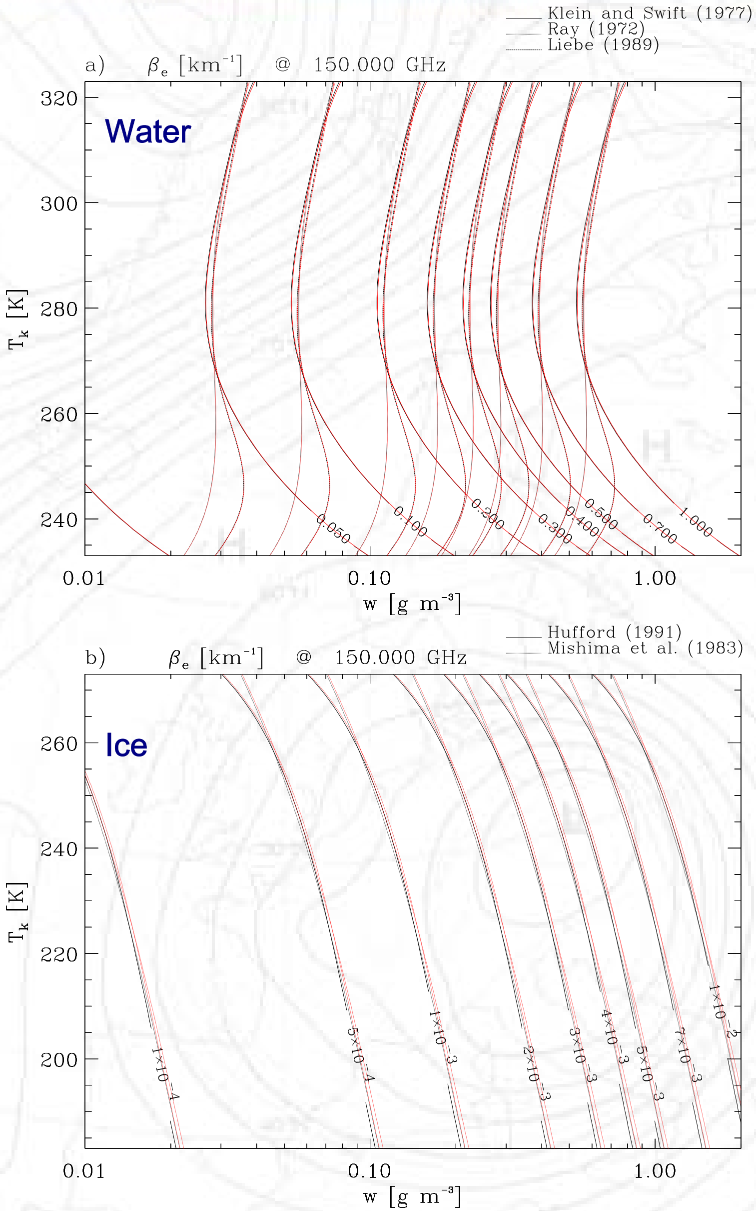


Cloud water/ice absorption

ECMWF

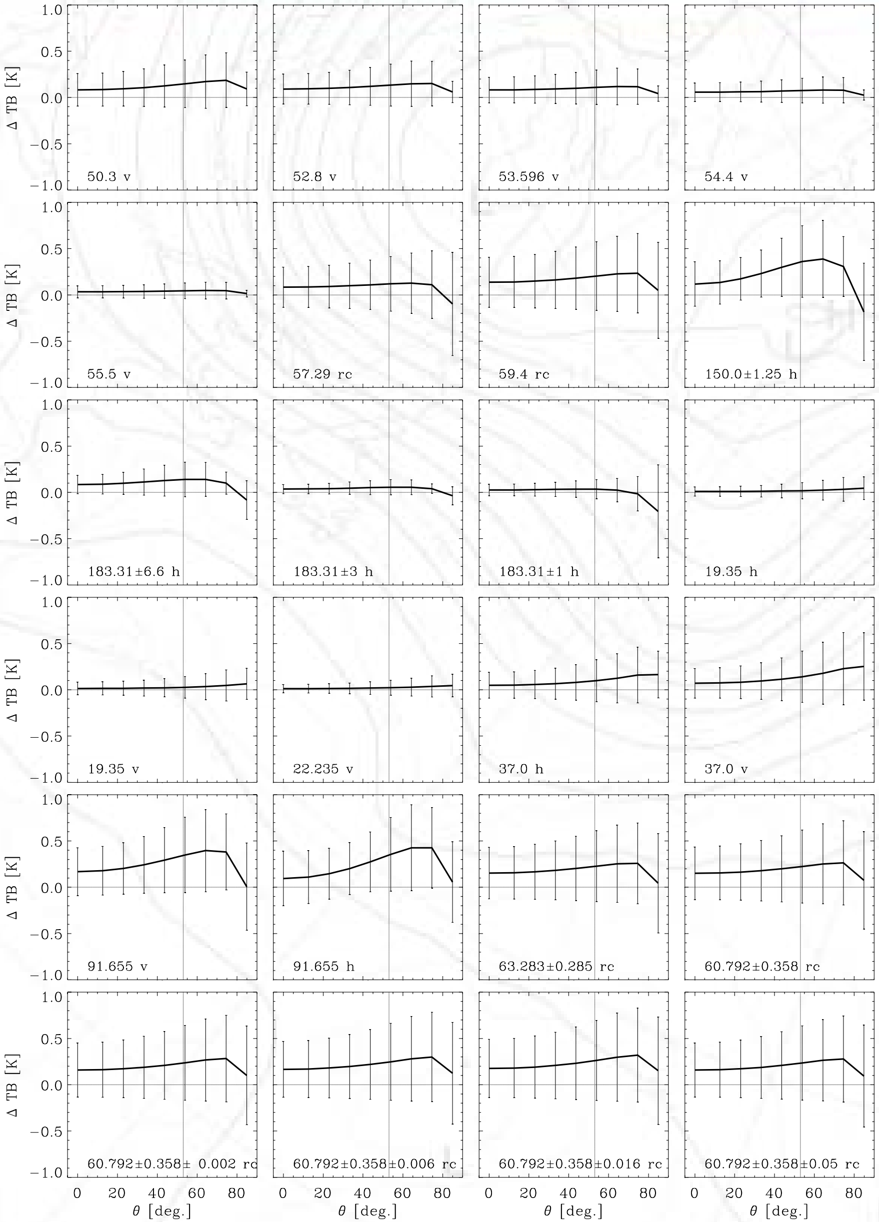
Cloud water mass absorption coefficient, κ, from various models (Westwater et al. 2001)





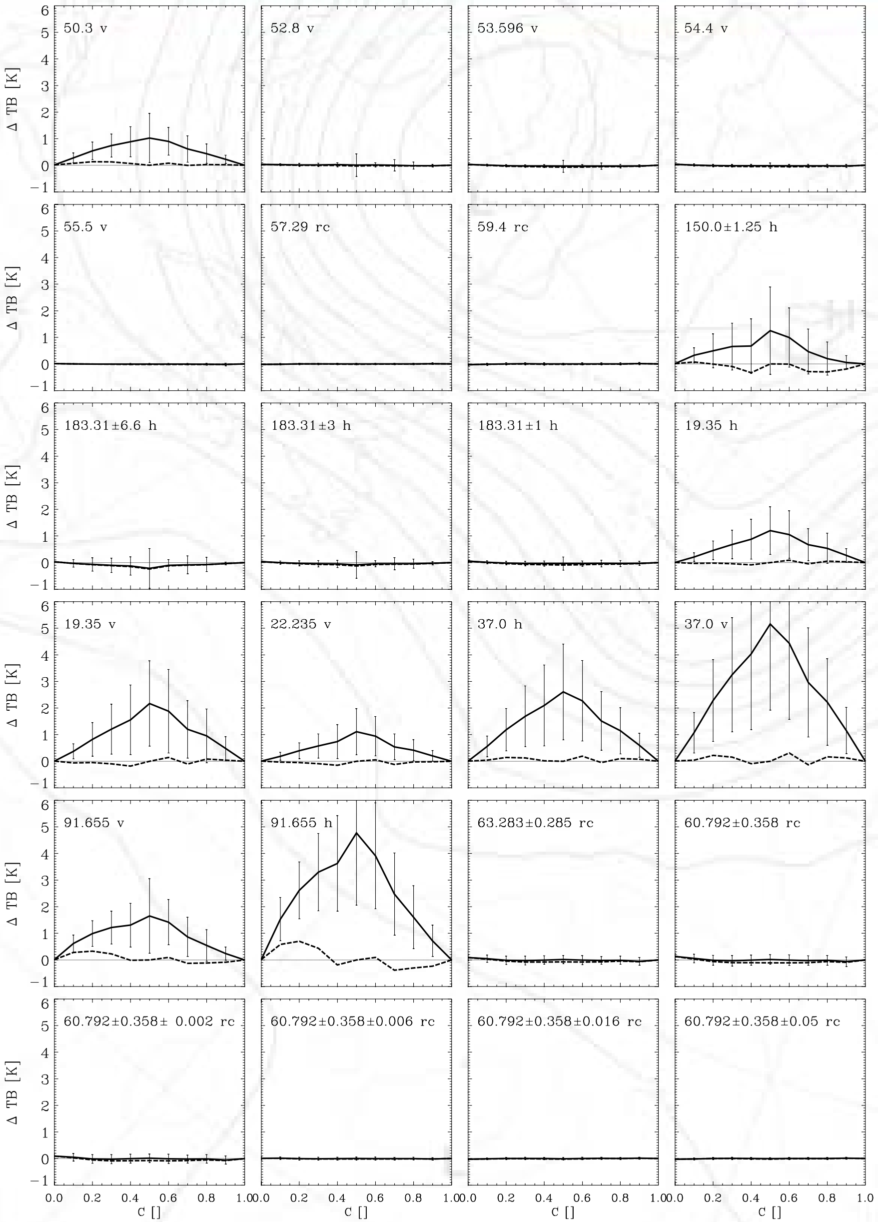
Cloud water/ice volume extinction coefficient , β, from various models and Rayleigh (black) and Mie (red) calculations at 150 GHz

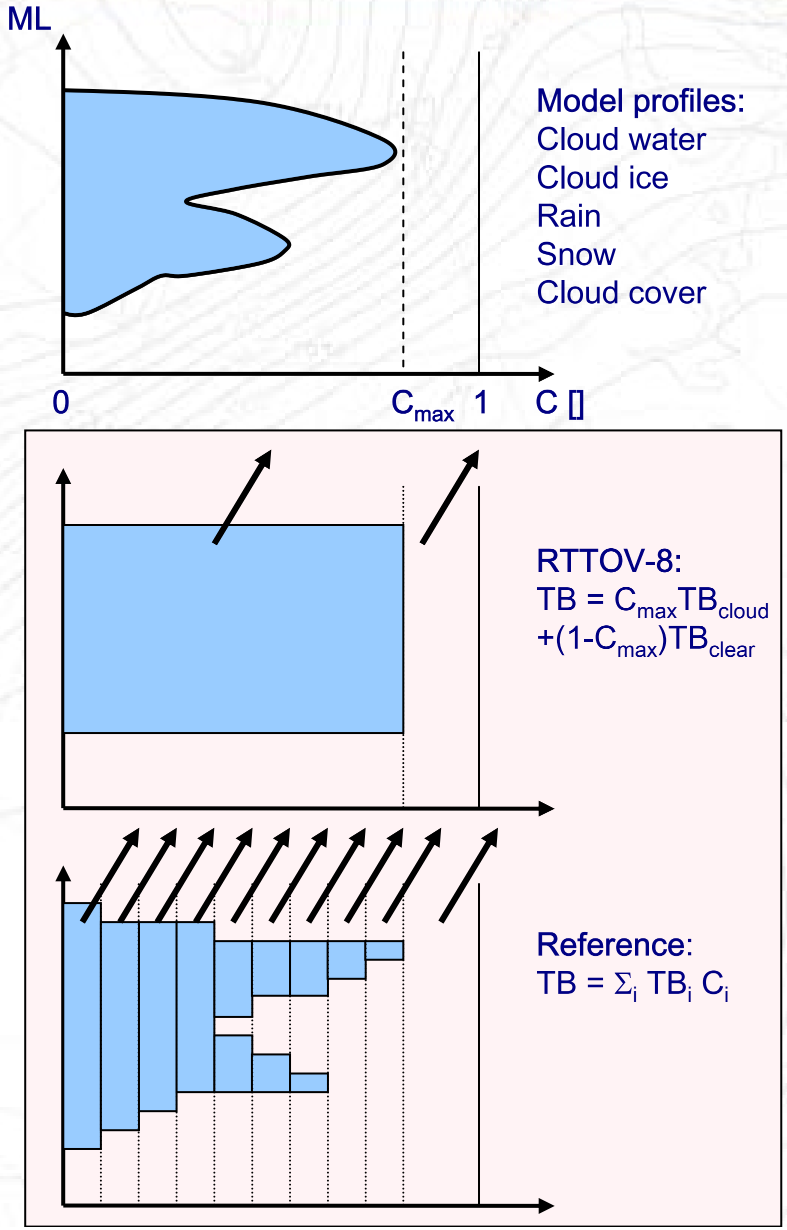
Multiple-scattering RT-Model comparison



RT-biases < 0.5 K!

Effect of fractional cloud cover





ECMWF/NWP-SAF Workshop on bias estimation and correction in data assimilation
8-11 November 2005, Reading, UK

SSM/I TB FG/AN-Departures, September 2004

SSM/I channel:

1: 19.35 GHz (v)

2: 19.35 GHz (h)

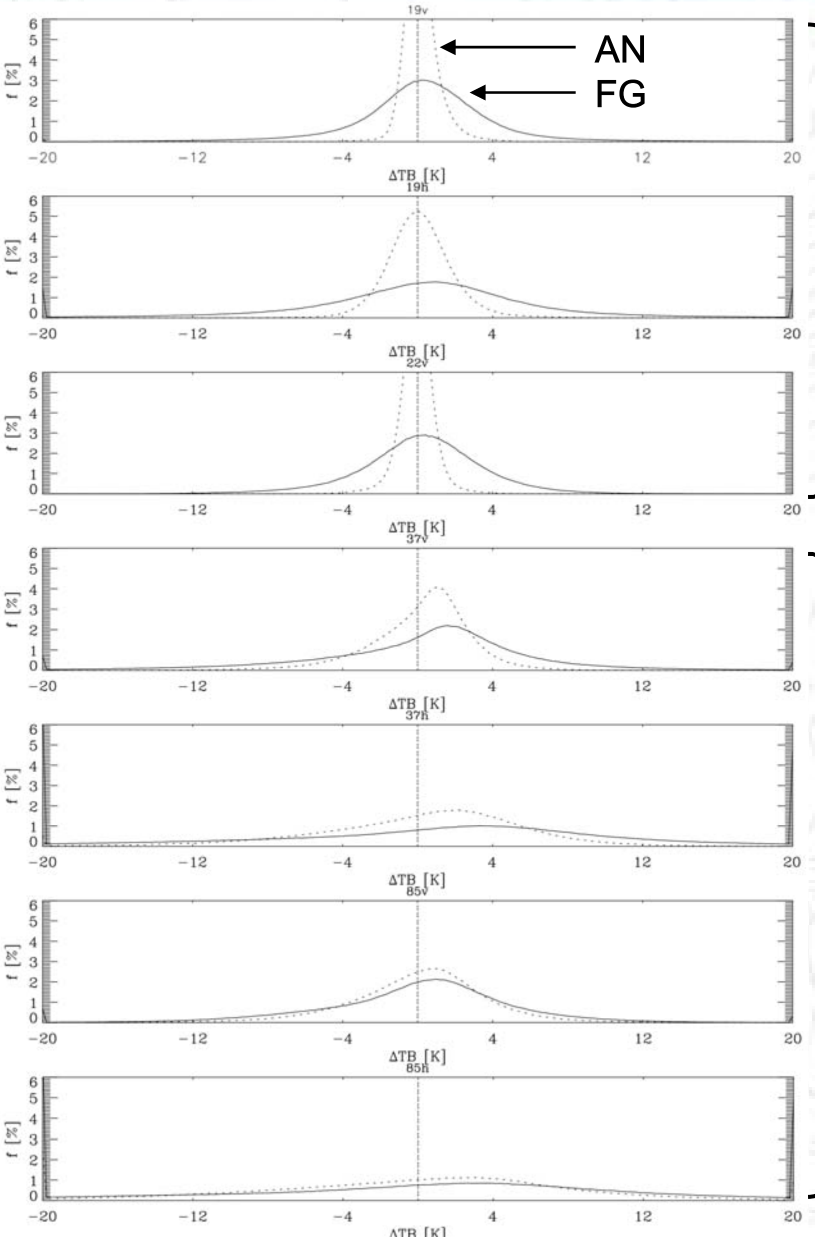
3: 22.235 GHz (v)

4: 37.0 GHz (v)

5: 37.0 GHz (h)

6: 85.5 GHz (v)

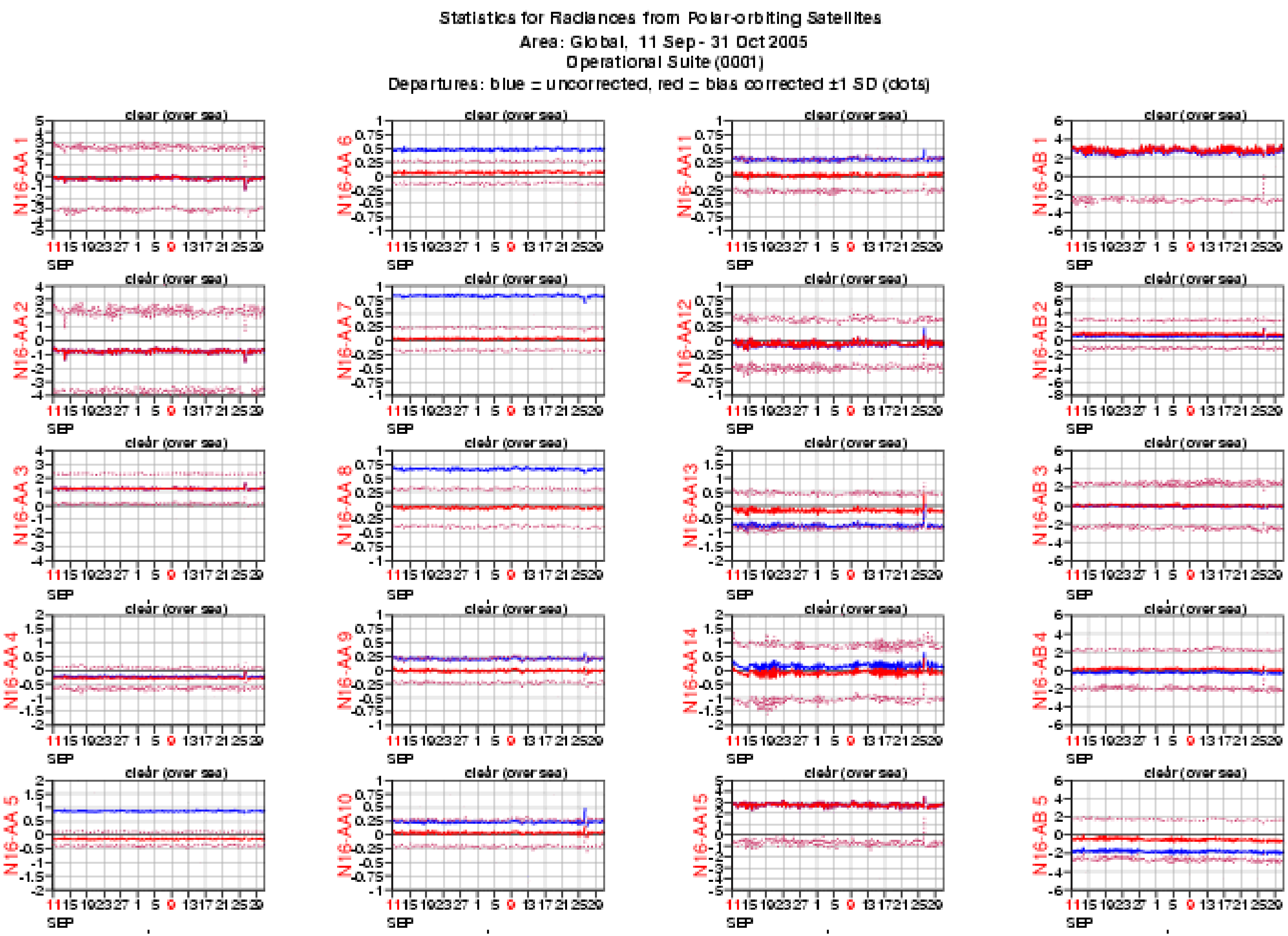
7: 85.5 GHz (h)



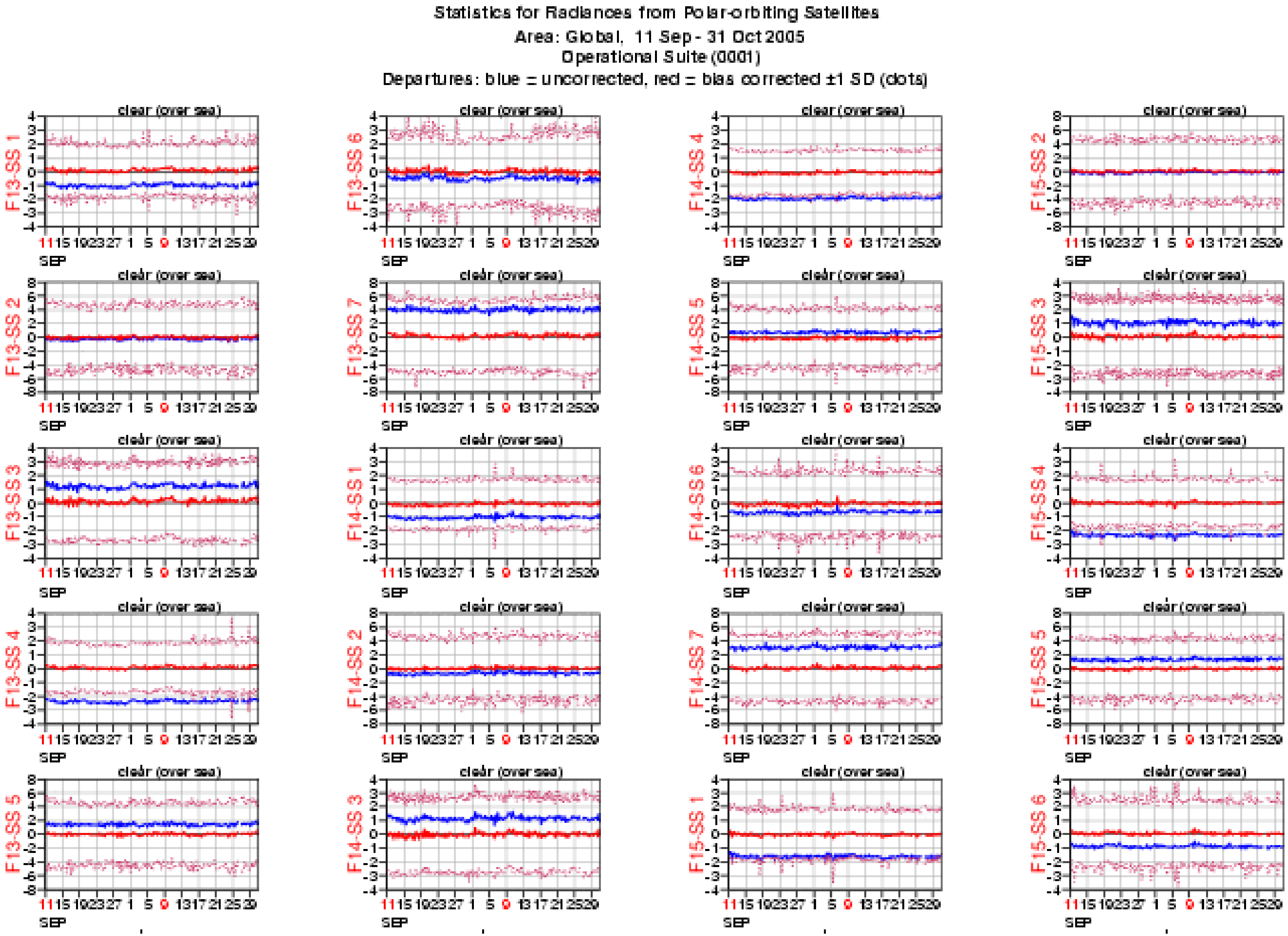
Bias corrected with TCWV-predictor only

Higher order effects (C-structure, PSD's etc.) become important

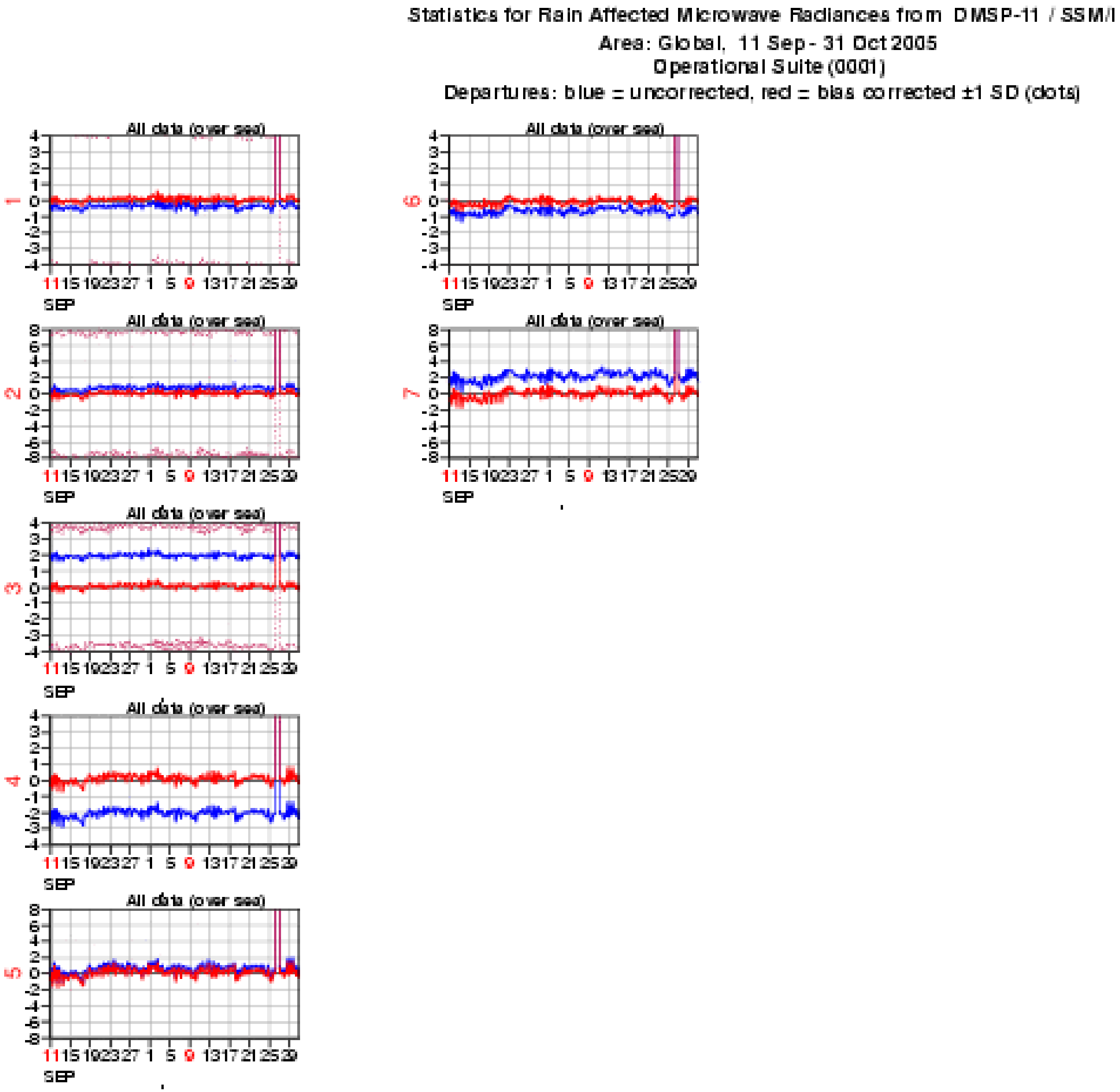
Departure time series NOAA-16 AMSU-A/B (Clear-sky)



Departure time series DMSP F-13/14/15 SSM/I (Clear-sky)



Departure time series DMSP F-13/14/15 SSM/I (RAIN)



Summary

ECMWF

Contribution/Effect	Frequencies	Comments
Atmospheric absorption:		
Spectroscopy, LBL	all	H_2O continuum problematic
Parameterized models	all	very accurate relative to LBL models
Zeeman splitting	O_2 lines	limited applicability (p < 10 hPa), SSMIS, MLS
Faraday rotation	1.4	limited applicability, SMOS
	20-300 GHz	Clear-sky *atmospheric* TB's accurate within 1-3%
Surface emission:		
Sea surface		
Permittivity	all	1 K between 20-150 GHz
Polarimetry	10-37	10% for 4 m/s < SWS < 12 m/s
Land surfaces		
Soil, vegetation	all	uncertain
Snow/ice		
Type, age, etc.	All	uncertain
Cloud droplet emission:		
Permittivity	all	well modelled between 5-500 GHz and T>273 K
	5-500 GHz	for T < 273 K models differ by 20-30%
Precipitation emission/scattering:		
PSD, Permittivity, Shape	all	uncertain
Radiative transfer modelling:		
Clear-skies	all	biases up to 3 K due to T(z), otherwise accurate
Clouds/precipitation		
multiple scattering	all	biases < 0.5 K
Layer inhomogeneity	all	biases up to 5 K, can be parameterized