Treatment of Surface Emissivity in Microwave Satellite Data Assimilation

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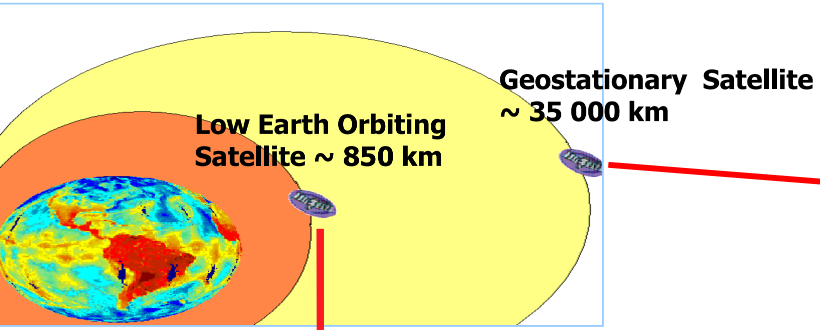
Conclusions

(a) Microwave observations: generalities

Satellite observations:

Good Coverage (good for areas with no or few in-situ measurements)
largely contribute to atmospheric humidity and temperature analysis
Indirect measures: need to solve the inverse problem (not linear)



Very high temporal coverage, not suitable for polar regions

Less good temporal coverage but suitable to sound the Atmosphere
Microwave & Vis/infrared

Microwave Observations are less sensitive to clouds than infrared observations

Infrared observations allow a better horizontal and vertical resolutions than microwaves

Infrared & microwave: complementary sources of information

(a) Microwave observations: generalities

Microwave instruments: 2 families

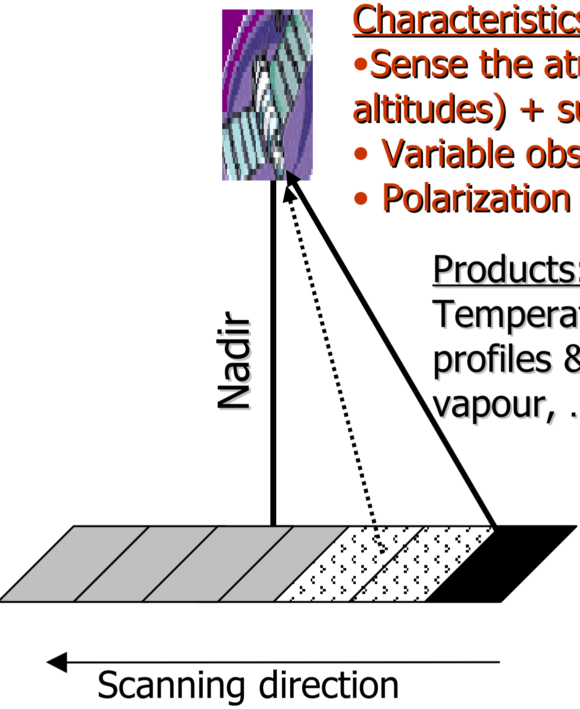
Sounder

AMSU-A, AMSU-B (NOAA, aqua, metop) , SAPHIR (Megha-Tropiques)

SSMI/S (DMSP)

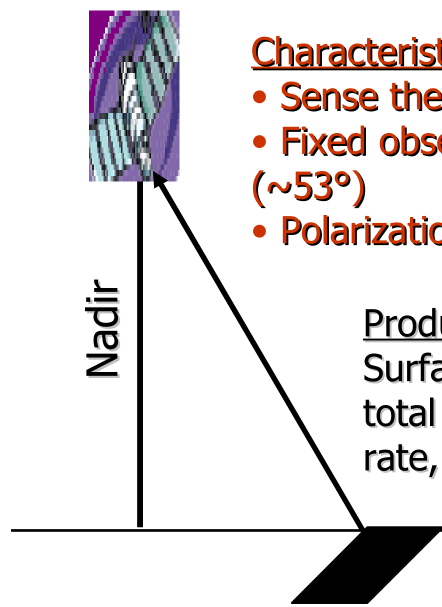
Imager

SSM/I (DMSP), TMI (TRMM), AMSR-E (aqua), MADRAS (Megha-Tropiques)



Characteristics:
- Sense the atmosphere (many altitudes) + surface emissions
- Variable observation angle
- Polarization is a mixture of V&H

Products:
Temperature & humidity profiles & total water vapour, …

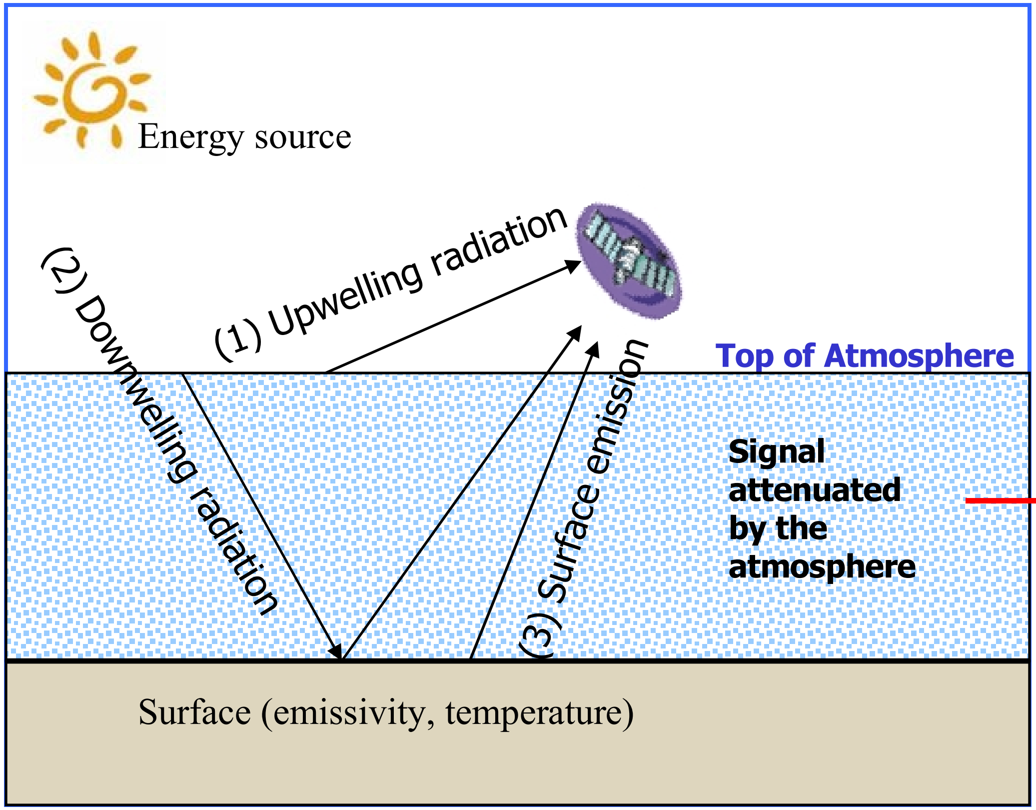


Characteristics:
- Sense the surface emission
- Fixed observation angle (~53°)
- Polarization V &/or H

Products:
Surface ocean wind speed, total water vapour, rain rate, …

(a) Microwave observations: generalities

Measurements at microwave frequencies: The instrument receives an electromagnetic signal

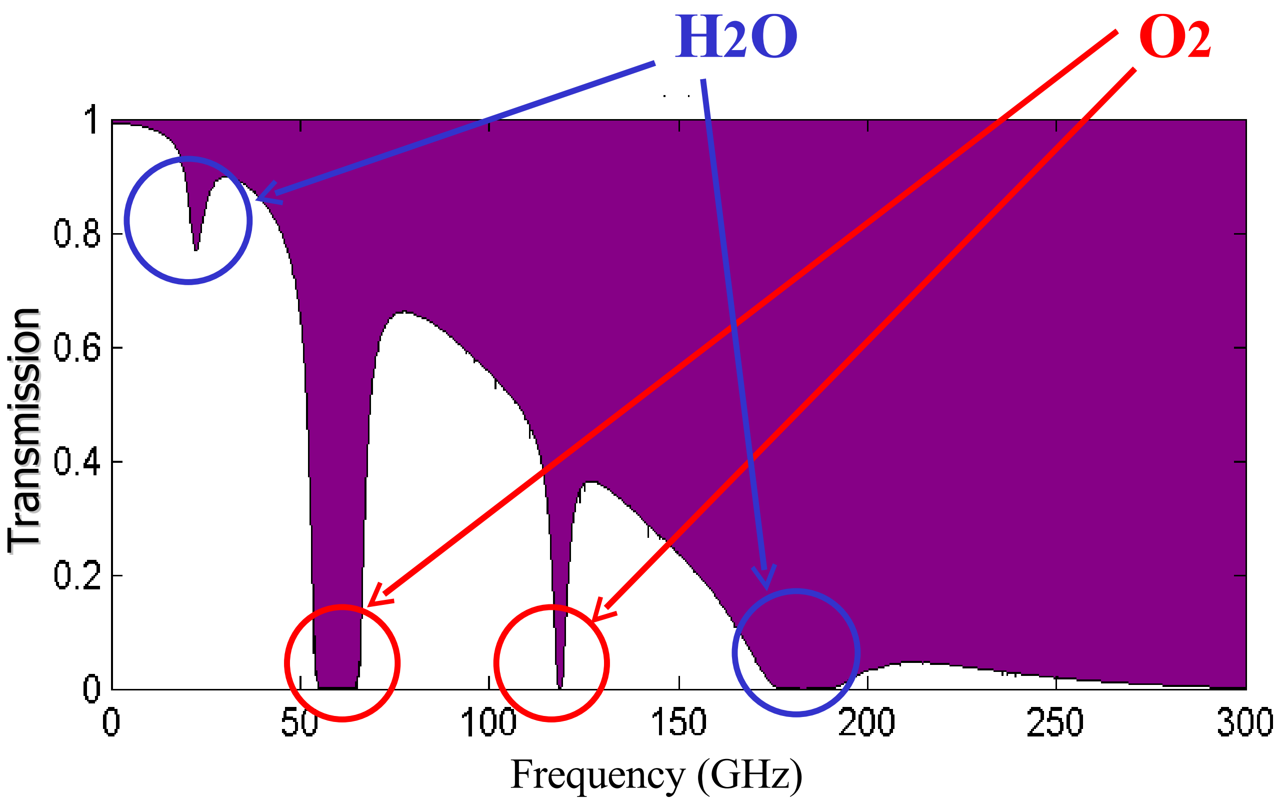


- Observation frequencies are chosen such as the total signal (2+3) is fully or party transmitted
- Choice is made based on the atmospheric transmission spectrum

(a) Microwave observations: generalities

Transmission at microwave frequencies:

The atmosphere is opaque to electromagnetic radiation at many frequencies. For some frequencies, radiation is fully (window channels) or partly transmitted.



Transmission changes due to Emission/Absorption or scattering:

- O2: 50-70 GHz, 118 GHz
- H2O: 22, 183 GHz
- clouds (rain, cloud water, cloud ice, …)
- Attenuation due to water vapor continuum and dry air continuum

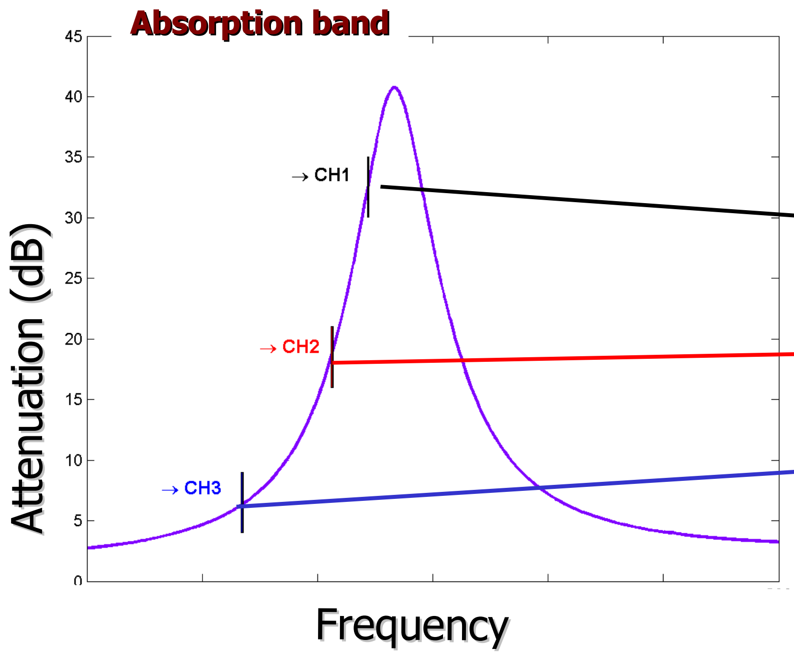
$$attenuation(dB) = e^{\frac{-transmission}{\cos(\theta)}}$$

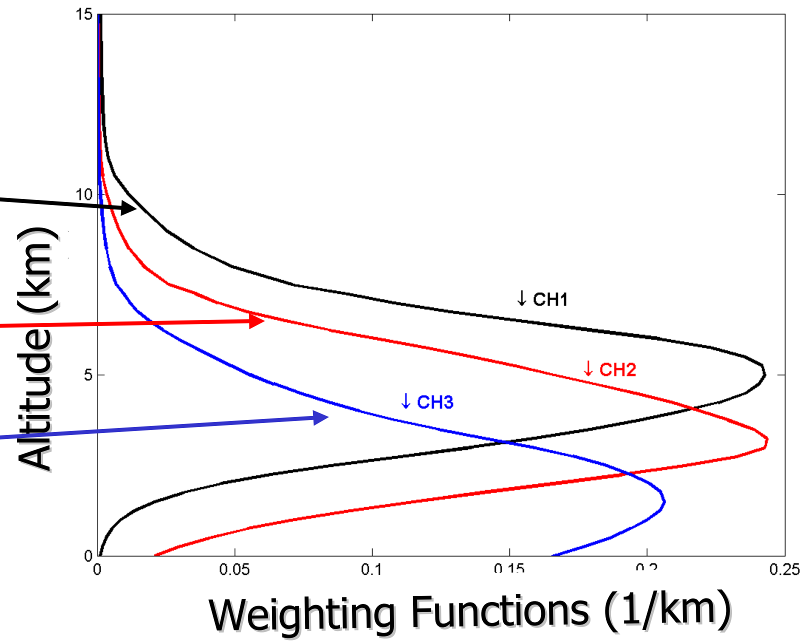
(a) Microwave observations: generalities

Sensing the atmosphere ?

- At microwaves, water vapour and oxygen absorption bands have the greatest impact on signals
- Pressure (altitude) is the most dominant factor that determines the width of absorption bands (at least bellow 60km)
- Absorption bands become larger with increasing pressure

<u>Measures far (close) from an absorption band: information about low (high) atmospheric levels</u>

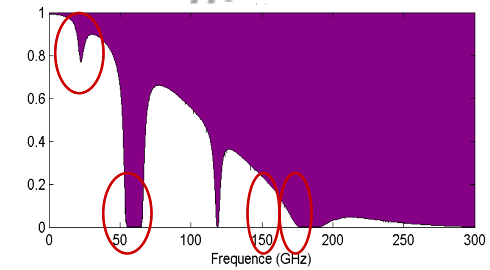


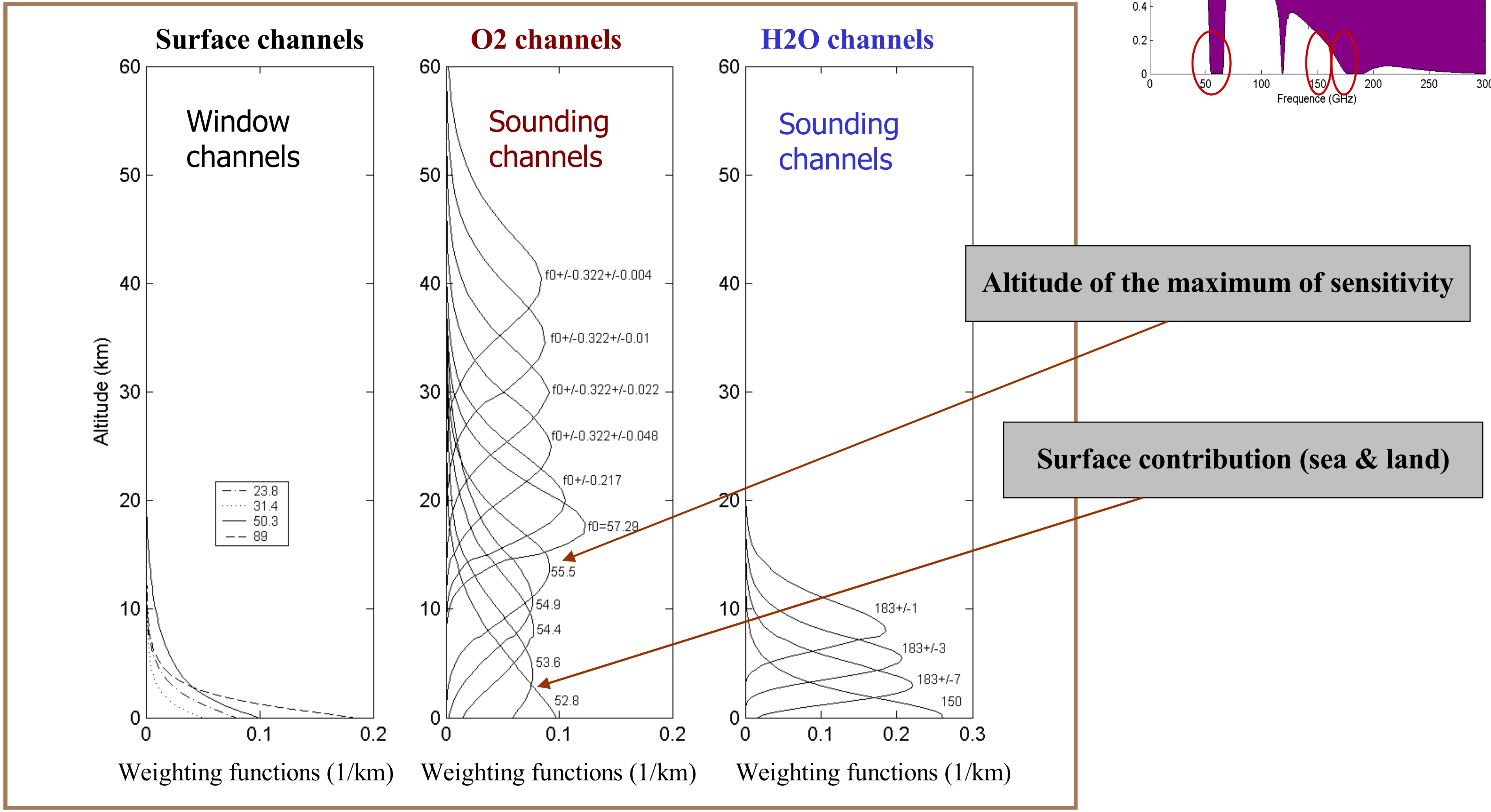


(a) Microwave observations: generalities

Sensing the atmosphere ?

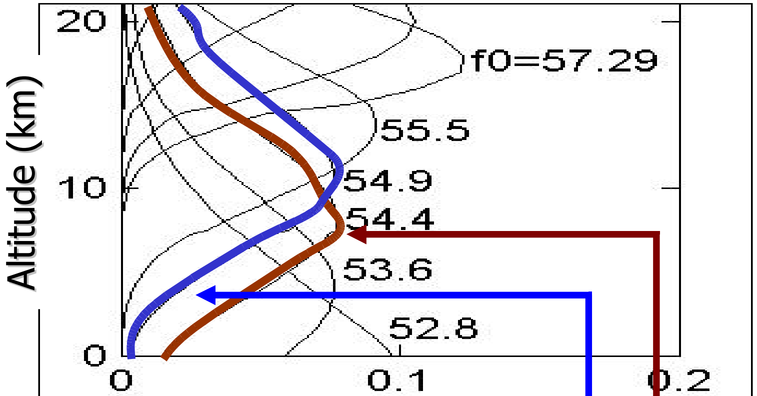
Weighting functions for AMSU-A & -B, standard atmosphere



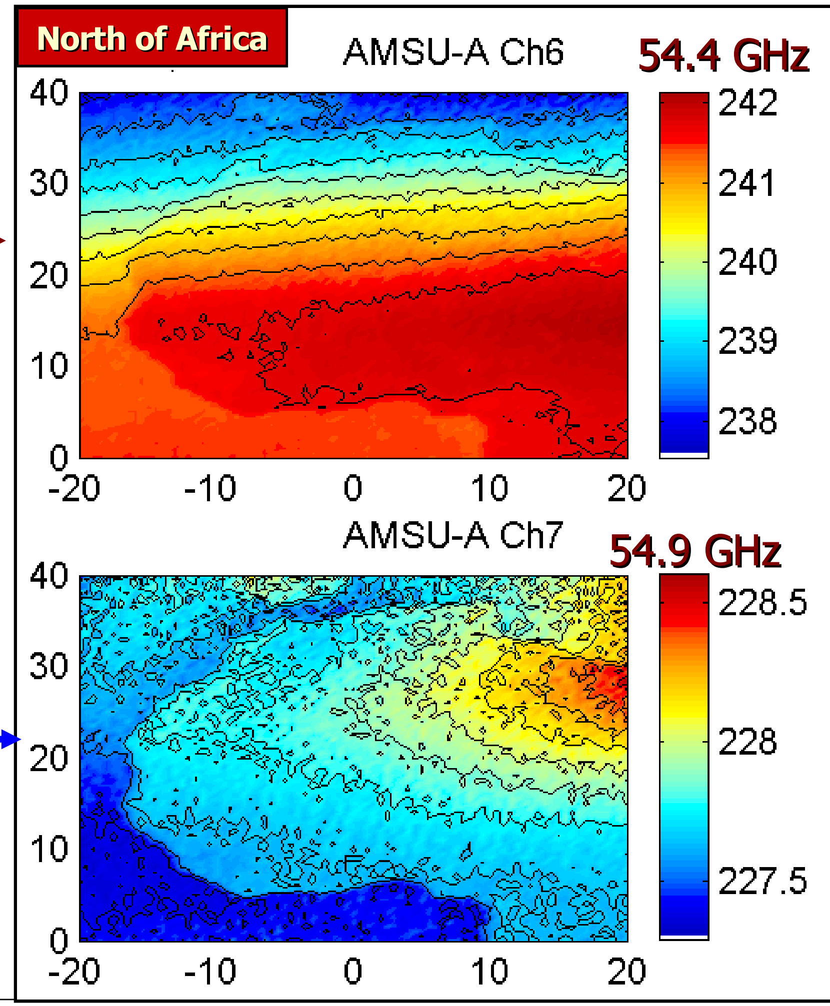


(a) Microwave observations: generalities

Sensing the atmosphere, But with surface contribution



Mean Tbs averaged over 8 months of year 2000 from Temperature channels (sensitive at z=8-10 Km)



- ❑ Some sounding channels receive a contribution from the surface
- ❑ Better use of observations: separate the effect of surface and atmosphere
- ❑ Data assimilation: Only channels that are the least sensitive to the surface are currently assimilated

Both Emissivity & surface temperature affect near surface and sounding channels (English, 2007)

(a) Microwave observations: generalities

The surface contribution is important even for sounding channels
Any differences between sea/land emissivity?

Over Oceans

- Emissivity ~ 0.5: the sea surface contribution to the measured signal is lower than the land contribution

- Emissivity models are good enough to meet the NWP requirements (remaining uncertainties: GO models work better at high frequencies than in the low frequency range, surface description)

Land

- The emissivity is high (~1.0)

- Difficulties to describe the emissivity variation with surface types, roughness, soil moisture, …

- This talk: about recent advances in the estimation of land surface emissivity to help surface & sounding channel assimilation

(b) Ocean : low emissivities (~0.5), good emissivity models

State-of-the-art for current and future applications

- RTTOV (operationally used at Met-Office, Météo-France, ECMWF, …):
  - NWPSAF Fastem-3 (English, S. and T.J.Hewison, 1998, Deblonde 2000)
  - Fast GO (Geometric Optics) model (series of reflecting plane facets)
  - Dielectric sea water model (requires skin temperature; salinity), Parameterization of surface roughness (requires wind speed or vector) & foam (requires wind speed)

- JCSDA CRTM (operationally used at NCEP):
  - FASTEM or NESDIS Ocean Model (Weng, F and Q.Liu, 2003)
  - Two scale model (sup-imposing small structures (small gravity waves ..) on the large undulations (gravity waves)).
  - The influence of small irregularities decreases with increasing frequency.
  - Combination of FASTEM3 and low frequency (<20GHz) model developed by Masahiro Kazumori.

(b) Ocean : low emissivities (~0.5), good emissivity models

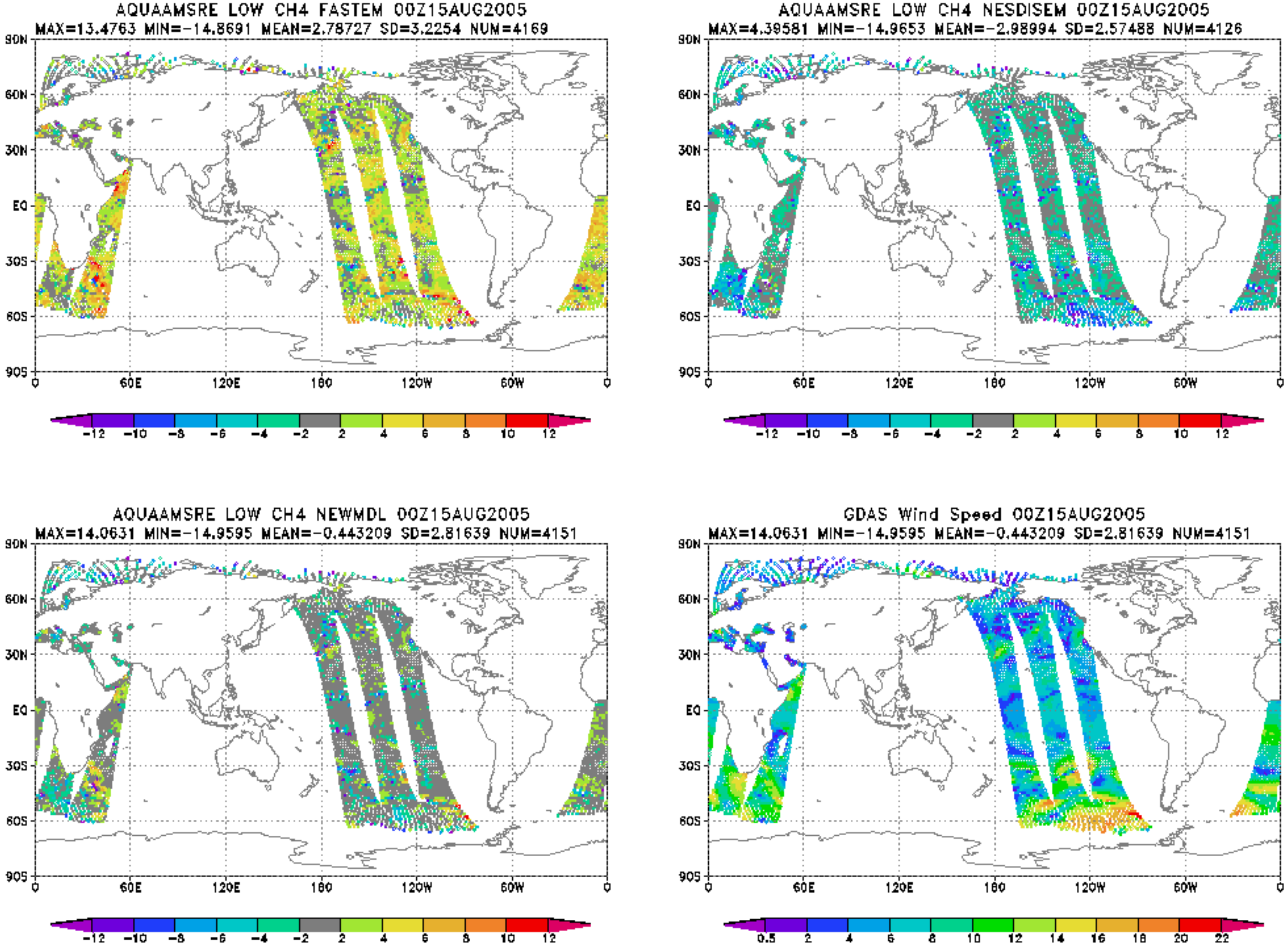
Simulated TB - Observed TB, AMSR-E 10.65GHz(H)

New low-frequency model reduces the error in model radiance simulation

FASTEM

NESDIS

LowFreq model



Masahiro Kazumori, JMA/JCSDA

(b) Land : High emissivities (~1)

Methods to estimate the land emissivity

- **In-situ measurements:**
  Different surface types (bare soils to forests)
  Calvet et al. (1995), Matzler (1994, 1990), Wigneron et al. (1997) among others

- **Airborne measurements:**
  Different surface types (forests, snow)
  Hewison and English (1999), Hewison 2001, …

- **Satellite estimations:**
  Regional to global scales, many frequencies, many sensors
  Choudhury (1993), Felde and Pickle (1995), Jones and Vonder Haar (1997), Karbou et al. (2005), Morland et al. (2000, 2001), Prigent et al. (1997, 1998), among others

- **Modelling approaches:**
  Limitations:
  - Complexity of interactions between radiation and the large variability of the medium
  - For atmospheric retrievals, need of accurate input parameters (vegetation characteristics, soil moisture, roughness) at a global scale.

  Grody (1998), Karbou (2005), Isaacs et al. (1989), Weng et al. (2001), …

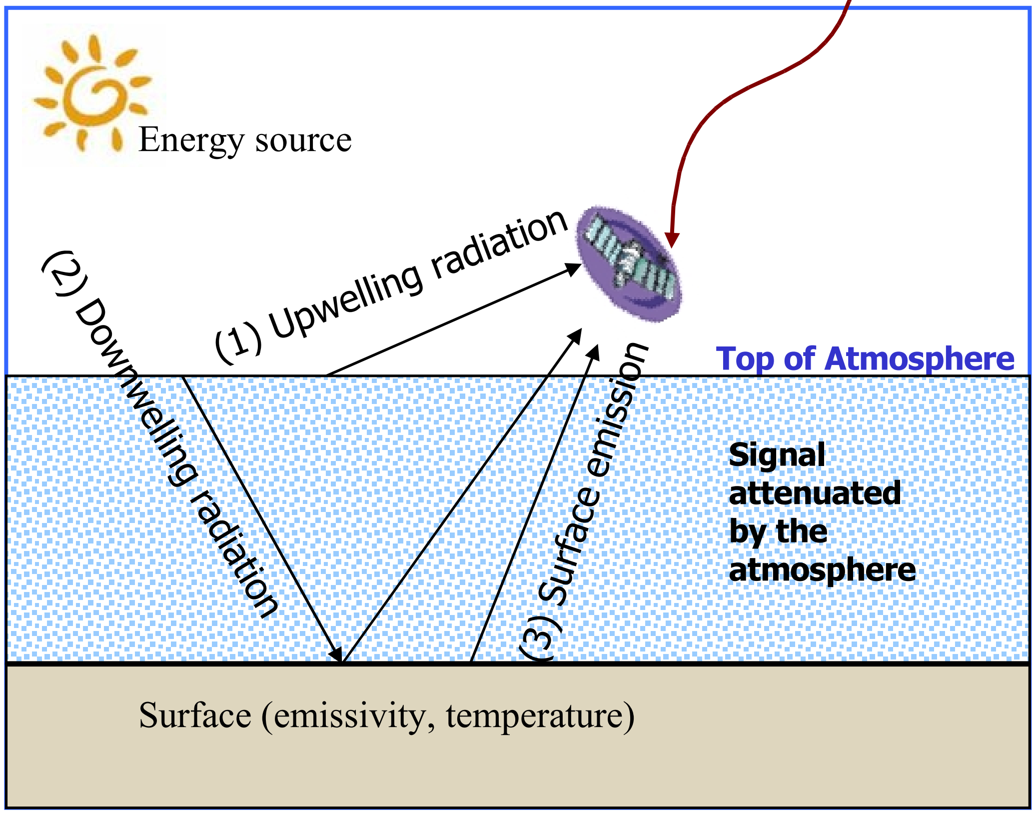
The land emissivity from satellite observations

Plane parallel non scattering atmosphere, specular surface

Observed Tb at polarization p and frequency υ

$$T(p,\upsilon) = \varepsilon(p,\upsilon).Ts.\tau + (1-\varepsilon(p,\upsilon)).\tau.T(\upsilon,\downarrow) + T(\upsilon,\uparrow)$$

Emissivity



Outputs of RT model:
T, Q short-range forecasts or radiosondes or reanalyses

$$\varepsilon(p,\upsilon) = \frac{T(p,\upsilon) - T(\upsilon,\uparrow) - T(\upsilon,\downarrow)\times\tau}{\tau\times(Ts - T(\upsilon,\downarrow))}$$

2- Land emissivity retrieval from satellite observations

(b) Sources of error

Calculated satellite emissivities are "spatially averaged" emissivities: Signal integrated according to the Field Of View of the instrument

No in-situ reference measurements at global scale and comparable with satellite estimates
Need to check the consistency, characteristics of computed emissivities, study sources of error

- Sources of error
  - Ts — **+/- 4 K ➔ 3%**
  - Humidity profiles — **+/- 15 % ➔ 3% 150 GHz**
  - Temperature profiles — **+/- 1 K ➔ 1%, 50 GHz**
  - Observed Tbs — **+/- 1 K ➔ small effect**
  - Surface assumption — **On snow-free areas ➔ < 1%**

Retrieved emissivity: could account for errors coming from many sources (Tbs, FOV, atmosphere, …)

(c) Emissivity variation

Satellite emissivity varies, at least, with:

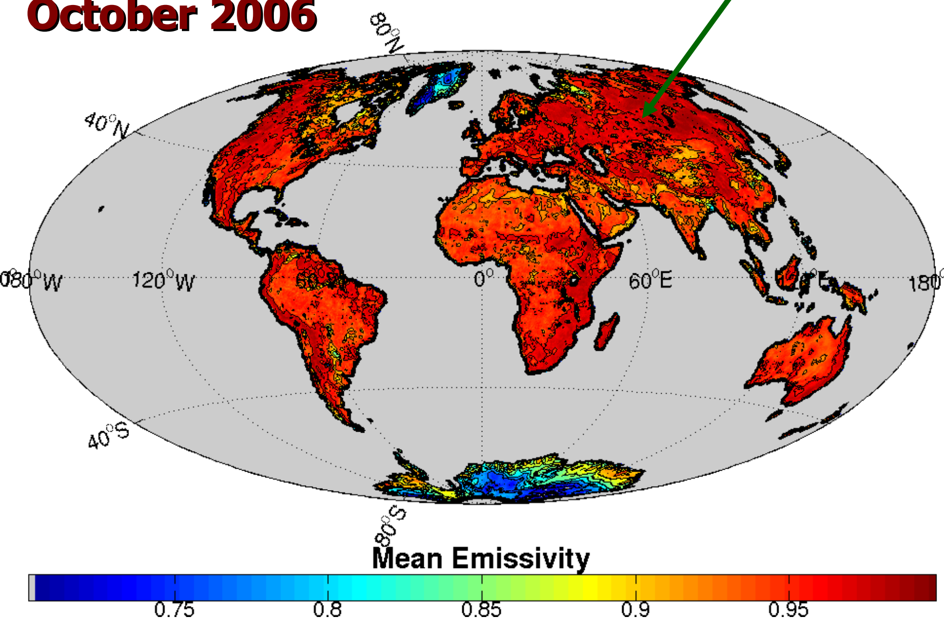
- Surface types
- Polarization
- Observation zenith angle (FOV)
- Frequencies

(c) Emissivity variation with surface types

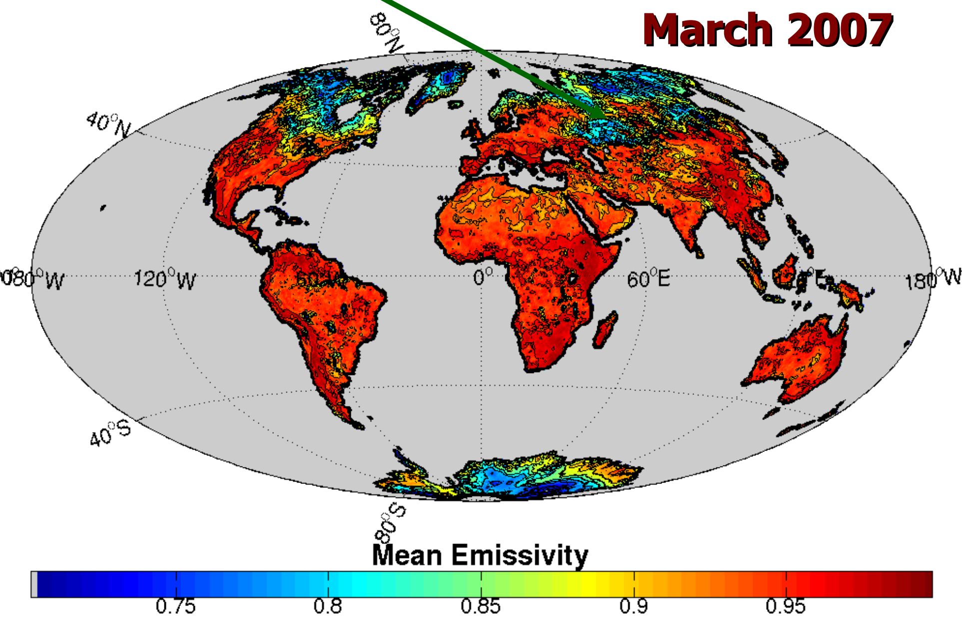
satellite emissivities (Ch3 (50.3 GHz) from AMSU-A)

- The emissivity varies with surfaces types, seasons
- Lakes and rivers are associated with lower emissivities
- Emissivity is generally higher over forests than over bare soils
- Emissivity reproduces any change of the surface conditions (rain, snow, …)

October 2006



March 2007

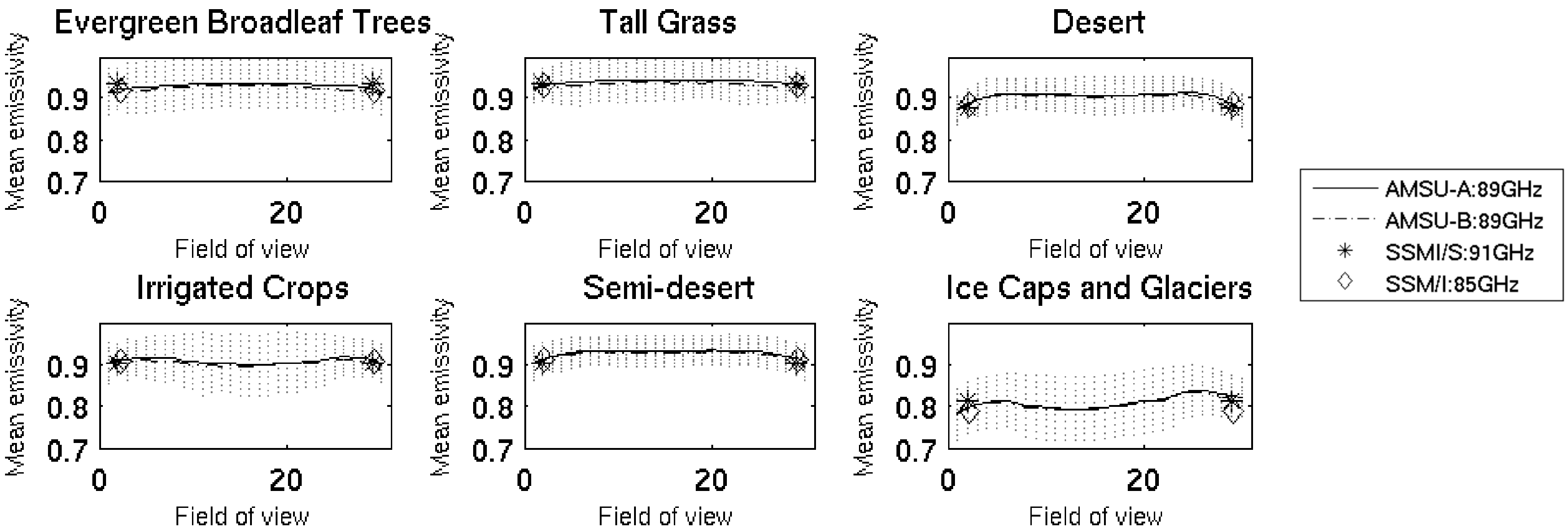


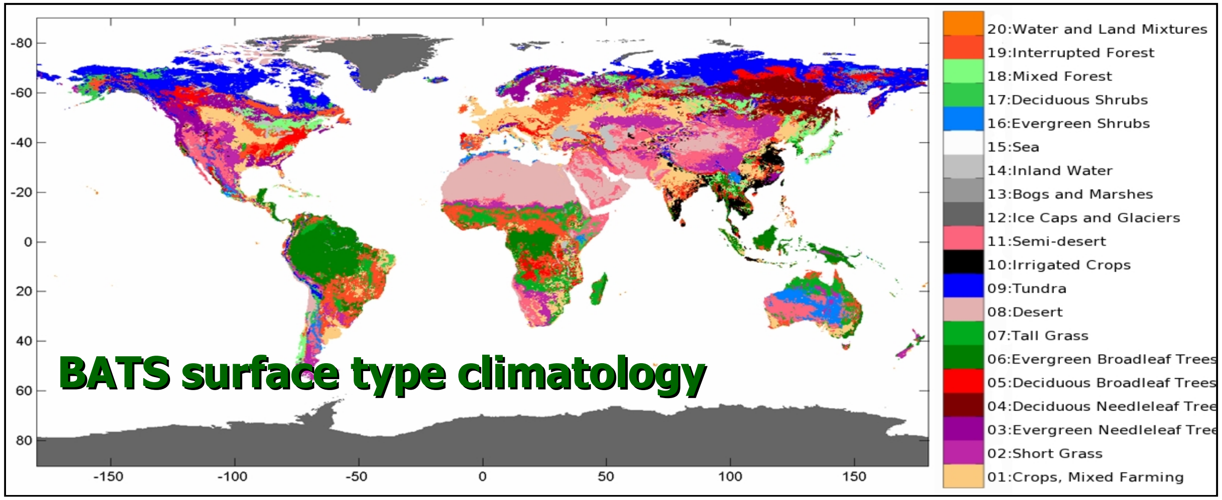
2- Land emissivity retrieval from satellite observations

(c) Emissivity variation with surface type

The emissivity from different sensors

AMSU-A, AMSU-B, SSM/I, SSMI/S, August 2006:





- emissivities retrieved from different sensors are in good agreement
- It is possible to use emissivities derived from an instrument to simulate Tbs of an other instrument

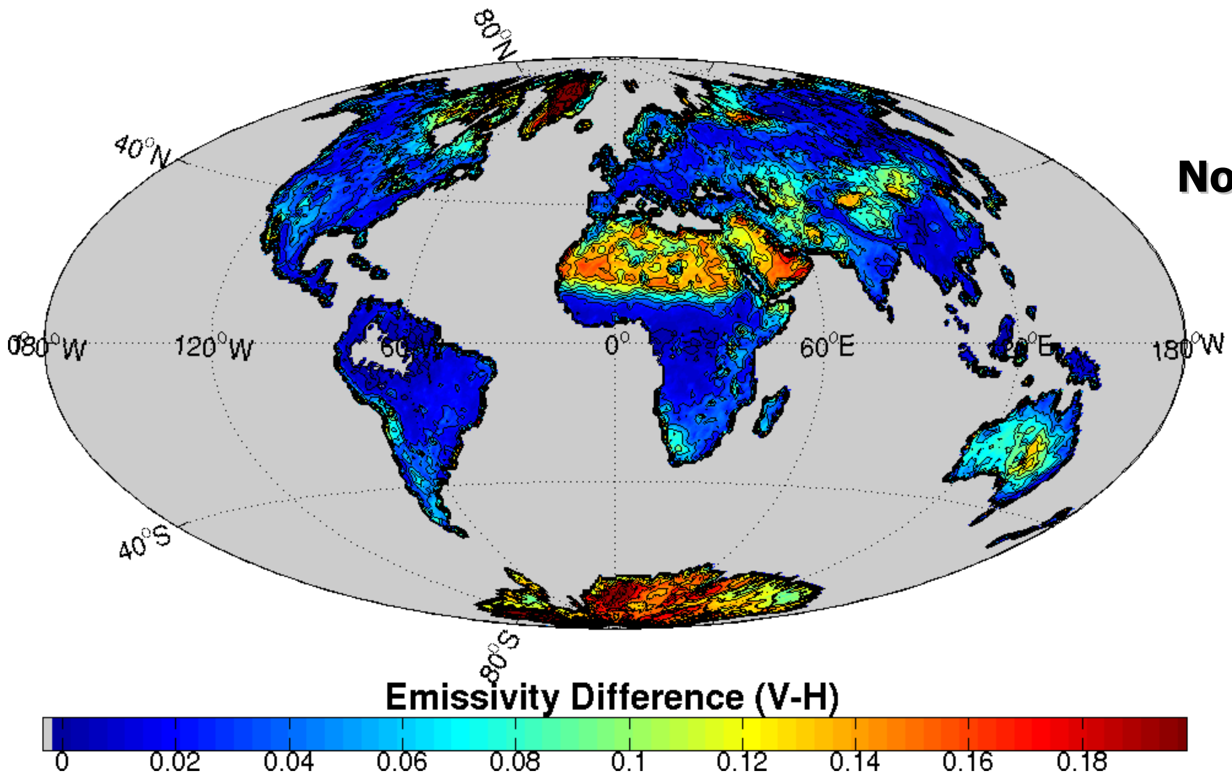
(c) Emissivity variation with polarization

satellite emissivities (Ch1-Ch2 (19V-19H) from SSM/I)

Desert: known to have larger emissivity polarization differences

Over snow:

- the emissivity is variable (large std); Depends on the physical properties of snow
- Strong contrast between wet & dry snow (Emissivity decreases with increasing frequency over dry snow (Matzler, 1994)

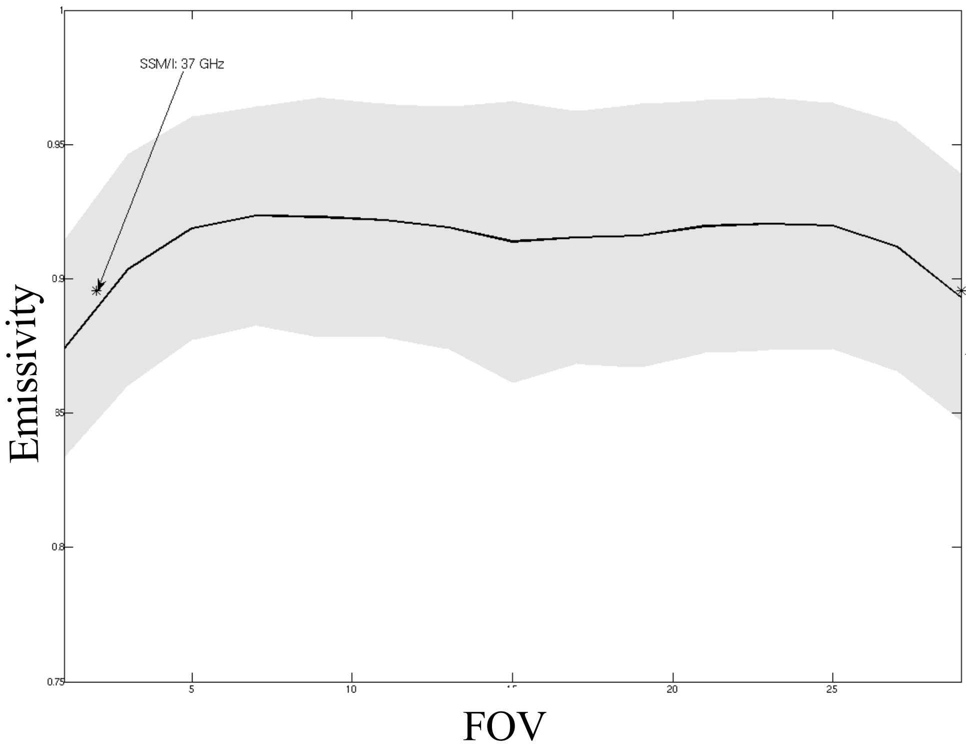


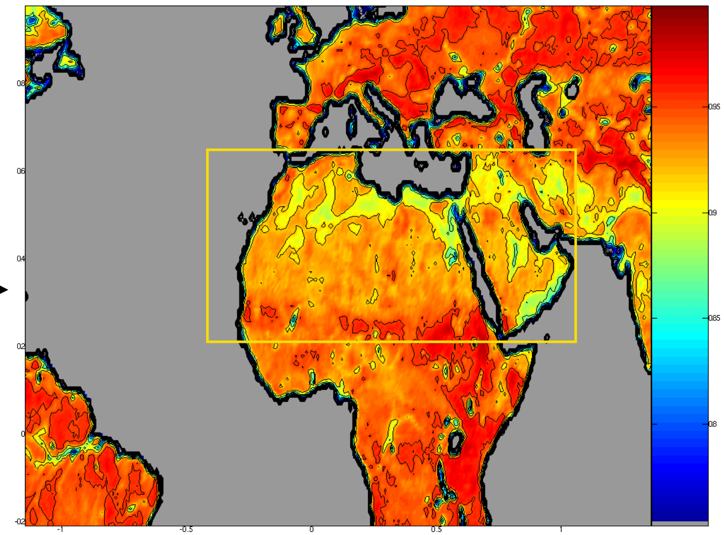
November 2006

2- Land emissivity retrieval from satellite observations

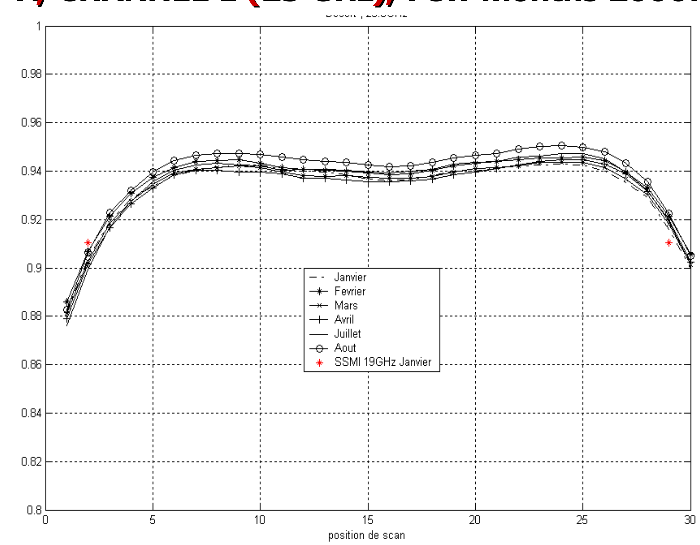
(c) Emissivity variation with scan angle

satellite emissivities (Ch2 (31 GHz), AMSU-A, November 2006)





AMSU-A, CHANNEL 1 (23 GHz), Few months 2000:



- The emissivity varies with the scan angle
- The angular variation is larger for bare soils than for forests
- For each surface type: the emissivity variation pattern is “stable”: It is possible to derive functions to reproduce the emissivity angular variability (Karbou, 2005)

2- Land emissivity retrieval from satellite observations

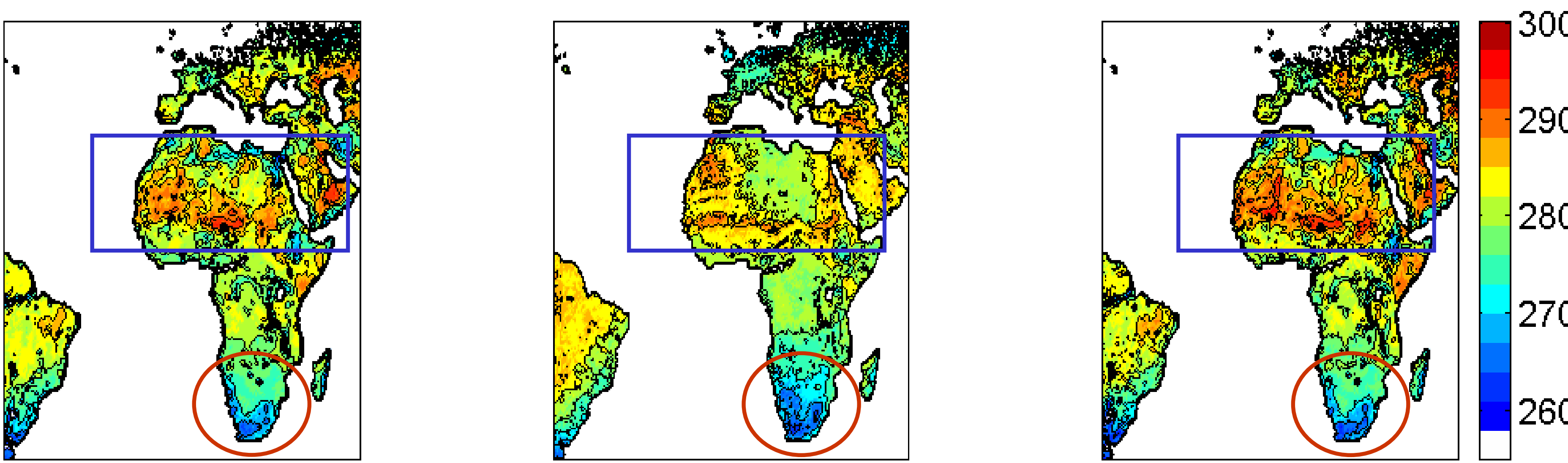
(c) Emissivity variation with scan angle

The importance of a good modelling of the emissivity

Observed Tbs
31GHz, August 2000
Zenith angles from
-58° to +58°

Simulated Tbs with
emissivity "best-fit
functions"

Simulated Tbs with
emissivity "best-fit
functions" + atlas



(c) Emissivity variation

Lessons from the land emissivity analysis

• The emissivity could be calculated at "window channels" for which the surface contribution is important

• The land emissivity experiences large variability with the surface type, conditions, … and also with the observation angle & polarization

• It is possible to describe the emissivity angular and spectral variations with polynomial best-fit functions

• For a specific surface type, the emissivity varies smoothly in frequency

• The transmission at "sounding channels" is very small (0.2 for Ch4-AMSU-A, ~0 for AMSU-B humidity channels) ➔ emissivity could not be retrieved at these channels

• Emissivities retrieved at "window channels" could be used, as a good approximation, to simulate Tbs at "sounding channels"

(a) Emissivity treatment in NWP centres

Current status:

- AMSU-A & AMSU-B:
  - Only channels that receive the least contribution from the surface are assimilated
  - A Scene classification (using land-sea mask, Ts, Tbs at 23.4, 31.8, 50.3, 89.0 GHz)
  - Grody (1998) and/or Weng et al. 2001 regression emissivity models
  - Emissivity at 50GHz is given to temperature channels and Emissivity at 89 GHz is given to humidity sounding channels
- SSM/I: Only over sea
- Many centres are testing the use of surface sensitive channels: Emissivity & skin temperature

Quantities used from radiative transfer

- Emissivity
  - Used in RT for Tb calculations
  - Used in estimating CLW for SSM/IS
- ∂(Tb)/∂(emissivity)
  - Used to modify observation error based on estimated error in surface emissivity
  - Estimate of change in emissivity necessary to fit observation use for QC of AMSU-A observations
- ∂(Tb)/∂(Ts)
  - Summed over percentages for each surface type (Land-Snow-Sea Ice-Water)
  - Used to modify observation error based on estimated error in Skin temperature
  - Estimate of change in skin temperature necessary to fit observation use for QC of IR observations
  - Used in skin temperature analysis
- $\partial(Tb)/\partial(u_{10})$, $\partial(Tb)/\partial(v_{10})$
  - Wind sensitivities can be used in wind analysis from microwave observations (option currently not exercised operationally)

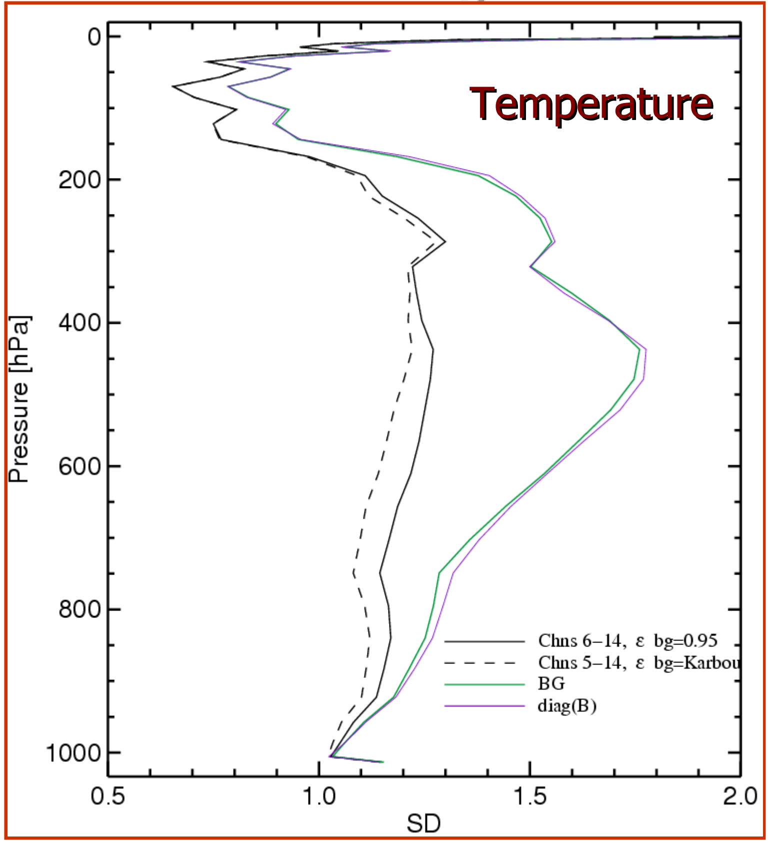
John DERBER, NCEP

(b) Recent data assimilation experiments

Met-Office

Sensitivity studies (1D-Var) are performed in order to allow the use of more microwave observations from sounding channels over land.

- AMSUA-A sensitivity studies to background Tskin, observation errors, emissivity errors have been performed.
- Improvement in performance when surface sensitive radiances are assimilated using the atlas emissivities rather than a fixed value of 0.95.



Control: operational 4Dvar
Exp: Retrieve Tskin and emissivity
Truth: Atmospheric profiles and surface variables from Chevallier dataset, emissivity from monthly averaged emissivities (From Karbou's dataset)
Background: add random Gaussian errors to the truth profile
Observations: add random Gaussian errors to RTTOV generated ATOVS radiances

More studies:

- Study the impact of emissivity climatology
- Improve the analysis of skin temperature

Sreerekha THONIPPARAMBIL, Met-Office

(b) Recent data assimilation experiments

Météo-France

Satellite land emissivities retrieved at "window channels" could be used, as a good approximation, to simulate Tbs at "sounding channels"

Study the feasibility of using satellite emissivities for data assimilation

- Study the impact of updated emissivity or skin temperature estimates within the French 4D-Var assimilation system
- Feasibility of assimilating microwave surface + additional sounding channels from AMSU, SSM/I (5 channels over land)
  - ❑ Comparison of emissivity estimates
  - ❑ Observation operator performances (RTTOV)
    - ✓ Comparison of Observed and Simulated Tbs (without applying a bias correction)
    - ✓ Number of assimilated observations
  - ❑ Analysis and forecast skills

Overview of experiments:

Comparison of three land surface parameterizations with increasing complexity (Karbou et al. 2006):

- **EXP_ATLAS: Averaged emissivities over 2 weeks** prior to the assimilation period; Ts is taken from the model' FG.
- **EXP_DYN: Dynamically varying emissivities** derived at each pixel using only one channel (or two) of each instrument; Ts is taken from the model FG.
- **EXP_SKIN: Averaged emissivities + dynamically estimated skin temperature** Ts at each pixel using one (or two) channel of each instrument

All surface parameterizations are handled by the RTTOV model (Eyre 1991; Saunders et al. 1999; Matricardi et al. 2004)

Overview of experiments:

EXP-SKIN:

An emissivity climatology + short-range forecast profiles

$$Ts = \frac{T(p,\upsilon) - T(\upsilon,\uparrow) - (1-\varepsilon_{atlas})T(\upsilon,\downarrow)\times\tau}{\tau\times\varepsilon_{atlas}}$$

• Ts calculated in order to replace Ts coming from the model first-guess.

Potential limitations :

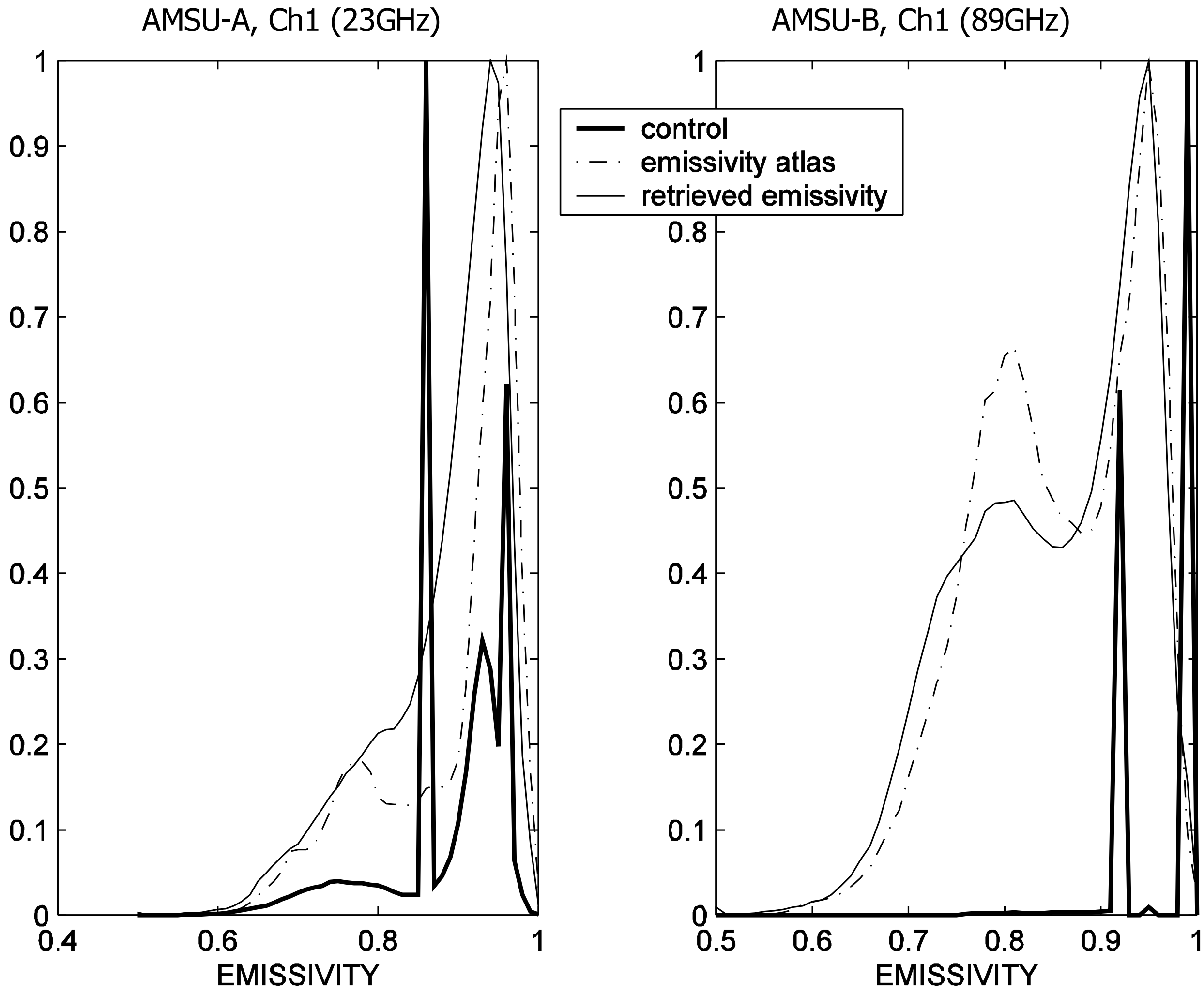
• Penetration depth: should not be a problem for AMSU frequencies

• Error Propagation: emissivity climatology should be unbiased.

• Ts should not be calculated when the transmission is weak : screening for clouds

• Increase usage of short-range forecasts: less important for channels with a high transmission

Satellite emissivity / control

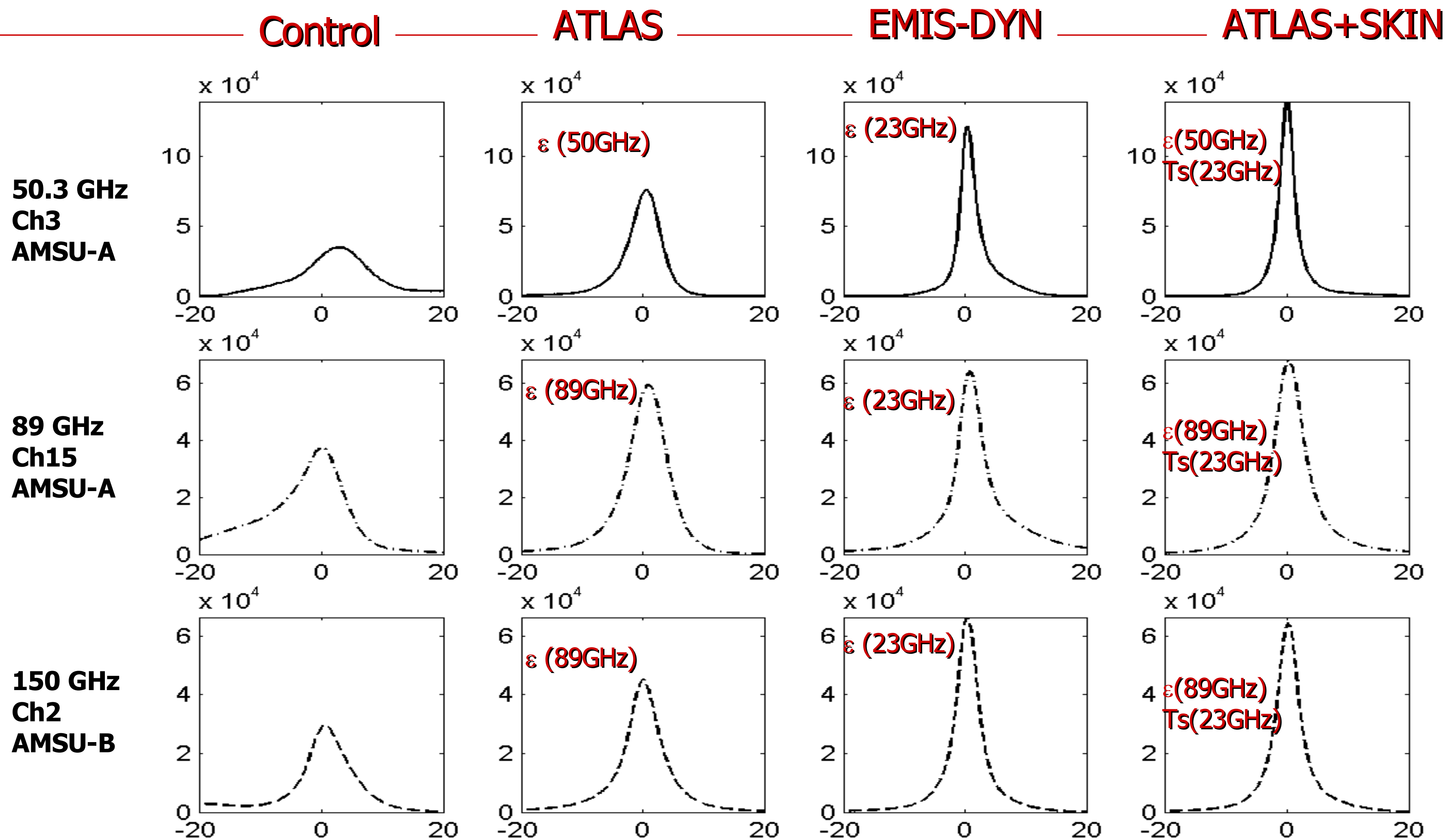


(b) Recent data assimilation experiments

Météo-France

Results: Observation operator simulations

Fg-departures (obs-guess) global histograms, 15-31 August 2005



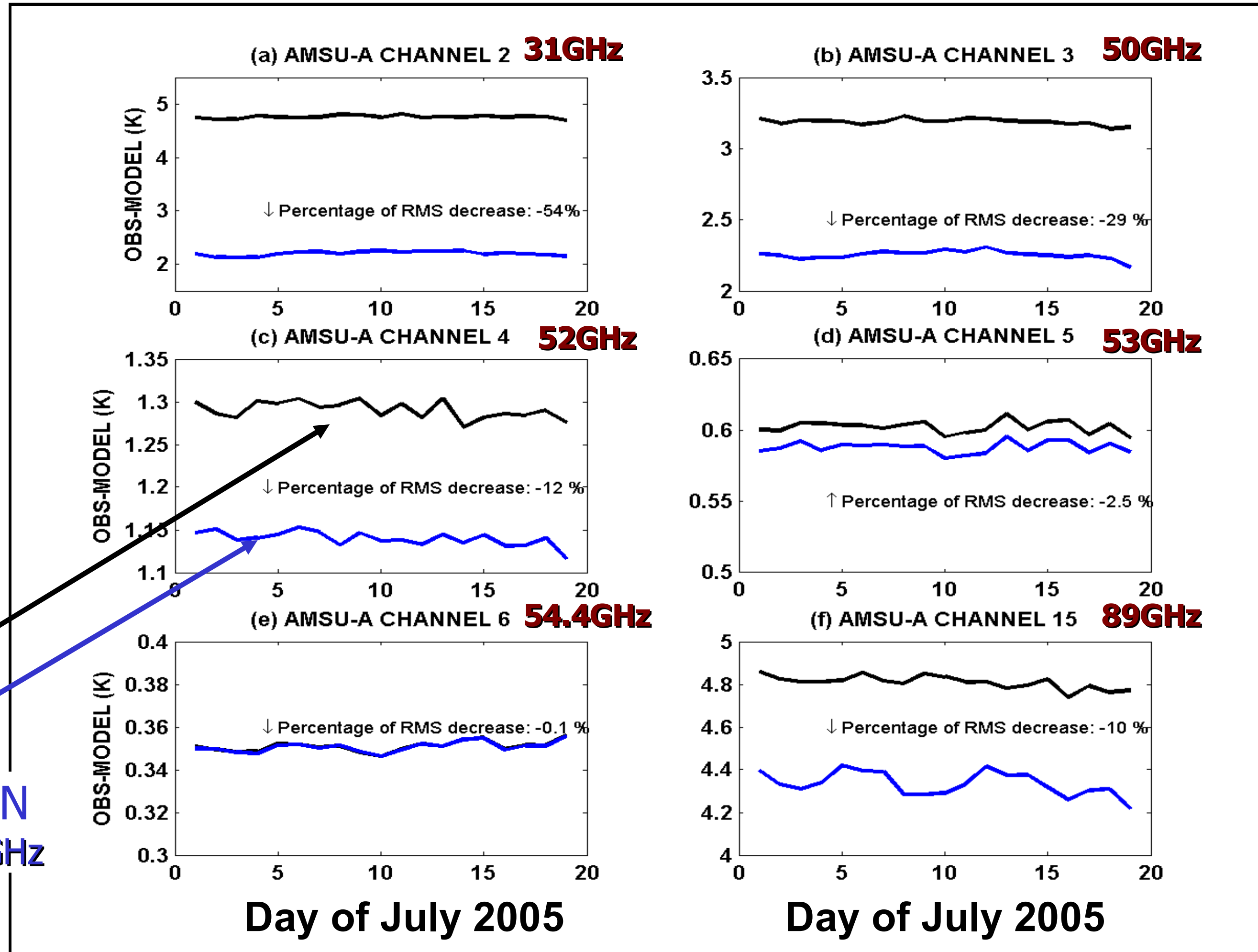
(b) Recent data assimilation experiments

Météo-France

Results: Observation operator simulations

RMS of error, Glob, Period: 01 to 19 July 2005

- Tb simulations are improved when using satellite emissivities
- Emissivities impact "window channels" as well as "sounding channels"
- The improvement for CH4 (AMSU-A) is very important for QC (higher sounding channels)



CTL

EXP_DYN
ε from 23GHz

Results: Channel selection for emissivity retrieval

Many experiments have been run with different strategies for emissivity calculation:

❖ Averaged emissivities (with or without Tskin):

- should be calculated over few weeks prior to the assimilation period
- should be unbiased (effect of clouds, rain, …)
- may not be adapted if there is a change in the surface condition
- AMSU instruments, the atlas should take into account the emissivity variation with scan angle (atlases by angle classes, add "functions" describing the angular variation)

❖ "non averaged emissivities":

- emissivity is calculated for each pixel
- Selection of channel for which the emissivity could be calculated
- AMSU-A has 4 window channels ➔ what is the best channel for emissivity calculation ?
    - possibility: choose the closet "window channel" in frequency to sounding channels: Ch50GHz is closer to Temperature sounding channels and 150 GHz is closer to humidity sounding channels. Problem: noise because the transmission is low (0.5-0.6 for CH50GHz, 0.2-0.6 for 150GHz)
    - Possibility: choose the channel for which the transmission is higher; Problem: should take the emissivity frequency dependence into account

Main results

- Improvement of the performance of the observation operator simulations: bias and standard deviations for all experiments (best results from EXP_DYN and EXP_SKIN)

- Increase of the number of observations that could be assimilated over land, including channels that are currently not assimilated (150 GHz, …)

- Forecast scores globally neutral to positive for humidity, temperature and geopotential height.

- Precipitation forecasts improved for West Africa. Further evaluation will be performed for AMMA (summer 2006) and with a limited area model for intense Mediterranean events.

- more experiments to better understand the impact of changes in the surface (emissivity/skin temperature), bias correction, cloud identification

(b) Recent data assimilation experiments

ECMWF

CNRS METEO FRANCE

Satellite-based emissivity calculations have been performed to prepare the assimilation of AMSU-A observations over land (Prigent et al. 2005)

Emissivities were derived at AMSU-A frequencies and compared with model's emissivities, were analyzed with respect to surface types, frequency

An extrapolation of SSM/I emissivities to AMSU-A frequencies was tested.

Assimilation experiment trial (1 cycle) suggests an increase of ~20% assimilated data (ch5 & 6)

Activities to allow the assimilation of microwave observations over land under cloudy/rainy situations :

Objective: use of cloudy/rainy SSMI/S observations over land (O'Dell, C., and P. Bauer, 2007, SAF-Hydro report)

- **1D+4D-VAR method (Bauer et al. 2006 (A & B)) to be used over land**
  - operational over sea for rainy SSM/I observations since June 2005
  - Use of SSM/I radiances within 1D-Var to produce Total Column Water Vapour (TCWV) in rainy situations
  - TCWV is given as "pseudo-observations" to the 4D-VAR
- **Land emissivities:**
  - Use of monthly derived SSM/I emissivities from 1992-2001 (Prigent et al. 2006)
  - Get the "True background" climatology of emissivity
  - Get the emissivity "backgroud" errors
  - Grody (1988) formula to fit SSMI emissivities to SSMI/S frequencies (6 fitting parameters)
  - 10years of emissivities: 1° box to calculate the fitting parameters variability ➔ Emissivity background error matrix

Christopher O'Dell, Peter Bauer, ECMWF

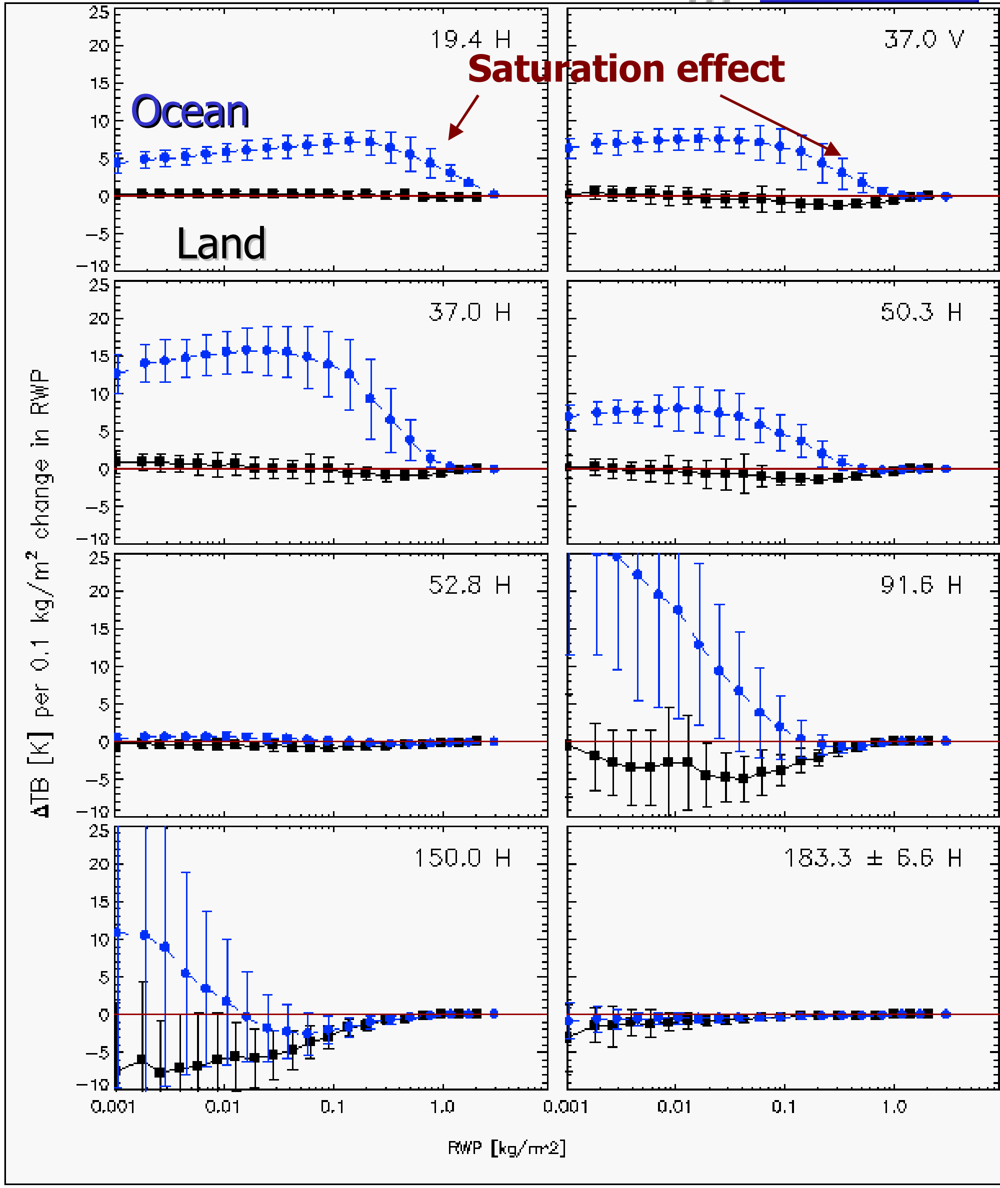
3- Land emissivity for data assimilation

(b) Recent data assimilation experiments

ECMWF

Sensitivity studies:

- Response of SSMI/S channels to clouds rain & snow
  - Change in Tbs for a 0.1 kg/m2 change in rain water path
  - Ocean responds strongly to a change in precipitation
  - Over land, 19, 37, 50 seem to have no sensitivity to rainfall over land (high emissivity)
  - 0ver land, 91 and 150 GHz show the maximum sensitivity
- Cloudy / clear Tbs tests
  - Lower frequency channels show larger differences over ocean; small over land
  - Channels 91 & 150 GHz show largest sensitivity to rain over land



- **The 1D-VAR**

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

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

Christopher O'Dell, Peter Bauer, ECMWF

(b) Recent data assimilation experiments

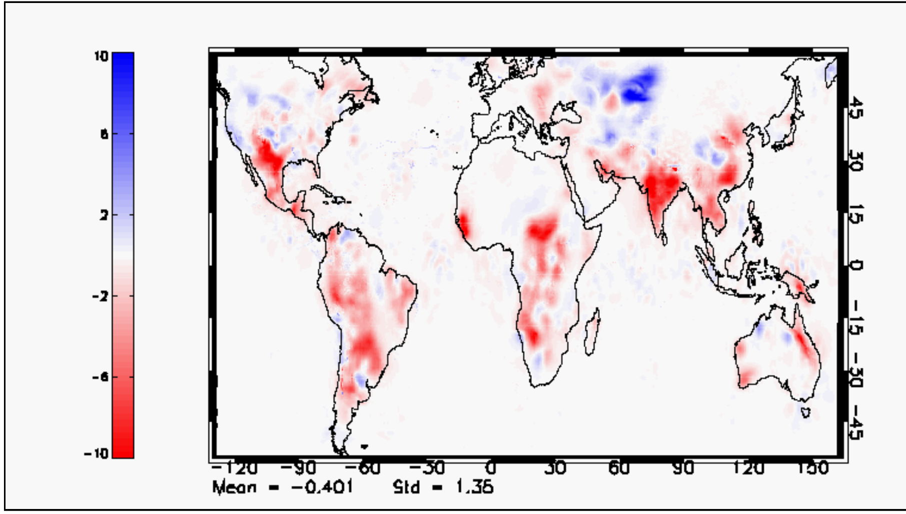
ECMWF

Assimilation experiments

- CONTROL
- 4 experiments that assimilate a selection of SSMI/S channels (with a sensitivity to clouds) using: emissivity or emissivity parameters

For all experiments, first-guess emissivity from atlas.

4D-Var analysis TCWV increments relative to control



Main results

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

Christopher O'Dell, Peter Bauer, ECMWF

(b) Recent data assimilation experiments

ECMWF

Studies to allow the assimilation of surface-sounding channels from AMSU-A/B & SSMI/S over land, clear sky

A land surface emissivity calculation module (Similar to MF one) has been implemented within the IFS system and have been adapted to SSMI/S, TMI, AMSR-E observations in addition to AMSU, SSM/I (Karbou et al. 2007, NWPSAF Report)

Several assimilation experiments have been conducted in order to assimilate MW observations over land within IFS:

- **SSMI/S temperature sounding channels over land**
  - CTR: The latest operational IFS global model configuration
  - EXP-DYN = CTR + assimilation over land of SSMI/S temperature channels with updated emissivity from 50 GHz allocated to temperature channels and emissivities from 91GHz given to humidity channels.
  - EXP-SKIN = CTR + temperature channels over land, emissivity from atlas and Skin temperature derived at 19V.
  - Period: 1 month
- **AMSU-A & -B sounding channels over land**
  - CTR: The latest operational IFS global model configuration
  - EXP-DYN: CTR + dynamically updated emissivities

    emissivities calculated at AMSU-A 31GHz & given to AMSU-A channels

    emissivities calculated at AMSU-B 89GHz & given to AMSU-B channels

    Without assimilating any additional channels % CTL
  - Period: 2 months

(b) Recent data assimilation experiments

ECMWF

SSMI/S temperature sounding channels over land

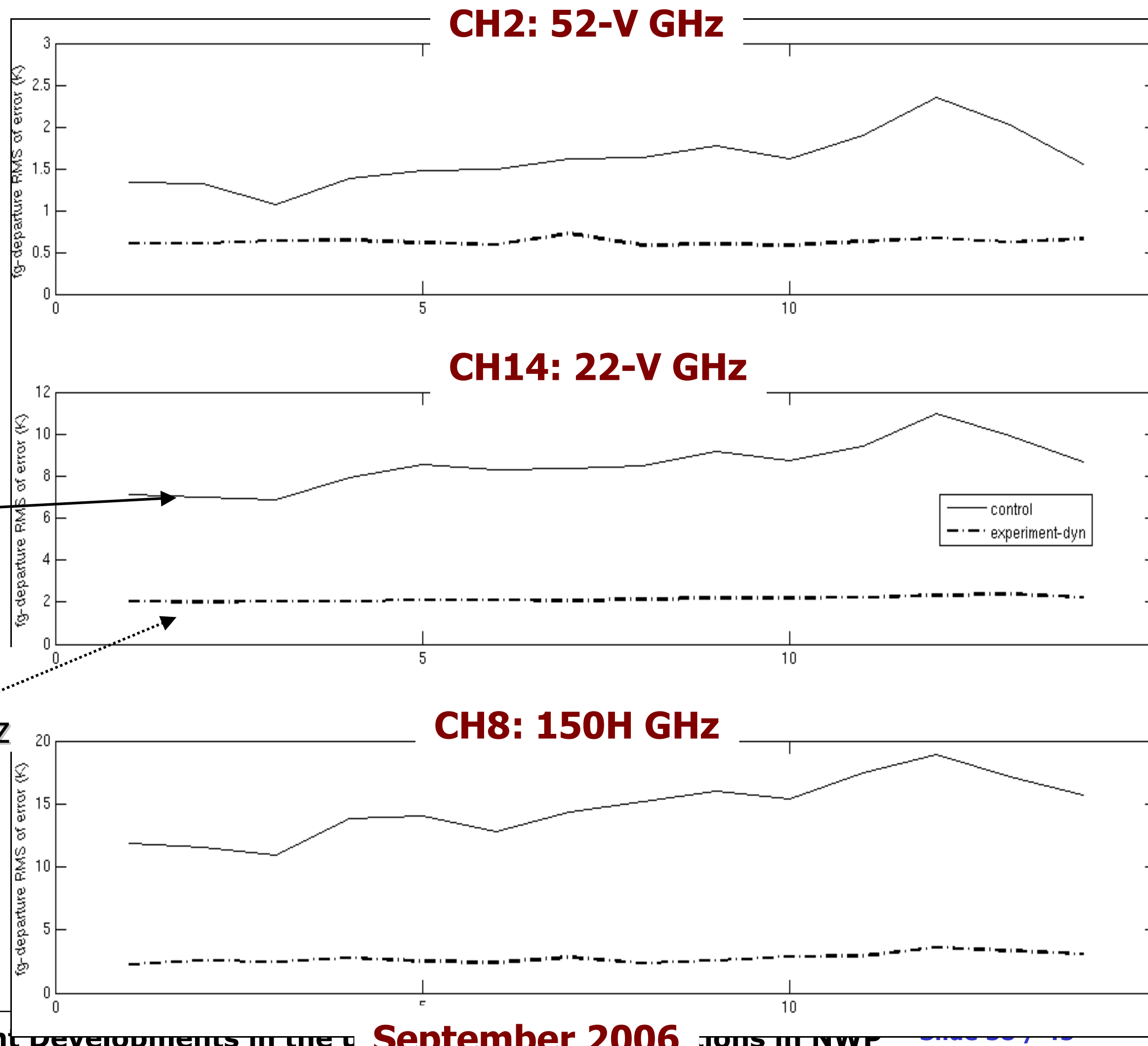
RTTOV Tb simulations over land are found to be closer to the observations, more data could be assimilated over land (+50% in sounding channels) without degrading the statistics (QC based on ch2 sensitive to the surface).

Obs-guess RMS of error time series for 52.8-V , 22.2-V, 150-H GHz

CTL

EXP_DYN

ε from 50V GHz

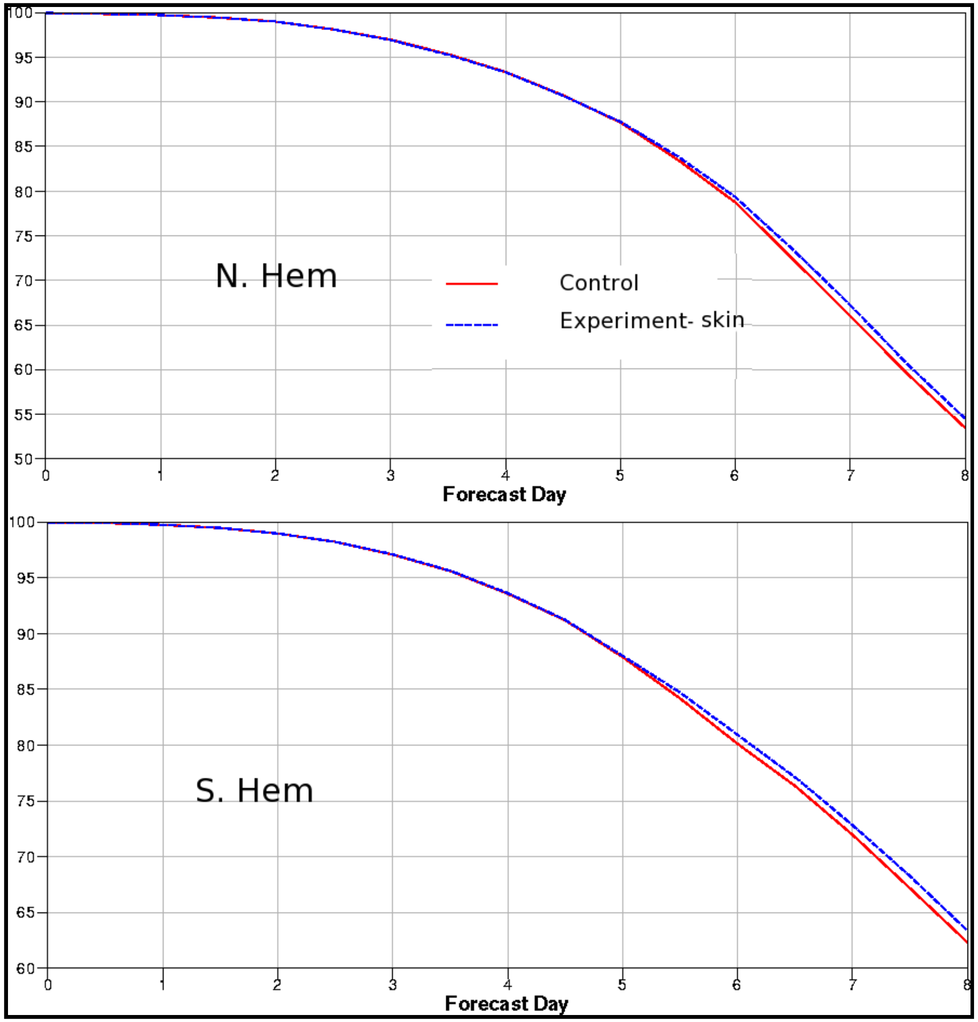


(b) Recent data assimilation experiments

ECMWF

SSMI/S temperature sounding channels over land

SCORES: small positive impact on the geopotential height has been noted for the S.hem (EXP-DYN), S. hem & N. Hem. (EXP-SKIN)



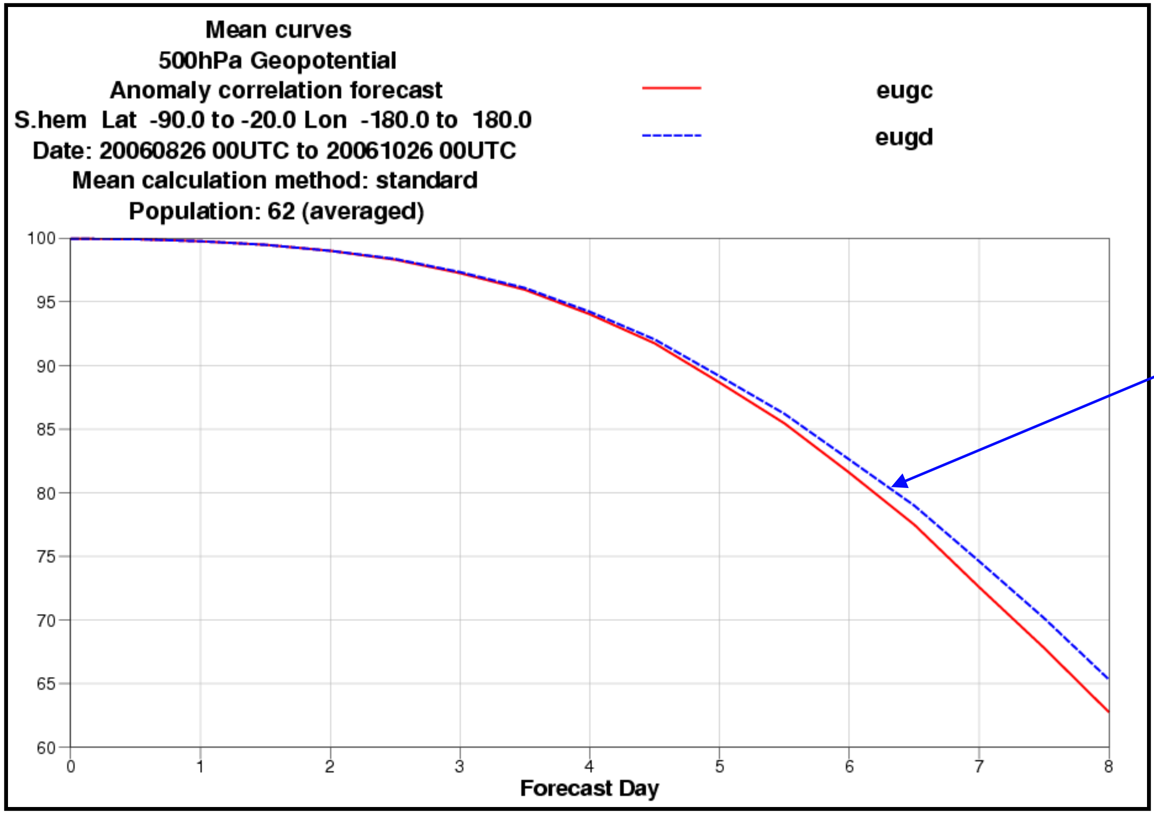
Scores: 1 month, experiment with emissivity (atlas) & skin temperature estimation at 19V GHz

(b) Recent data assimilation experiments

ECMWF

AMSU-A & -B with an updated emissivity over land

The fg-departures statistics are improved over land, and many more data are assimilated compared to the control experiment (+27% for AMSU-B humidity channels) without degrading the statistics.



EXP_DYN (Updated ε)

Scores, *2 months* (26/08/2006-26/10/2006)
S. Hem.: positive impact, statistically significant, Geopotential from 1000 to 200 hPa
N. Hem: Neutral

(b) Recent data assimilation experiments

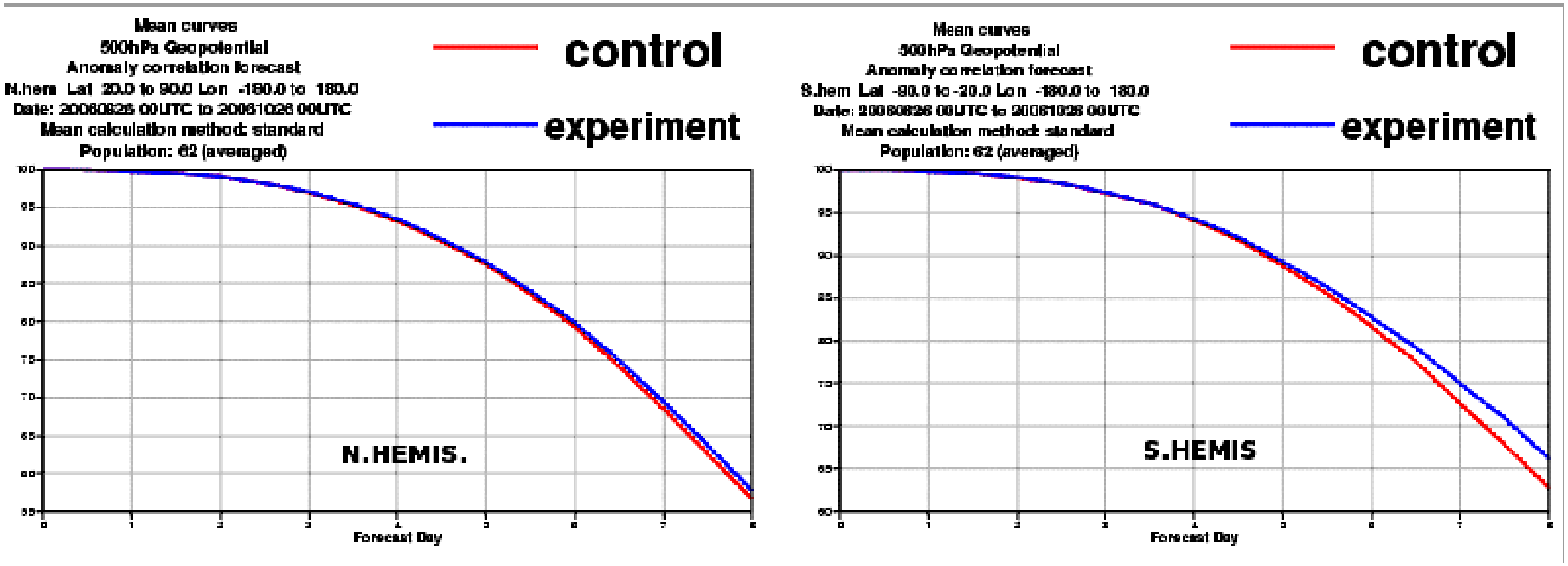
ECMWF

Ongoing studies to assimilate surface-sounding microwave channels over land, clear sky

- Sensitivity studies: emissivity, Tbs, Ts were perturbed and response of the simulated Tbs as a function of scan angle was analysed)

- Experiments: channel selection for emissivity, bias correction over land

Scores, *2 months, Exp_dyn:* ε from 50 GHz (AMSU-A) ε from 89 GHz (AMSU-B)



Blazej KRZEMINSKI (ECMWF)

Conclusions

- Promising results to improve the assimilation of microwave observations over land

- Deeper studies are still needed to assimilate new channels
  - bias corrections
  - channel quality control
  - effect of clouds

- Short-to-medium term plans (if nothing wrong with experiments) are to probably move to the dynamic retrieval method, either for emissivity or skin temperature for Météo-France

- At ECMWF, the potential of satellite emissivities is also explored with ongoing studies.

The NWPSAF new web site based facility for infrared and microwave emissivity databases and models:

http://www.metoffice.gov.uk/research/interproj/nwpsaf/rtm/emissivity/index.htm