Evaluation and improvements of the microwave ocean surface emissivity model FASTEM

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A Reference Quality Model For Ocean Surface Emissivity And Backscatter From The Microwave To The Infrared

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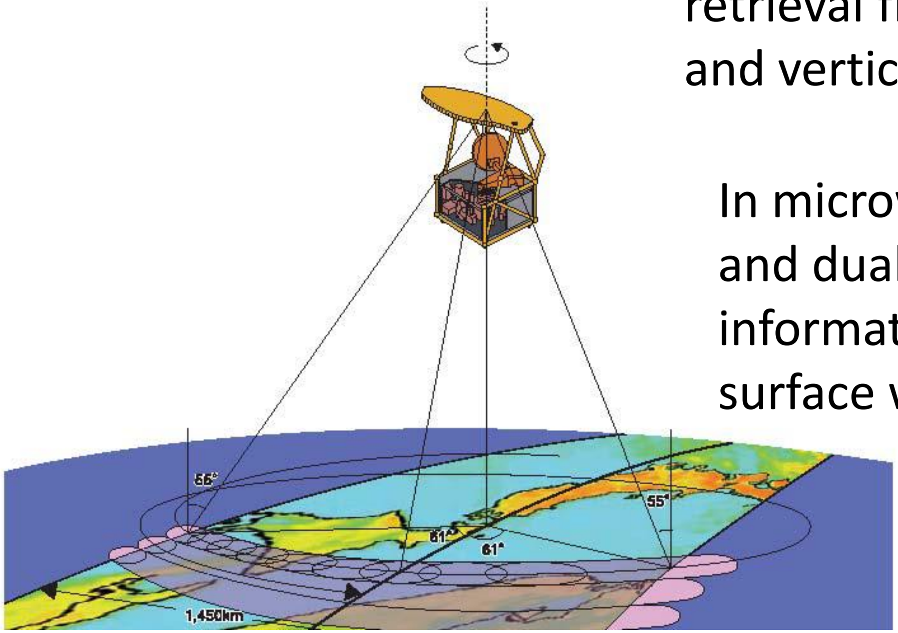
Conical scanning microwave imager

1. Fixed incidence angle (e.g. 55 degree) allows uniform observation during the scan.

2. Dual polarization measurement (V and H). Minimum incidence angle dependence in surface emissivity for vertically polarized channel (e.g. surface wind speed retrieval from a large differential between horizontally and vertically polarized signals for ocean case).

In microwave observations, low surface emissivity and dual polarization measurements can provide information on water vapor, cloud, rain, and surface wind over oceans.



GCOM-W/AMSR2 scanning geometry

Assimilation of microwave imager observation

- **Oceanic** microwave radiance data contain information on various geophysical parameters: **water vapor**, **atmospheric hydrometeors** and **ocean surface condition** (sea surface temperature, surface wind speed, salinity).

- Microwave imager observation are assimilated as brightness temperatures by means of **radiative transfer calculation.**

- The sensitivity needs to be included in the radiative transfer calculations in order to make consistent changes in initial states for NWP.

Microwave Ocean Emissivity Model (FASTEM)

- RTTOV(Fast radiative transfer model) uses FASTEM
  for the calculation of microwave ocean emissivity
  - **Specular Ocean surface emissivity**
    Largest part of ocean emissivity calculated by Fresnel Law, depend on frequency, incidence angle, SST, Salinity and the complex dielectric constant of sea water.
    - Dielectric constant (Permittivity) calculation is based on a double-debye formula. Coefficients are derived based on laboratory measurements.
  - **Small scale correction**
    Radiation from small scale (capillary) wave caused by wind
    Isotropic wind-induced emissivity
  - **Large scale correction**
    Radiation from large scale (swell) wave caused by wind
    - Corrections by foam cover (foam emissivity and foam coverage)
    - Correction on Downwelling atmospheric radiation

- Azimuthal component (**R**elative **W**ind **D**irection effect)
  - Dependence on wind direction relative to the sensor azimuthal look

History of FASTEM

FASTEM is a FAST microwave Emissivity Model used for satellite radiance assimilation. FASTEM is used in RTTOV and CRTM for ocean surface emissivity calculation

- **FASTEM-1** (English and Hewison, 1998)
  - Based on a geometric optics model simulation
- **FASTEM-2** (Deblonde and English 2001)
  - An updated version of FASTEM-1 and released in RTTOV-7
- **FASTEM-3** (Liu and Weng 2003)
  - <u>An azimuth variation model function</u> was introduced and released in RTTOV-8
- **FASTEM-4** (Liu et al., 2011)
  - Updated permittivity calculation, a new parameterizations of the roughness effect, foam parameterization and <u>a new azimuthal model function</u>, released in RTTOV-10
- **FASTEM-5**
  - Modified the large scale roughness and foam parameterization
- **FASTEM-6**
  - <u>Improved azimuth variation model function for V-pol. and H-pol.</u> (Kazumori and English 2015)

Components of ocean emissivity

$$\varepsilon = \varepsilon_0(\theta, T_s, S) + \Delta\varepsilon_{\mathrm{iso}}(\theta, W_s, F) + \underline{\Delta\varepsilon_{\mathrm{dir}}(W_s, \phi_R)}$$

$$\varepsilon_0(\theta, T_s, S)$$

The first term: Specular sea surface emissivity, This is dominant term of the ocean emissivity and depends on incidence angle, sea surface temperature, and salinity. The value can be theoretically calculated. (Fresnel formula)

$$\Delta\varepsilon_{\mathrm{iso}}(\theta, W_s, F) = (1-F)\Delta\varepsilon_{\mathrm{W}}(\theta, W_s) + F\Delta\varepsilon_{\mathrm{F}}(\theta, W_s)$$

The second term: Wave-induced isotropic emissivity. This term depends on sea surface wind speed, and fractional coverage of foam ***F***

This term contains the large scale and small scale wave contribution. The effects are parameterized with wind speed and incidence angle, and foam emissivity.

$$\Delta\varepsilon_{\mathrm{dir}}(W_s, \phi_R)$$

The third term: Wind directional dependent part of the emissivity. Asymmetric distribution of foam and small scale wave contribute this variation. The value can be parameterized with wind speed and relative wind direction.

Characteristics of oceanic microwave radiance

Measurements from Airborne Microwave Radiometer and Buoy

Ocean surface microwave radiations have surface wind directional signals.

The azimuthal variation should be considered correctly in radiative transfer calculation for geophysical parameter retrievals (TPW, SST etc.) and radiance assimilations.

Microwave radiances (brightness temperature) are assimilated for Numerical Prediction Model. However, the directional information are not used because of a lack of sensor azimuth angle information in real time data and insufficient modeling.

The variation of Tv and Th in terms of relative wind direction is expressed by harmonic cosine function.

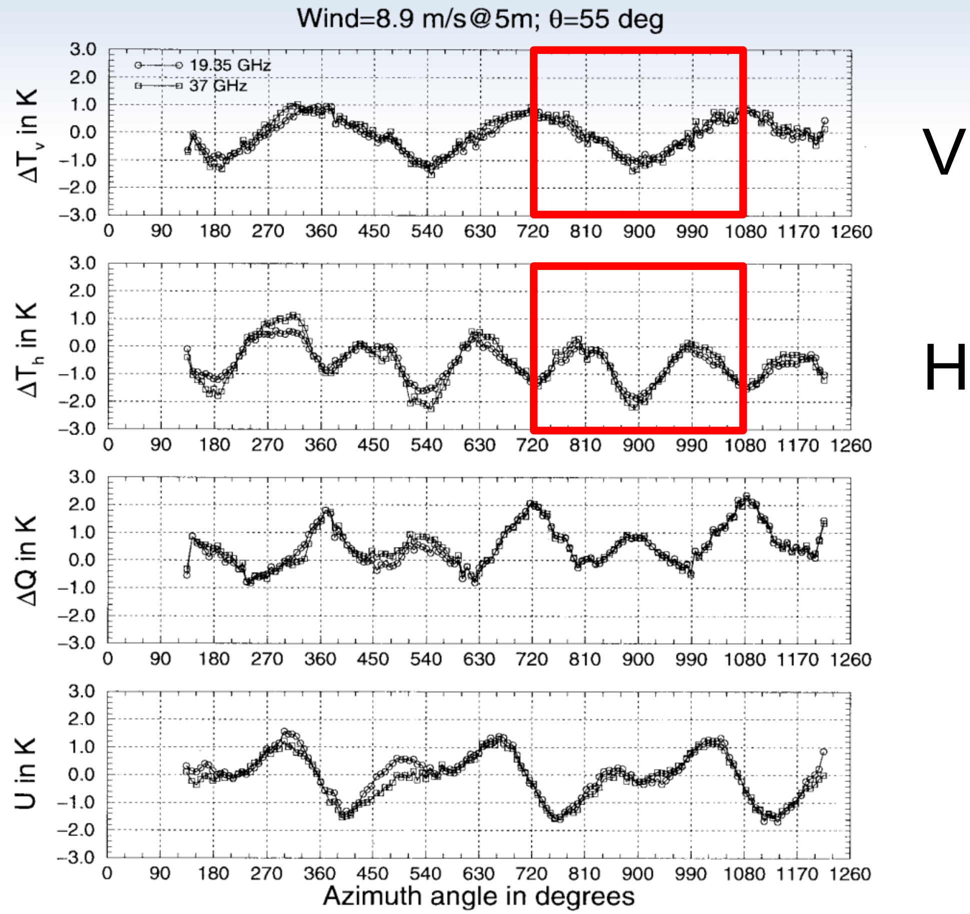
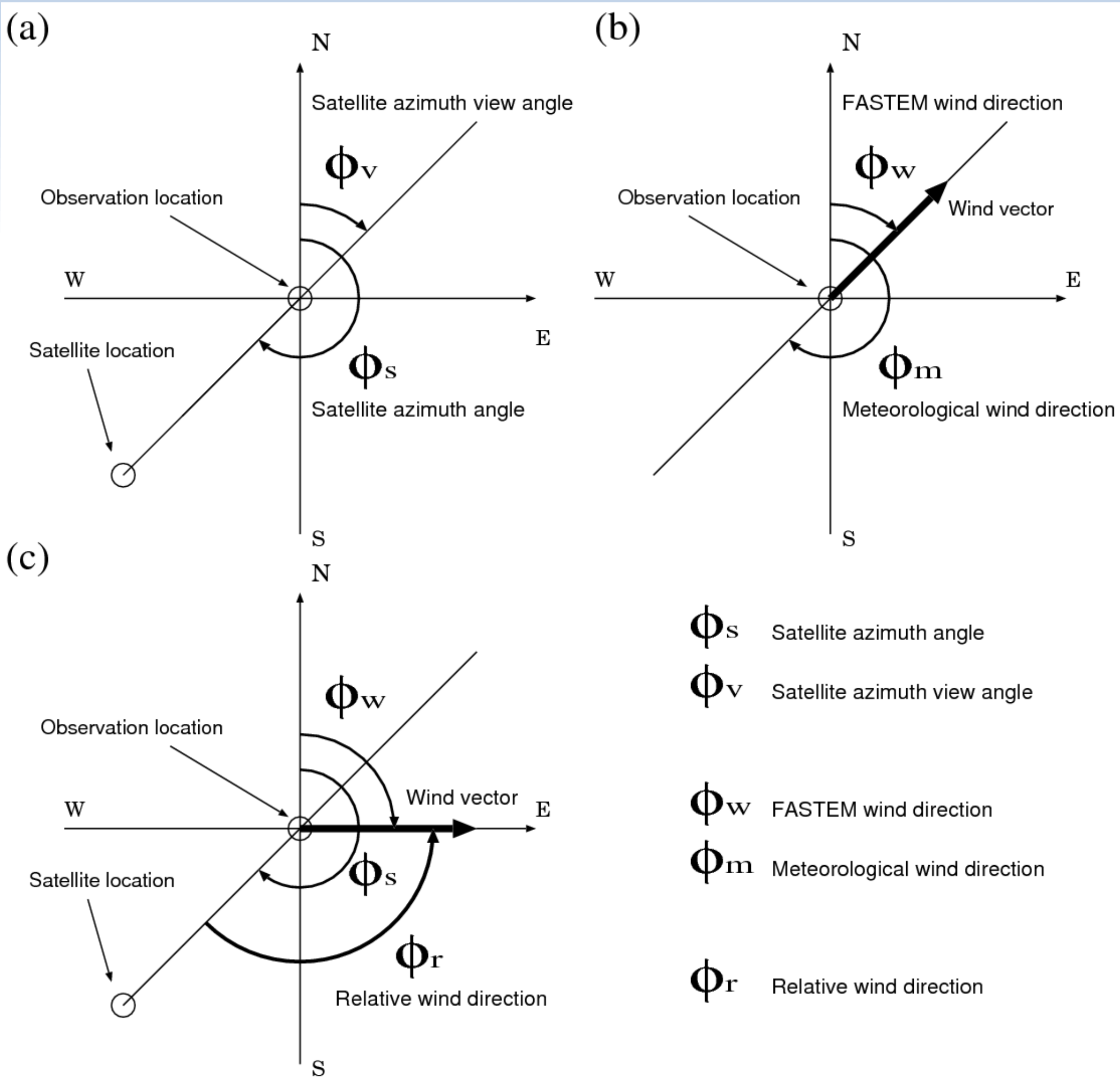


Fig. 2. Wind direction signals in polarimetric brightness temperatures of ocean surfaces acquired by JPL K- and Ka-band radiometers at 55° incidence angle. The data were acquired on 17 April, 1995, with NASA DC-8 flights over NDBC buoy 46005. The skies were mostly clear with some small scattered clouds. The buoy wind speed is 8.9 m·s^{-1} at 5 m elevation, which corresponds to 9.6 m·s^{-1} at 10 m elevation and 10.1 m·s^{-1} at 19.5 m elevation based on the correction of a boundary layer model [12]. For ease of comparison, T_v, T_h, and Q at 19.35 GHz have been offset by 187.5, 119.3, and 68.2 Kelvin, respectively, while those at 37 GHz have been offset by 203.9, 136.8, and 67.1 Kelvin.

Yueh, S. H., & Wilson, W. J. (1999)

Definitions of angles



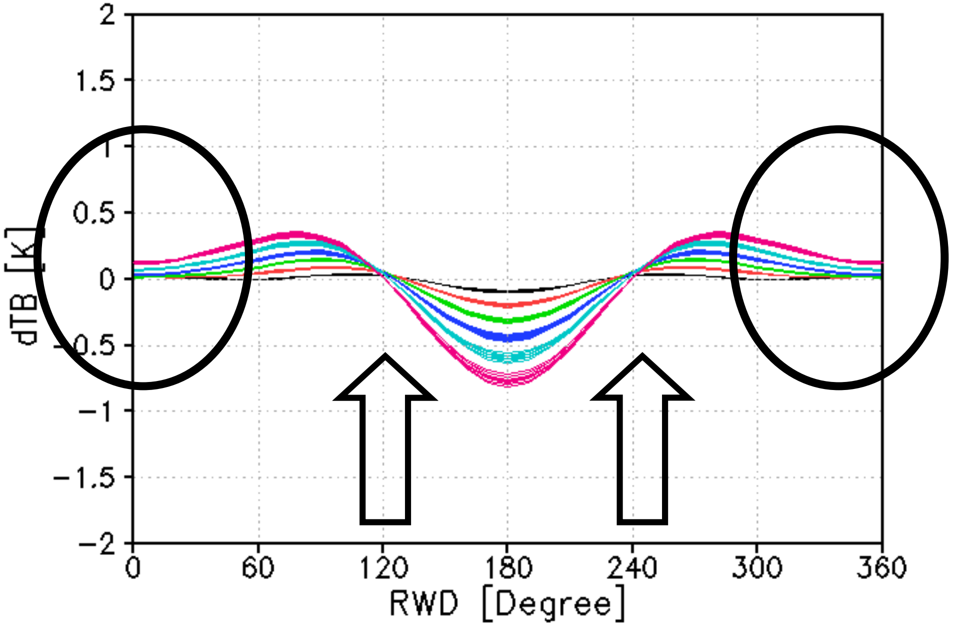
(a): Satellite azimuth view angle and Satellite azimuth angle.

(b): FASTEM wind direction and Meteorological wind direction.

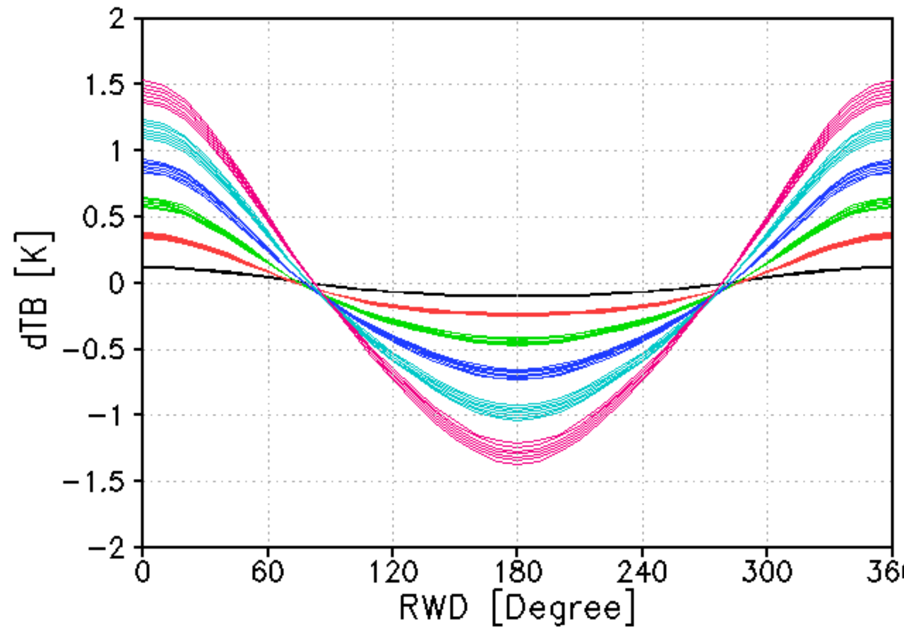
(c): Relative wind direction (westerly wind case). Wind vector is drawn in thick black arrow.

The Variations of Simulated Brightness Temperature 19 GHz V-pol. from FASTEM-5 and 3

FASTEM-5 RWD model function



FASTEM-3 RWD model function



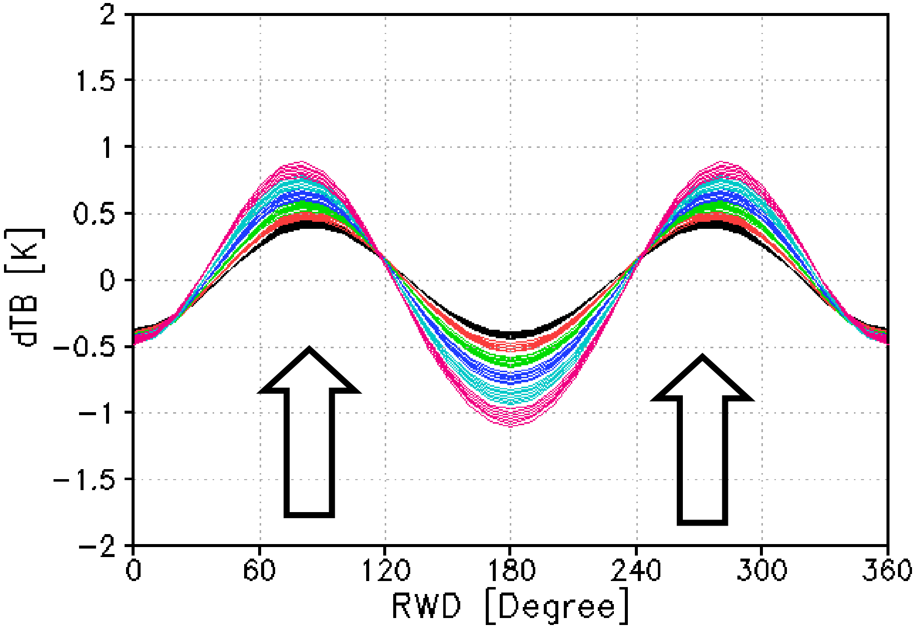
RTM: RTTOV-10.2, **Instrument:** AMSR-E
Input profile: US standard atmosphere (T,Q)
Wind Speed
Black: 3m/s Red: 6 m/s Green: 9 m/s Blue: 12 m/s
Light Blue: 15 m/s Pink: 18m/s
SST range: From 0 to 30 Celsius
RWD:
Relative Wind Direction is wind direction relative to sensor azimuth angle

dTB= TBsim – Ave(TBsim)

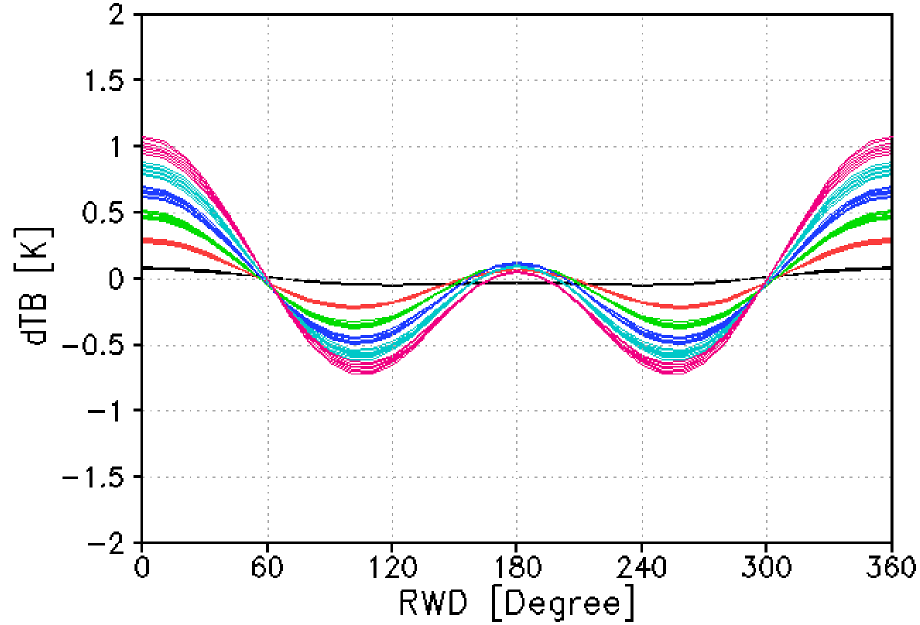
Unrealistic features
Behavior at RWD=0,360
Behavior at RWD=120,240
Magnitude of Amplitude

The Variations of Simulated Brightness Temperature 37 GHz H-pol. from FASTEM-5 and 3

FASTEM-5 RWD model function



FASTEM-3 RWD model function



RTM: RTTOV-10.2, **Instrument:** AMSR-E

Input profile: US standard atmosphere (T,Q)

Wind Speed

Black: 3m/s Red: 6 m/s Green: 9 m/s Blue: 12 m/s Light Blue: 15 m/s Pink: 18m/s

SST range: From 0 to 30 Celsius

RWD:
Relative Wind Direction is wind direction relative to sensor azimuth angle

dTB= TBsim – Ave(TBsim)

Unrealistic features

FASTEM5's Large sensitivity w.r.t RWD in low wind speed

Bugs in implementation of FASTEM3 RWD model into RTTOV?

Design of new RWD model

Emissivity variation with regard to RWD is modeled with a series of harmonic functions. This is normal approach adapted by many literatures.

$$E_i = E_{i0} + E_{i1} \cdot \cos(\varphi) + E_{i2} \cdot \cos(2\varphi) + \cdots$$

$$\boxed{\Delta E_i = E_i - E_{i0} = E_{i1} \cdot \cos(\varphi) + E_{i2} \cdot \cos(2\varphi) + \cdots \quad i = v \text{ or } h}$$

$$E_{i1} = E_{v1} = a_{v1}\left[\exp\left(-\alpha_v x^2\right) - 1\right]\left(b_{v1}x + c_{v1}x^2 + d_{v1}x^3\right)$$

x : wind speed

$$E_{i2} = E_{v2} = a_{v2}\, x$$

Dependency on incidence angle (Meissner 2012, Etkin 1991)

$$E_{i1} = E_{h1} = a_{h1}\, x$$

$$E_{i2} = E_{h2} = a_{h2}\left[\exp\left(-\alpha_h x^2\right) - 1\right]\left(b_{h2}x + c_{h2}x^2 + d_{h2}x^3\right)$$

$$\Delta T_{\mathrm{b}} = \beta_i \Delta E_i,$$
$$\beta_i = T_s e^{-\tau(0)\sec\theta}.$$

The coefficients (a, b, c, d, alpha) are derived for each channels. They were determined based on simultaneous measurements of radiance and surface wind speed by ADEOS-II (AMSR and SeaWinds) under clear-sky condition.

AMSR series

- **A**dvanced **M**icrowave **S**canning **R**adiometer (**AMSR**)

GCOM-W1/AMSR2
May, 2012 -

Aqua (US)/AMSR-E
May, 2002 - Oct, 2011

ADEOS-II/AMSR
Dec, 2002 - Oct, 2003

Simultaneous measurement of SeaWinds surface wind data are available

Determination of coefficients

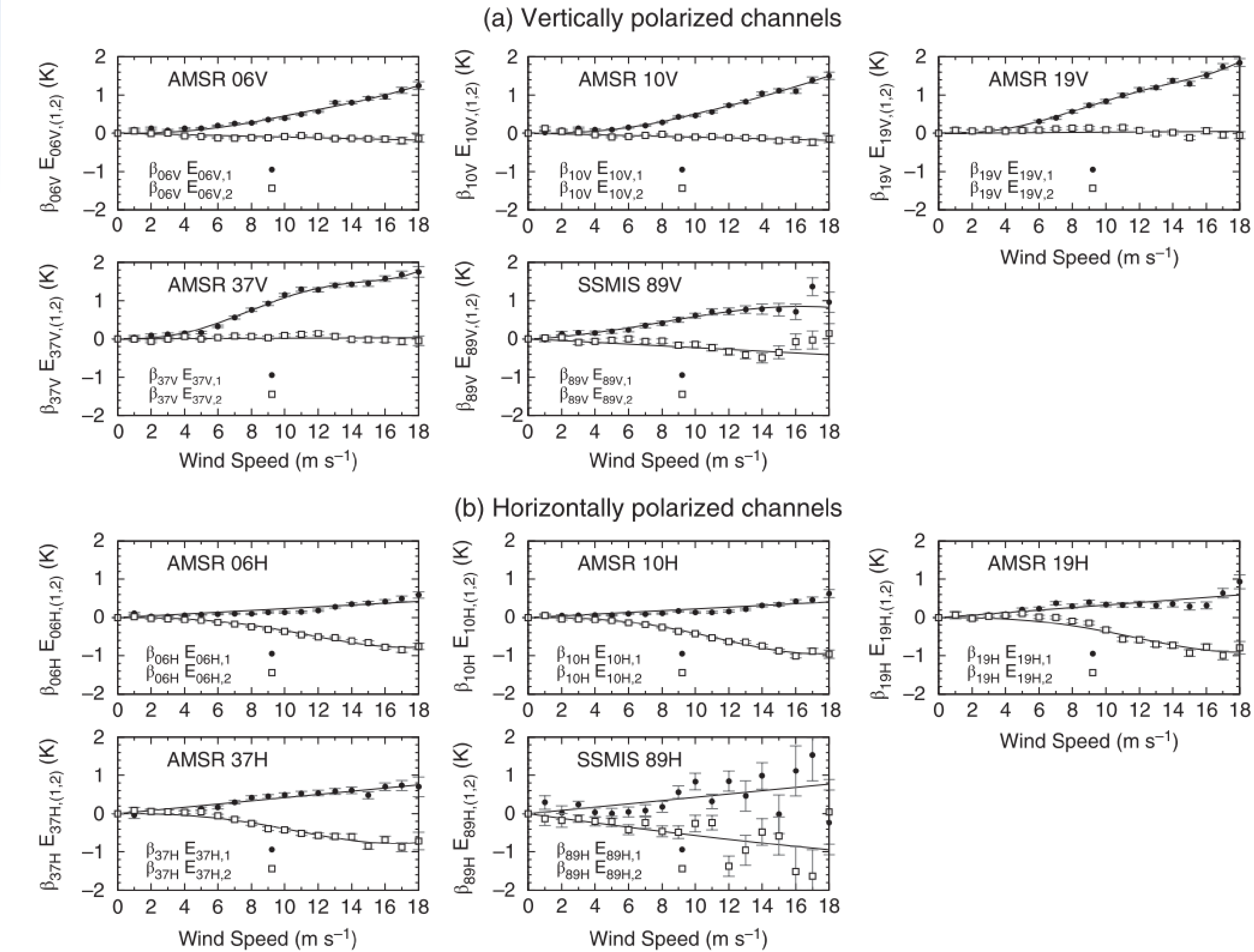
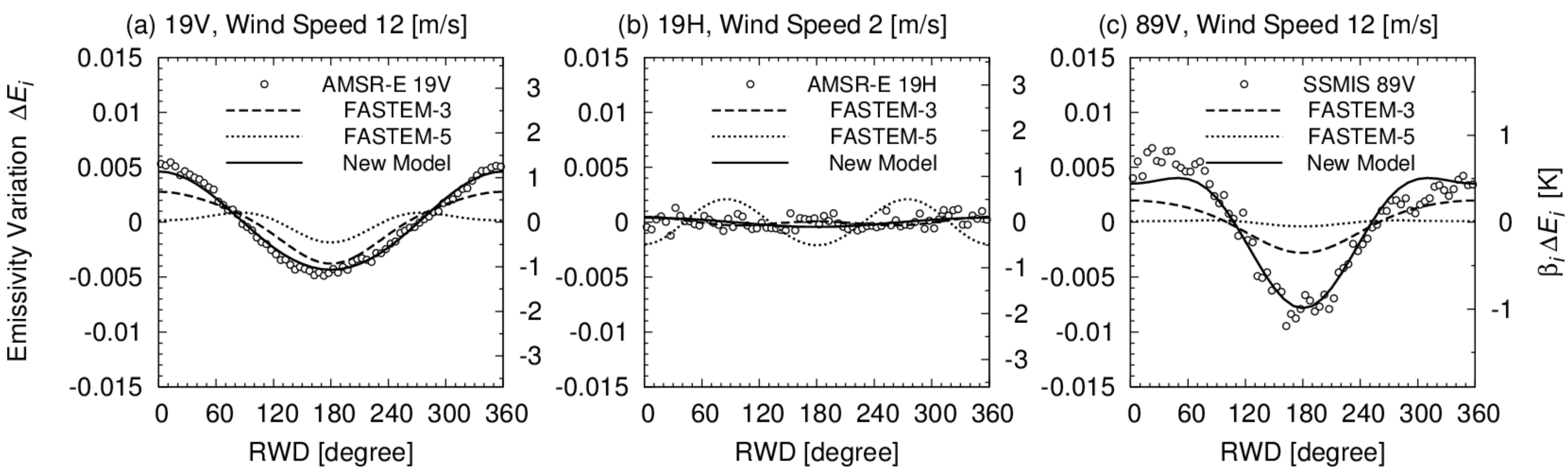


Figure 3. The amplitude of the harmonic cosine functions from the azimuthal variation. Black filled circles are the first harmonic term E_{i1} and white squares are the second harmonic term E_{i2} in Eq. (1). (a) Fitted functions for vertical channels in terms of wind speed with solid curves (Eqs (2) and (3)). (b) Same as (a) but for horizontal channels with solid curves (Eqs (4) and (5)). 06V, 06H, 10V, 10H, 19V, 19H, 37V, 37H are AMSR results and 89V and 89H are F17 SSMIS results.

Comparison between model and observation

FASTEM-3
FASTEM-5
New Model

Satellite Observation



New Model can represent RWD dependence **in high wind speed condition**

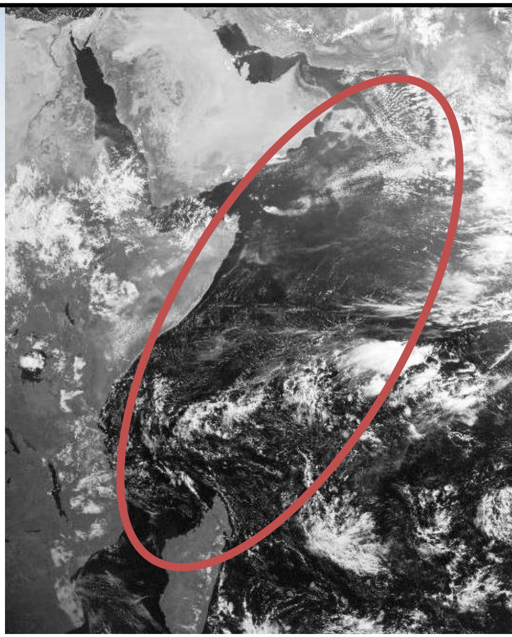
New Model can represent **no wind speed dependence in low wind speed condition**

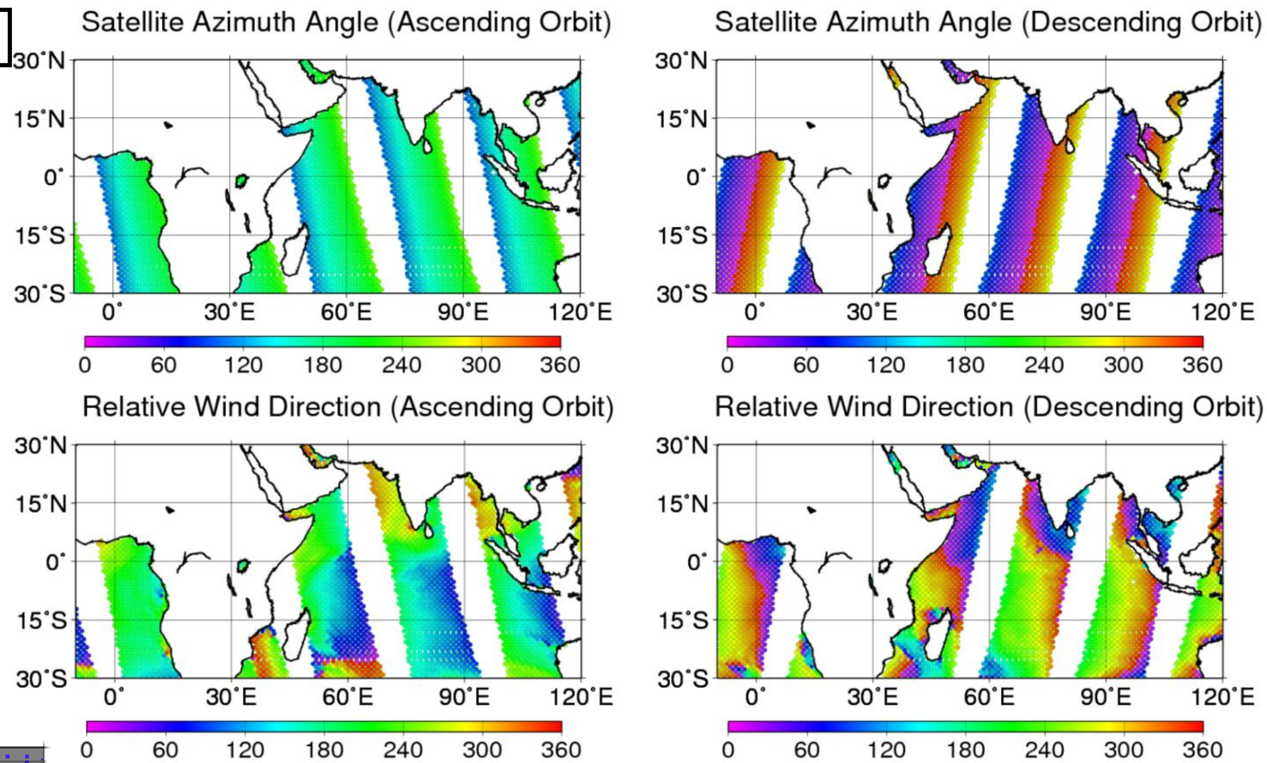
New Model can represent RWD dependence **in high frequency channels**

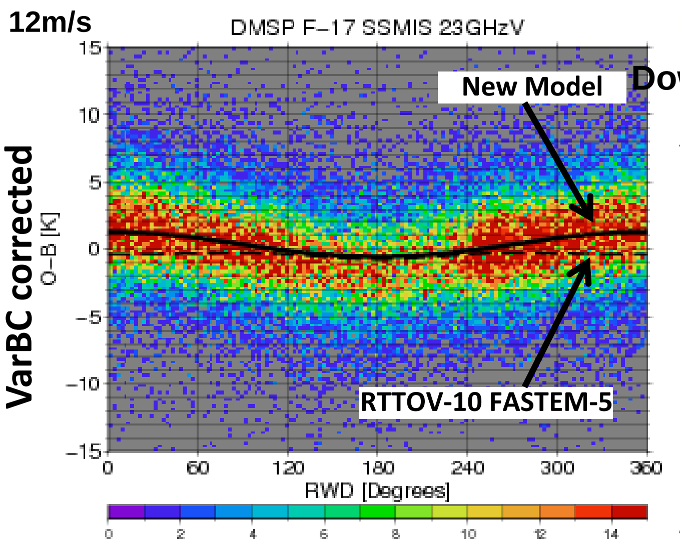
New Model represents much realistic RWD dependence than previous FASTEM

Somali Jet: Strong southwesterly wind (>12m/s) in Arabian Sea

Meteosat Image 06UTC 1 July 2013







Ocean surface radiations have surface wind directional signals. The variation of T_v and T_h in terms of **R**elative **W**ind **D**irection (**RWD**) is expressed by harmonic cosine function. The RWD variation should be considered correctly in radiative transfer calculation for the radiance assimilation.

However, the directional information are not used because of a lack of sensor azimuth angle information.

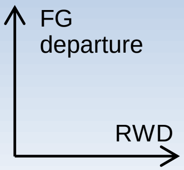
A new emissivity model (RWD model) was developed based on simultaneous measurements of radiance and wind vector from ADEOS-II (AMSR & Seawinds).

Impact study with ECMWF IFS system

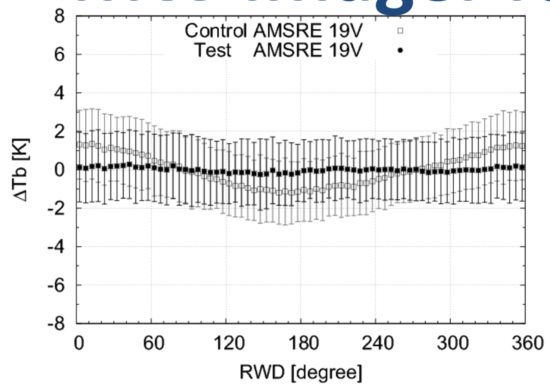
Assimilation Experiment

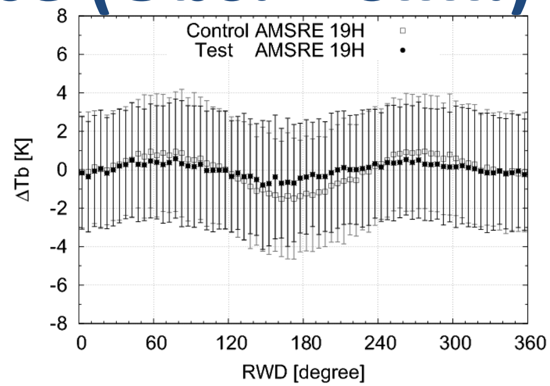
- **Purpose:**
  - Investigation of the impact of the new RWD model. The new model changes simulated brightness temperature
    - AMSU-A, MHS, ATMS, SSMIS, TMI and AMSR-E
- **Experiment Setting**
  - Control : CY38R2 T511
  - Test : Modified FASTEM5 (NEW RWD MDL introduced)
    - <u>No change in QC</u>
- **Experiment Period**
  - June 20 – Oct 03, 2011 (AMSR-E, SSMIS, TMI are available)

Comparison of FG departures of assimilated MW imager radiance (Obs. – Sim.)



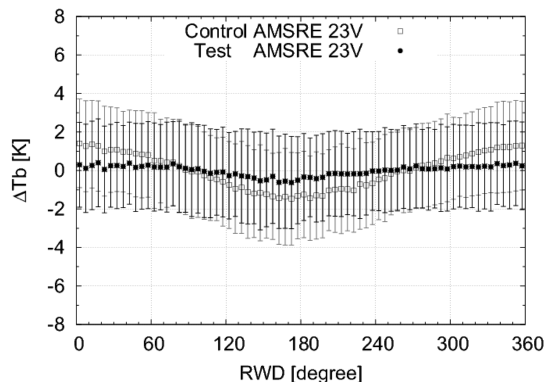
AMSRE
19V

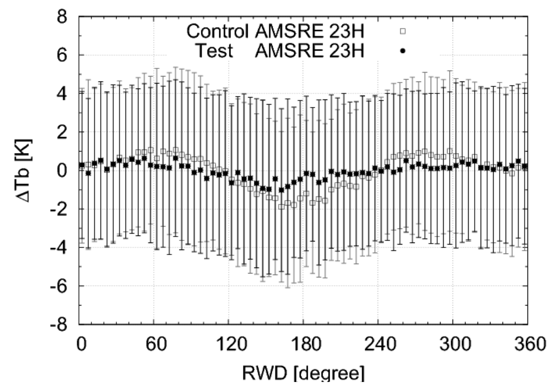




AMSRE
19H

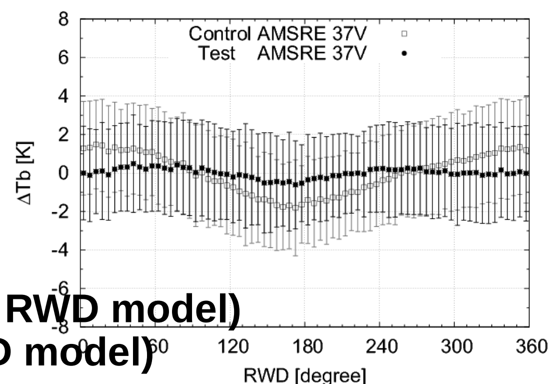
AMSRE
23V

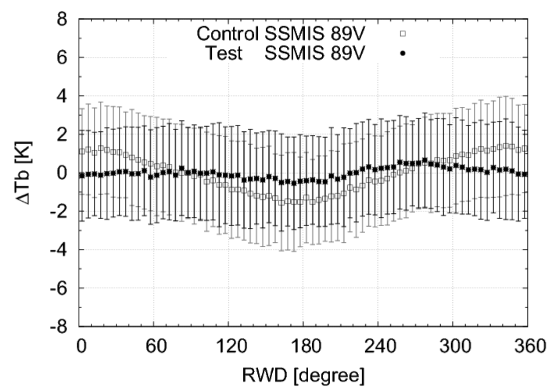




AMSRE
23H

AMSRE
37V





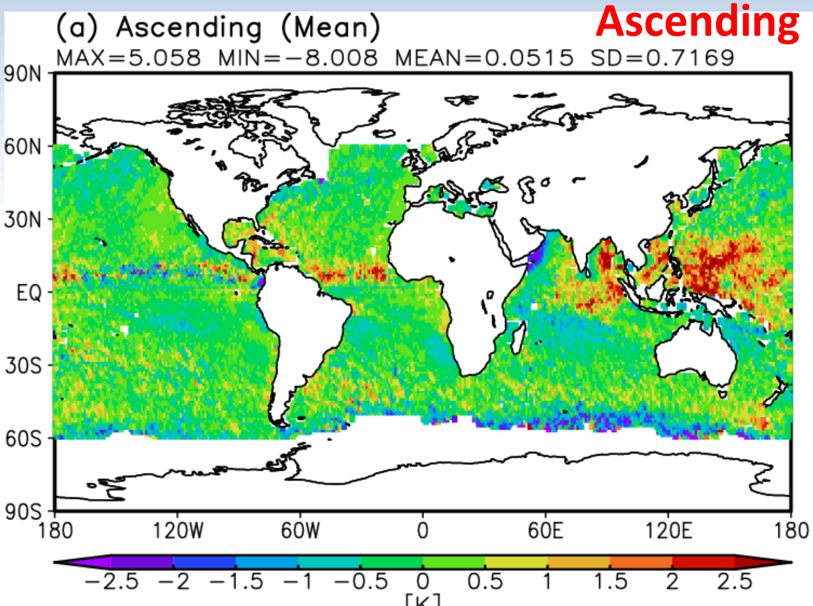
SSMISS
89V

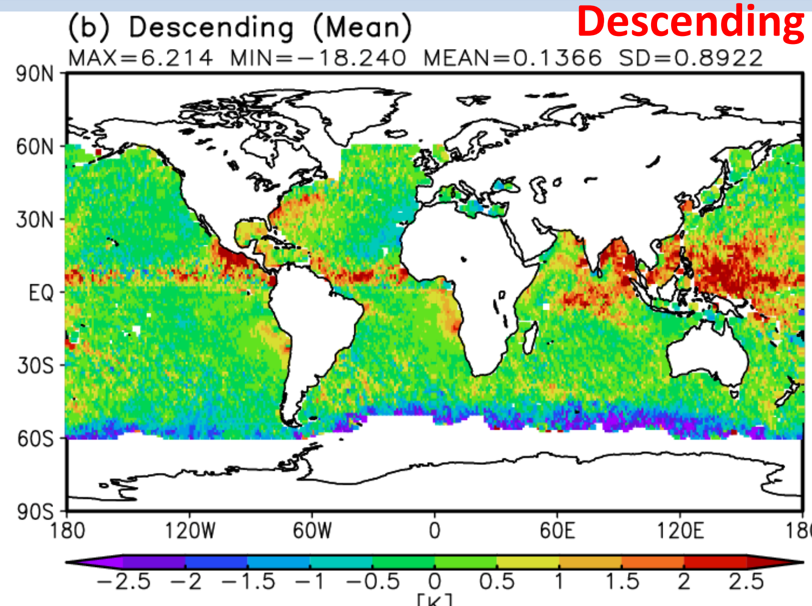
□Control (wo RWD model)
●Test (w RWD model)
SSW 12 m/s case

Mean FG departure (O-B) distribution(all-sky case)

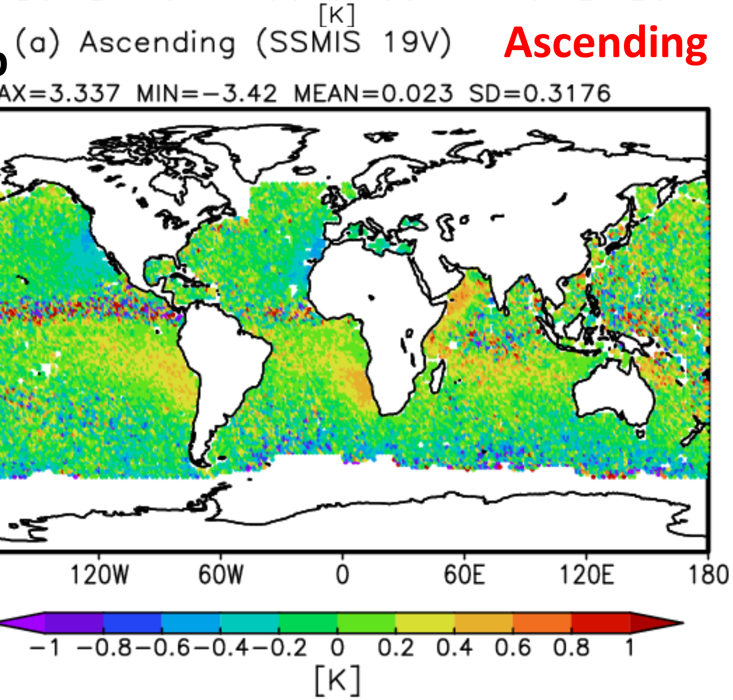
SSMIS 19V Period: Jun. 20～Oct. 3, 2013

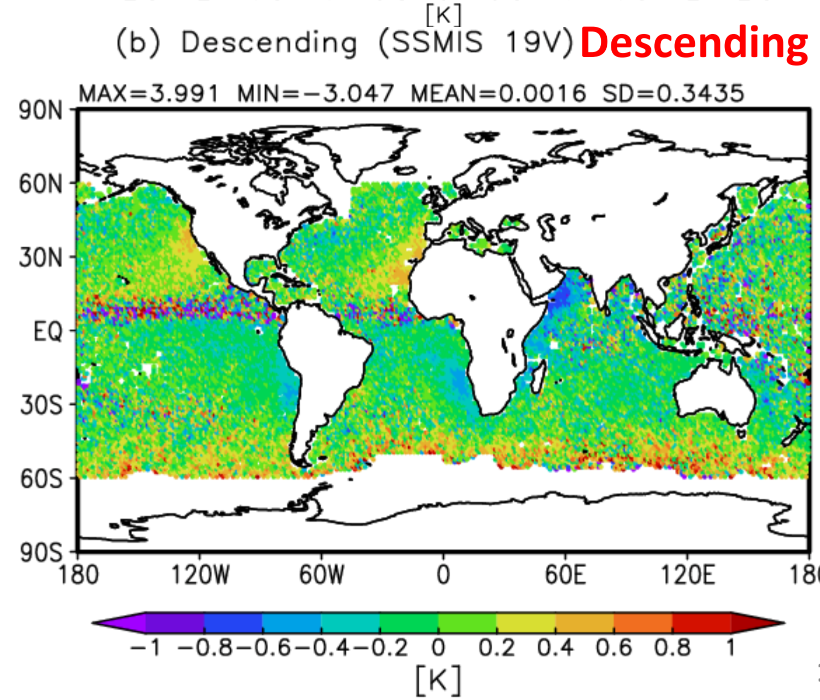
O-B BIAS





Diff. Simulated Tb





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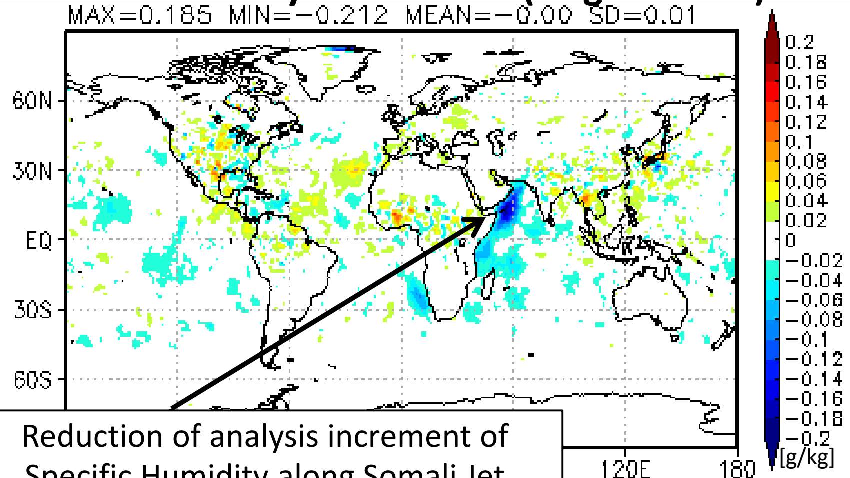
The impact of RWD model function

Analysis Increment of Specific Humidity and RMS error of RH and T forecast

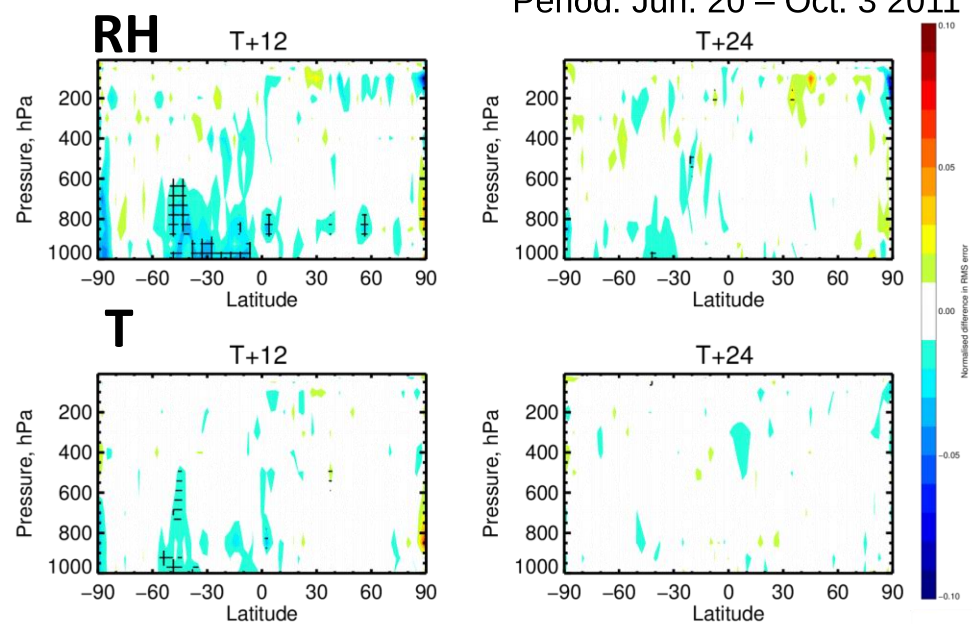
RMS difference Analysis Increment of Specific Humidity at 1000hPa (August 2011)



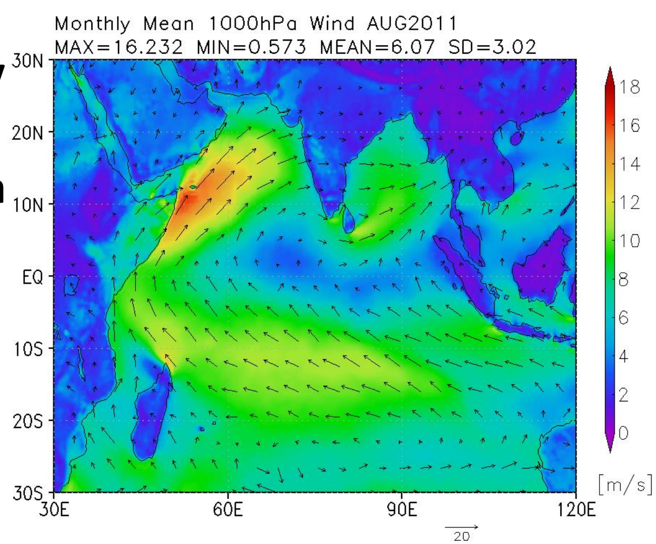
Reduction of analysis increment of Specific Humidity along Somali Jet

Normalized difference in RMS error of forecasts (against own analysis)

Period: Jun. 20 – Oct. 3 2011



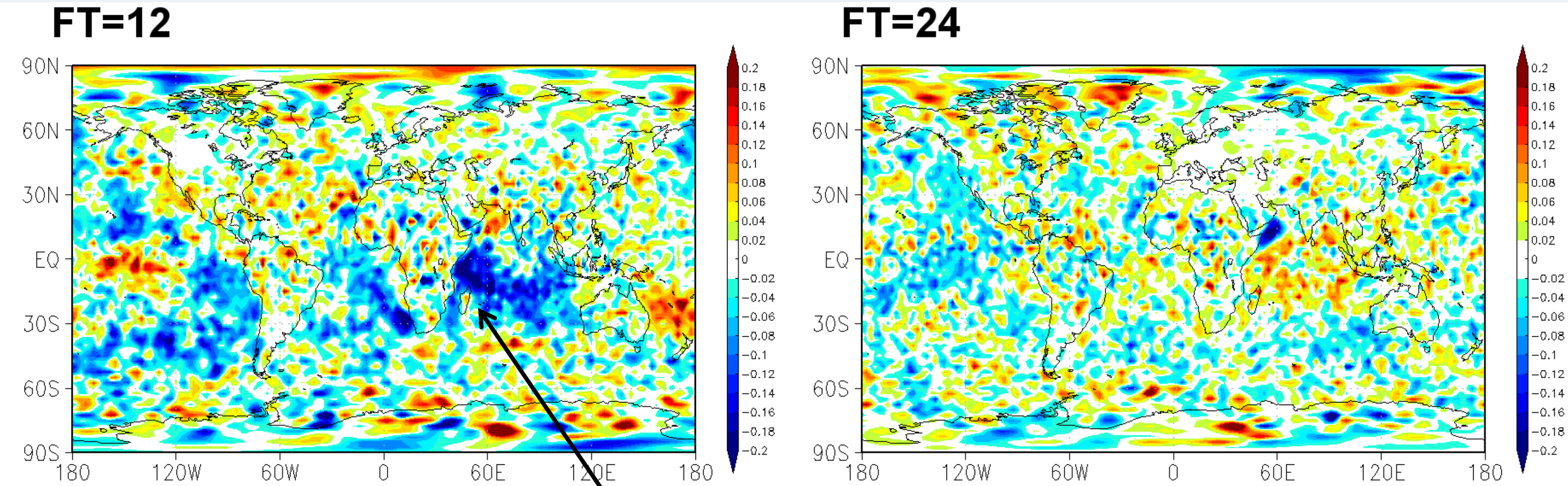
Monthly Mean 1000hPa wind speed



The use of surface wind directional signals with RWD model reduced RH and T forecast errors significantly.

Difference of RMS error of RH forecast

1000hPa

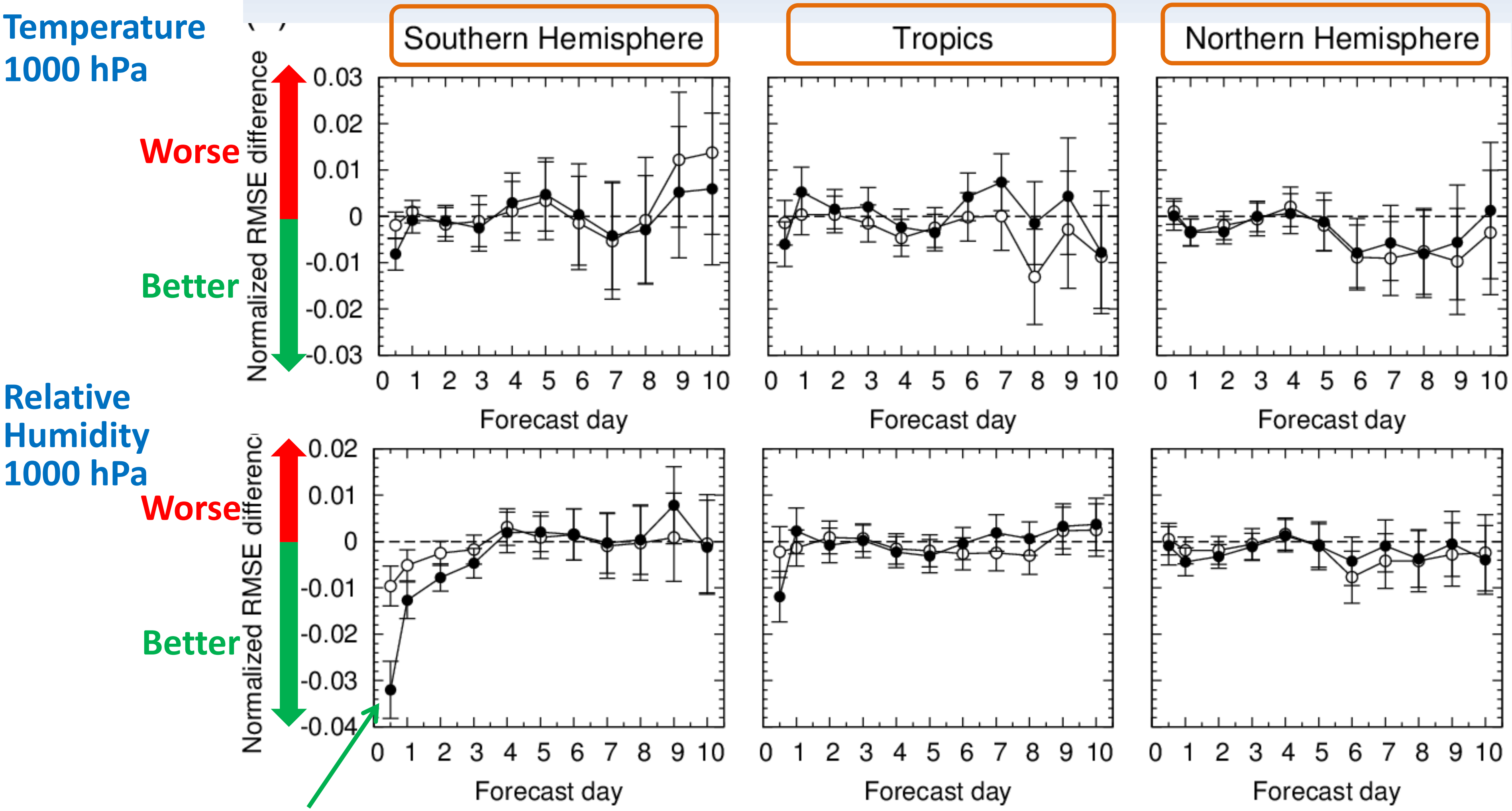


The use of surface wind directional signals with RWD model reduced RH forecast errors for high wind speed areas significantly.

Impact on temperature, relative humidity forecasts

○ FASTEM-5's RWD model
● NEW RWD model

Reference: own analysis



3 % error reduction in short range RH forecast in SH with NEW RWD model

Summary

- **A new RWD model for ocean emissivity (V-pol. and H-pol.) was developed** for microwave imager radiance assimilation
- The new RWD was developed based on simultaneous measurements of surface wind vector (SeaWinds) and microwave radiance (AMSR) of ADEOS-II.
- **The new RWD model can represent the ocean emissivity variation of RWD dependency under high wind speed conditions.**
- Use of the new RWD model reduced biases in FG departure of microwave imagers in high wind speed condition
  - The RWD model has better performance than FASTEM-5 RWD model
  - Results of the impact study (Period: 20 June to 3 Oct. 2011)
    - Reductions of analysis increment of specific humidity were found in high wind speed and low wind direction variability areas (Arabian sea in boreal summer).
    - In short range forecasts, reductions of RMS errors of RH and T fields in lower troposphere were significant.
- **Inclusion of the azimuth variation in the ocean emissivity modeling improved the analysis and forecast accuracy in ECMWF system.**
- The new RWD model function is incorporated in **FASTEM-6**.

Thank you for your attention.

Reference:

M. Kazumori and S. J. English, Use of the ocean surface wind direction signal in microwave radiance assimilation, *Quarterly Journal of the Royal Meteorological Society*, Vol. **141**, Issue 689, 1354 – 1375, 2015.