Perspective on all-sky radiance assimilation over land in the FV3GFS

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OUTLINE

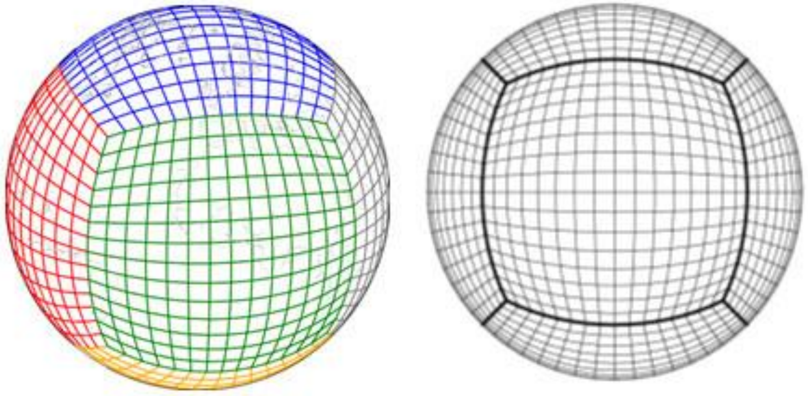
- Challenges in radiance assimilation over land
- Approaches to all-sky radiance assimilation over land in the FV3GFS
- Preliminary results on emissivity retrievals from the GSI

FV3GFS hybrid 4DEnVar data assimilation system

$$J(\mathbf{x}'_c,\mathbf{a}) = b_c \frac{1}{2}(\mathbf{x}'_c)^T \mathbf{B}_c^{-1}(\mathbf{x}'_c) + b_e \frac{1}{2}\mathbf{a}^T \mathbf{L}^{-1}\mathbf{a} + \frac{1}{2}\sum_{k=1}^{K}(\mathbf{H}_k \mathbf{x}'_{(t)k} - \mathbf{y}'_k)^T \mathbf{R}_k^{-1}(\mathbf{H}_k \mathbf{x}'_{(t)k} - \mathbf{y}')$$

$$\mathbf{z} = \mathbf{B}^{-1}\mathbf{x}'_c \qquad \mathbf{v} = \mathbf{L}^{-1}\mathbf{a}$$

- FV3 dynamic core, cubed-sphere grid, non-hydrostatic option, GFDL microphysics,
- C768 (~13km) L64 (55km top)
- Stochastic physics *SPPT+SHUM only*
- Ensemble and increment resolution have been increased to ~25 km (currently ~39km), 80 ensemble members



Courtesy of GFDL

Status of radiance data assimilation in the FV3GFS

Currently assimilated radiance observations:

Microwave:

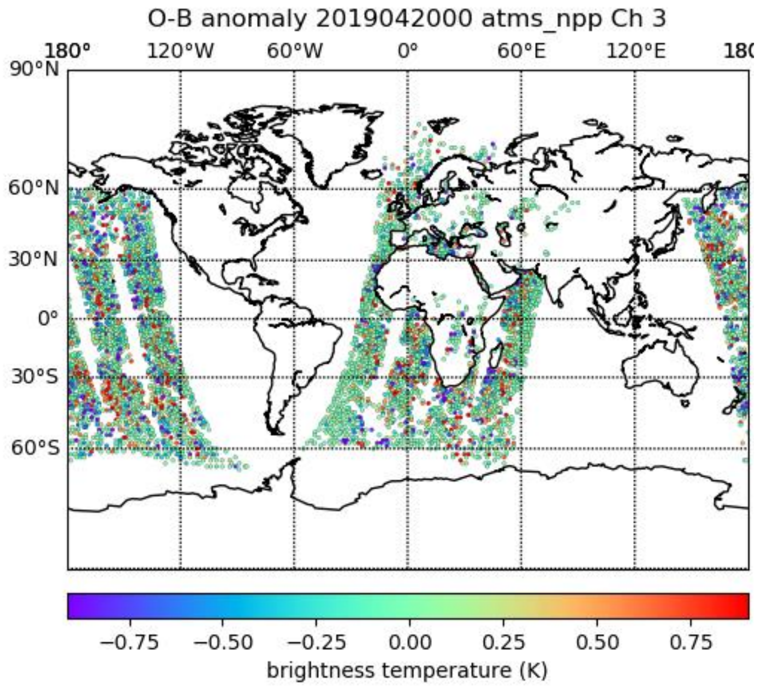
- AMSU-A: NOAA-15, 18, 19, MetOp-A, MetOp-B, Aqua
- ATMS: NPP, NOAA-20
- MHS: NOAA-18, 19, MetOp-A, MetOp-B
- SSMIS: DSMP-F17
- SAPHIRE: Megha-Tropique

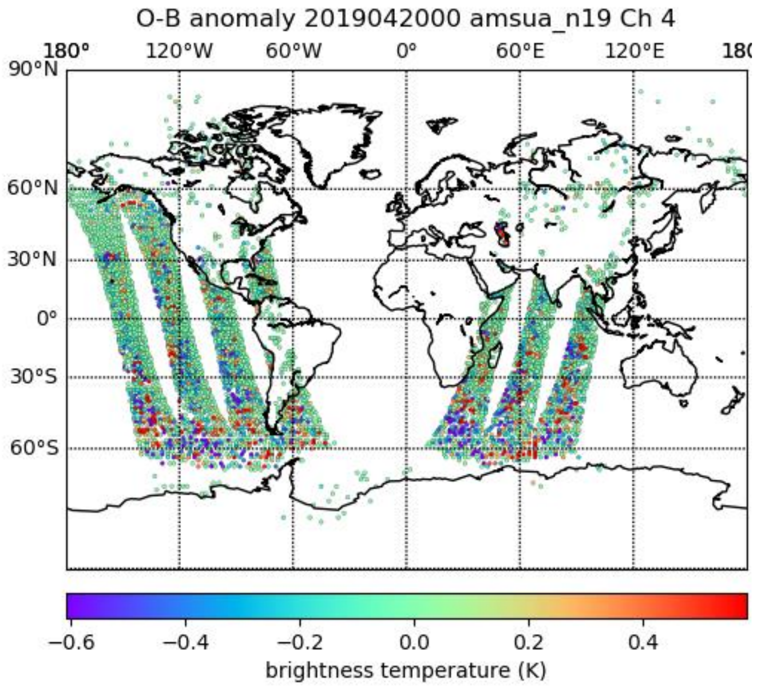
Infrared:

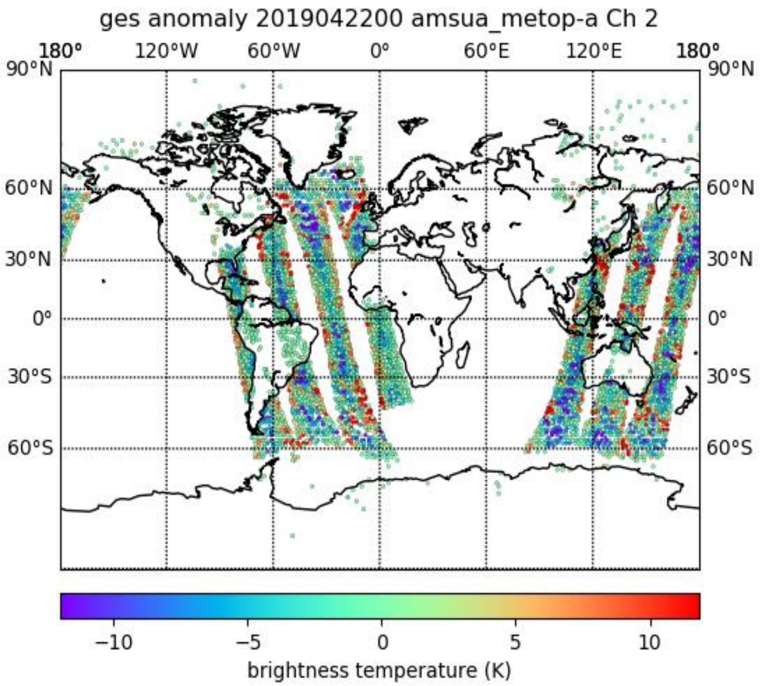
- AIRS: Aqua
- GOES-15 Sounder
- IASI: MetOp-A, MetOp-B
- CrIS: NPP, NOAA-20
- SEVIRI: MeteoSat-8, 11
- AVHRR: MetOp-A, NOAA-18

- ❑ Both clear-sky and cloudy radiances from AMSU-A and ATMS over ocean FOVs are assimilated in the **all-sky** approach (Zhu et al. 2016; Zhu et al. 2019)
- ❑ Only clear-sky radiances are assimilated from other sensors and over land

Operational GDAS Radiance Monitoring: NPP ATMS, NOAA-19 AMSU-A, METOP-A MHS







- Large amount of radiance data are used over ocean
- Far fewer radiances are used over land, and only clear-sky radiances are used

Challenges in assimilating radiances from surface-sensitive channels over land

- The uncertainty in simulating microwave land emissivity is still a major obstacle that affects uses of satellite data over land. Various techniques:
  - Retrieve the microwave emissivity directly from observations with auxiliary data (Prigent et al 2006; Karbou et al 2005, 2010; Baordo and Geer 2016)
  - 1DVAR retrieval, e.g. MiRS developed at NESDIS
  - Surface emissivity models developed over a variety of land surface conditions. Highly complex land emissivity calculation due to additional surface factors
    - NESDIS microwave land physical emissivity model (Weng et al 2001; Chen and Weng 2015; etc)

NESDIS_MWLand_V1
Two-stream isothermal three-layer (Air-Canopy-Soil) RT model structure *(Weng et al, 2001)*
Leaf & Canopy optical property model of parallel stacked-leaves *(Wegmuller et al., 1995)*
Single-layer Fresnel soil emission
Soil surface roughness model *(Choudhury et al., 1979)*
Soil dielectric model *(Dobson, 1985)*
No TL & AD models
19 ~ 89 GHz

Courtesy of Ming Chen

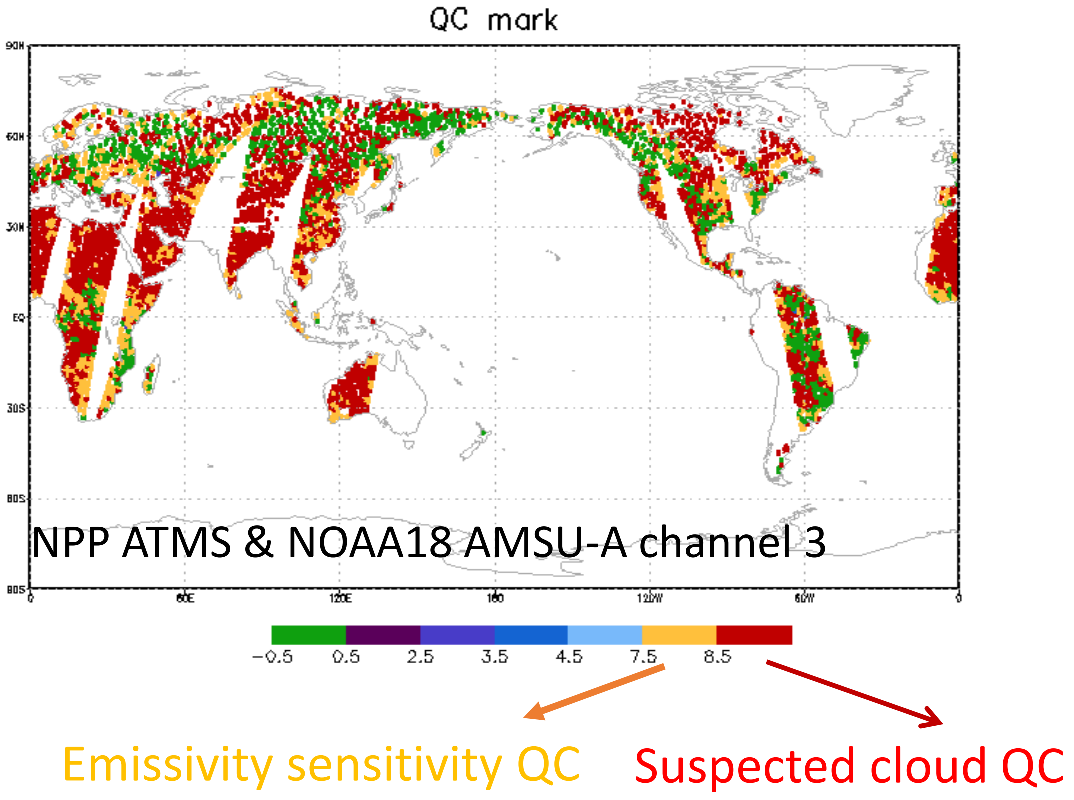
- **Land surface model component in the forecast model: Uncertainties of land surface properties, e.g. land surface skin temperature (LST) and soil moisture**
  - Surface soil moisture is one of the key factors that affect the emissive and scattering characteristics of the soil surface. Precipitation can change soil moisture/land surface emissivity significantly
  - LST is also affected by land surface variability, e.g. soil moisture, roughness, wetness

Challenges in assimilating radiances from surface-sensitive channels over land (continued)

- ❑ Cloud detection is problematic over land. Extension of all-sky approach to radiances over land

Currently only clear-sky radiances are assimilated over land, large amount of radiances are rejected

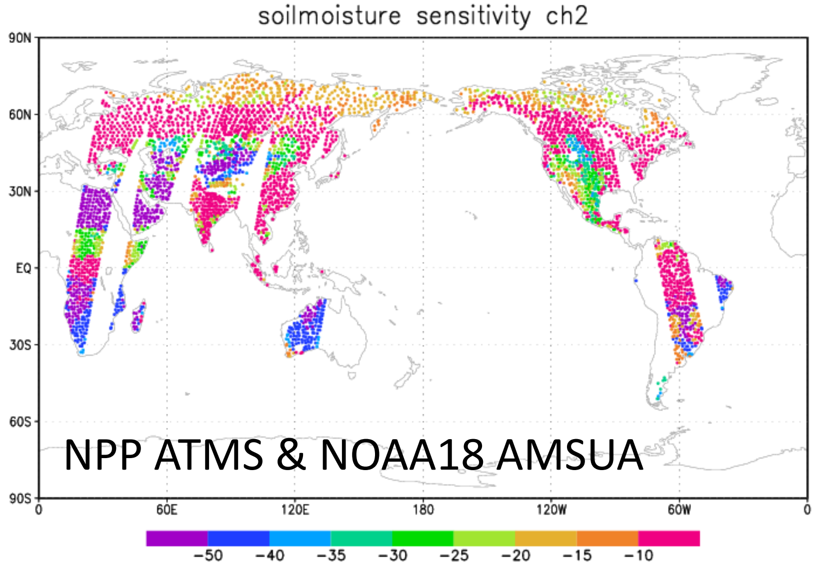
- Emissivity sensitivity check
  - if |OmF|/(emissivity jacobian) > threshold for 23.8, 31.4, 50.3, and 89.0 GHz, reject the radiance
- Suspected cloud contamination: Obs are compared with the equivalent clear-sky TBs
  - $factch4 = 0.6^2 + [OmF(52.8GHz)/1.8\,]^2$
  - $factch6 = 0.8^2 + [OmF(54.4GHz)/0.8]^2$
  - if (factch6 > 1.0) or (factch4>0.5), e.g. |OmF(52.8GHz)|>0.67K or |OmF(54.4GHz)|>0.48K, Reject the radiance

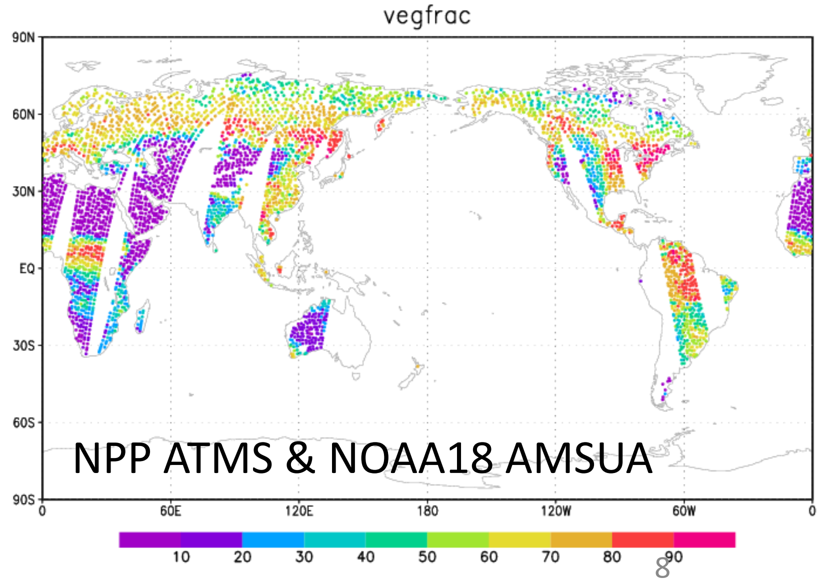


- Over land, the clear-sky surface emission is typically very similar to the cloud emission, making this type of cloud detection problematic
- Collocated VIIRS cloud product (Wolf & Heidinger's groups) may help cloud detection
- **All-sky radiance assimilation over land**

Two approaches for dynamically varying land surface emissivity will be developed and compared at EMC

- **Intermediate goal**: Real-time analytical emissivity retrieval combined with TELSEM atlas (with or w/o filter update)
  - help Community Surface Emissivity Model (CSEM) developer to improve CSEM climatology
- **Long-term goal**: with the improved CSEM, soil moisture and LST analyses using radiances from low-frequency (e.g.L-band) microwave satellite sensors, such as AMSR2, SMOS, GMI
  - Near-surface temperature and humidity observations, currently not assimilated in FV3GFS, will help to constrain radiance assimilation
  - Radiance observations involve variables from more than one components: both atmosphere and land data assimilations. Coupled data assimilation (Kleist 2019, personal communication)
    - Research on the coupling strategies: weakly or strongly coupled, with coupled background error covariances
    - The uncertainties of each component
    - How to handle different spatial and temporal scales from different components

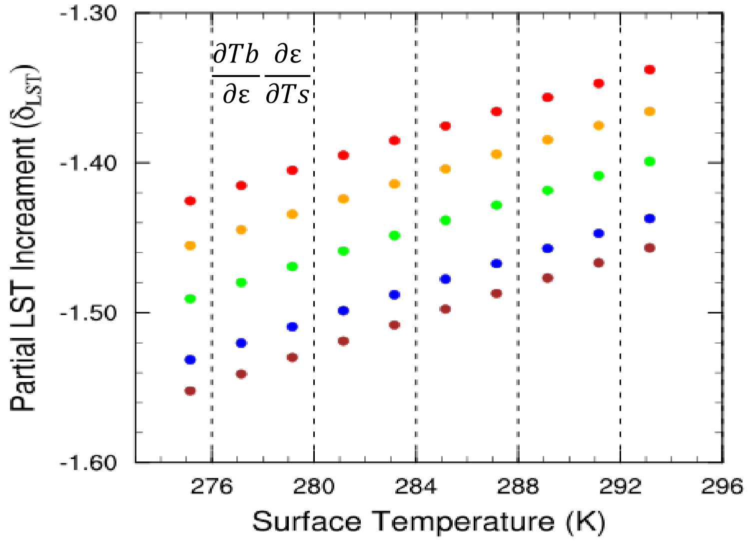


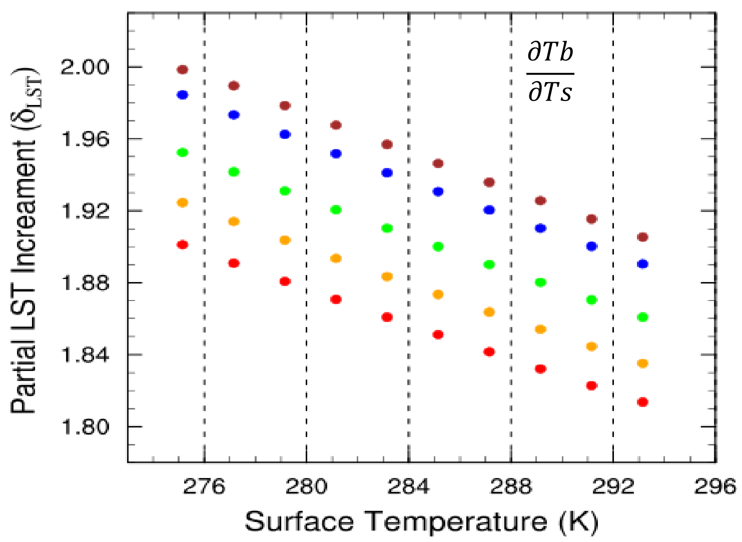


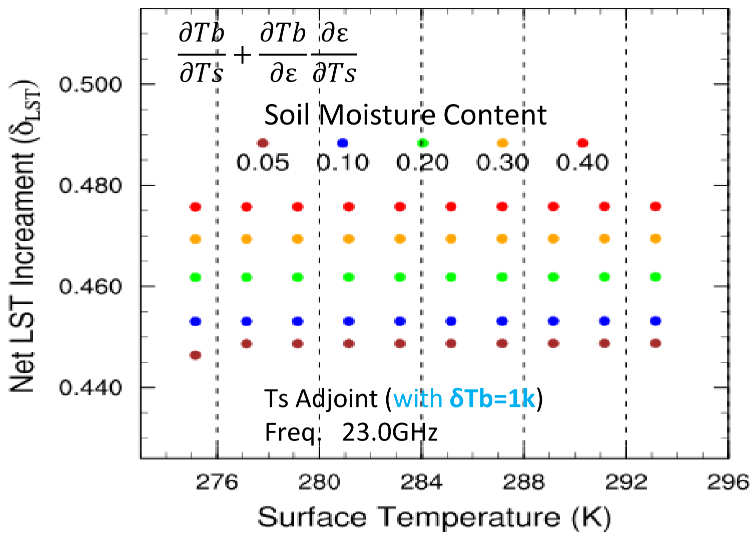
Other efforts are also underway at JCSDA/NESDIS (Biljana)

- A parameter β is applied to TELSEM2 emissivity values (β is a control variable)
- Future plan: MIRS retrieval of emissivity

Sensitivity to land surface skin temperature (Chen 2018)







Tb = ε●Ts

ε = ε(**Ts, SMC, VFR**…)

$$\frac{\delta Tb}{\delta Ts}=\frac{\partial Tb}{\partial Ts}+\frac{\partial Tb}{\partial \varepsilon}\frac{\partial \varepsilon}{\partial Ts}$$

If Emissivity is used as an independent control variable, the property of the adjoint (K-matrix) will be different from the truth, which will direct the optimization algorithm of the cost function in a somewhat wrong way, resulting in a misleading Ts analysis increment.

All-sky radiance assimilation over land in FV3GFS: clear-sky, cloudy and precipitating scenes

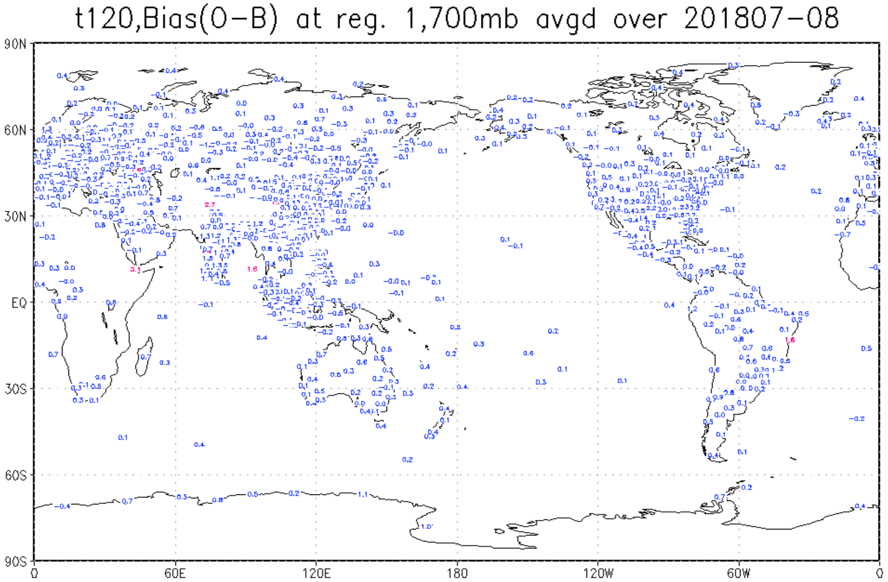
- Radiative transfer model: CRTM 2.3.0 released in 2017
- Simulated radiance and quality control: Assess and select effective cloud fraction scheme for radiances over land along with the bulk optical properties for hydrometeors, globally across all microwave frequencies in all weather conditions
  - Assess and choose from available LUTs. LUTs from several studies on improving precipitating hydrometeor scattering properties over ocean by modelling frozen particles as non-spherical particles (Stegmann et al 2018; Sieron et al 2018; Kim et al 2019; etc)
  - The presence of model error, especially displacement and phase errors of clouds, may compensate the errors from the CRTM, thus leading to different choice of a particle model.
- Observation error model:
  - A function of a symmetric cloud amount (given by the average of observed and simulated) is commonly used in the all-sky work (Geer and Bauer 2011)
  - Situation-dependent observation error inflation (SDOEI) to handle large cloud discrepancies and mislocations between observations and first guess (Zhu et al 2016)
  - Application of variational quality control (Purser 2018) along with SDOEI
- Land surface emissivity retrieval, or soil moisture & LST analyses. (See slide 7)
- Changes in the bias correction: more radiances assimilated over land will make the bias correction more reliable and robust
- The assimilation of near-surface conventional T and q observations, e.g. METAR data, which are not used in the GFS, can provide important constraint and information to the radiance assimilation.

Impact on radiance bias correction

In the GSI, Variational bias correction framework (Derber and Wu 1998; Zhu et al 2014)

$$\tilde{h}\,(x, \beta) = h(x, \beta) + \sum_{i=1}^{N} \beta_i\, p_i(x)$$

- Radiance bias can be much larger than signal
- Interaction between bias correction and quality control
- Radiance data sample used in radiance bias estimation – avoid OmFs with large forecast model bias
- Bias predictors p_i applied globally: constant, quadratic form of tlap, fourth order polynomial of scan angle
- Bias predictor only applied to radiances over land: emissivity sensitivity



Courtesy of Xiujuan Su

- Radiances over ocean dominate the bias term estimates that are applied globally
- Un-bias corrected conventional observations act as anchor, helping to distinguish forecast model bias and radiance observation bias. They are largely concentrated over land (Aircraft temperature observations are bias corrected)
- All-sky radiance assimilation over land will make the radiance bias correction more robust

Emissivity retrieval from the GSI

For a scattering-free atmosphere, assuming a flat and specular surface, observed brightness temperature BT can be expressed as:

BT_{obs} = ε T_s Γ + BT_{up} + Γ (1 - ε) BT_{down}

- BT_{up} atmospheric upwelling radiation
- BT_{down} atmospheric downwelling radiation
- Γ atmospheric surface-to-space transmittance
- T_s surface skin temperature (effective radiating temperature of the surface at the relevant frequency)

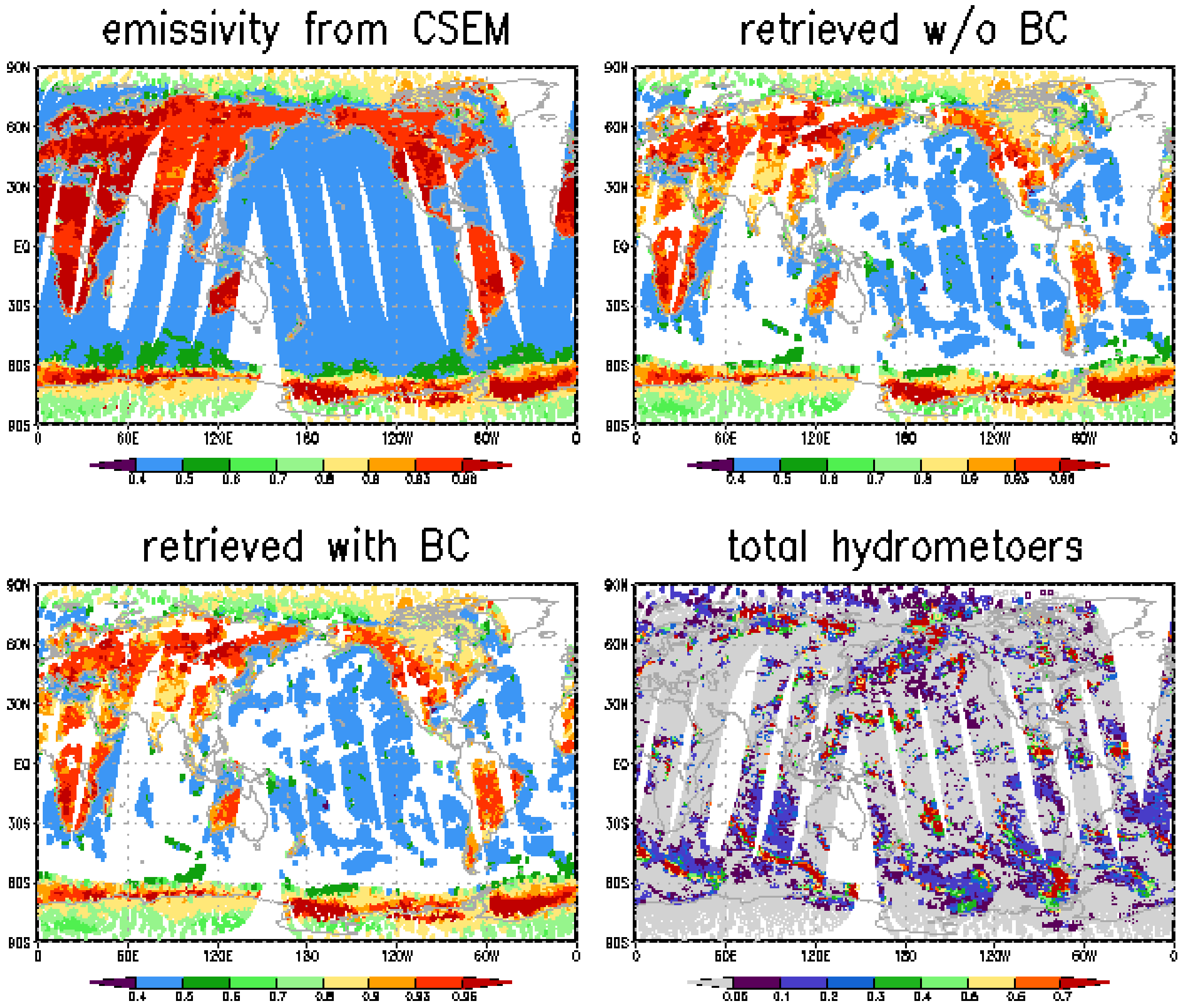
Surface emissivity can be calculated as:

$$\varepsilon = \frac{BT_{obs} - BTup - BTdown\,\Gamma}{(T_s - BTdown)\,\Gamma}$$

Or with effective cloud fraction C

$$\varepsilon = \frac{BT_{obs} - (1-C)\left(BT_{up}^{clr} + BT_{down}^{clr}\,\Gamma^{clr}\right) - C\,(BT_{up}^{cld} + BT_{down}^{cld}\,\Gamma^{cld})}{(1-C)\,(T_s - BT_{down}^{clr})\Gamma^{clr} + C(T_s - BT_{down}^{cld})\Gamma^{cld}}$$

NPP ATMS & NOAA18 AMSU-A 23.8GHz



Emissivity retrievals can be retrieved in the situations where the maximum single scattering albedo profile value (for the first guess) is not greater than 1.0E-10

- Over water, emissivity from CSEM is comparable to the retrievals
- Over land,
    - CSEM emissivity is generally larger than the retrievals
    - CSEM Emissivity has less spatial variability
    - CSEM emissivity is set to be a constant 0.95 for 89GHz and above

Factors affect the emissivity retrievals

- Assumptions used: non-scattering, specular surface
- Uncertainties in the atmospheric profiles
- Uncertainties in land surface skin temperature
- Radiance bias correction

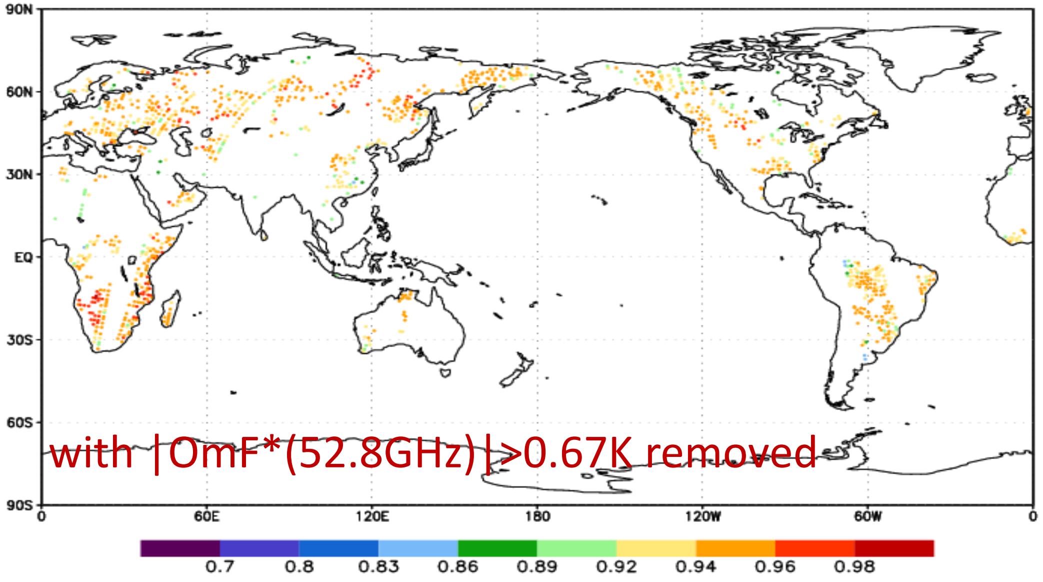
Quality control for retrieved emissivity

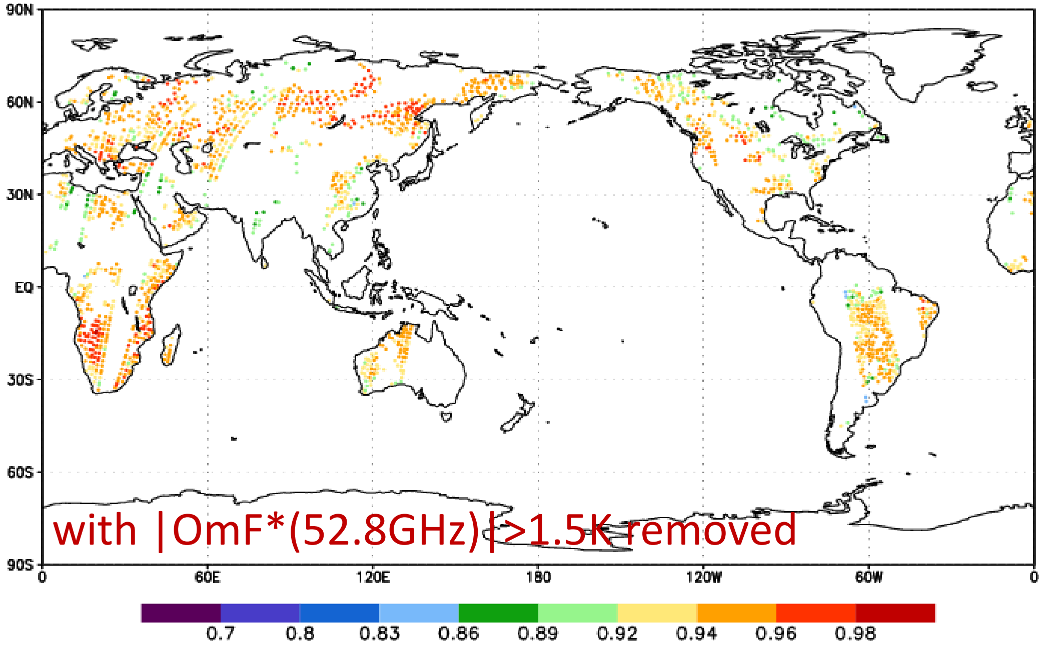
Land surface emissivity are retrieved in the situations where the scattering in the first guess is not significant

Avoid locations where first guess has no strong scattering but the observations are affected by strong scattering; and vice verse.

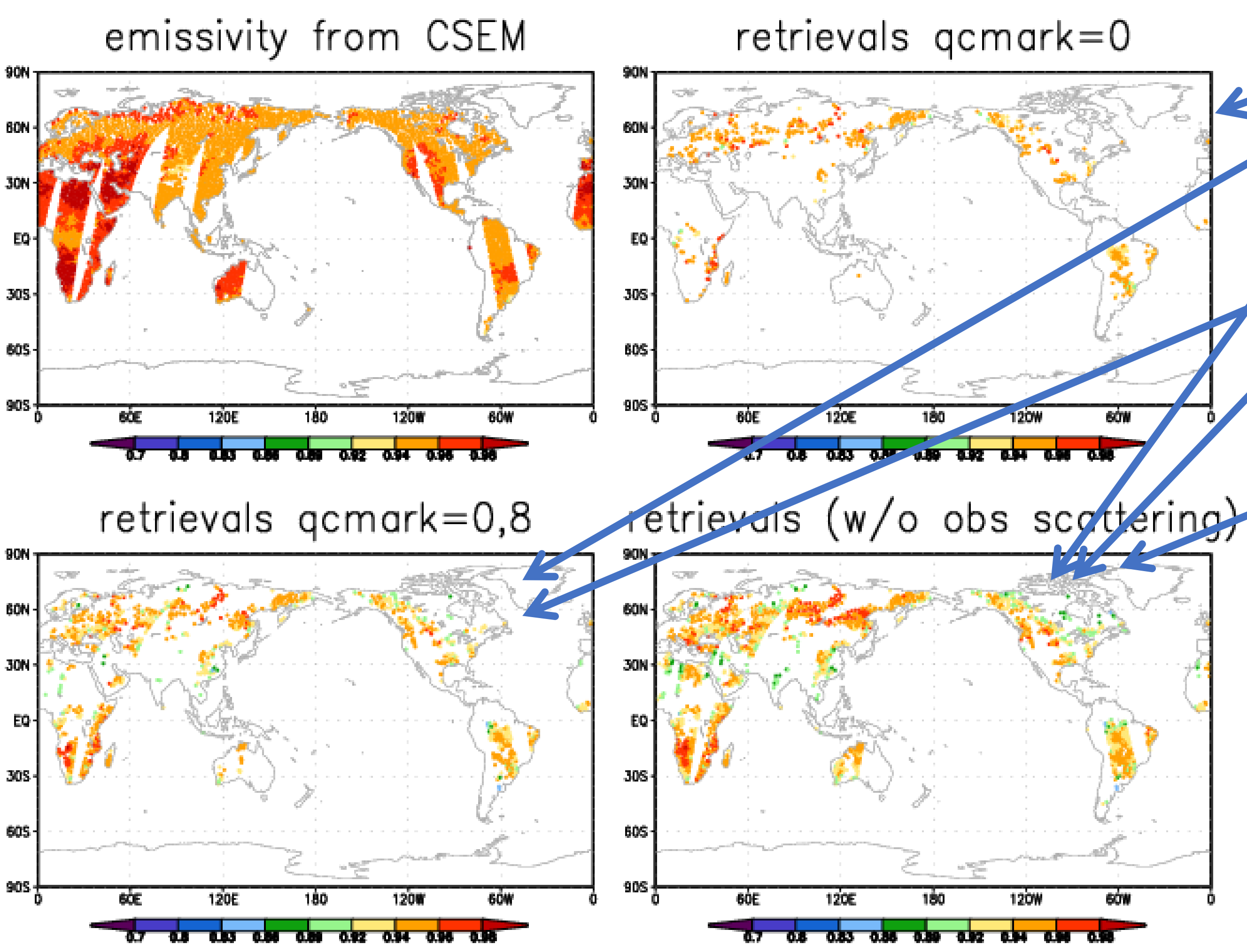
Quality control applied to reject emissivity retrieval where:

- Cloud detection in observations: Obs are compared with the equivalent clear-sky TBs (OmF*). Threshold values is relaxed
  from |OmF*(52.8GHz)|>0.67K
  to |OmF*(52.8GHz)|>1.50K
- Transmittance Γ <= 0.1
- Surface type land fraction<0.99





Emissivity retrievals for 31.4GHz

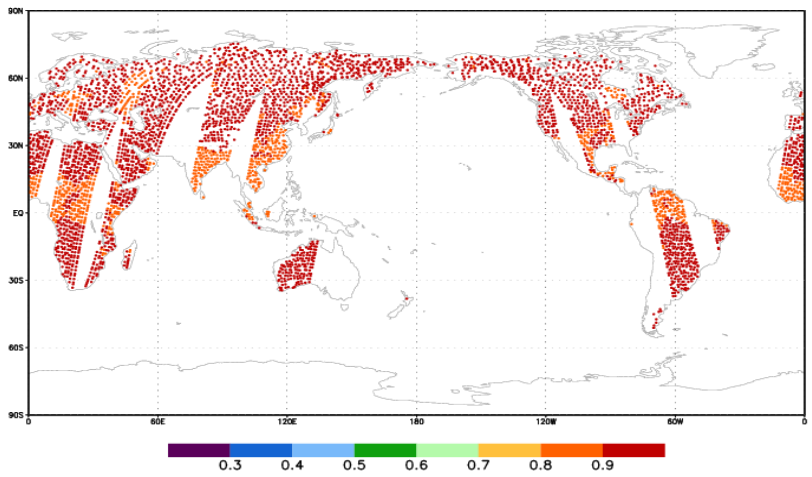


qcmark=0 radiances that passed clear-sky quality control

qcmark=8 radiances that are affected by emissivity check

Relaxed cloud check |OmF(52.8)|>1.5K

Emissivity for NPP ATMS & NOAA18 AMSU-A 31.4GHz



Surface-to-space transmittance

Channel	1	2	3	4	5	6	16	17	18
Emissivity retrieval_clr	0.946	0.945	0.936	0.935	0.935	0.947	0.929	0.894	0.920
Emissivity retrieval_cld	0.944	0.943	0.932	0.931	0.932	0.947	0.926	0.898	0.931
Data increase (%)	71..7	70.5	72.9	70.9	64.4	2.7	71.1	73.5	34.4

The spectral variability of emissivity is small for most surface types. As an approximation, the emissivity retrieved from window channels can be used for sounding channels

Ongoing work and future plan

- Preliminary emissivity results showed that analytical emissivity retrievals are smaller than CSEM emissivity overall, and have larger temporal and spatial variability than CSEM emissivity.
- Generate and assess month-long emissivity retrievals for warm and cold seasons, and provide the retrievals to NESDIS CSEM developer for the CSEM parameters tuning study
- Assess simulated brightness temperature with the selected effective cloud fraction scheme together with the bulk optical properties for the all-sky radiance assimilation over land, and assess the impact of emissivity retrievals on the simulated radiances
- Develop the emissivity estimate framework combining with TELSEM atlas in the all-sky radiance assimilation over land
- Develop observation error model, quality control, and bias correction for the all-sky radiance assimilation over land