Impact of microwave radiance assimilation over land using dynamic emissivity in the global NWP system of JMA

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Motivation

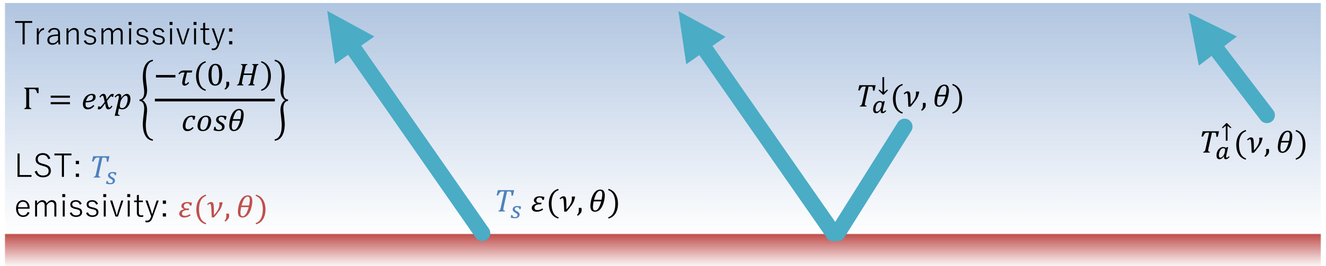
- It is important to estimate land surface emissivity for the radiance assimilation in the NWP systems.
  - The emissivity spatiotemporally varies depending on surface conditions.
- In the current global NWP system of JMA, the climatological atlas emissivity is used for the microwave (MW) radiance assimilation over land.

- JMA/MRI is working on applying a dynamic emissivity (DE, Karbou et al. 2006) method to the global NWP system of JMA to reduce uncertainty related to the radiative transfer calculation.
  - In addition to the emissivity, land surface temperature (LST) is also important as one of parameters for radiative transfer model.
  - Based on the DE, a Bayesian method is developed to dynamically estimate the emissivity and LST simultaneously by using satellite observations.

Dynamic Emissivity (Karbou et al. 2006)

- Radiative transfer equation under clear sky condition

$$T_b(\nu,\theta) = T_s\varepsilon(\nu,\theta)\Gamma + \{1-\varepsilon(\nu,\theta)\}\,\Gamma\, T_a^{\downarrow}(\nu,\theta) + T_a^{\uparrow}(\nu,\theta)$$



$T_b(\nu,\theta)$: brightness temp.
ν: frequency
θ: zenith angle
T_s: land surface temp. (LST)
$T_a^{\downarrow}$: downwelling T_b
$T_a^{\uparrow}$: upwelling T_b
Γ: transmissivity

- Estimated emissivity $\varepsilon(\nu,\theta)$

$$\varepsilon(\nu,\theta) = \frac{T_b(\nu,\theta) - T_a^{\downarrow}(\nu,\theta)\Gamma - T_a^{\uparrow}(\nu,\theta)}{\left(T_s - T_a^{\downarrow}(\nu,\theta)\right)\Gamma}$$

$\varepsilon(\nu,\theta)$ is estimated from observed T_b and atmospheric model variables.
Here, a model surface temperature is used as T_s.

- In addition to the emissivity, the LST should be estimated simultaneously to calculate more accurate T_b.
  - The model LST has some biases which come from insufficient land surface processes in a numerical model.

Bayesian estimation method based on the DE

- Estimated emissivity in DE method

$$\varepsilon(\nu,\theta) = \frac{T_b(\nu,\theta) - T_a^{\downarrow}(\nu,\theta)\Gamma - T_a^{\uparrow}(\nu,\theta)}{\left(T_s - T_a^{\downarrow}(\nu,\theta)\right)\Gamma}$$

  - Errors of observed T_b and model LST T_s should be considered.

To treat the errors of observed T_b and model LST T_s, the DE method is extended.
→ A Bayesian estimation method based on the DE (named as BDE)

- Estimated $\mathbf{X}^a = \begin{pmatrix} T_{s\_est} \\ \varepsilon_{est} \end{pmatrix}$ is written as follows,

$$\mathbf{X}^a = \mathbf{X}^b + \mathbf{B}\mathbf{H}^{\mathrm{T}}\left(\mathbf{H}\mathbf{B}\mathbf{H}^{\mathrm{T}} + \mathbf{R}\right)^{-1}\left(\mathbf{y} - h\left(\mathbf{X}^b\right)\right)$$

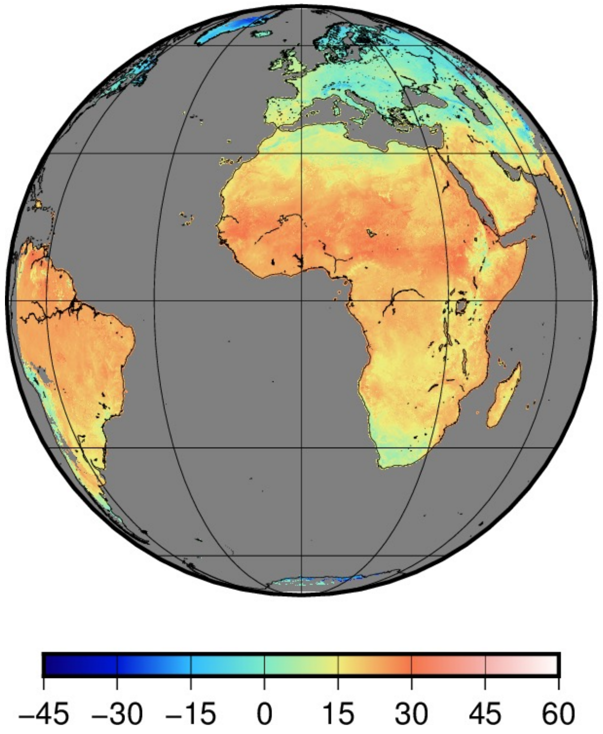
  - h: Nonlinear radiative transfer equation
  - $\mathbf{H}$: Linearized radiative transfer equation
  - $\mathbf{B}$: background error variance of $\mathbf{X}^b = \begin{pmatrix} T_{s\_model} \\ \varepsilon_{atlas} \end{pmatrix}$
  - $\mathbf{R}$: observation error variance of brightness temperature $\mathbf{y}$
  - $\mathbf{y}$: observation (multiple channels are available.)

Comparison of LSTs

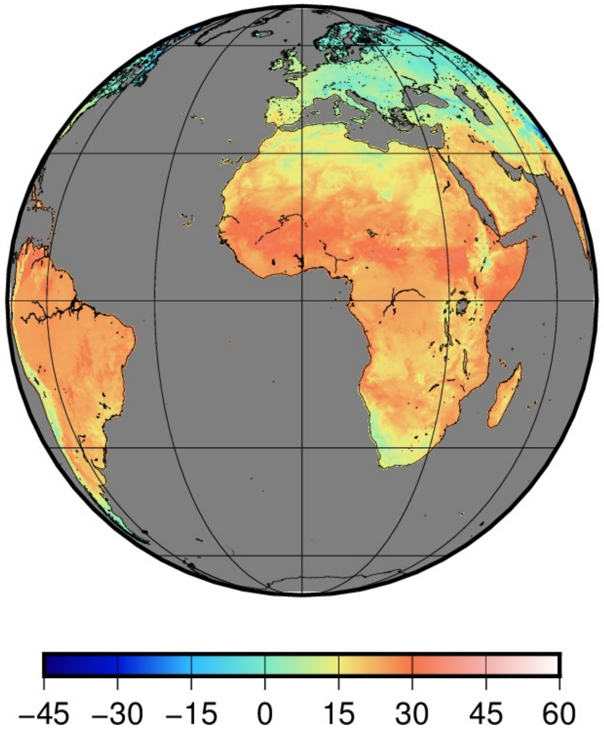
- Comparison of LST by the BDE with the Meteosat LST.

10 Apr. 2023, 00 UTC

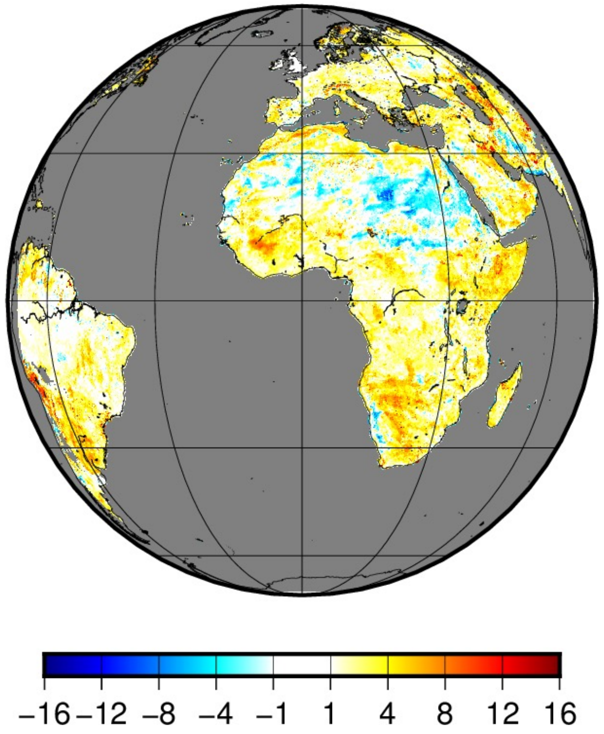
Meteosat LST



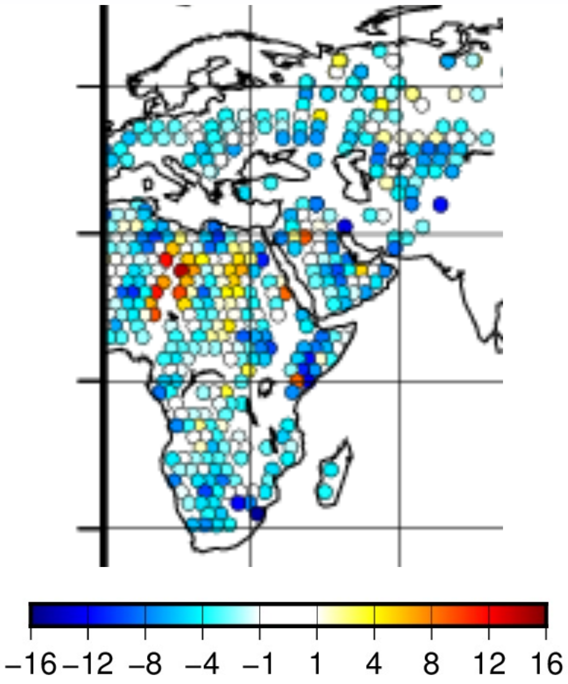
Model LST



Diff LST (model-Meteosat)



LST increment of BDE



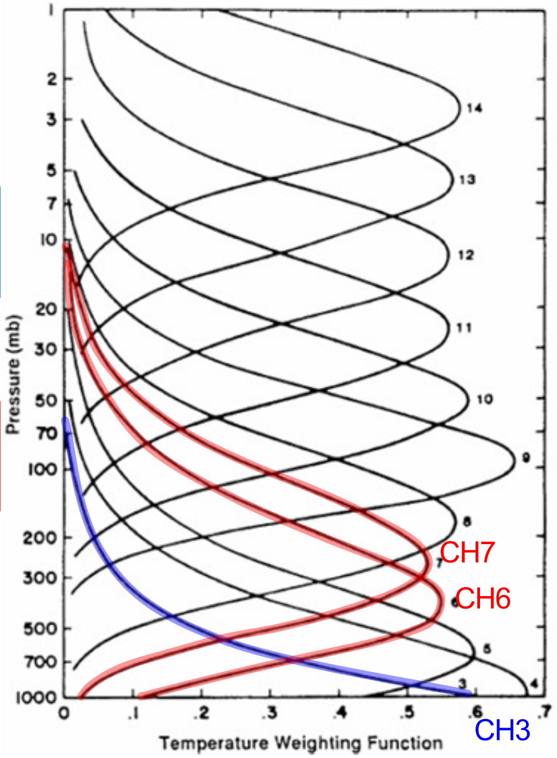
- The model LST has a warm bias(higher than Meteosat LST) on 00 UTC.
  - In the central Sahara Desert, the model LST has a cold bias.
- The BDE can compute an increment of LST to cancel the warm bias of model LST.

Target sensors of DE

- Target sensors : AMSU-A, ATMS
- LST is estimated at 50.3 GHz.
- DE is estimated at 31.4 GHz or 50.30 GHz (Bormann et al. 2017).
- DE is used at surface-sensitive CHs over land.
  - AMSU-A
    - 54.40 GHz (ch6)
    - 54.94 GHz (ch7)
  - ATMS
    - 54.40 GHz (ch7)
    - 54.94 GHz (ch8)

CHs. 4 and 5 are not assimilated over land.

CH	Central frequency	Absorption	Assimilation
1	23.800 GHz	H_2O	
2	**31.400 GHz**	**window**	
3	**50.300 GHz**	**O_2**	
4	52.800 GHz	O_2	○ (sea)
5	53.595 GHz ± 115 MHz	O_2	○ (sea)
6	**54.400 GHz**	**O_2**	○
7	**54.940 GHz**	**O_2**	○
8	55.500 GHz	O_2	○
9	57.290 GHz (=f0)	O_2	○
10	f0±217 MHz	O_2	○
11	f0±322.2 MHz±48 MHz	O_2	○
12	f0±322.2 MHz±22 MHz	O_2	○
13	f0±322.2 MHz±10 MHz	O_2	○
14	f0±322.2 MHz±4.5 MHz	O_2	○
15	89.000 GHz	window	



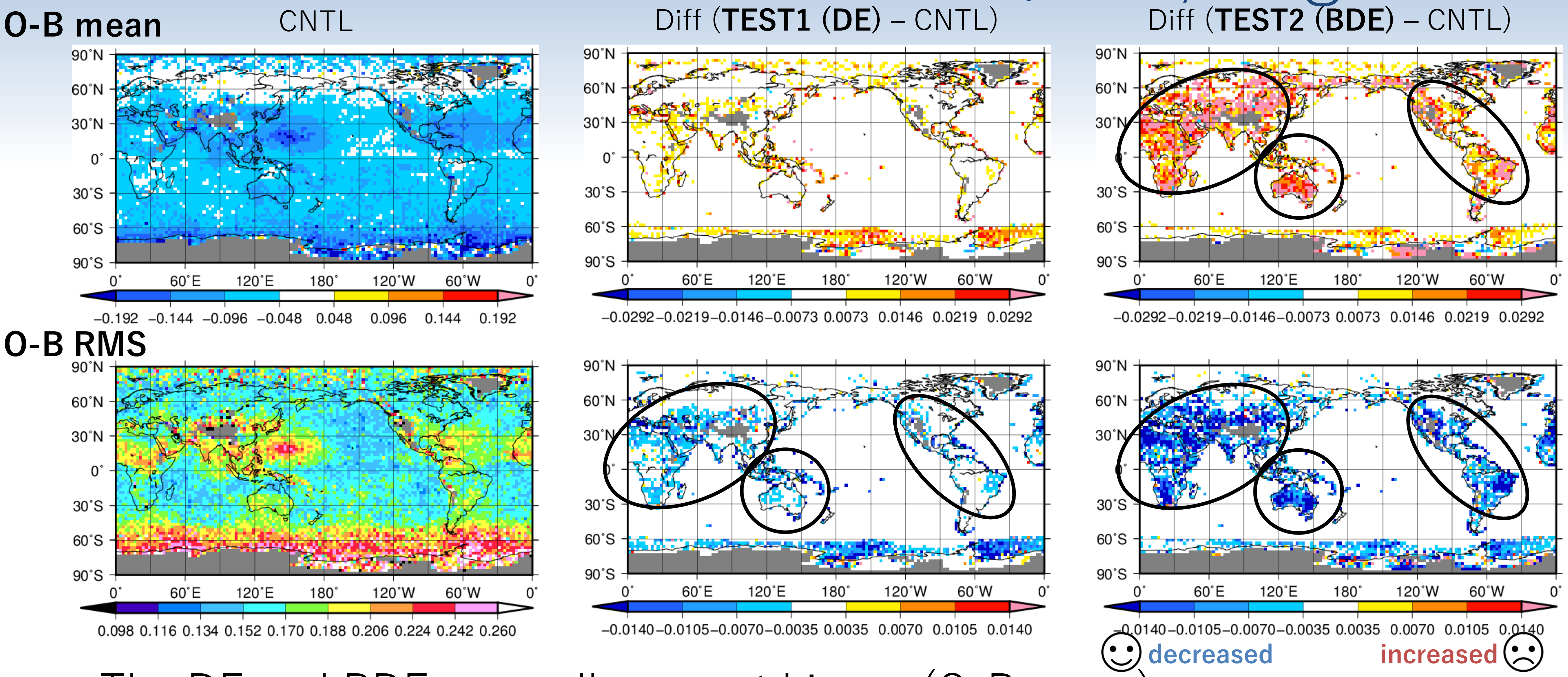
Weighting Functions for AMSU-A (Janssen,1993)

Preliminary investigation (Passive cycle)

- To investigate impacts of DE and BDE, calculating radiative transfer model and QC are performed without DA cycles.
  - Background brightness temperature (TB) is calculated from the given first guess.
  - The calculated TBs by non-DE, DE, BDE are compared with observed TB.
  - This is not a DA cycle experiment.
- Global NWP system of JMA (operational system as of Jul. 2022)
  - Hybrid 4D-Var system (Outer: TL959L128 (20 km), Inner: TL319L128 (55 km))
- Experimental settings
  - The DE is applied to AMSU-A/chs. 5, 6, 7 and ATMS/chs. 6, 7, 8 over land.
    - AMSU-A/ch5 and ATMS/ch6 are not used over land in the operational system of JMA because they contaminated analyses and degraded forecasts.
    - However, this experiment is not a DA cycle, therefore the contaminated analyses are not used.
- Period: Aug. 2022, Jan. 2023

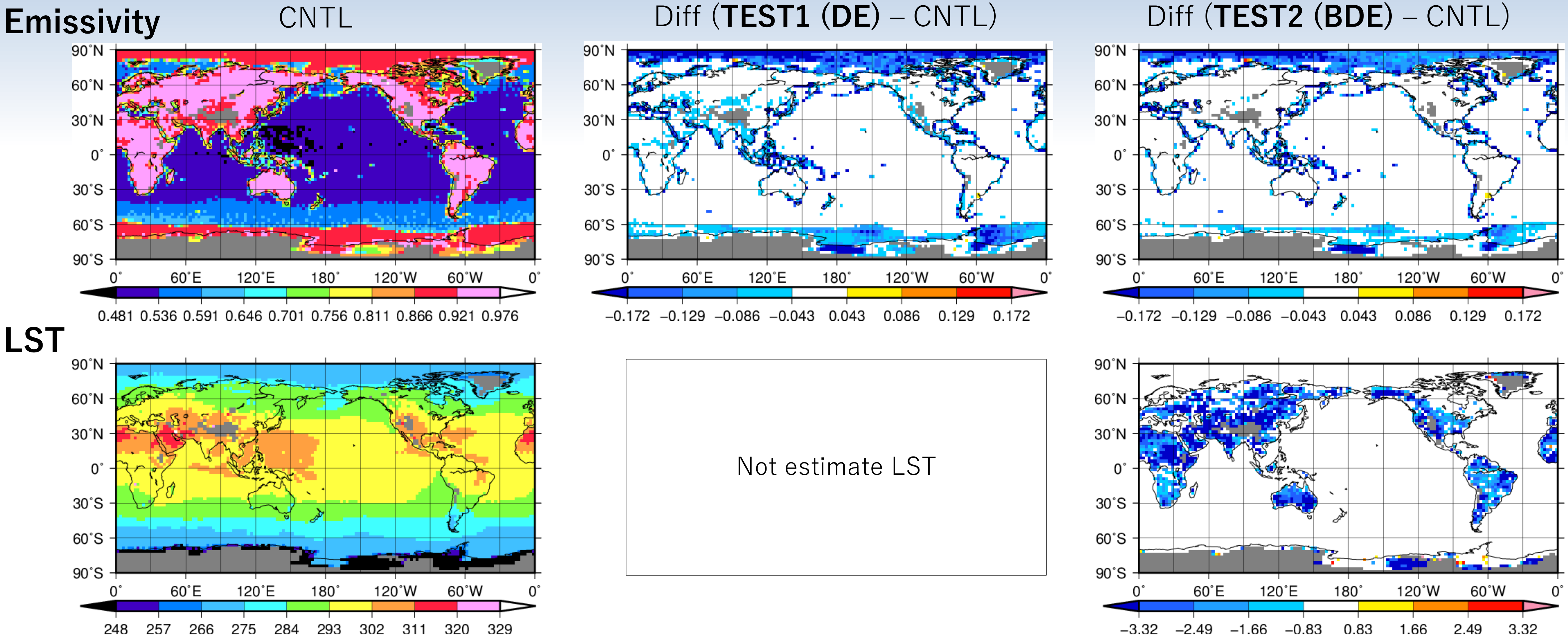
Name	Emissivity	LST	note
CNTL	Atlas emissivity	Model LST	operational settings
TEST1 (DE)	**Estimated**	Model LST	
TEST2 (BDE)	**Estimated**	**Estimated**	

O-B statistics: AMSU-A/ch6, Aug.



- The DE and BDE generally correct biases (O-B mean).
- The BDE degreases the O-B RMS more than the DE.
  - The Impact of estimating LST is great.

Emissivity, LST: AMSU-A/ch6, Aug.

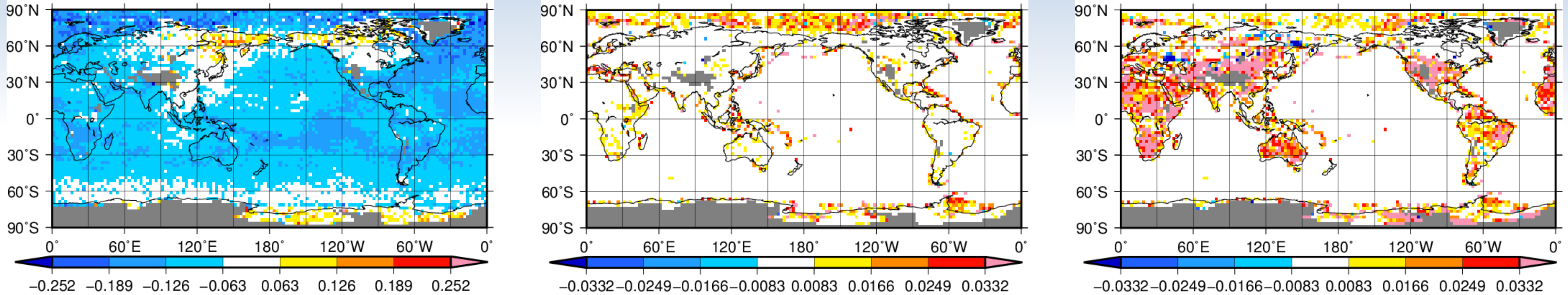


- The estimated emissivities are almost the same or the emissivity of DE is slightly smaller.
- The BDE estimates the LST lower than model.

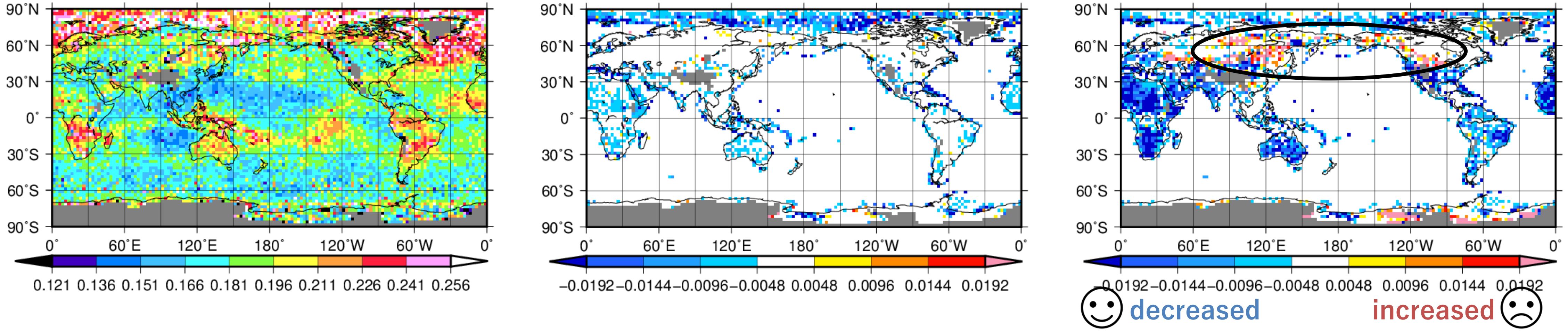
O-B statistics: AMSU-A/ch6, Jan.

O-B mean

CNTL | Diff (**TEST1 (DE)** – CNTL) | Diff (**TEST2 (BDE)** – CNTL)



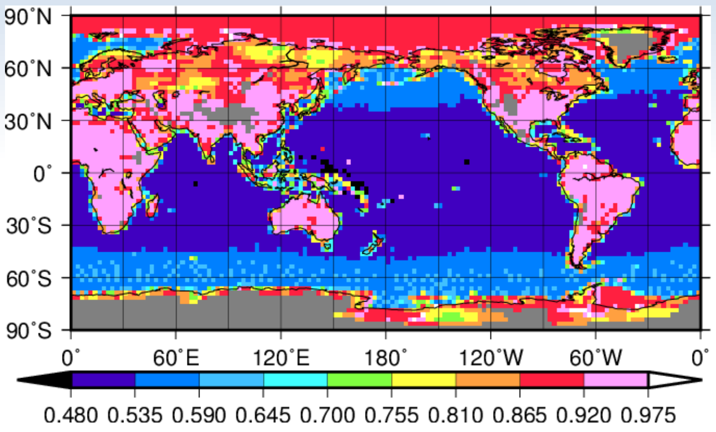
O-B RMS

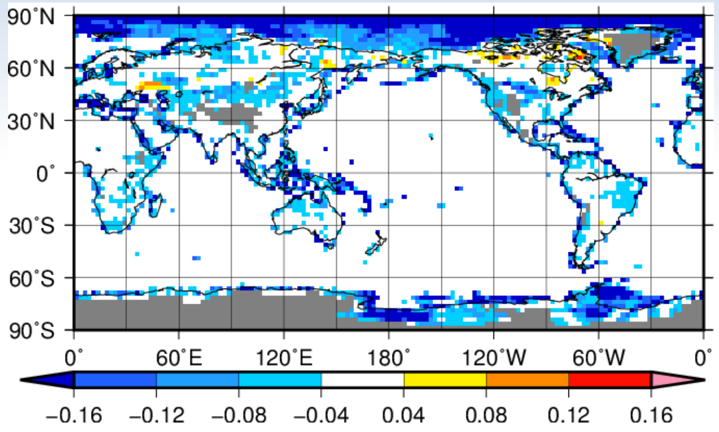


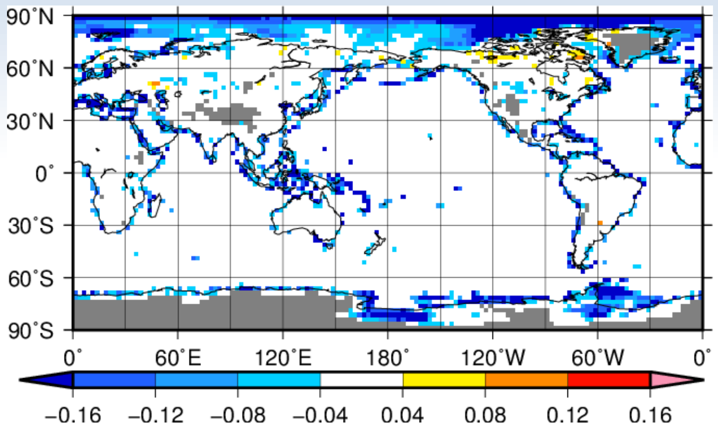
- The BDE degreases the O-B RMS more than the DE (similar to Aug.).
  - The Impact of estimating LST is great.
- Over Siberia, Tibet and Alaska, O-B RMS increases in the BDE.

Emissivity, LST: AMSU-A/ch6, Jan.

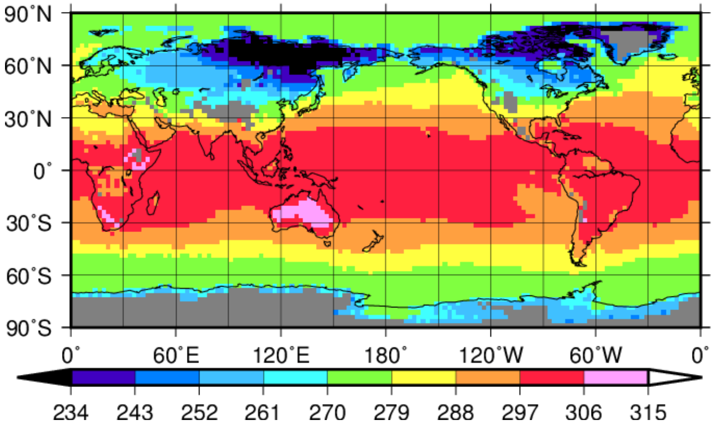
Emissivity CNTL | Diff (**TEST1 (DE)** – CNTL) | Diff (**TEST2 (BDE)** – CNTL)



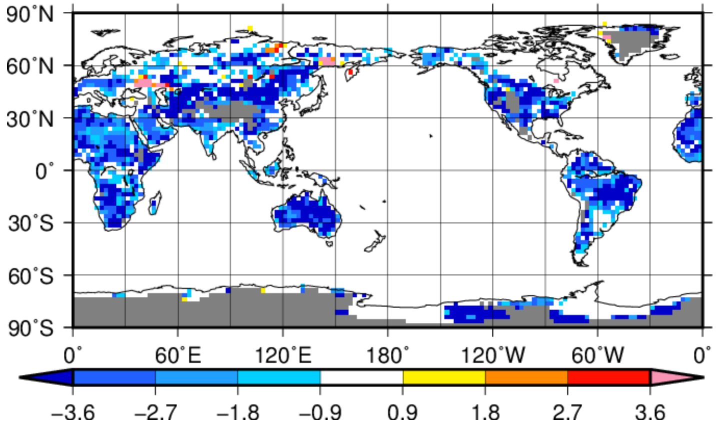




LST



Not estimate LST

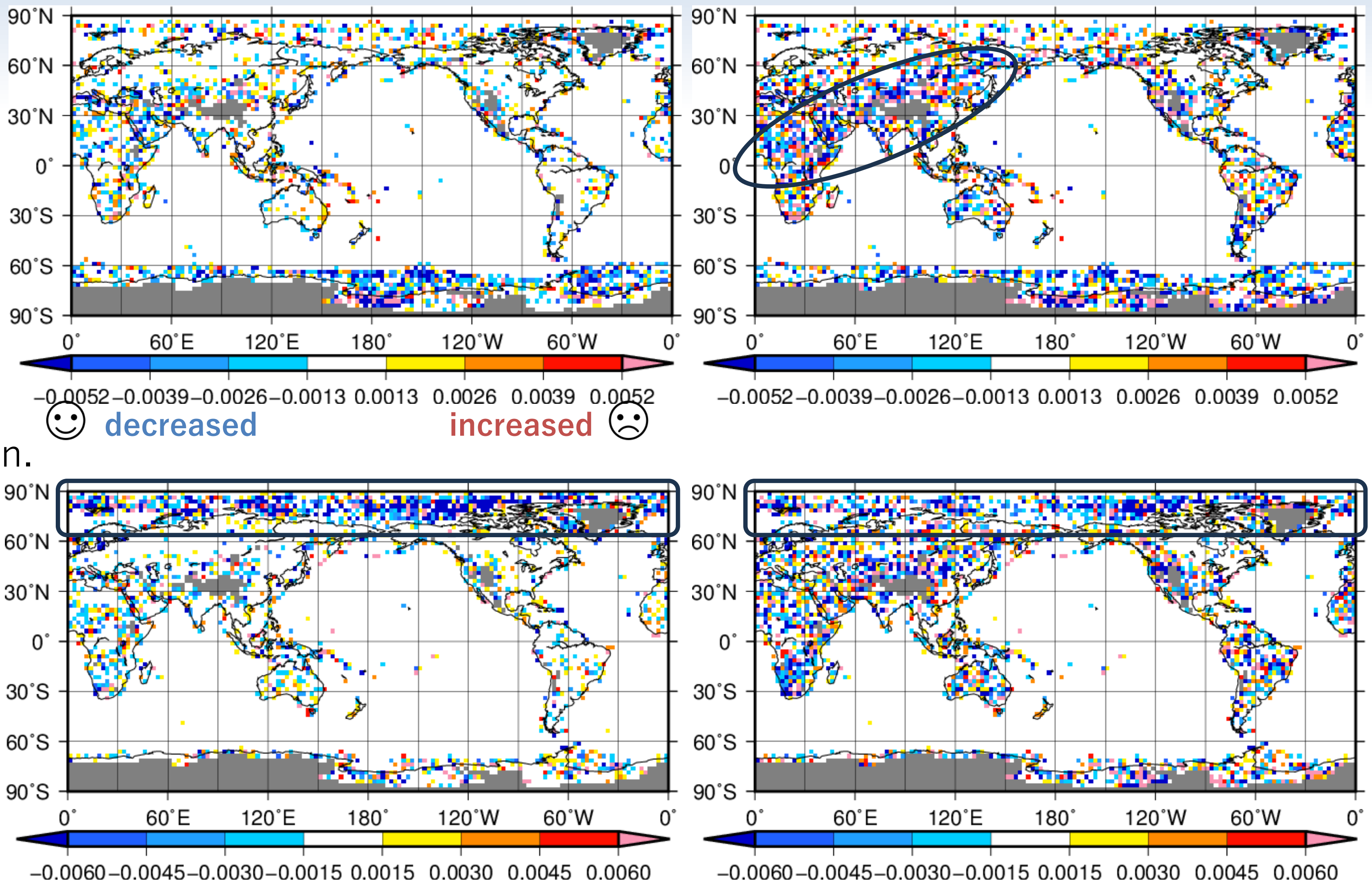


- The BDE has slightly smaller increments of emissivity than the DE.
- The BDE estimates the LST lower than model.
  - Over Siberia, Tibet and Alaska where O-B RMS increases, the estimated LSTs are also smaller.

Impacts of DE or BDE to non-Gaussianity of O-B

Aug. Diff (**TEST1 (DE)** – CNTL) Diff (**TEST2 (BDE)** – CNTL)

Jan.



- Non-Gaussianity is measured by Kullback–Leibler divergence (KLD).

$$D_{KL} = \int p(x) \log \frac{p(x)}{q(x)} dx$$

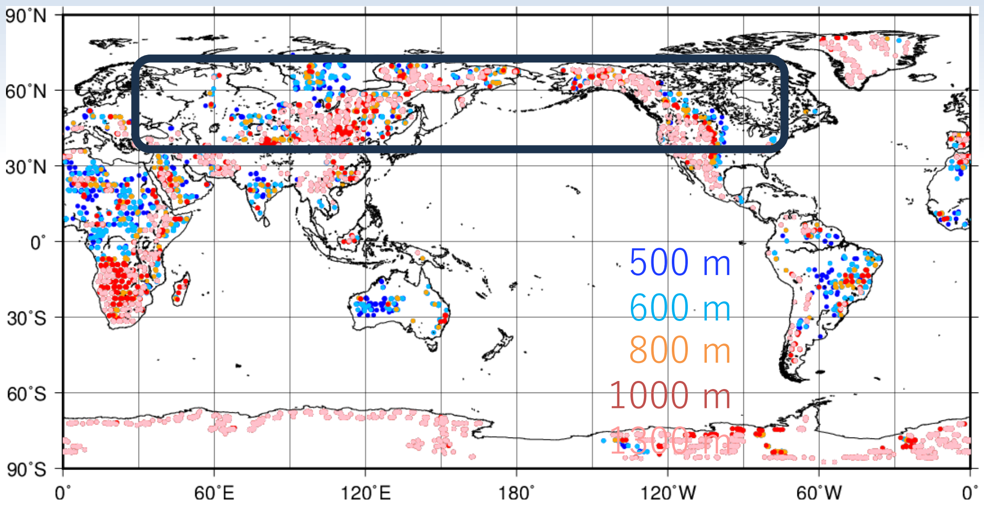
p(x): O-B histogram

q(x): Gaussian function

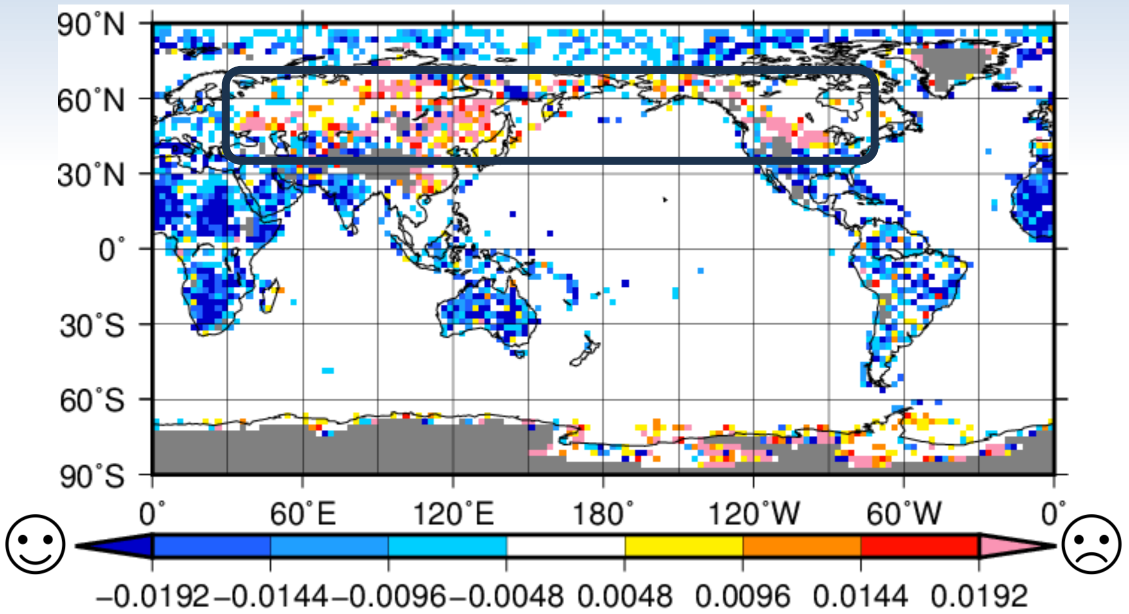
  - KLD = 0 → Gaussian PDF
  - KLD > 0 → non-Gaussian PDF
- Non-Gaussianity is reduced by the DE and BDE.
  - The BDE makes the non-Gaussianity much smaller than DE.
  - Such small non-Gaussianity is useful to assimilate observational information because the 4D-Var is based on the Gaussian assumption.

Large O-B RMS, altitude and snow cover (Jan.)

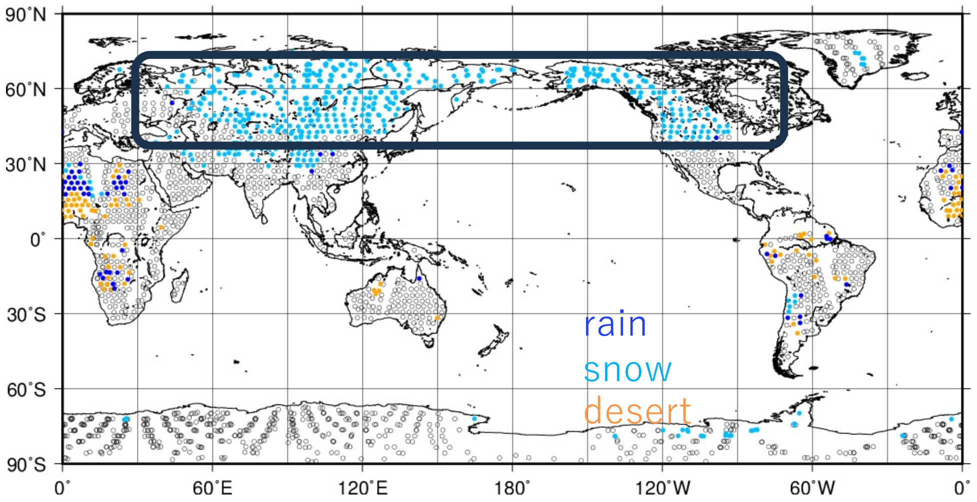
Model elevation



O-B RMS (CNTL vs. BDE, Metop-C/AMSU-A/ch6)



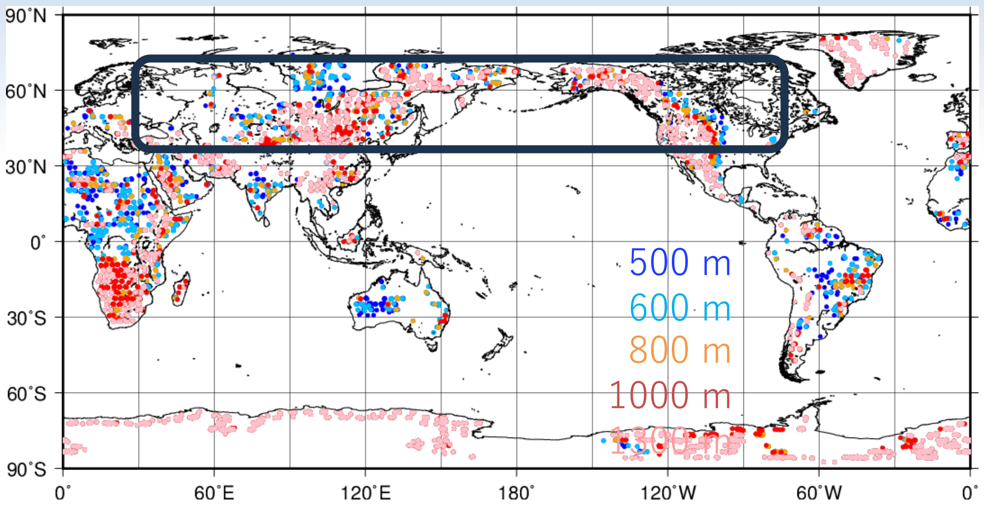
Estimated surface types (Grody 1999)



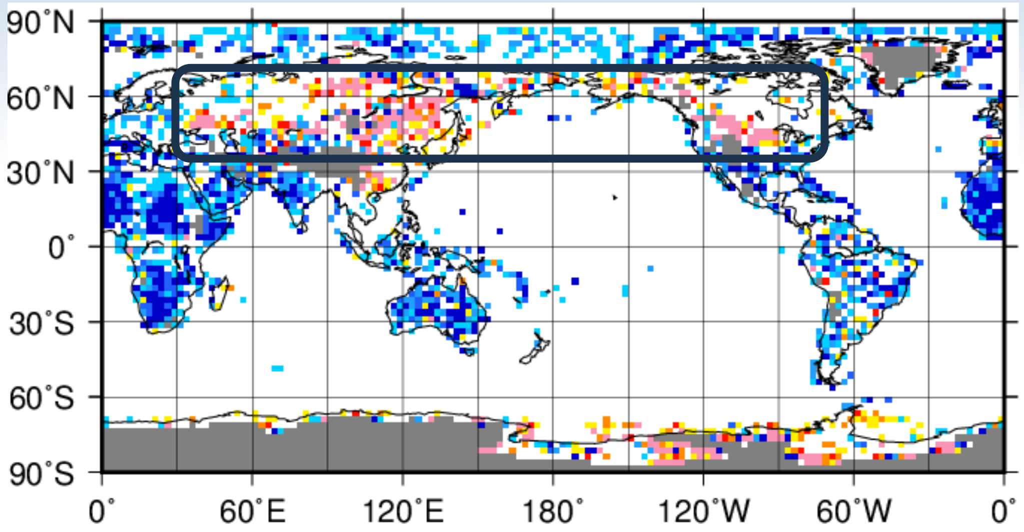
- Over the Central Siberian Plateau, Tibet and Alaska, O-B RMS increases in the BDE.
  - The model elevation or snow are considered as factors.
- To avoid increasing the O-B RMS, the emissivity is set to the atlas instead of being estimated by BDE at high elevation and high latitudes.
  - In the future, we would like to treat the BDE over the snow cover areas.

Large O-B RMS, altitude and snow cover (Jan.)

Model altitude

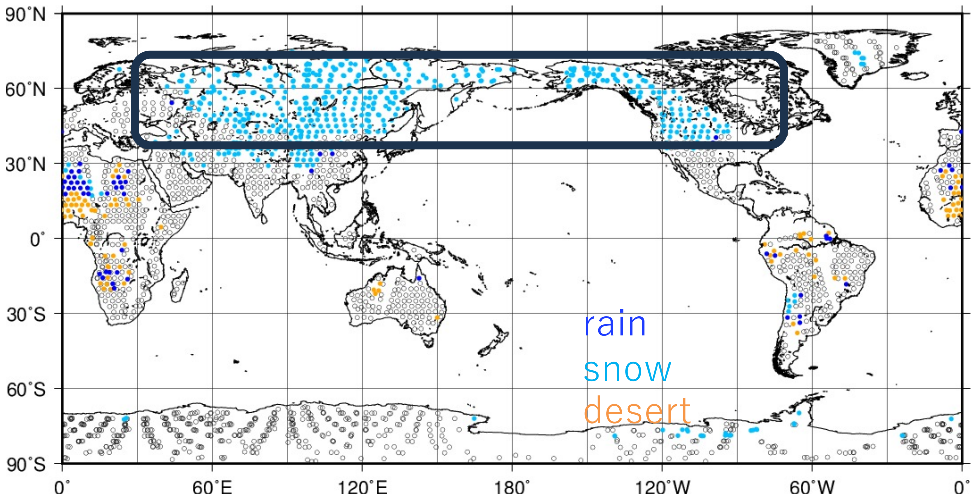


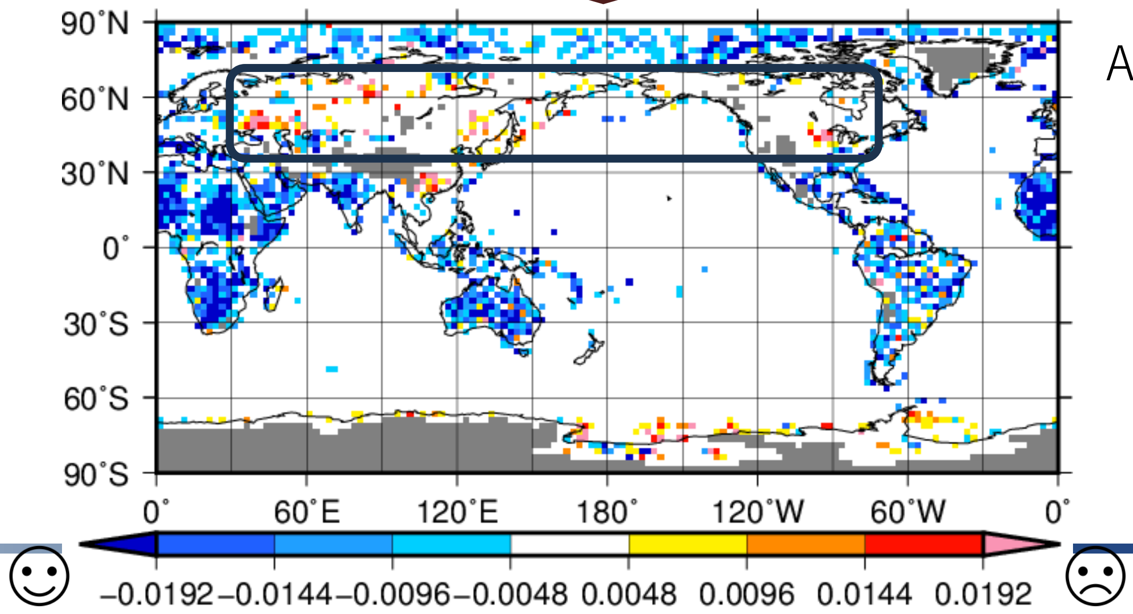
O-B RMS (CNTL vs. BDE, Metop-C/AMSU-A/ch6)



Before

Estimated surface types (Grody 1999)





After

Summary of preliminary investigation

- The DE and BDE generally correct biases (O-B mean).
- Non-Gaussianity of O-B is reduced by the DE and BDE.
- The BDE decreases the O-B RMS more than the DE.
  - The Impact of estimating LST is large.
- However, over Siberia, Tibet and Alaska, the O-B RMS increases.
  - The model altitude or snow are considered as factors.

- To avoid increasing the O-B RMS, the emissivity is set to the atlas instead of being estimated by BDE at high elevation and high latitudes.
  - The brightness temperature is the same as CNTL over such areas.
- This QC almost eliminated the deterioration of O-B.

The BDE with the QC is compared with the DE in DA cycle experiments.

Experimental settings of DA cycle

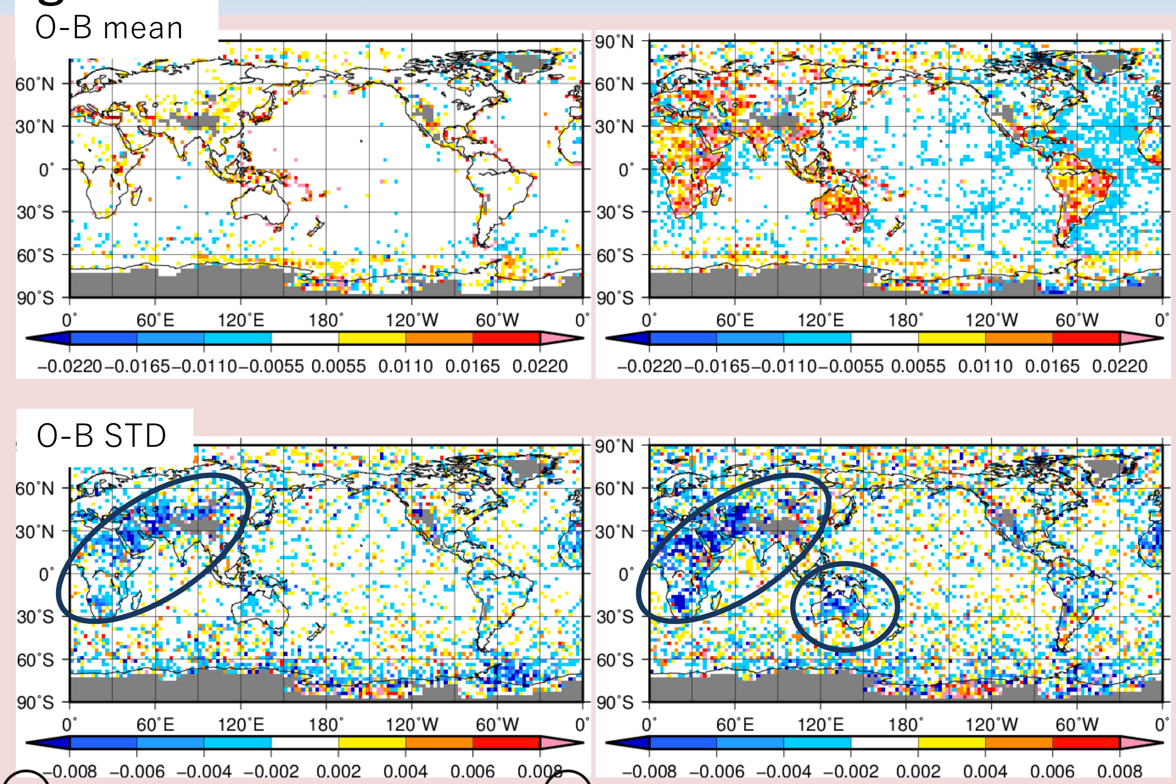
- Global NWP system of JMA (operational system as of Jul. 2022)
  - Hybrid 4D-Var
  - Outer model: TL959L128 (20 km)
  - Inner model: TL319L128 (55 km)
- Experimental settings
  - The DE and BDE are applied over land and sea ice.

Name	Emissivity	LST	note
CNTL	Atlas emissivity	Model LST	Operational settings
TEST1 (DE)	**Estimated**	Model LST	
TEST2 (BDE)	**Estimated**	**Estimated**	QC (high latitude and high altitude)

- Target period: Aug. 2021, Jan. 2022
- Target DE or BDE: AMSU-A and ATMS

O-B statistics (AMSU-A/ch6, against CNTL)

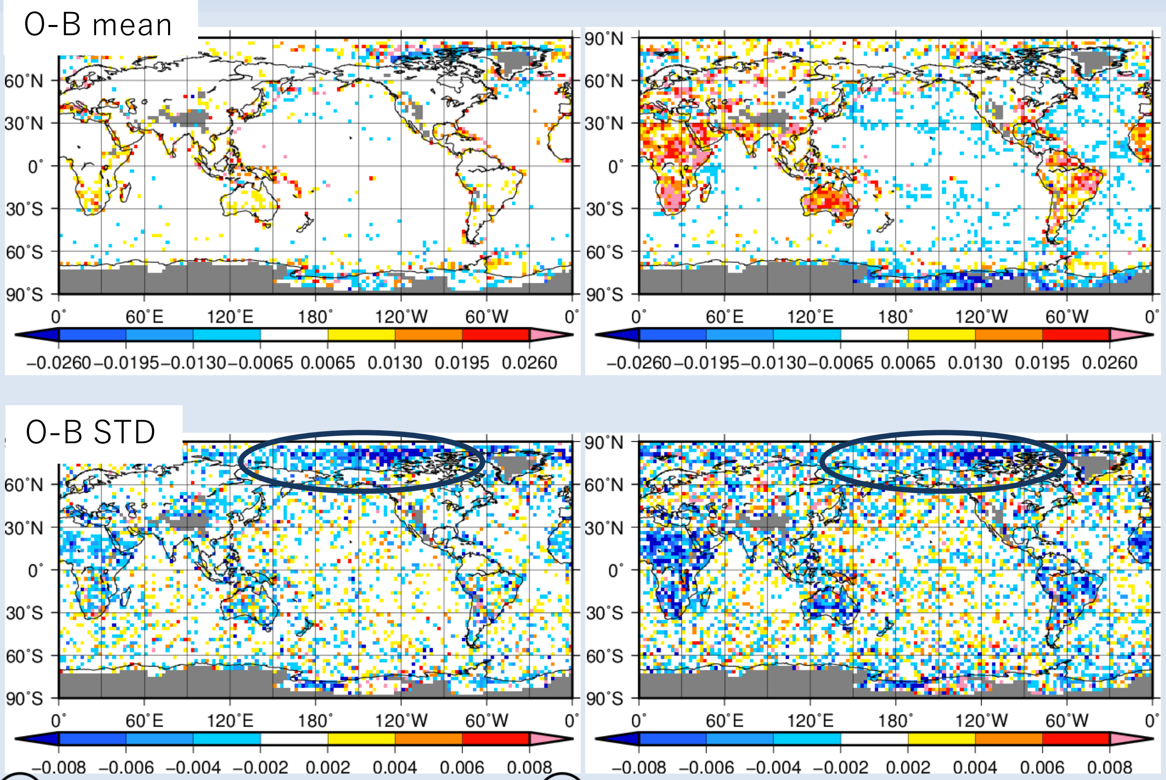
Aug. **TEST1 (DE)**-CNTL **TEST2 (BDE)**-CNTL



☺decreased increased ☹

- The DE and BDE improve the background TB, and decrease the O-B STD.
- The BDE has larger impacts than the DE, particularly over Africa, the Middle East and Australia.

Jan. **TEST1 (DE)**-CNTL **TEST2 (BDE)**-CNTL



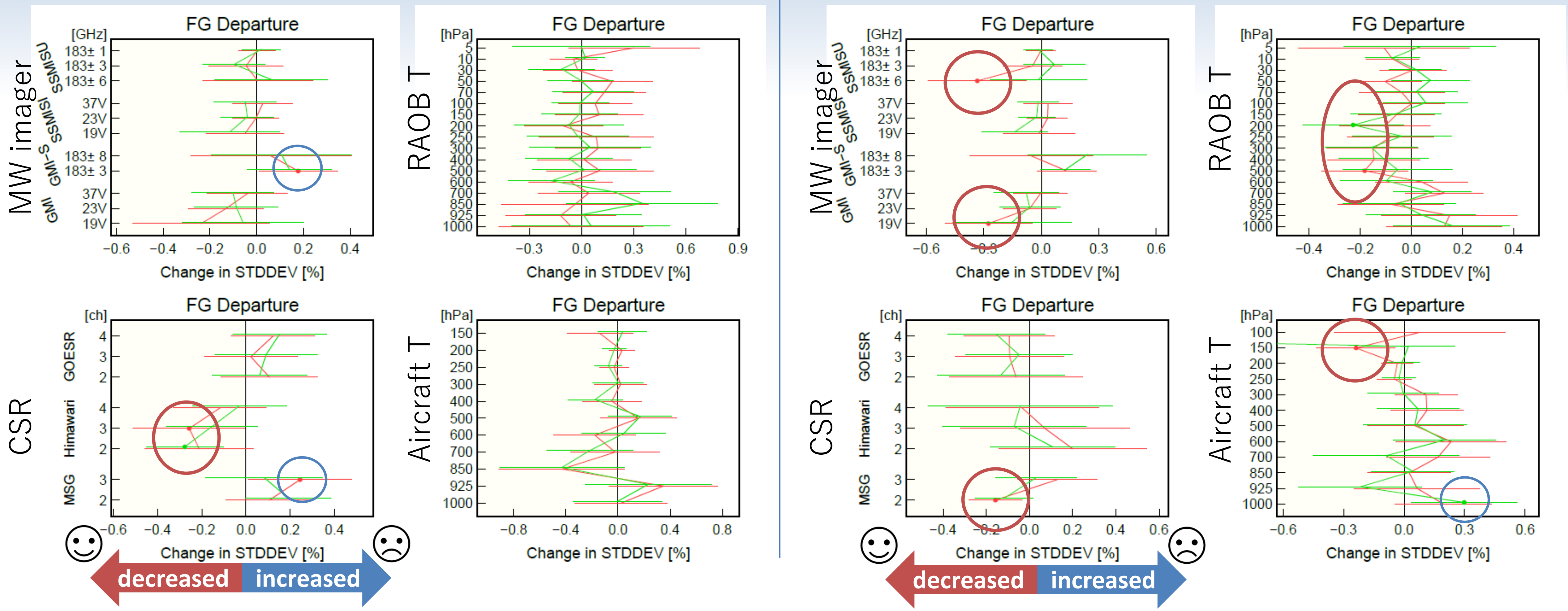
☺decreased increased ☹

- Similar to Aug.
- The DE and BDE decrease the O-B STD over the sea ice.
  - CNTL: the emissivity is fixed at 0.9
  - DE and BDE: the emissivity is estimated.

Statistical verification of O-B STD (against CNTL)

TEST1: DE
TEST2: BDE

Aug. | **Jan.**



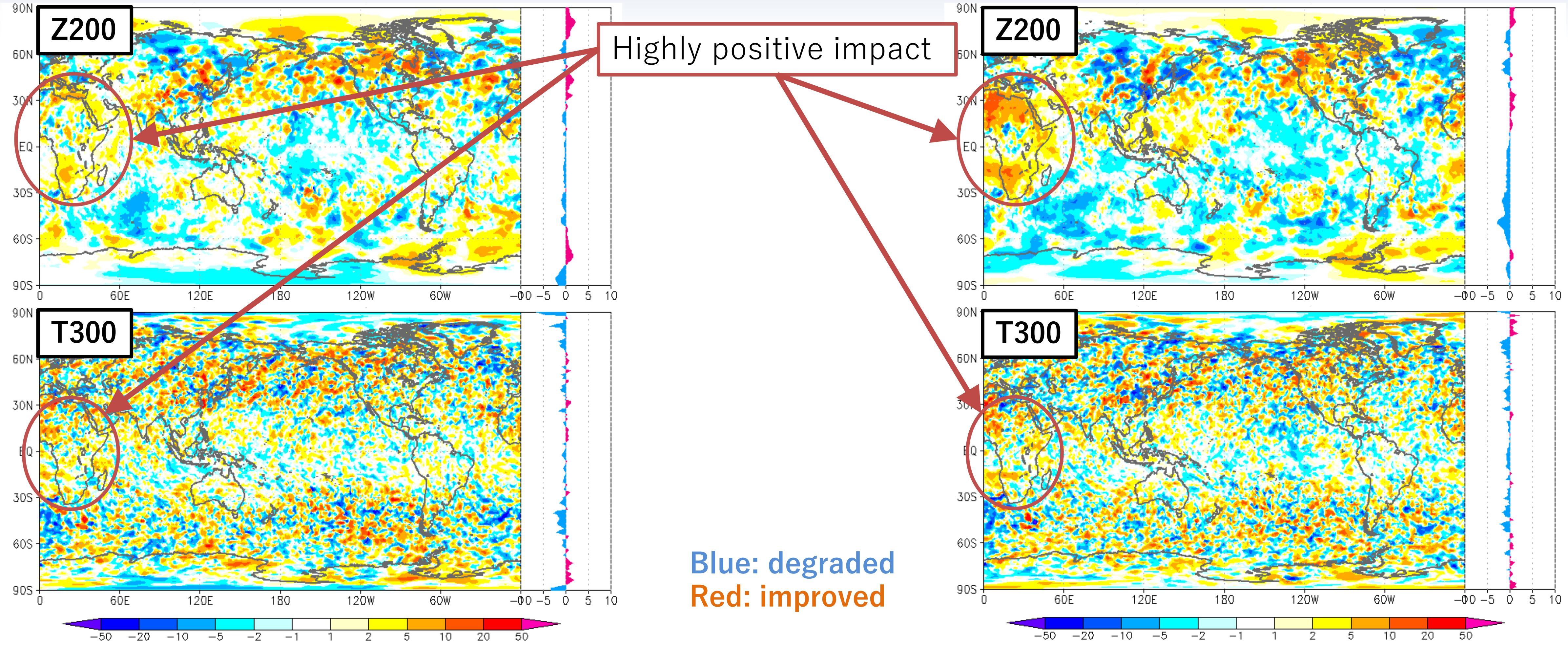
- The first guess is slightly improved by the DE and BDE.

Improvement of forecast RMSEs (against ECMWF analysis, FT=24 hr)

- Verification at 200 and 300 hPa where weighting functions for AMSU-A chs. 6, 7 have a peak.

RMSE improvement (%), TEST1 (DE), Aug.

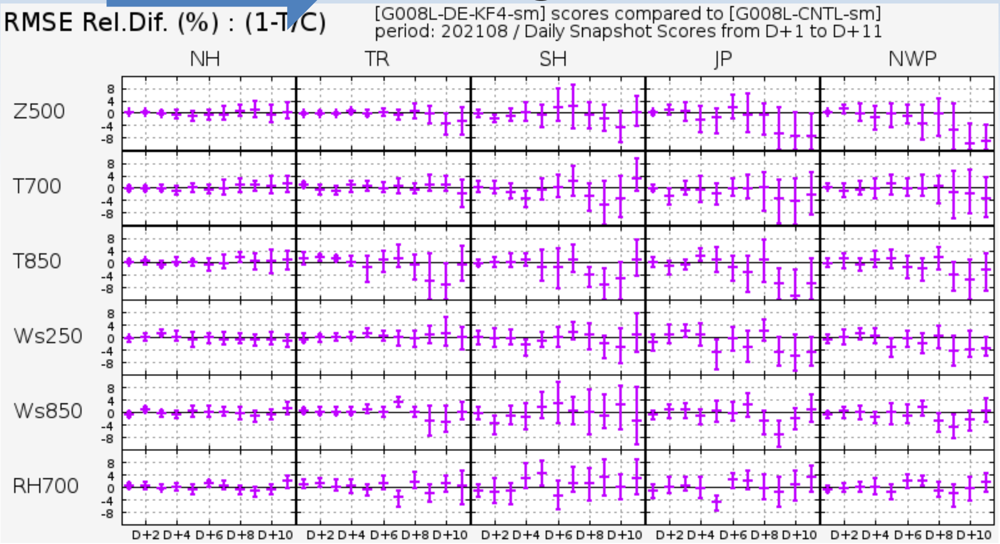
RMSE improvement (%), TEST2 (BDE), Aug.



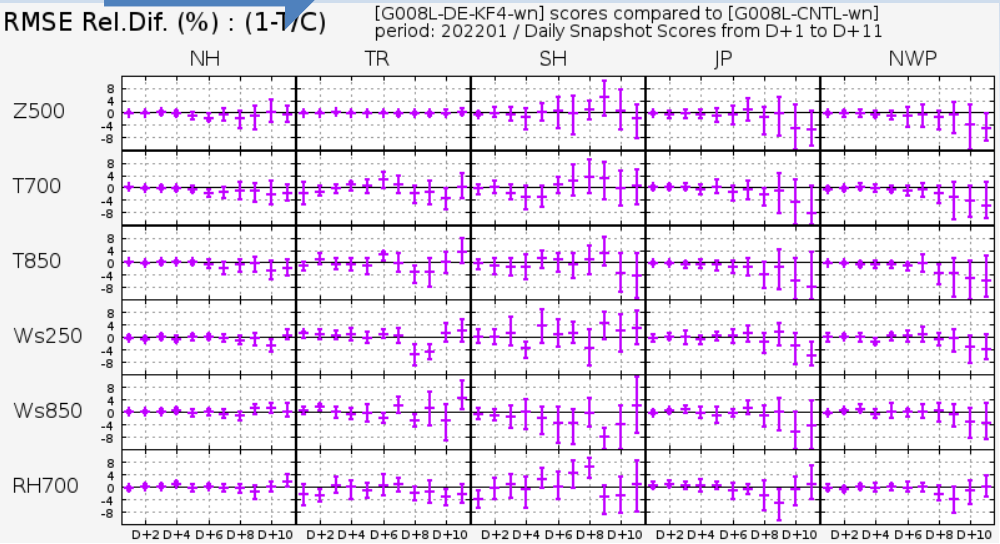
- The BDE has larger impacts than the DE.

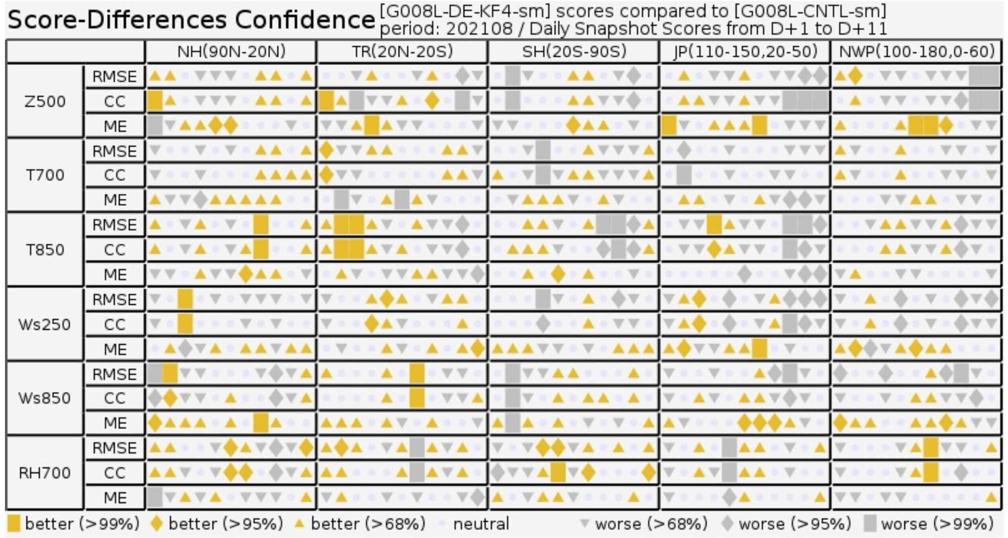
Impacts of TEST2 (BDE) to the forecast (against RAOB)

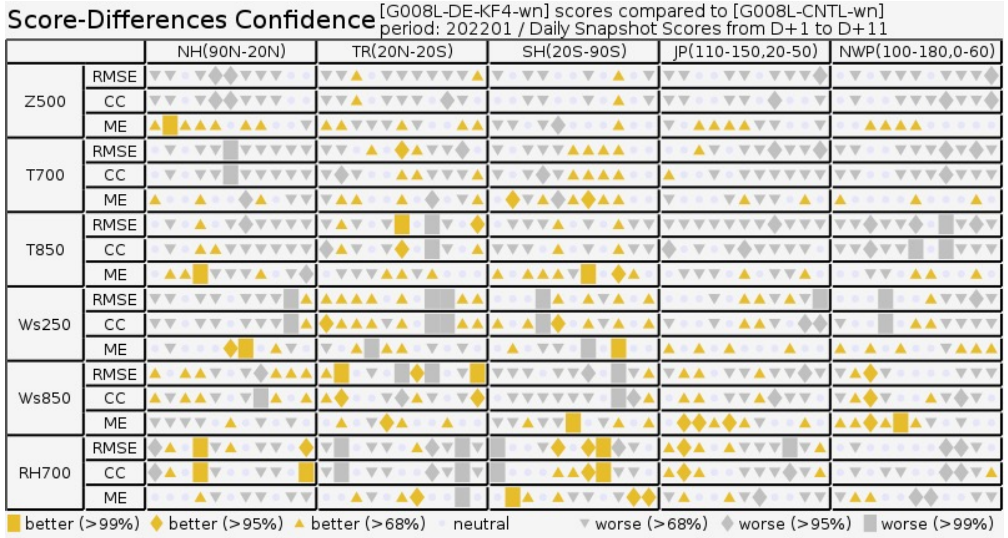
FT = 1-11 days **Aug.**



FT = 1-11 days **Jan.**







yellow : **improved**
gray : **degraded**

The impacts of BDE to the medium-range forecast are neutral.

Summary of DA cycle experiments

- The BDE was compared with the DE by using the global NWP system of JMA for MW temperature sounders over land.
  - The BDE improves the first guesses better than the DE and non-DE, particularly over Africa, the Middle East and Australia.
  - Also, the short-range forecast (FT=24 hr) is improved by the BDE mainly over Africa.
  - The impacts of DE and BDE to the medium-range forecast (up to 11 days) are neutral.

Future works

- It is necessary to improve the treatment of BDE over snow.
- Assimilating more surface-sensitive channels (AMSU-A/ch5, and ATMS/ch6) over land should be investigated to improve forecasts of lower atmosphere.

THANK YOU VERY MUCH!