Assimilation of cloud-affected infrared radiances

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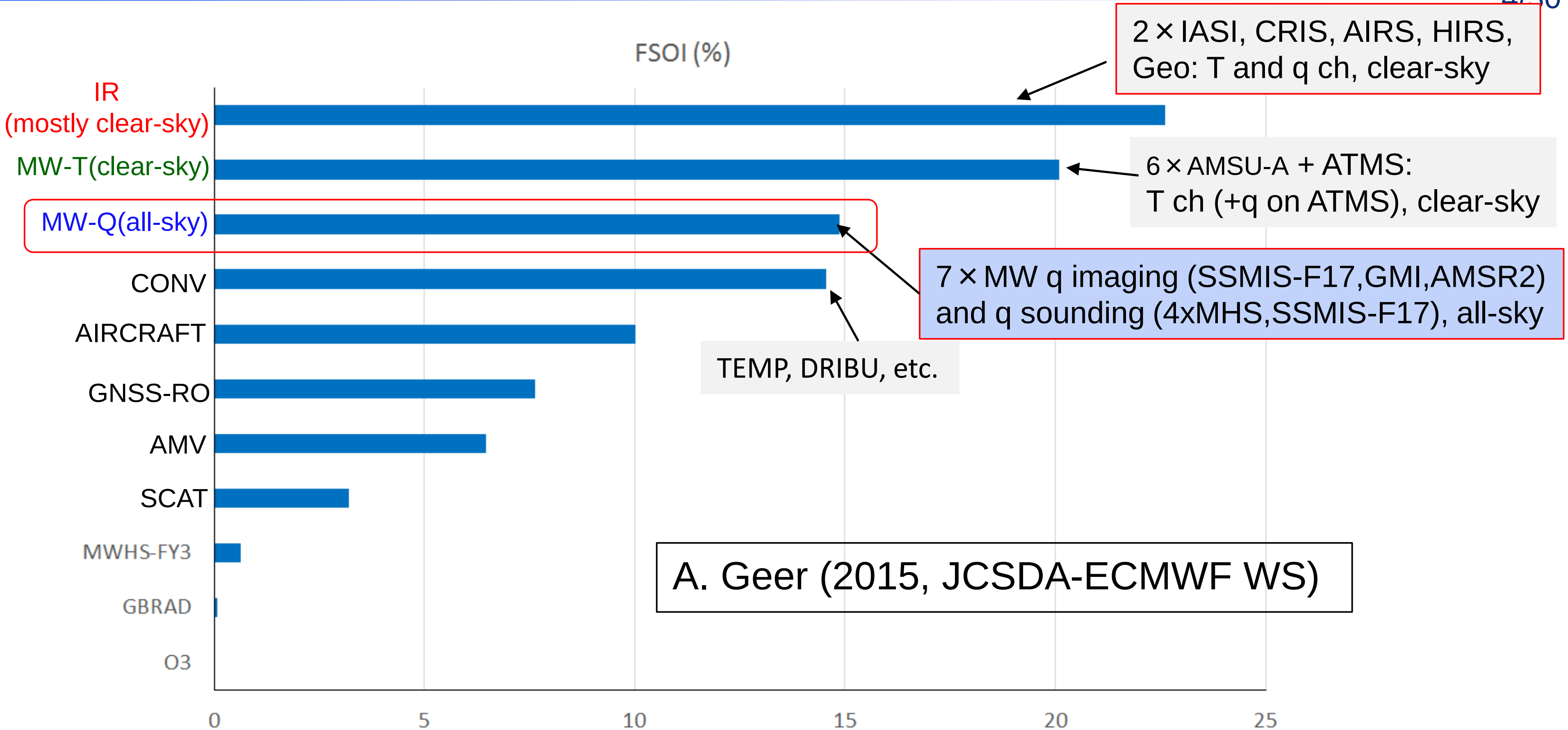
3. All-sky approach
4. Summary and plans

1. Background(1/2)

- Satellite radiance data from sounders/imagers have been playing significant roles in NWP data assimilation
- But the use of cloud-affected radiances is still limited especially for infrared (IR) spectral region
  - Mostly clear-sky region only
    - Issues: limited area, meteorologically less active, dry bias
  - Cloud-affected Micro Wave (MW) radiances have been operationally assimilated at ECMWF since 2009, and steadily improved

Forecast impact at ECMWF
Cy41r1, 1-10 Nov. 2015



- All-sky water-vapour, cloud and precipitation assimilation improves medium-range dynamical forecasts
- 4D-Var “tracing” adjusts dynamical initial conditions to fit WV, cloud and precipitation features in the analysis
- Going from “clear-sky” to “all-sky” roughly doubles the impact of WV channels

Background (2/2)

- Pros & Cons of IR radiance, compared with MW
  - Pros
    - Many instruments and satellites available
    - High spatial resolution: smaller footprint size & higher vertical resolution
    - High temporal resolution from geo-satellite (and many LEO satellites)
  - Cons: strong cloud absorption
    - High nonlinear response to clouds
    - Little information in and below (modest to thick) clouds

- Goal of this study is effective assimilation of cloud-affected IR radiances, in addition to clear-sky IR radiances, to improve analysis and forecasts

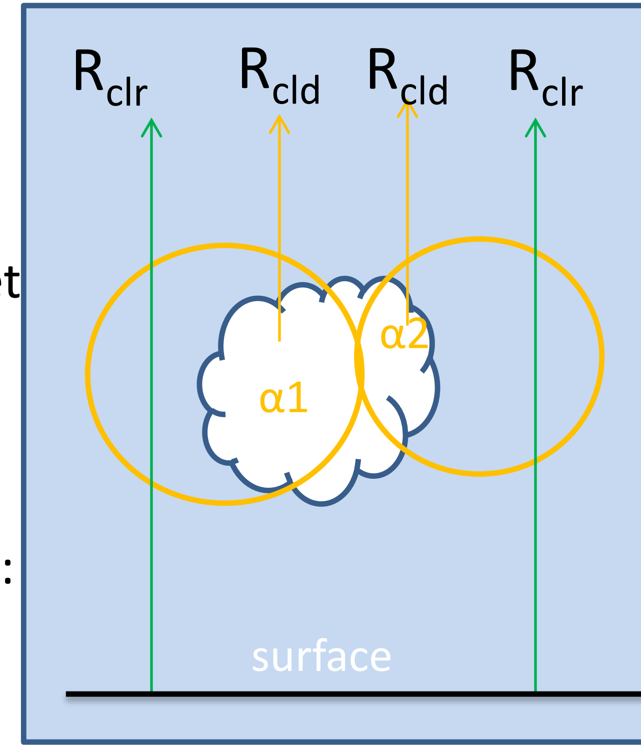
Four approaches to assimilate cloudy IR data

- 1. Retrieval
  - Cloud top height (temperature), (effective) cloud fraction,,,
  - Issues: Inconsistent definition for model and obs
- 2. Cloud-cleared radiance (CCR)
  - Construct pseudo clear-sky rad from adjacent pixel rads
  - Issues: hard to estimate obs error of the CCR
- <u>3. Simple cloud radiance</u>
  - Assume homogeneous single-layer cloud to simplify RT calculation
  - Implemented in the ECMWF operational system
- <u>4. All-sky radiance</u>
  - Handle general clouds (multi-layer, from thin to opaque)
  - Implemented in the ECMWF operational system only for MW humidity ch

Cloud-Clearing Methodology (NCEP)

FOV1: $R_1 = (1-\alpha_1).Rclr + \alpha_1.R_{cld}$

FOV2: $R_2 = (1-\alpha_2).Rclr + \alpha_2.R_{cld}$



Assume: R_{clr} and R_{cld} in the 2 adjacent FOVs are same

After eliminating R_{cld} from above 2 equations, we can get

$R_{ccr} = R_{clr} = R_1 + \eta.(R_1-R_2),$

where $\eta = \alpha_1/(\alpha_2 - \alpha_1)$ and $\alpha_1 \neq \alpha_1$

Extend to multiple cloud layers and more adjacent pixels:

$R_{ccr} = R_1 + \eta_1.(R_1-R_2) + \eta_2.(R_1-R_3) + \ldots\ldots + \eta_k.(R_1-R_k)$,

η_1, η_2 … are cloud-clearing parameters which depend on the α only. They can be estimated using a set of cloud-sounding channels to solve an over-constrained least-squares problem.

A. Collard (2015 JCSDA-ECMWF WS)

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2. Simple cloud approach

from Okamoto (2013, QJRMS)

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Simple cloud approach

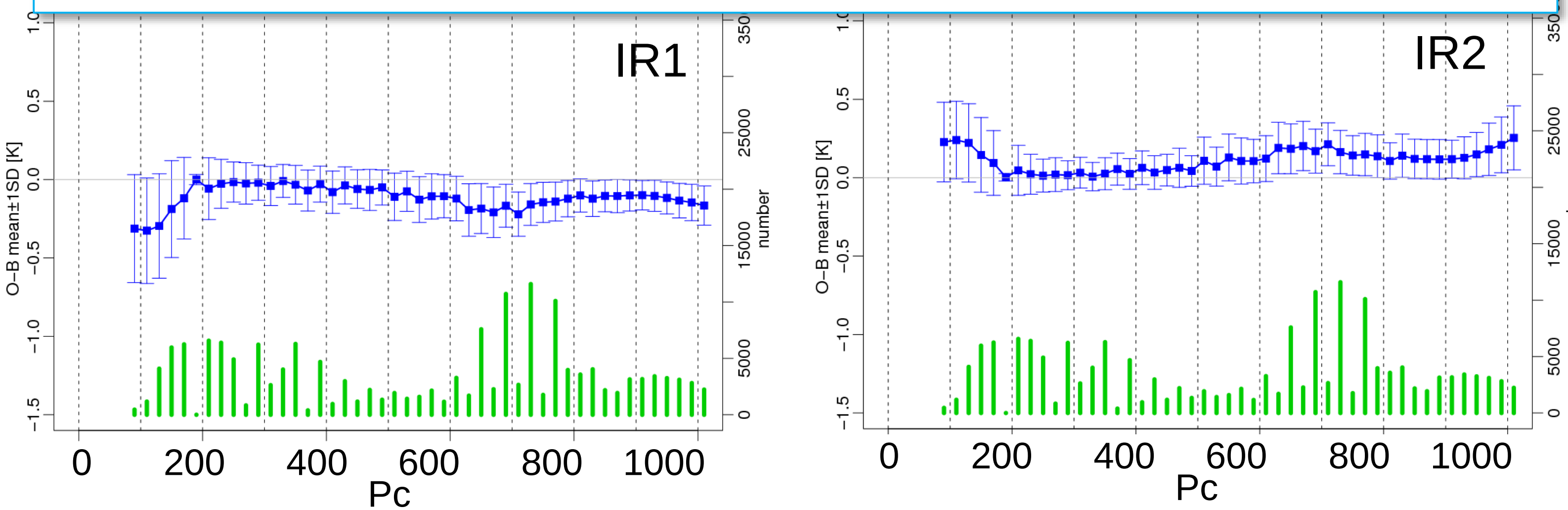
- Radiative Transfer Model (RTM) for simple cloud
  - $R^i = R^i_{clr}(1 - N_e) + R^i_{ovc} N_e$
    - R^i_{clr} : clear-sky radiance of channel I
    - R^i_{ovc} : completely overcast radiance from a blackbody cloud at top pressure P_c
    - N_e : effective cloud fraction = (geometric fraction N)*(cloud emissivity e)
    - Cloud effect is simulated by only N_e & P_c
  - **Condition 1**: cloud is homogeneous, single-layer
- N_e & P_c are estimated by minimizing $J = \Sigma_i^{Nch}(R^i_m - R^i)^2$
    - R^i_m : observed radiance at channel i
  - **Condition 2**: N_e is the same at all channels in J (emissivity consistency or gray cloud)
- Note that no model cloud variables are used

- Key is how to identify cases that satisfy these conditions

Okamoto (2013, QJRMS)
Assimilate cloudy rad of MTSAT-1R with the simple cloud approach

- Developed QC procedures to satisfy the conditions for MTSAT-1R
  - N_e>0.8
  - Clear-sky pixel ratio<5%, and standard deviation of pixel TB < 4.5
    - Super-ob is created by tens of original pixels to better handle representative diff between obs and model (30km in radius)
  - Consistent OB-FG at different ch → 160<P_c<650hPa
  - Strict gross error QC : |OB-FG|<0.6K
- → We call these radiances OR (overcast radiance)

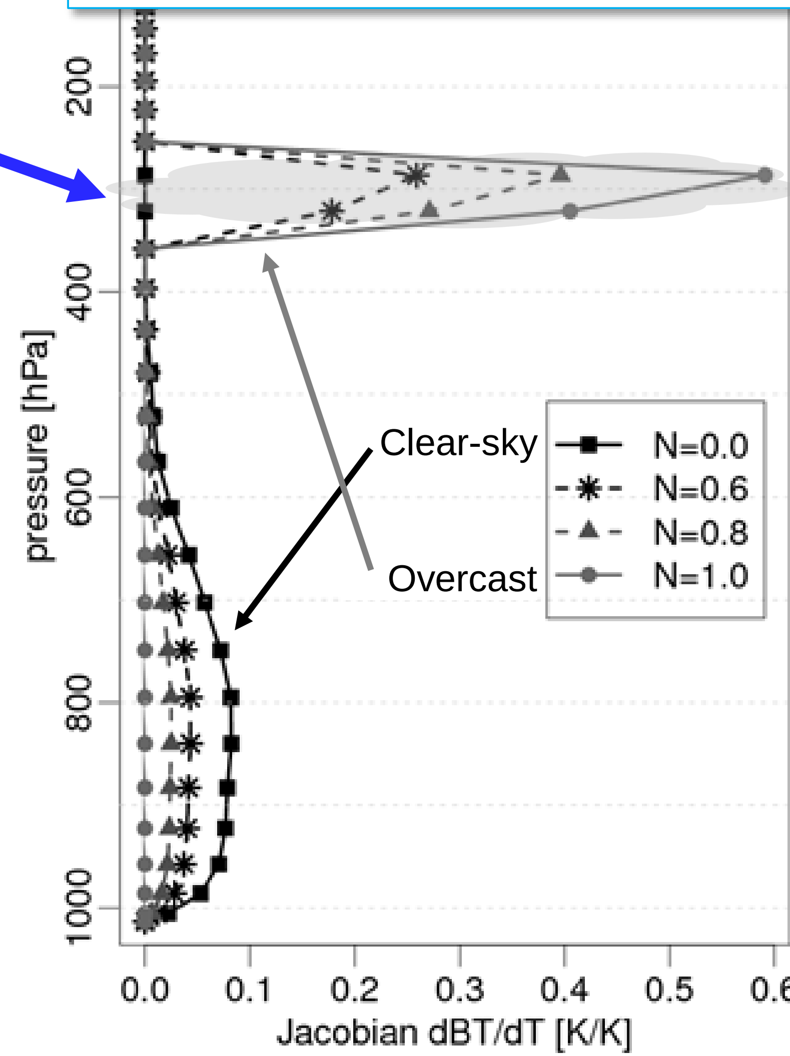
OB-FG mean and number with Pc



Unique characteristics of ORs from geo-sat

- Highly resolved vertical information of temperature at the cloud top
- Highly resolved temporal information
  - Every hour for full disk region
  - Tracer effect through linearized forecast model in 4D-Var
    - Lupu & McNally (2012)

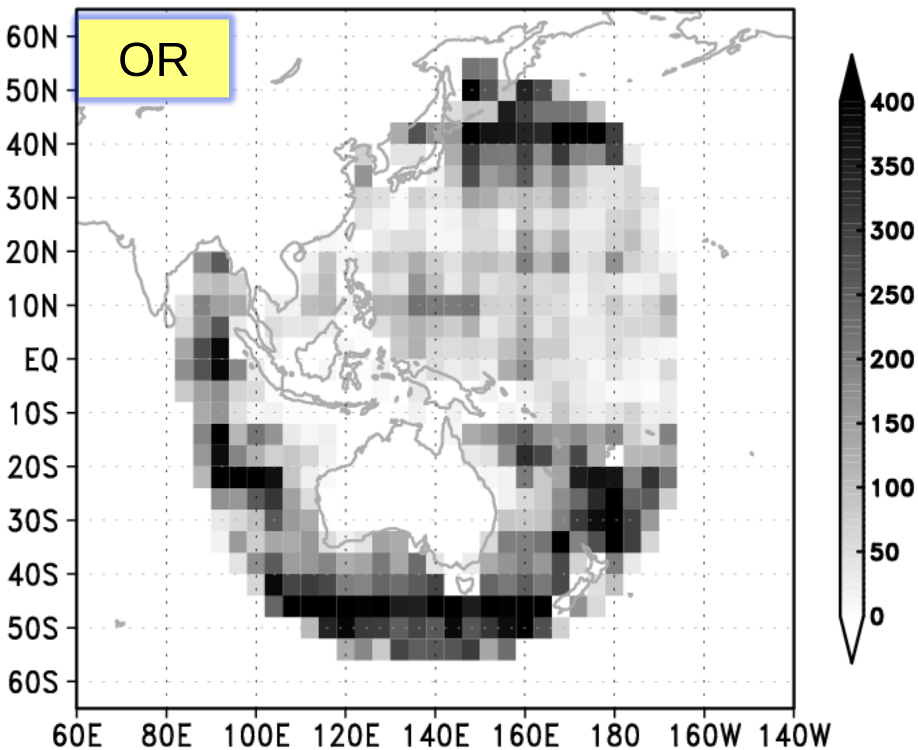
dTB/dT for clouds with
Ne=0.0~1.0 at Pc=300hPa
MTSAT-1R IR1 ch

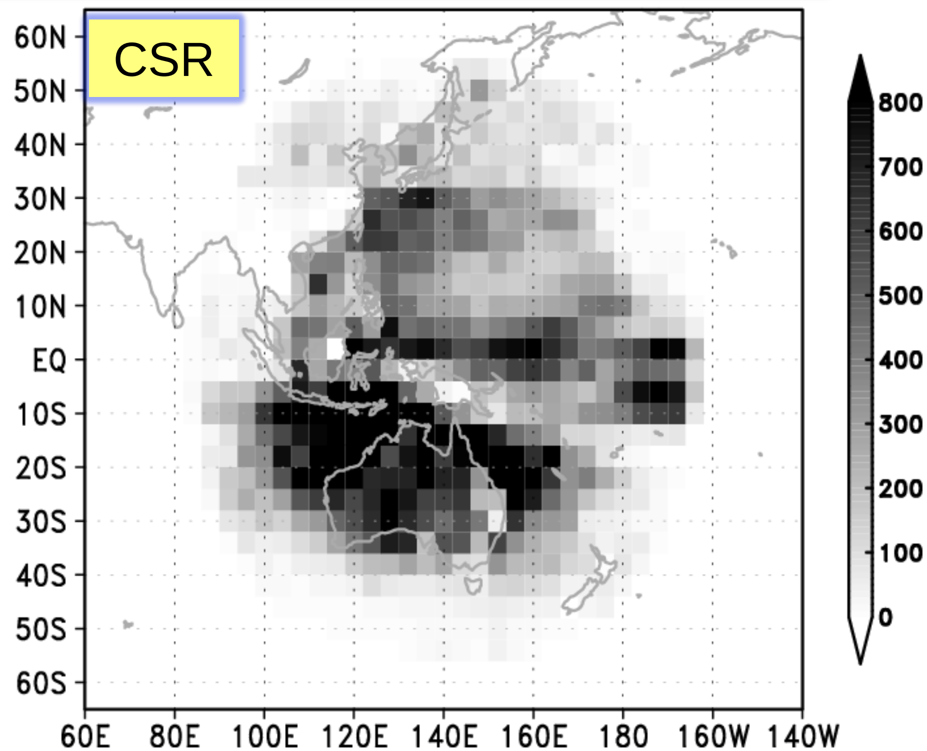


Assimilation of MTSAT-1R ORs

- Assimilate ORs at IR1 (11um) channel of MTSAT-1R in JMA global 4D-Var
  - N_e & P_c are given from background and fixed in minimization
- Complement operationally used CSRs (clear-sky radiances)
  - Half the number of CSRs

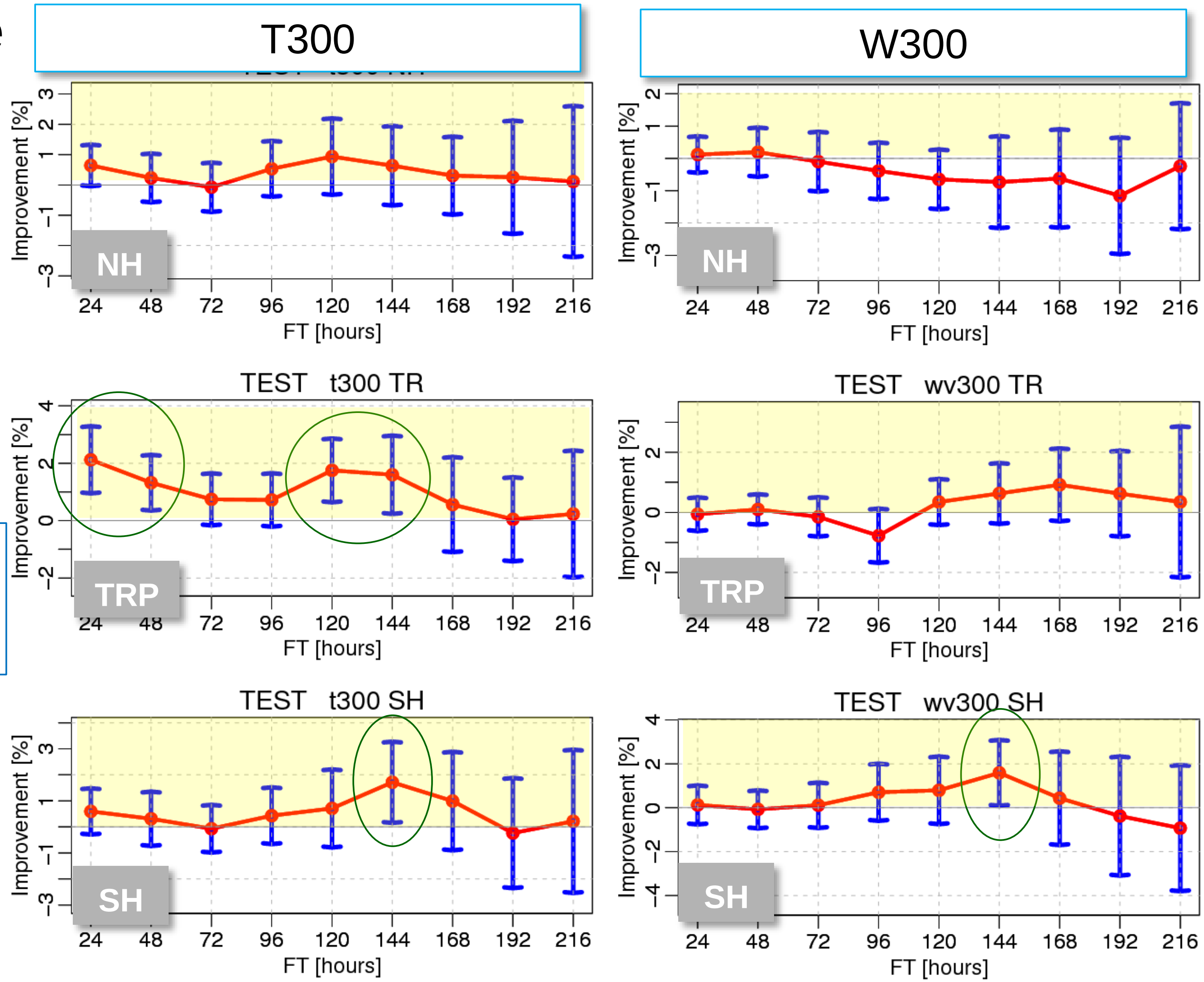
One month accumulated number of assimilated data in August 2009





Forecast improvement by ORs

- Neutral or slightly positive impact



Relative changes in forecast RMSE :
・positive → improvement

Summary of simple cloud approach

- Easy implementation
  - 1. Estimate Pc and Ne from FG and OB
  - 2. QC
  - 3. Add cloud effect by including Pc and Ne in RTM
- However, cloudy radiance data are <u>still limited in use</u>
  - Applicable to homogeneous single-layer cloud cases only
  - Model cloud variables are not directly used (corrected) in the analysis
- Exploit IR radiances in more general cloud cases
  → all-sky radiance assimilation
  - Use more general RTM and cloud profiles
  - Apply all-sky MW radiance assimilation approach to IR

Content

1. Background
2. Simple cloud approach

3. All-sky approach

from Okamoto et al. (2014, QJRMS),
Okamoto & Kazumori (2015, JCSDA-ECMWF WS)

4. Summary and plans

Approach	Clear-sky	Simple-cloud	All-sky
Target	Clear-sky rad	Homogeneous single-layer cloudy rad	General cloudy rad
RTM and inputs	$R_{clr}(T_i,Q_i)$ ✓ no cloud effect	$(1-N_e)*R_{clr} + N_e*R_{ovc}$ ✓ $R_{ovc}(T_i,Q_i,P_c)$	$R(T_i,Q_i, C_i, F_i)$ ✓ full cloud effect
Initialize cloud	No	No or Partially yes	Yes
Challenges	✓ Clear-sky identification	✓ Retrieve Ne,Pc ✓ Simple cloud identification	✓ Non-Gaussianity, Non-linearity ✓ Cloud predictability ✓ RTM
Status	Operational at many NWP centers	Operational at ECMWF and MeteoFrance	Not operational except for MW at ECMWF

- T_i: temperature profile, Q_i: humidity profile
- P_c: cloud top pressure, N_e: effective cloud fraction
- C_i: cloud content profile, F_i: cloud fraction profile

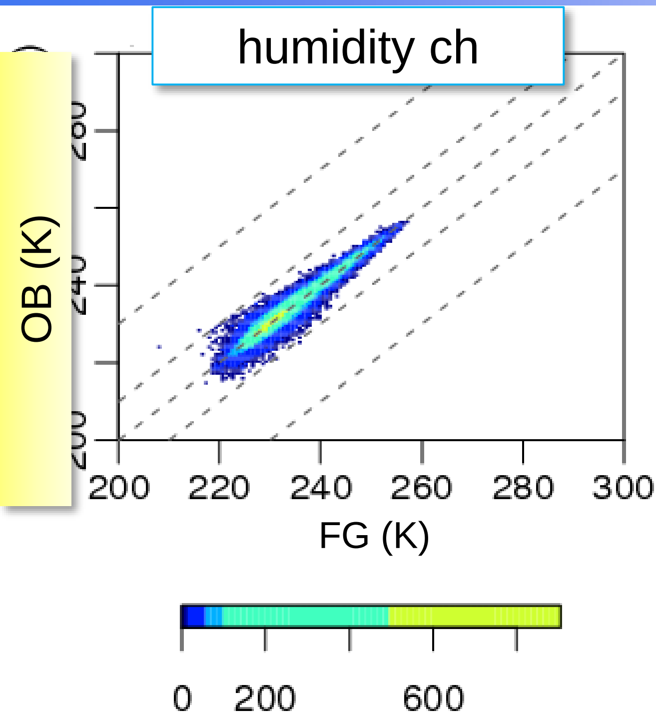
As the first step of all-sky IR rad assimilation,

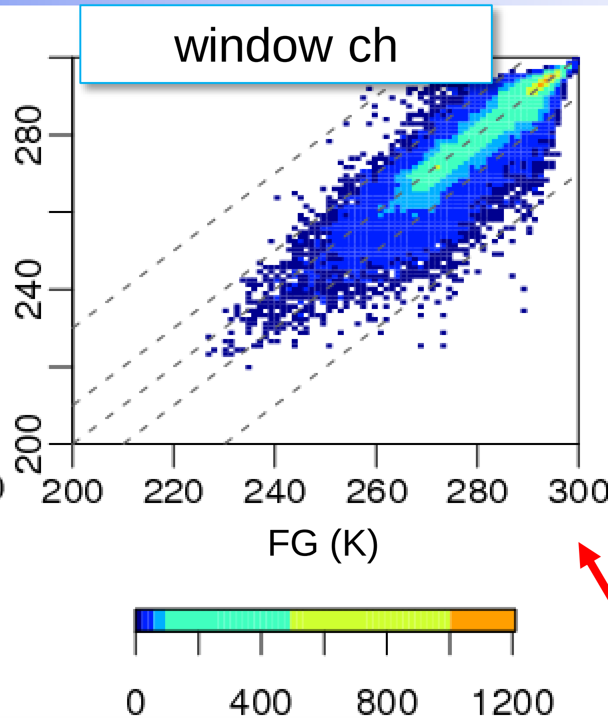
- Examine model reproductivity of cloudy radiances
  - Compare obs and model simulation
- Develop a parameter to estimate cloud effect in radiance space
  - Predict OB-FG statistics using the parameter
    - Cloud plays dominant effect on OB-FG
  - Apply cloud-dependent QC and obs.error assignment using the parameter

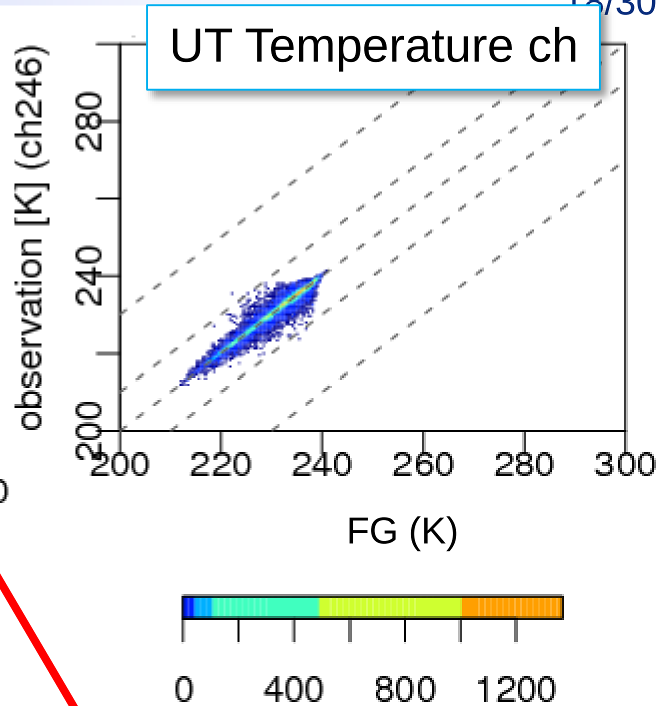
- Assimilation experiment is under preparation

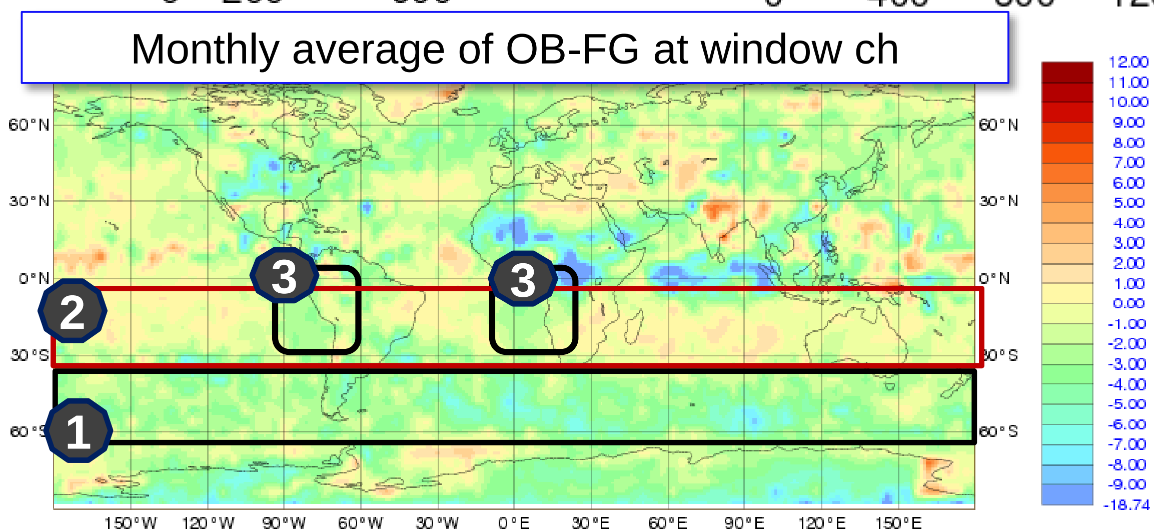
- Results of the comparison and applying the cloud effect parameter
  - Metop/IASI in global system (ECMWF-IFS)
    - T511L91 (~40km)
    - RTTOV10.2, Cloud water/ice/fraction from moist physics model
    - 1~15 Aug. 2011, over the sea
  - Himawari-8/AHI in meso-scale cloud resolving system (JMA-NHM)

IASI comparison in ECMWF global system







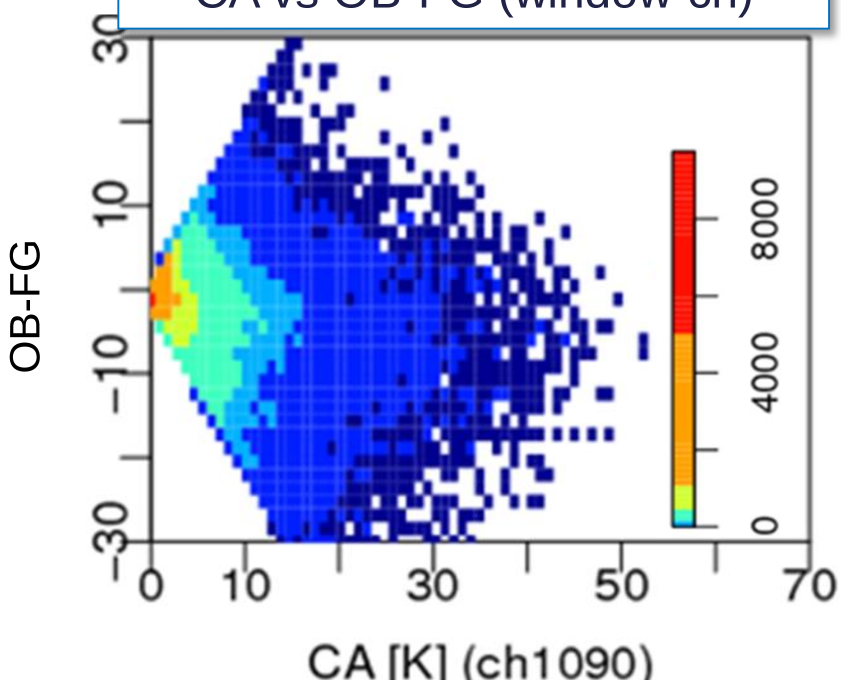


85% (69%) satisfies
|OB-FG|<10K (5K)

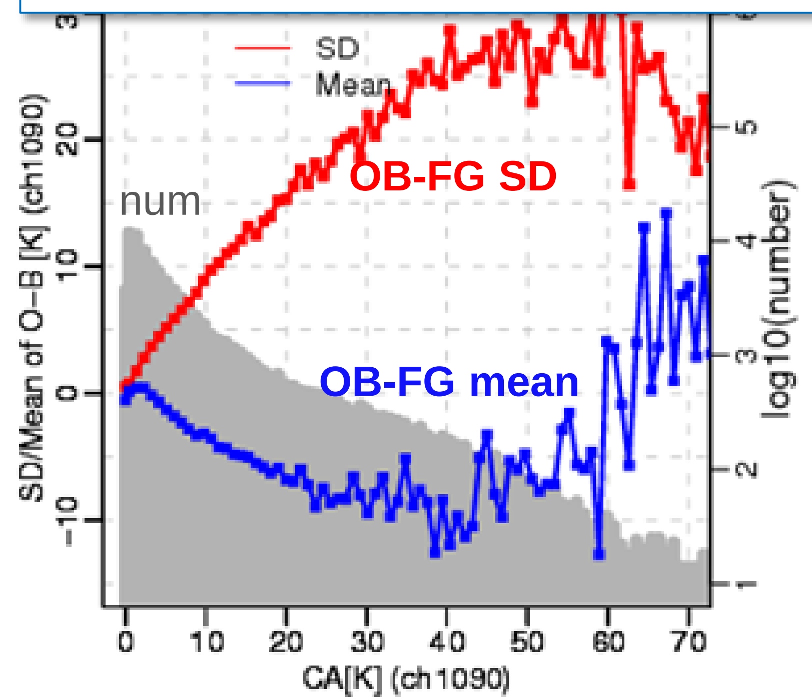
Cloud effect on OB-FG

- Develop a new parameter representing cloud effect : CA
  - CA = 0.5*(|FG-FGclr|+|OB-FGclr|), FGclr=clear-sky FG
- As CA increases, OB-FG variability monotonically increases. After saturation, it decreases (in overcast condition)
- This simple relationship between CA and OB-FG SD enables us to predict (cloud-dependent) OB-FG SD using CA

CA vs OB-FG (window ch)

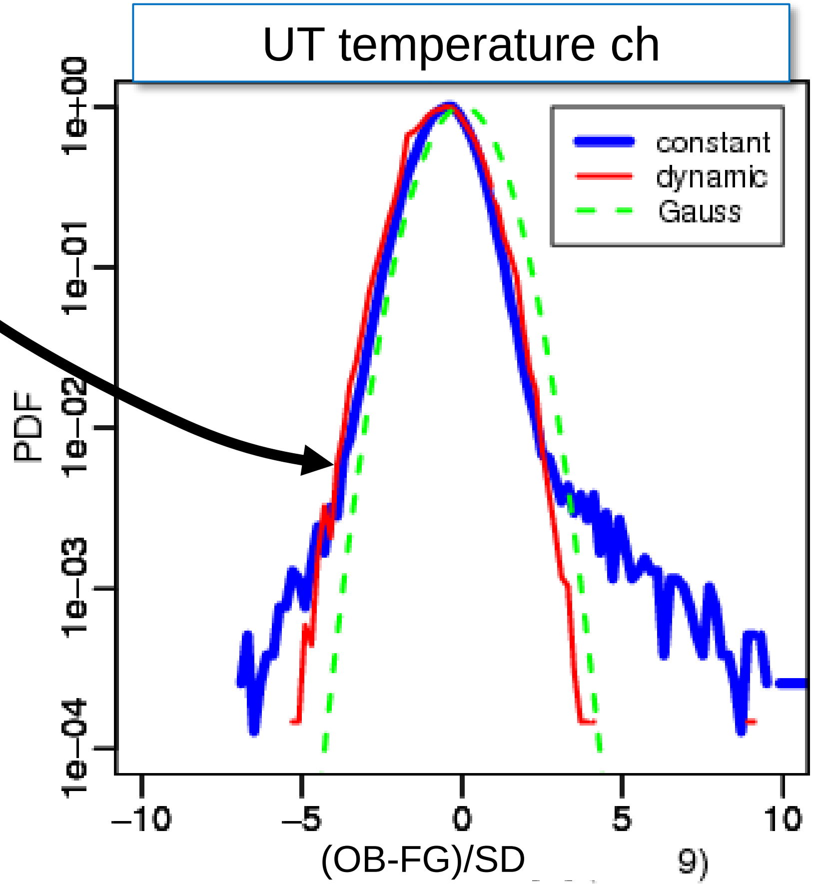


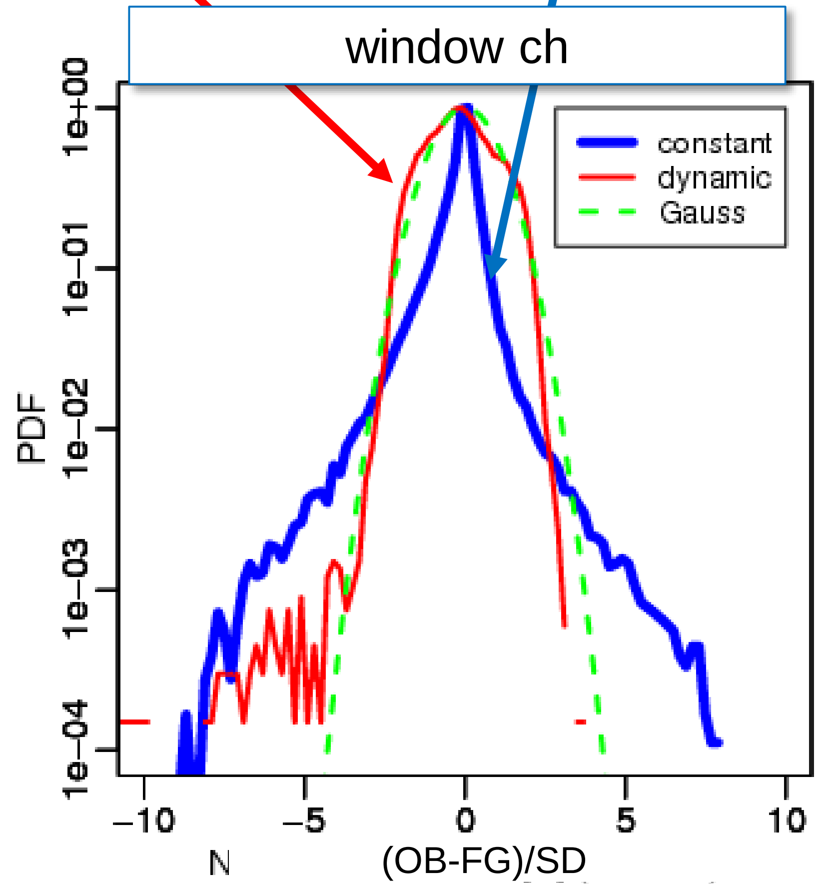
CA vs OB-FG SD & OB-FG mean



Gaussianity of normalized OB-FG PDF

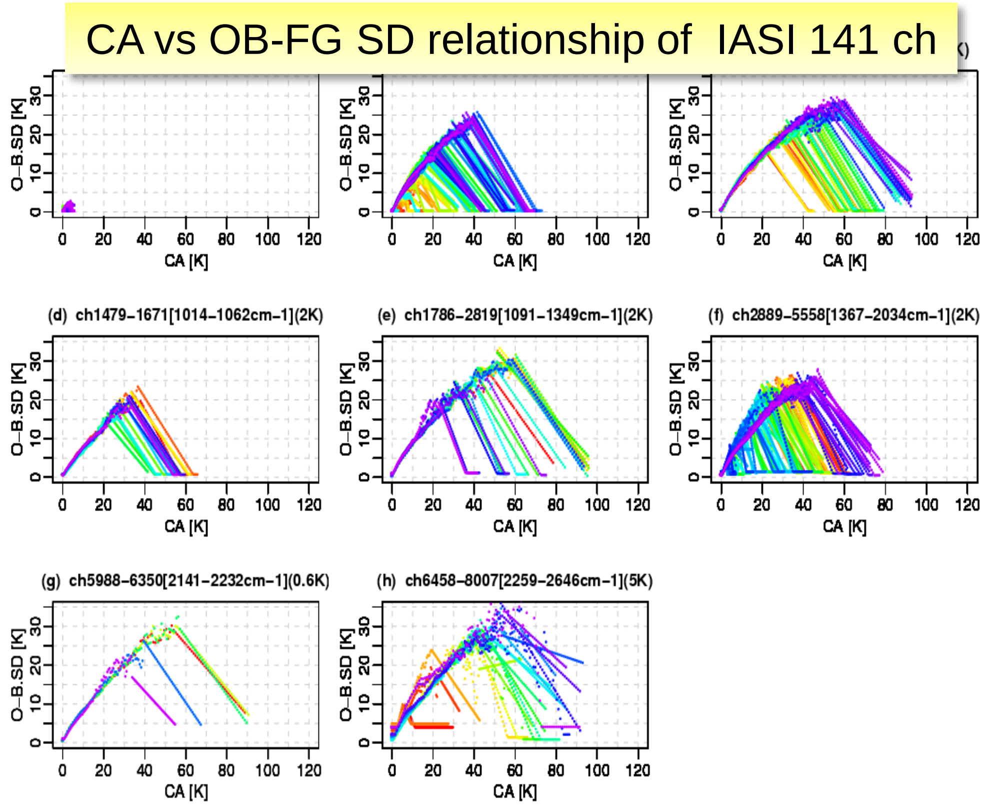
- Normalized OB-FG PDF shows
  - Gaussian form for ch that is not strongly affected by clouds
  - Excessively sharp peak and long tail when cloud-dependency of SD is ignored
  - Gaussian form if cloud-dependent SD is used





Application of predicting OB-FG SD

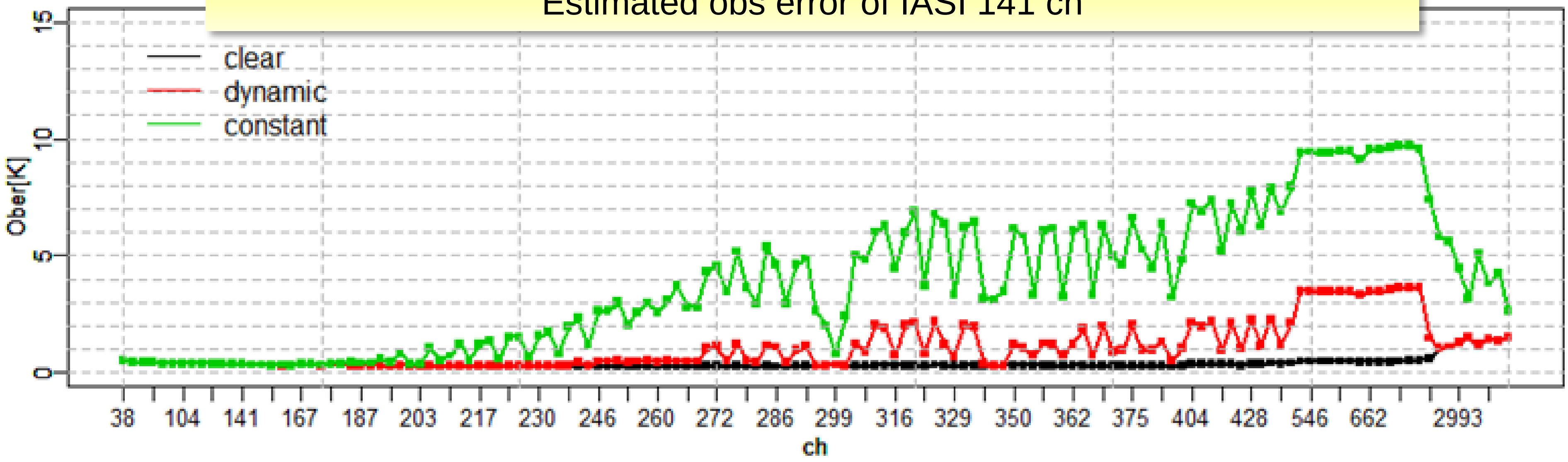
- The predicted OB-FG SD can be used for
  - Cloud-dependent QC
    - Vary the threshold dependent on cloud effects
  - Cloud-dependent obs error
    - Increase (decrease) obs error for data with large (small) cloud effect



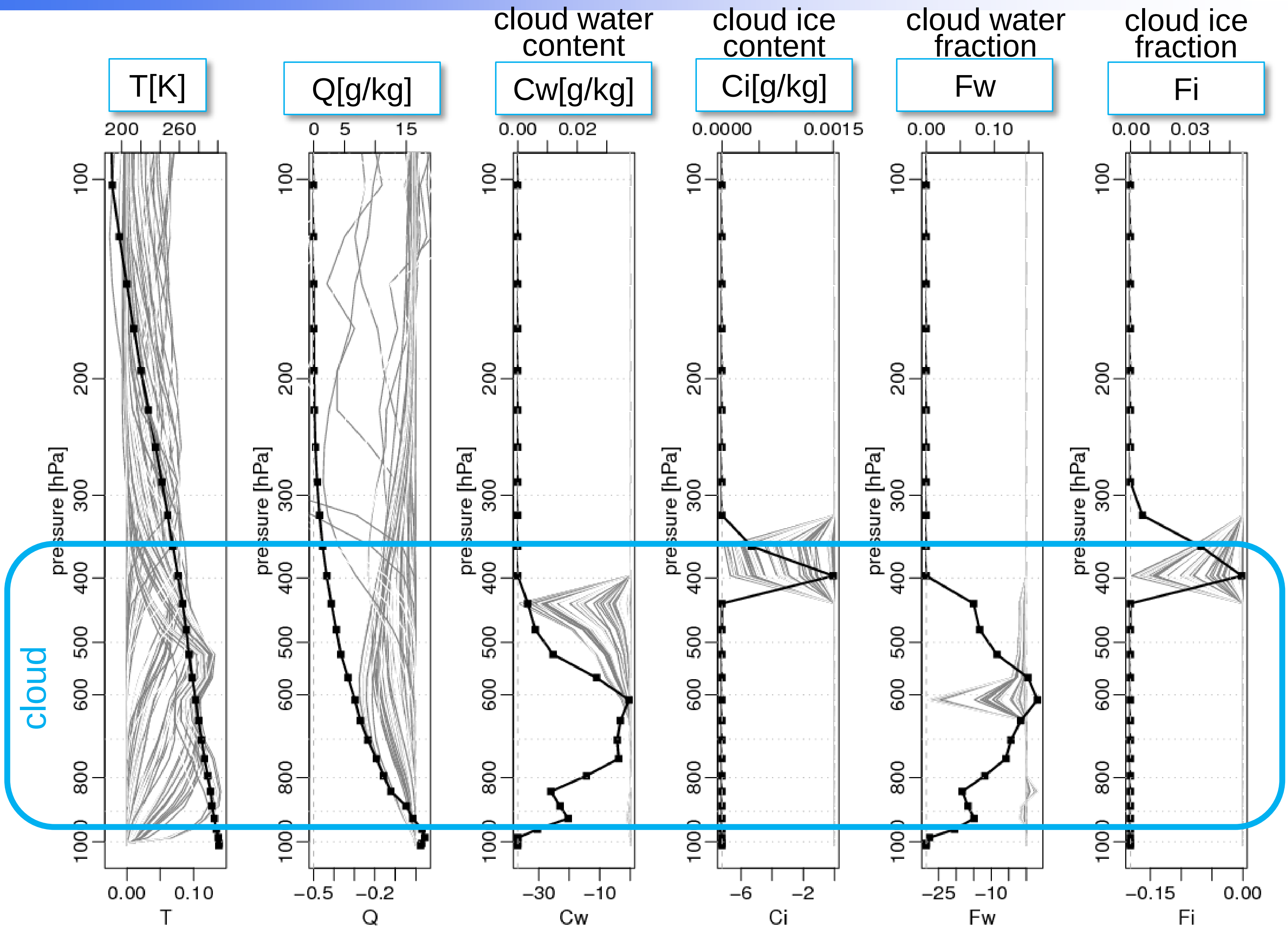
Example: cloud-dependent obs error

- Calculate observation errors in thin cloud case
  - Assume OB-FG SD equals obs error
  - **Black**: obs error for clear-sky rad, used in the ECMWF operational system
  - **Green**: constant obs error, from the whole sample → excessively large
  - **Red**: cloud-dependent obs error, predicted from CA-SD LUT
    - In this example, due to thin cloud, cloud-dependent obs error is much smaller than constant obs error

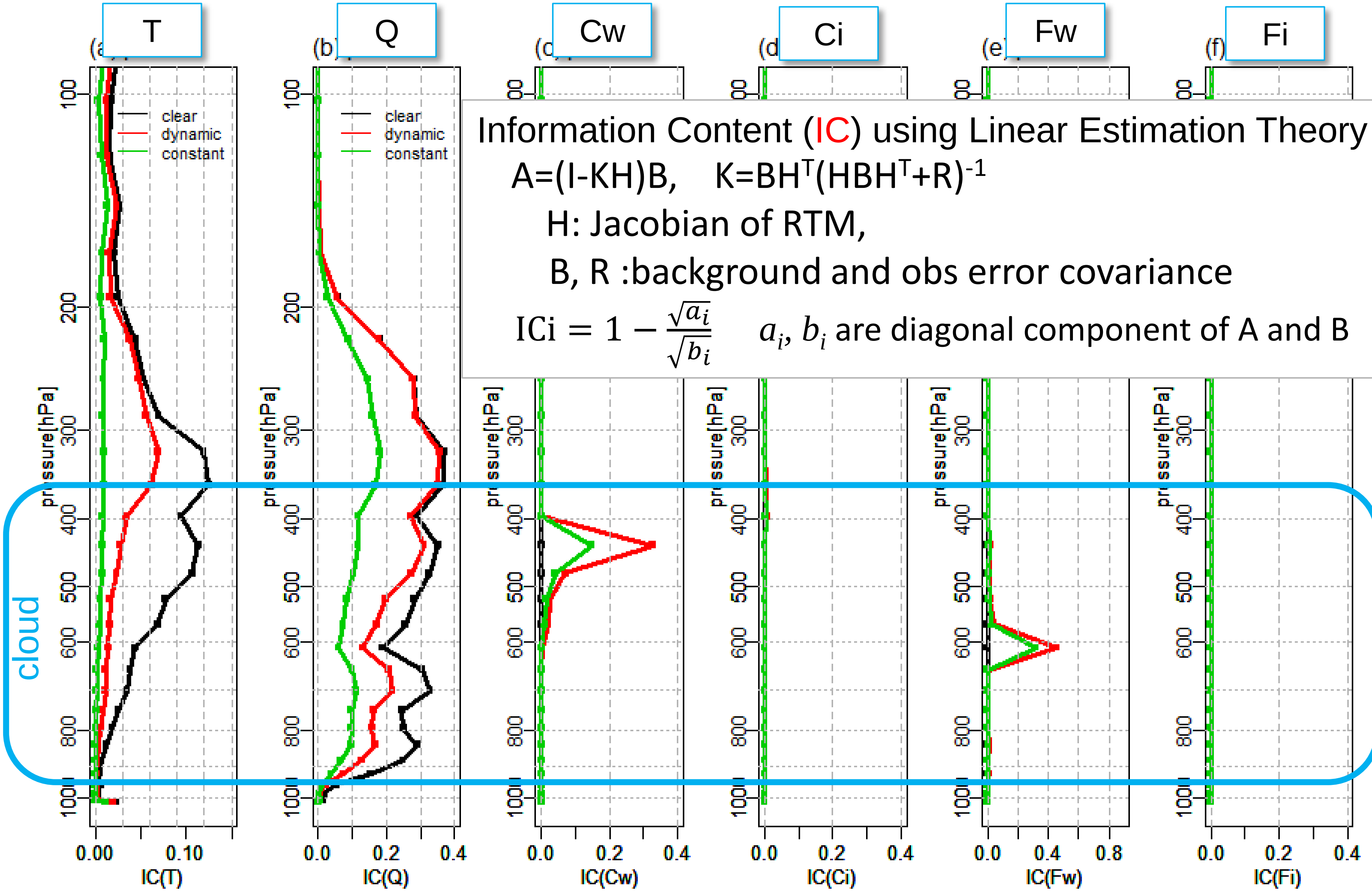
Estimated obs error of IASI 141 ch



Profiles (black) and Jacobians (gray) of the thin cloud case



Information content (IC) for **clear-sky**, **cloud-dep**, **const** obs.error



Information Content (IC) using Linear Estimation Theory

A=(I-KH)B, $K=BH^T(HBH^T+R)^{-1}$

H: Jacobian of RTM,

B, R :background and obs error covariance

$$\mathrm{ICi} = 1 - \frac{\sqrt{a_i}}{\sqrt{b_i}}$$

a_i, b_i are diagonal component of A and B

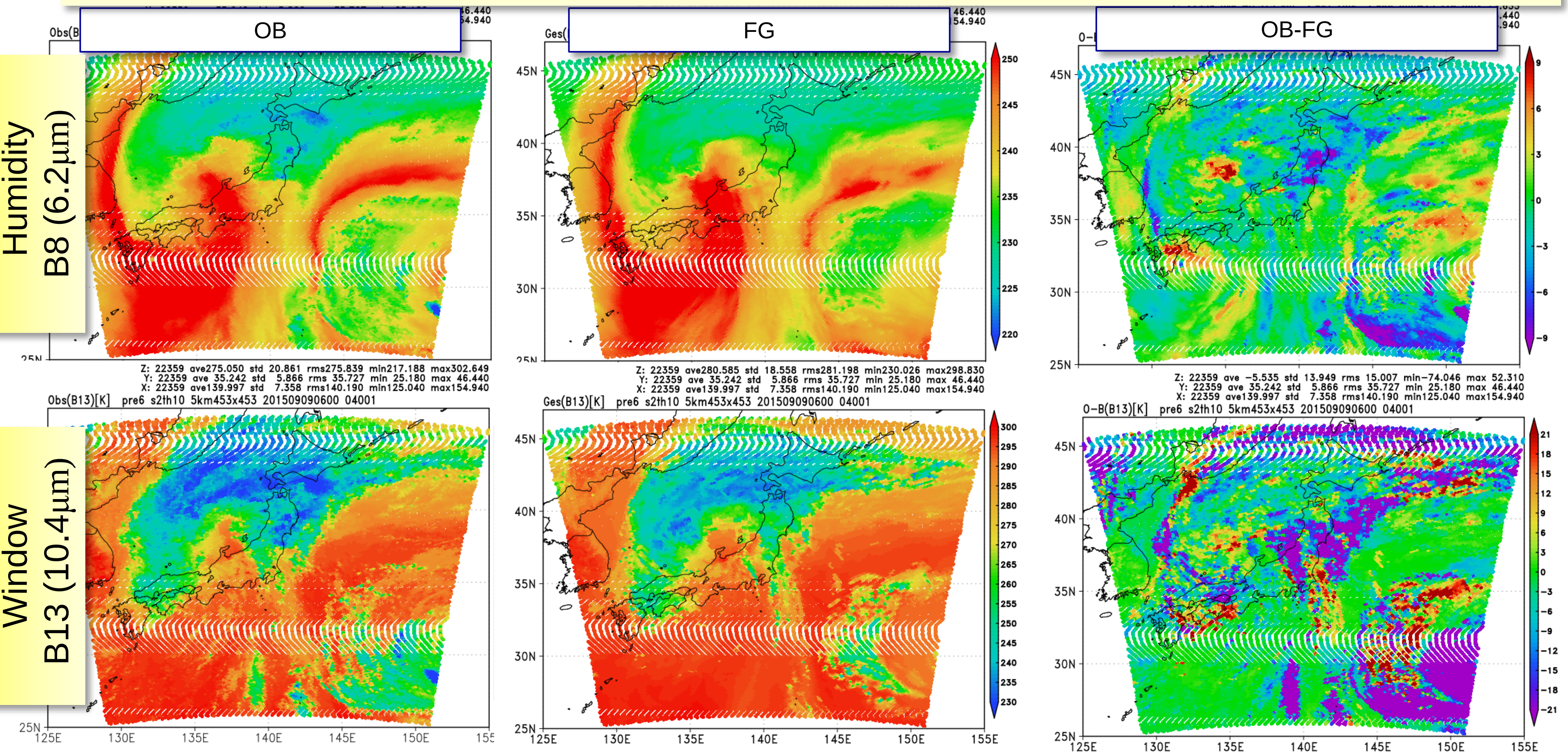
Himawari8/AHI comparison with JMA-NHM

- Himawari-8/AHI
  - 10 IR bands with 2.0 km resolution
- JMA-NHM
  - Cloud-resolving, Non-Hydrostatic Model, used for operational meso-scale system
  - 5 hydrometeors
  - 5km-res, 50 layers,
- RTTOV11.2
  - Input clouds from micro-physical process (grid-scale cloud)
  - Cloud fraction is set to one
- Pre-processings
  - Super-ob : Averaging 2x2pixels
  - Remove data with |OB-FG|>30K or 50K
- Case : 03~09 UTC on 7~11 Sep 2015
  - ~220,000 samples

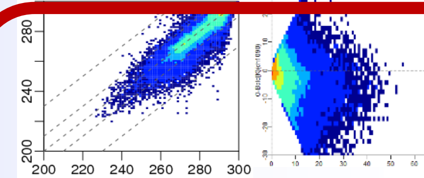
Himawari-8,9/AHI		
Band	Wavelength [μm]	Spatial Resolution
1	0.43 - 0.48	1km
2	0.50 - 0.52	1km
3	0.63 - 0.66	0.5km
4	0.85 - 0.87	1km
5	1.60 - 1.62	2km
6	2.25 - 2.27	2km
7	**3.74 - 3.96**	**2km**
8	**6.06 - 6.43**	**2km**
9	**6.89 - 7.01**	**2km**
10	**7.26 - 7.43**	**2km**
11	**8.44 - 8.76**	**2km**
12	**9.54 - 9.72**	**2km**
13	**10.3 - 10.6**	**2km**
14	**11.1- 11.3**	**2km**
15	**12.2 - 12.5**	**2km**
16	**13.2 - 13.4**	**2km**

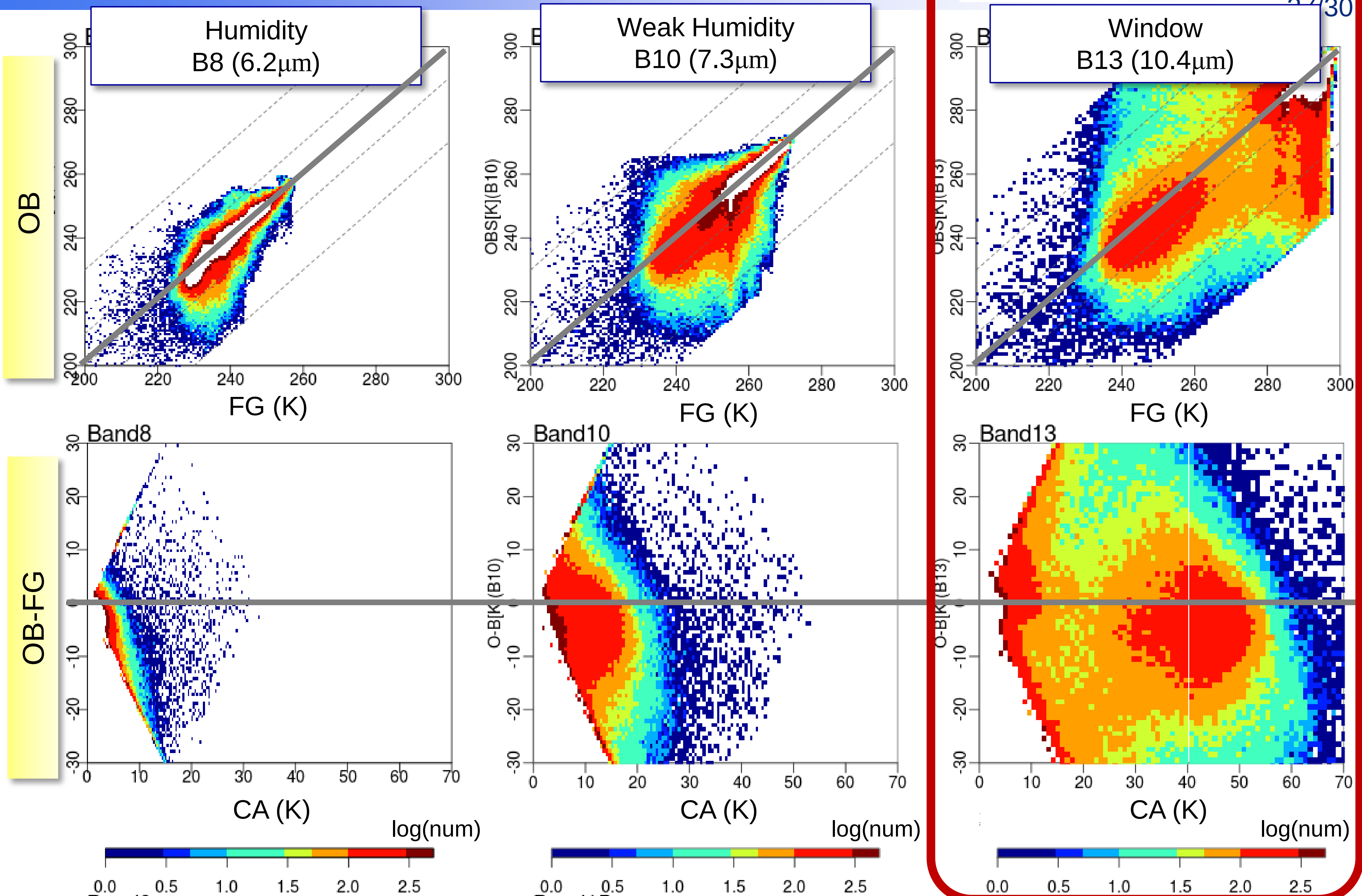
Himawari8/AHI comparison with JMA-NHM

Example at 06 UTC on 20150909

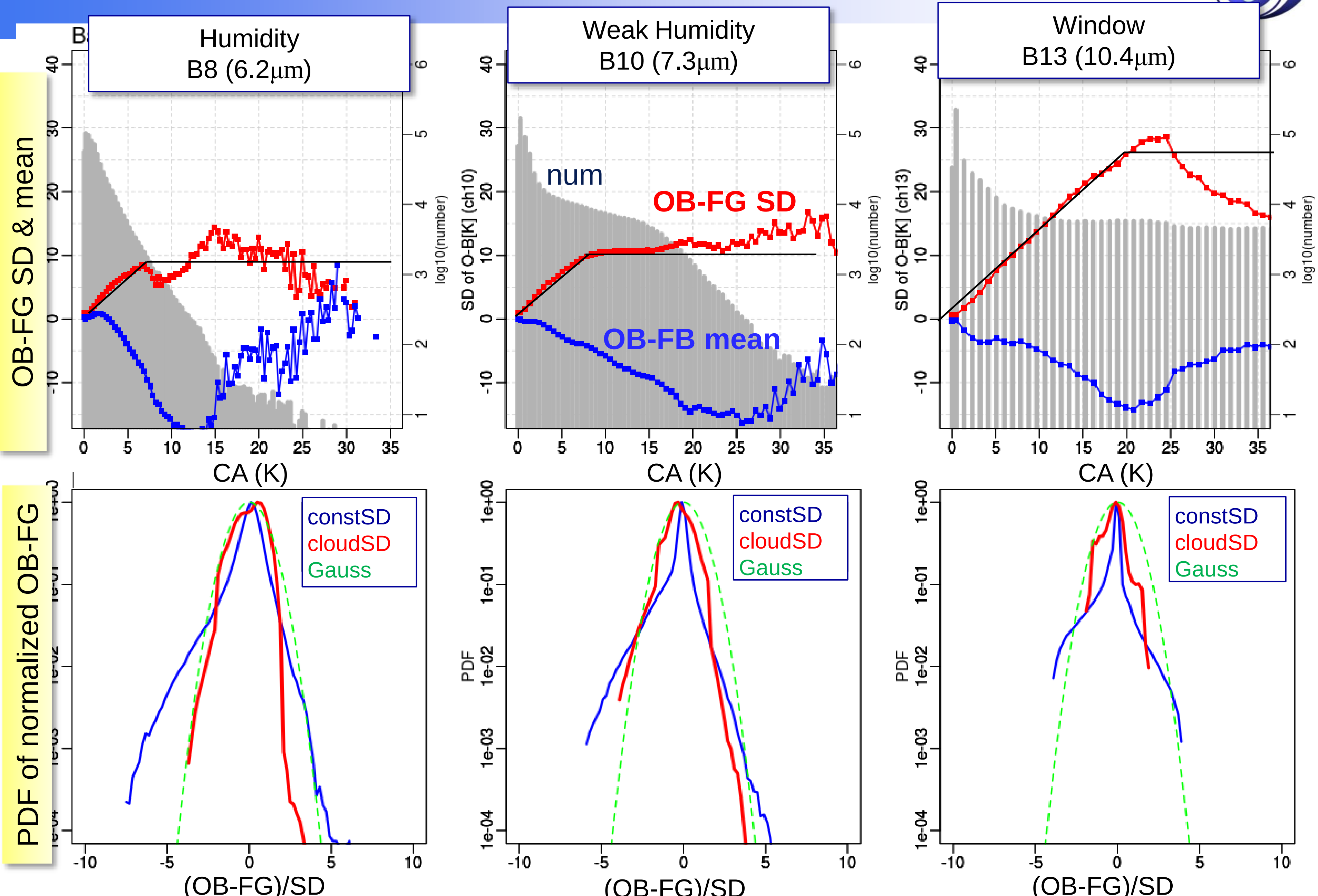


AHI comparison with JMA-NHM





AHI OB-FG variability and PDF



Summary and plans

- Cloud-affected IR radiances contains unique info of T/Q/C with high spatial/temporal resolution
- Simple cloud approach
  - Assume homogeneous single-layer clouds
  - Easy implementation but small impacts due to restricted additional data and indirect adjustment of cloud variables
- All-sky approach
  - Handle general clouds → require NWP and RT models to well simulate cloud (effect)
  - Cloud effect parameter CA was developed to predict OB-FG variability
    - → Cloud-dependent QC and obs error (and BC?)
  - Assimilation experiments with AHI and JMANHM-Letkf is under preparation