Improvement of Simulated Cloud-Radiation Database for PMW Rain Retrieval in East Asia: *EOF+1dVAR Optimization*

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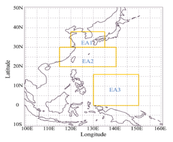
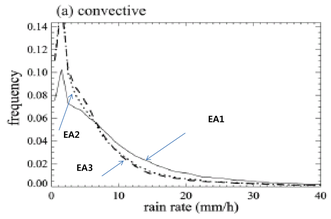
BACKGROUND & NECESSASITY

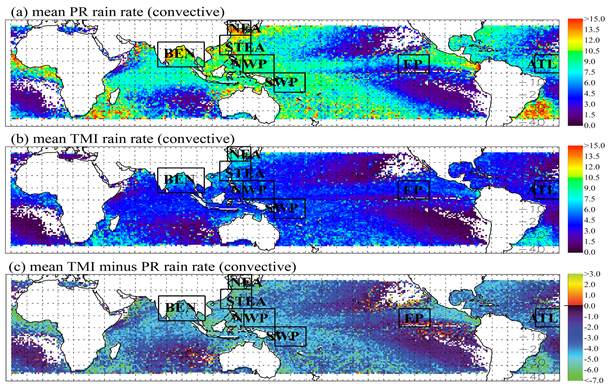
- The Korean Peninsula (EA1) and its surroundings have unique geographical and geophysical environments such as peninsula, surrounding oceans, strong baroclinicity, mid-latitude and monsoon.



- Those characteristics are clearly reflected in TB(85GHz) – rain rate relations (Seo 2009; Ryu et al. 2012).
- The region shows a large discrepancy between TMI and PR rain (Seo et al. 2015).

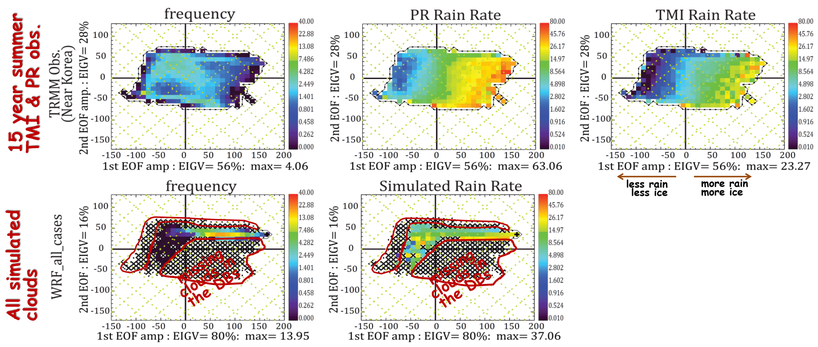


- The PMW rain retrieval is very challenging in this region.
- For Bayesian rainfall retrieval algorithms, the representativeness of a priori DB to natural phenomena in the atmosphere becomes a critical issue.



REPRESENTATIVENESS of SIMULATED DBs

- Five representative cases of summer rainfall in the vicinity of the Korean Peninsula are simulated using the WRF model.
- Simulated TB manifolds in the observational TMI TB EOF space

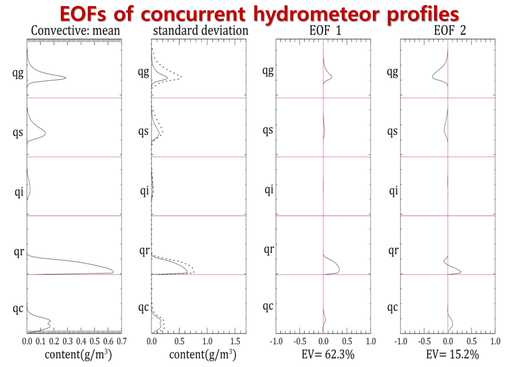


- The five simulated cases show serious lack of representing clouds occurring in NATURE.
- Therefore, (1) we need to remove some unrealistic cloud profiles in the DB, (2) repair the cloud profiles which are not consistent to TMI and PR observations, and (3) add missing clouds in the DB.

HOW TO OPTIMIZE SIMULATED DBs

- In order to repair the simulated clouds, we need to utilize cloud observations such as TMI and PR measurement.
- To do so, we need to deal with the variables in 5*nz (five hydrometeor species x the number of vertical levels) dimension. This is a huge dimension, resulting in very heavy computation.
- To mitigate the high dimension, we use coefficients (amplitudes) of concurrent hydro EOFs since the coefficients retain five hydrometeor structures.
- By efficiently alleviating the mathematically ill-posed problem, **we did not have to make a strong assumption to remove a certain hydrometeor species or to use simple relations among hydrometeor species.**

EOFs of concurrent hydrometeor profiles



$$\boldsymbol{Q}_i = \begin{bmatrix} \boldsymbol{q}_c \\ \boldsymbol{q}_r \\ \boldsymbol{q}_i \\ \boldsymbol{q}_s \\ \boldsymbol{q}_g \end{bmatrix} \begin{matrix} \text{cloud liquid water} \\ \text{profile} \\ \text{rain} \\ \text{cloud ice} \\ \text{snow} \\ \text{graupel} \end{matrix}$$

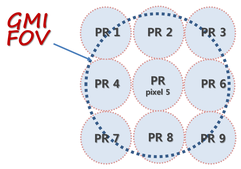
$$\boldsymbol{Q}_i = \bar{\boldsymbol{Q}} + \boldsymbol{Q}_i' = \bar{\boldsymbol{Q}} + \sum_{k=1}^{N} \alpha_{i,k}\, \hat{\boldsymbol{e}}_k$$

coefficients of concurrent EOFs — concurrent EOFs

SETUP of EOF+1dVAR OPTIMIZATION with EOFs

- Setup of the hybrid 1D-VAR combined with the major (about 12-16) EOFs
- Two stepwise approaches with the two different FOV scales and scale factor adjustment

$$\tilde{\boldsymbol{Q}}_{m,k} = \begin{bmatrix} \tilde{\boldsymbol{q}}_{c,k} \\ \tilde{\boldsymbol{q}}_{r,k} \\ \tilde{\boldsymbol{q}}_{i,k} \\ \tilde{\boldsymbol{q}}_{s,k} \\ \tilde{\boldsymbol{q}}_{g,k} \end{bmatrix} = \bar{\boldsymbol{Q}} + \sum_{j=1}^{m} x_j \hat{\boldsymbol{e}}_j \qquad \mathbf{X} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$



Step 1. Set up the first cost function (Ψ_k) using the PR observations for the kth PR pixel and then find X which minimizes Ψ_k.

k^th PR pixel

$$\begin{aligned}\Psi_k(\mathbf{X}, N_{0r}) = {} & [\boldsymbol{Z}^o_{Ku} - \boldsymbol{Z}^m_{Ku}(\mathbf{X}, N_{0r})]^T \boldsymbol{O}_Z^{-1} [\boldsymbol{Z}^o_{Ku} - \boldsymbol{Z}^m_{Ku}(\mathbf{X}, N_{0r})] + \\ & [PIA^o_{Ku} - PIA^m_{Ku}(\mathbf{X}, N_{0r})]^T O_{PIA}^{-1} [PIA^o_{Ku} - PIA^m_{Ku}(\mathbf{X}, N_{0r})] + \\ & [\boldsymbol{Z}^o_{Ku} - \boldsymbol{Z}^m_{Ku}(\mathbf{X}, N_{0r})]^T \boldsymbol{O}_Z^{-1} [\boldsymbol{Z}^o_{Ka} - \boldsymbol{Z}^m_{Ka}(\mathbf{X}, N_{0r})] + \\ & [PIA^o_{Ku} - PIA^m_{Ka}(\mathbf{X}, N_{0r})]^T O_{PIA}^{-1} [PIA^o_{Ku} - PIA^m_{Ka}(\mathbf{X}, N_{0r})] + \\ & \textstyle\sum_{j=1}^{m} \left(\frac{x_j^2}{\sigma_j}\right)\end{aligned}$$

Step 2. Set up the second cost function (Φ_k) with the ratio, r, using the TMI observations and then find r which minimizes Φ_k.

GMI FOV

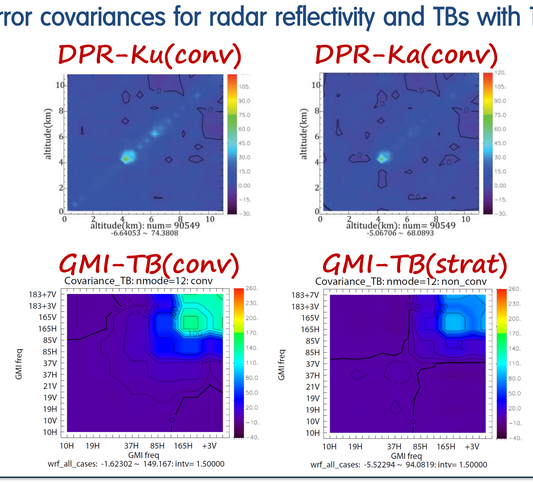
maintaining the vertical structure of hydros obtained from PR obs.

$$\tilde{\boldsymbol{Q}}_{m,k} = \begin{bmatrix} \tilde{\boldsymbol{q}}_{c,k} \\ \tilde{\boldsymbol{q}}_{r,k} \\ \tilde{\boldsymbol{q}}_{i,k} \\ \tilde{\boldsymbol{q}}_{s,k} \\ \tilde{\boldsymbol{q}}_{g,k} \end{bmatrix} = \bar{\boldsymbol{Q}} + \sum_{j=1}^{m} x_j \hat{\boldsymbol{e}}_j \qquad \boldsymbol{Y}_k(\boldsymbol{r}) \equiv \boldsymbol{r} * \tilde{\boldsymbol{Q}}_{m,k} = [r_c, r_r, r_i, r_s, r_g] \begin{bmatrix} \tilde{\boldsymbol{q}}_{c,k} \\ \tilde{\boldsymbol{q}}_{r,k} \\ \tilde{\boldsymbol{q}}_{i,k} \\ \tilde{\boldsymbol{q}}_{s,k} \\ \tilde{\boldsymbol{q}}_{g,k} \end{bmatrix}$$

$$\Phi(\mathbf{r}) = \left[\boldsymbol{TB}^o - \sum_{k=1}^{n} g_k\, tb^m(\boldsymbol{Y}_k(\mathbf{r}))\right]^T \boldsymbol{O}_{TB}^{-1} \left[\boldsymbol{TB}^o - \sum_{k=1}^{n} g_k\, tb^m(\boldsymbol{Y}_k(\mathbf{r}))\right]$$

the number of PR pixels — the kth antenna gain function (weighting)

- The error covariances for radar reflectivity and TBs with 16 EOFs



EOF+1dVAR OPTIMIZED CLOUDs with VARIABLE N_0r

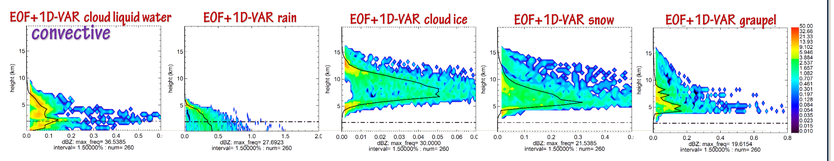
- To fix the underestimation of rain in the EOF+1dVAR optimization, we employed variable N_0r as a function of rain rate in the optimization.

```
N0r_org=8.*10^6 ;  rain
iN0r=0          ; PR pixels
if(raintype eq 'convective') then begin ; convective
    if(rec(i).pr_strain ge 0 and rec(i).pr_strain lt 5)   then um_N0r_pixel_best(iN0r)=N0r_org*7.5
    if(rec(i).pr_strain ge 5 and rec(i).pr_strain lt 10)  then um_N0r_pixel_best(iN0r)=N0r_org*10.5
    if(rec(i).pr_strain ge 10 and rec(i).pr_strain lt 15) then um_N0r_pixel_best(iN0r)=N0r_org*13.5
    if(rec(i).pr_strain ge 15 and rec(i).pr_strain lt 20) then um_N0r_pixel_best(iN0r)=N0r_org*16.5
    if(rec(i).pr_strain ge 20 and rec(i).pr_strain lt 30) then um_N0r_pixel_best(iN0r)=N0r_org*19.5
    if(rec(i).pr_strain ge 30 and rec(i).pr_strain lt 40) then um_N0r_pixel_best(iN0r)=N0r_org*22.5
    if(rec(i).pr_strain ge 40 and rec(i).pr_strain lt 50) then um_N0r_pixel_best(iN0r)=N0r_org*25.5
    if(rec(i).pr_strain ge 50)                            then um_N0r_pixel_best(iN0r)=N0r_org*28.5
endif else begin  ; other than convective rain type
    um_N0r_pixel_best(iN0r)=N0r_org
endelse
```

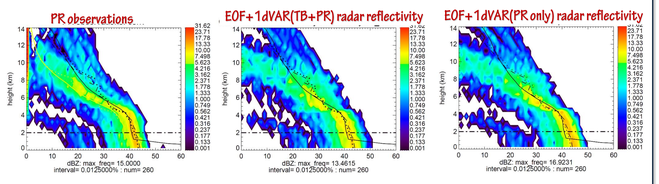
- **The N_0r adjustments consisted preponderantly in increases relative to the initial values**, which is more likely to be consistent with the microphysics of convective clouds, in particular, of summer stationary fronts occurring near the Korean Peninsula. This region exhibits strong rain rate more frequently than any other regions for comparable radar observations (e.g., Seo 2011; Ryu et al. 2012; Sohn et al. 2013).

EOF+1dVAR OPTIMIZED CLOUDs with FIXED N_0r

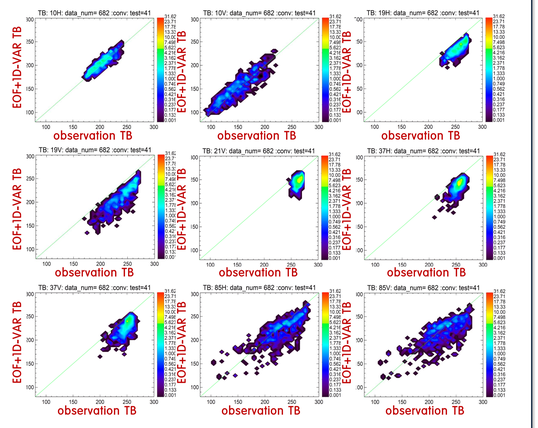
- Hydrometeor (cloud liquid water, rain, cloud ice, snow & graupel) content profiles are optimized by solving the hybrid EOF+1D-VAR cost functions.



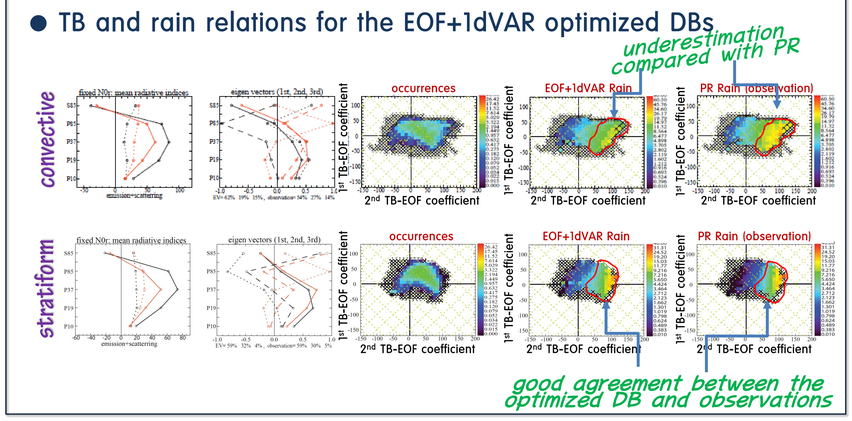
- Optimized hydrometeor Profiles → EOF+1dVAR dBZ



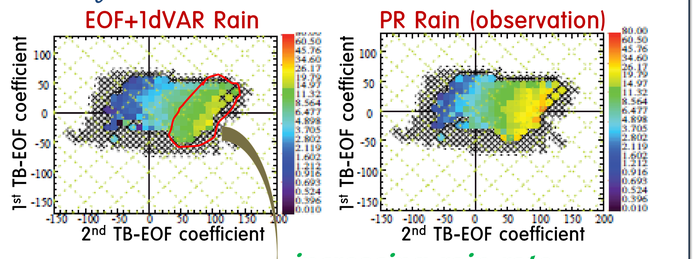
- Optimized hydrometeor Profiles → EOF+1dVAR TBs



- TB and rain relations for the EOF+1dVAR optimized DBs

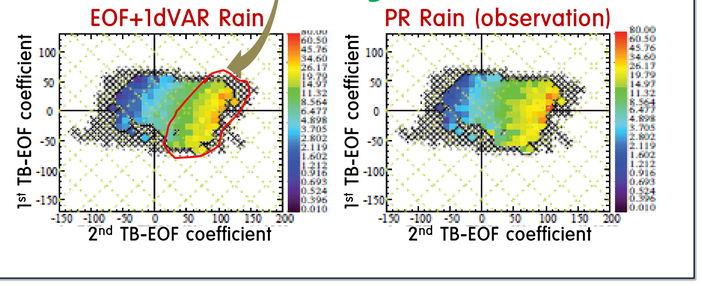


- with fixed N_0r



increasing rain rate for a given TBs !!!

- with variable N_0r



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