Assimilating precipitation observations into HWRF while avoiding the pitfalls of microphysical representations

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Say we want to reconcile μwave brightness temperatures $T_1, \ldots, T_9$ measured over a horizontal pixel (lon_0, lat_0) with the model forecast values $x_1, \ldots, x_{504}$ for the model state variables:

Will need to find $a_1, \ldots, a_{504}$ that bridge the gap, i.e. which minimize

$$(a - x)^t B (a - x) + (H(a) - T)^t R (H(a) - T)$$

where "$H(a)$" is the forward observation operator expressing how the brightness temperatures depend on the variables.

Problems:

1) $H(a) = H(a;b)$, with b crucial for H but not tracked by the model
2) T most sensitive to subset of variables a' whose correlation with remaining ones is not well quantified or well represented in B
3) Model representation of a' and b not very realistic
4) H very non-linear $\Rightarrow$ need care in representing dependence of H (and of its gradient) on a'

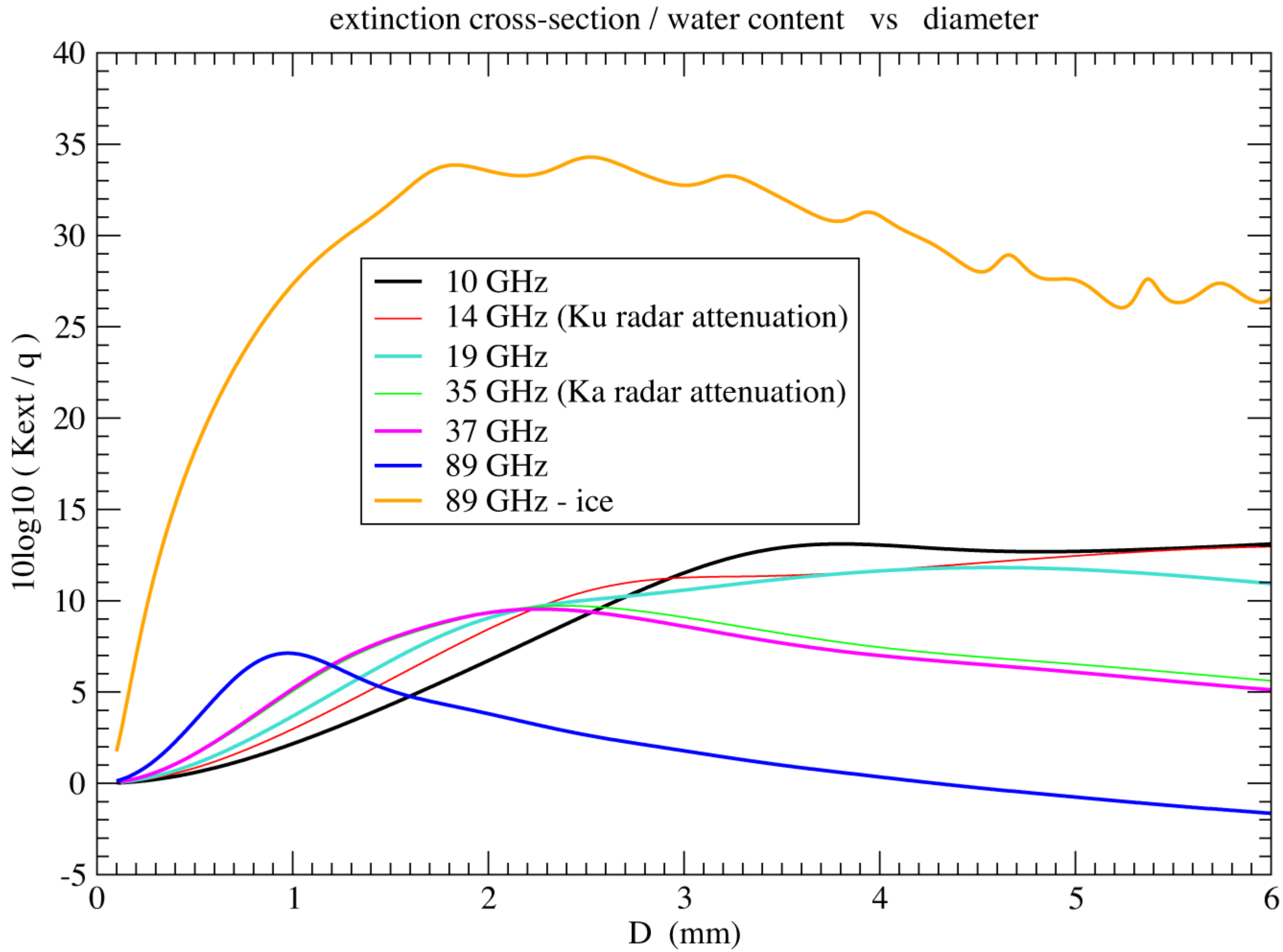
“unrealistic realism” in hydrometeor size distributions:

The size of the hydrometeors is very important to correctly interpret the microwave observations:

Crucial to know how the water content values

q (g/m³)

are distributed in size ...



⇒ Assume closed-form diameter distributions (e.g. exponential or Γ)

“unrealistic realism” in hydrometeor size distributions:

$\Rightarrow$ Assume closed-form diameter distributions (e.g. exponential or Γ):

$$N(D) = N_0 \; D^{\mu} \; e^{-\Lambda D}$$

Let’s try to interpret the parameters in terms of physically meaningful quantities:

$$D_m = \frac{\int D \; D^3 N(D) \; dD}{\int D^3 N(D) \; dD} = \frac{\mu + 4}{\Lambda}$$

$$q = \int \frac{4}{3}\pi\left(\frac{D}{2}\right)^3 \rho \; N(D) \; dD = \frac{\pi}{6} \frac{\rho \; \Gamma(\mu+1) \; D_m^{\mu+1}}{(\mu+4)^{\mu+1}} \; N_0$$

$$\sigma_m = \left(\frac{\int (D - D_m)^2 \; D^3 N(D) \; dD}{\int D^3 N(D) \; dD} \right)^{1/2} = \frac{D_m}{\sqrt{\mu + 4}}$$

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What that implies is:

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$$= \frac{\pi\rho}{24} N_0 \; D_m$$

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In particular,

- D_m/q = constant, and
- max(D_m)/min(D_m) = max(q)/min(q)

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But 3.5 mm / 0.5 mm ≠ max($R^{0.9}$)/min($R^{0.9}$) ≈ 100 mm/hr / 0.1 mm/hr

“unrealistic realism” in hydrometeor size distributions:

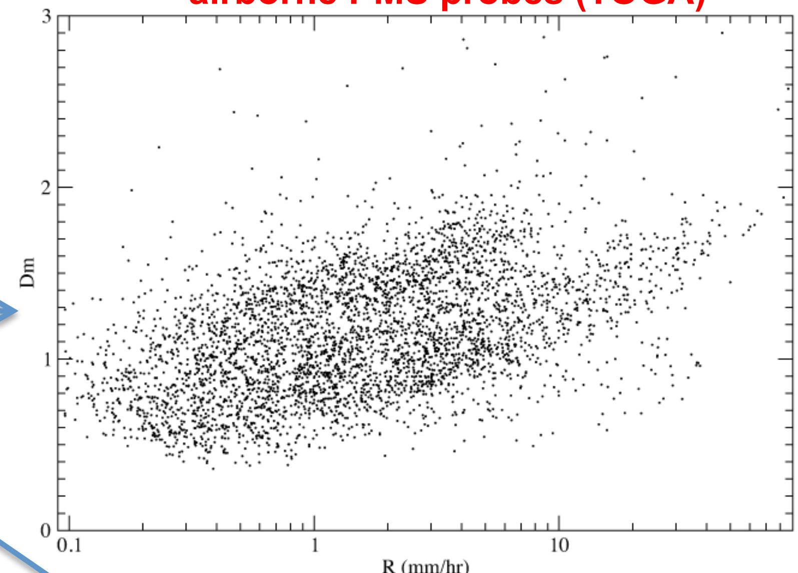
⇒ In fact, hydrometeor data suggests $D_m \sim q^{0.17}$ ± white noise

$D_m \sim q^{0.17}$ behavior in profiler data

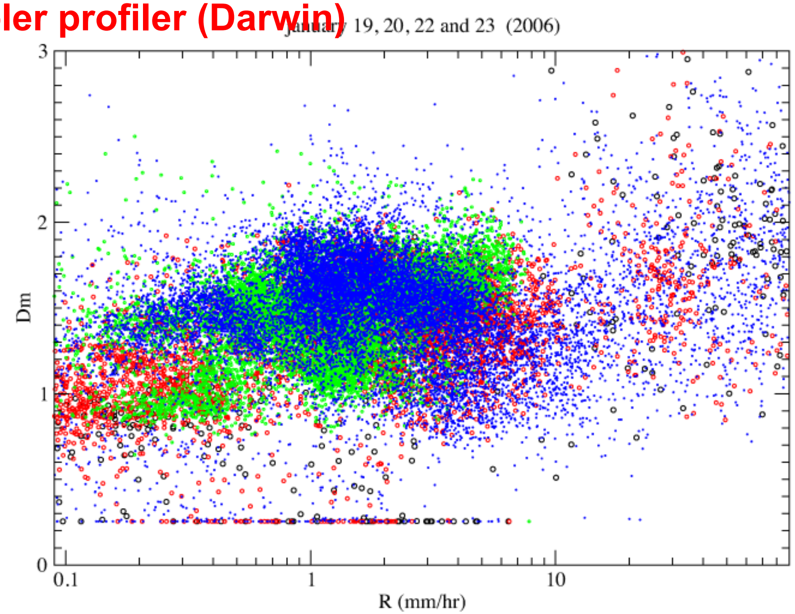
is consistent with TOGA-COARE

and Kwajex data …

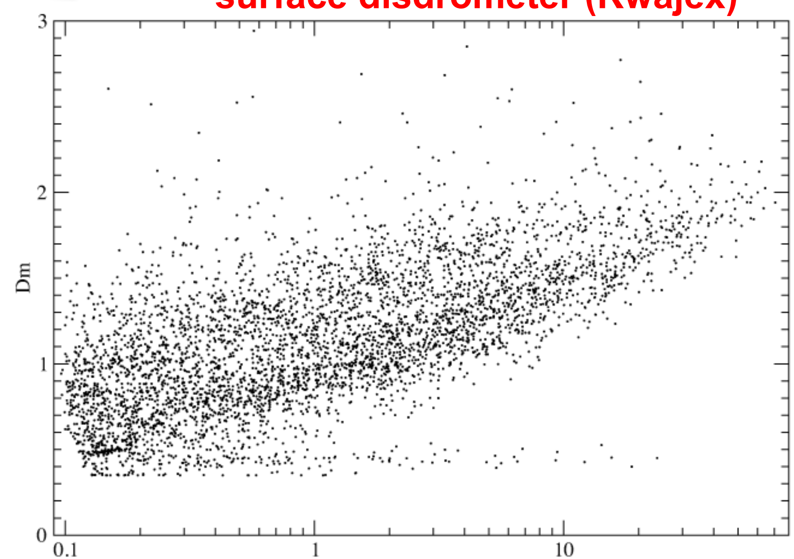
airborne PMS probes (TOGA)



Doppler profiler (Darwin)



surface disdrometer (Kwajex)



“unrealistic realism” in hydrometeor size distributions:

$\Rightarrow$ Assume closed-form diameter distributions (e.g. exponential or Γ):

$$N(D) = N_0 \; D^{\mu} \; e^{-\Lambda D}$$

Fixing Λ is at least as problematic:

$$D_m = \frac{\int D \; D^3 N(D) \; dD}{\int D^3 N(D) \; dD} = \frac{\mu + 4}{\Lambda}$$

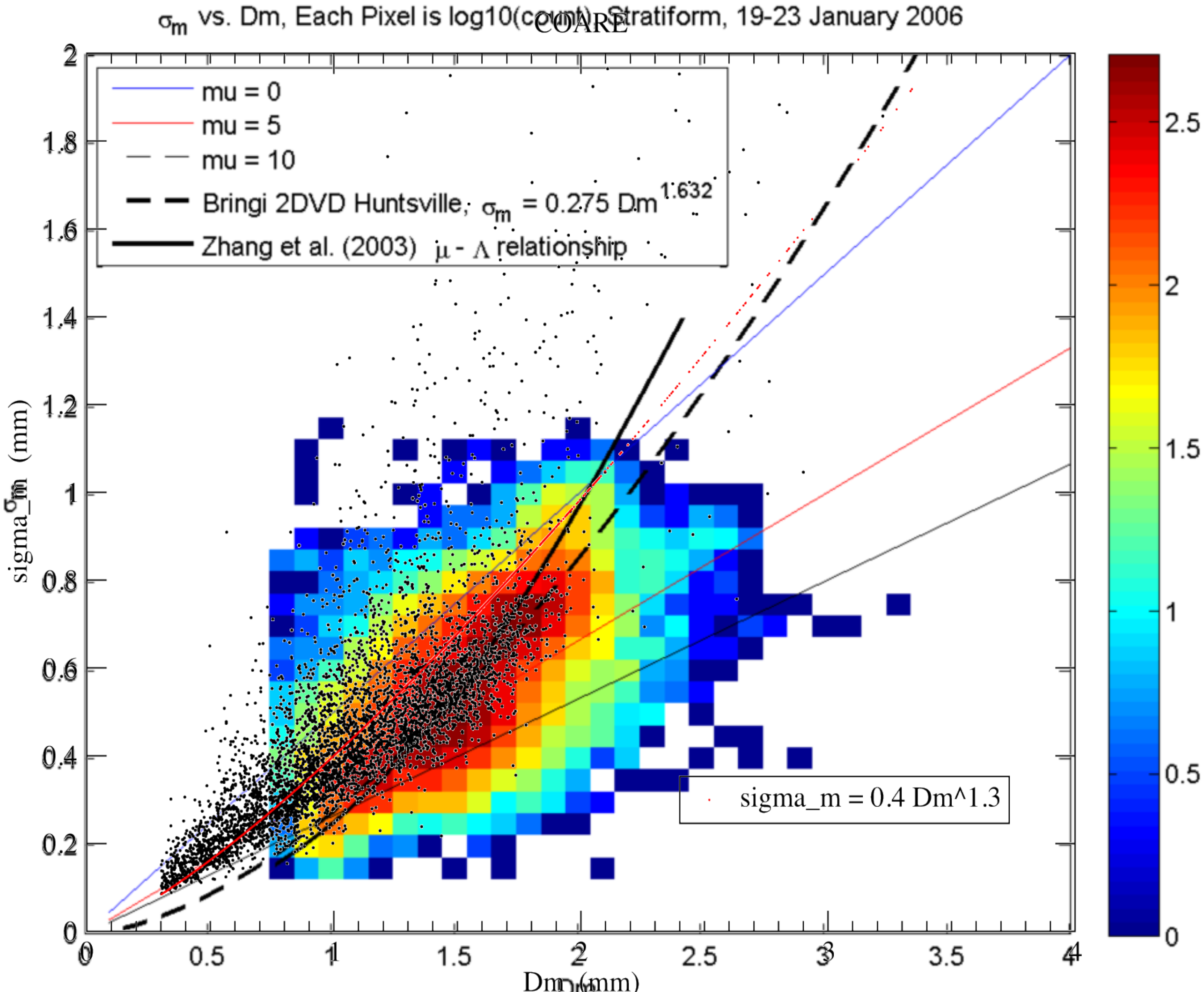
$$\sigma_m = \left(\frac{\int (D - D_m)^2 \; D^3 N(D) \; dD}{\int D^3 N(D) \; dD} \right)^{1/2} = \frac{D_m}{\sqrt{\mu + 4}}$$

The above imply:

$$D_m = \frac{D_m^2 / \sigma_m^2}{\Lambda} \quad \Rightarrow \quad \frac{D_m}{\sigma_m^2} = const \qquad \text{, i.e.} \qquad \sigma_m = const \; D_m^{0.5}$$

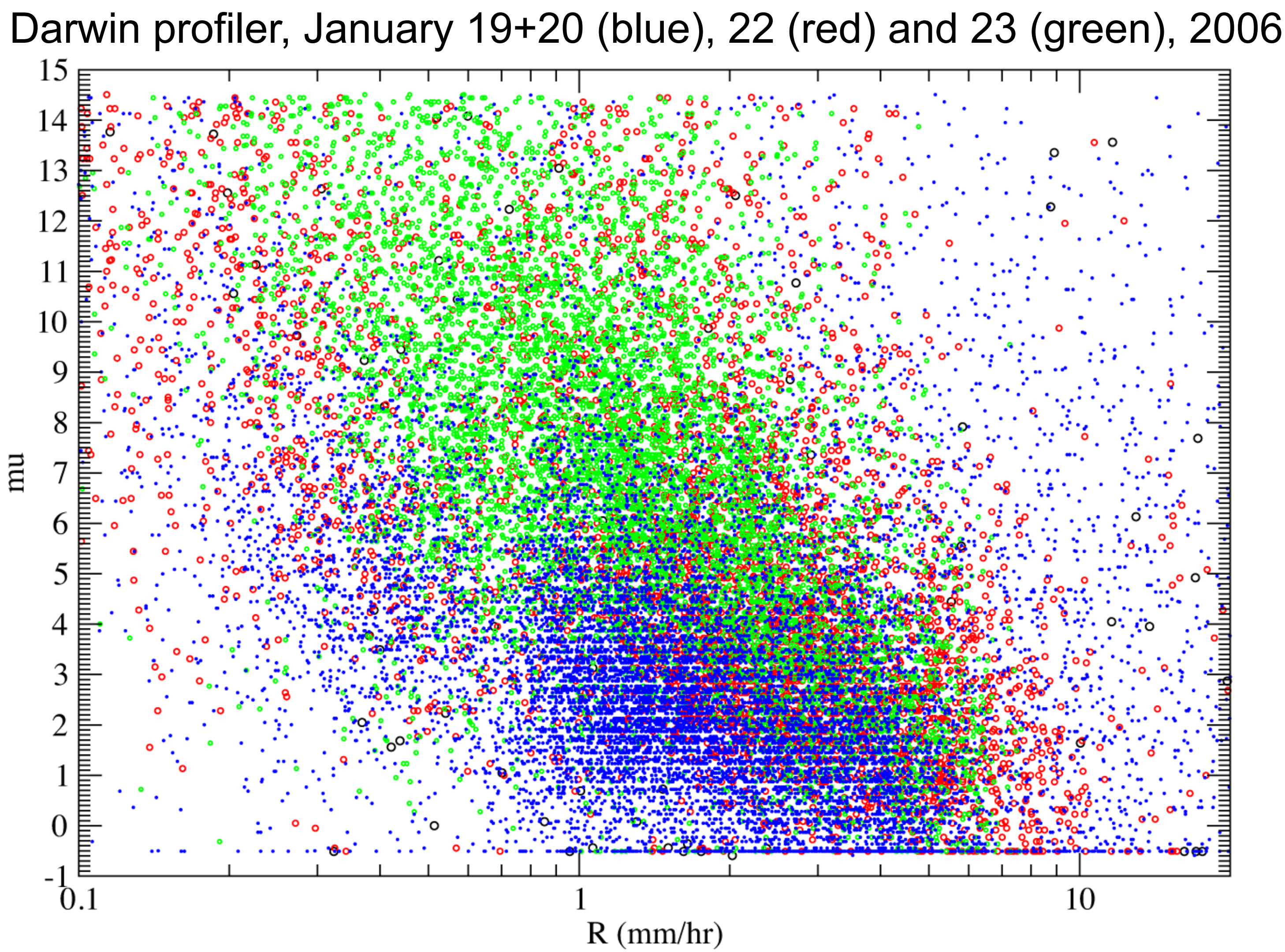
“unrealistic realism” in hydrometeor size distributions:

$\Rightarrow$ Observations indicate: $\sigma_m = const \cdot D_m^{1.5} \pm noise$



$(\sigma_m \neq const \ D_m^{0.5})$

Furthermore, μ is neither 0 nor constant (& neither are N_0, Λ):



Coup de grâce:

$$\frac{\partial \mu}{\partial t} + V \cdot \nabla \mu = ? \qquad \frac{\partial \sigma_m}{\partial t} + V \cdot \nabla \sigma_m = ?$$

(and neither parameter is passed on to the radiative transfer …)

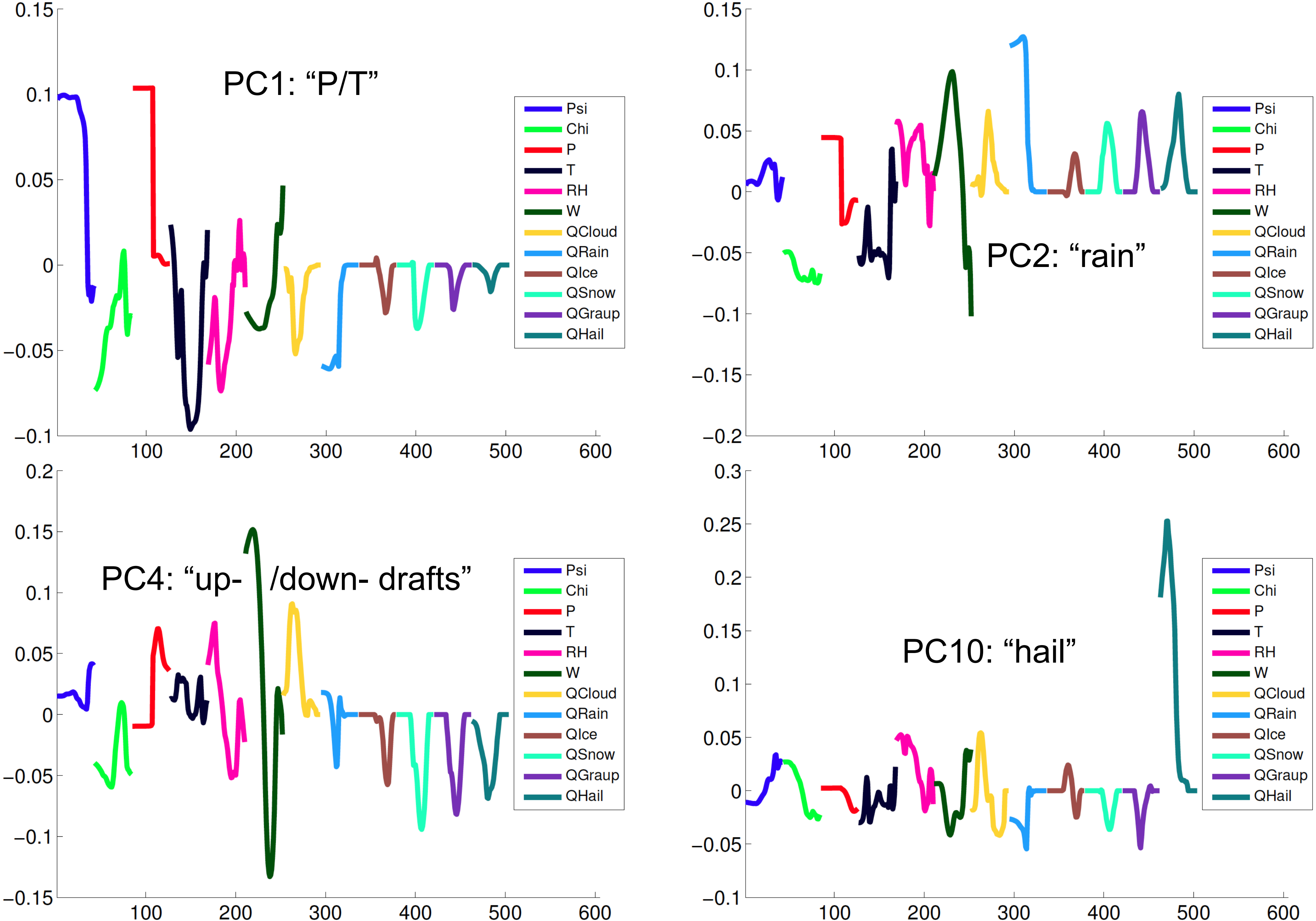
Alternative:

Change model variables to a new set which

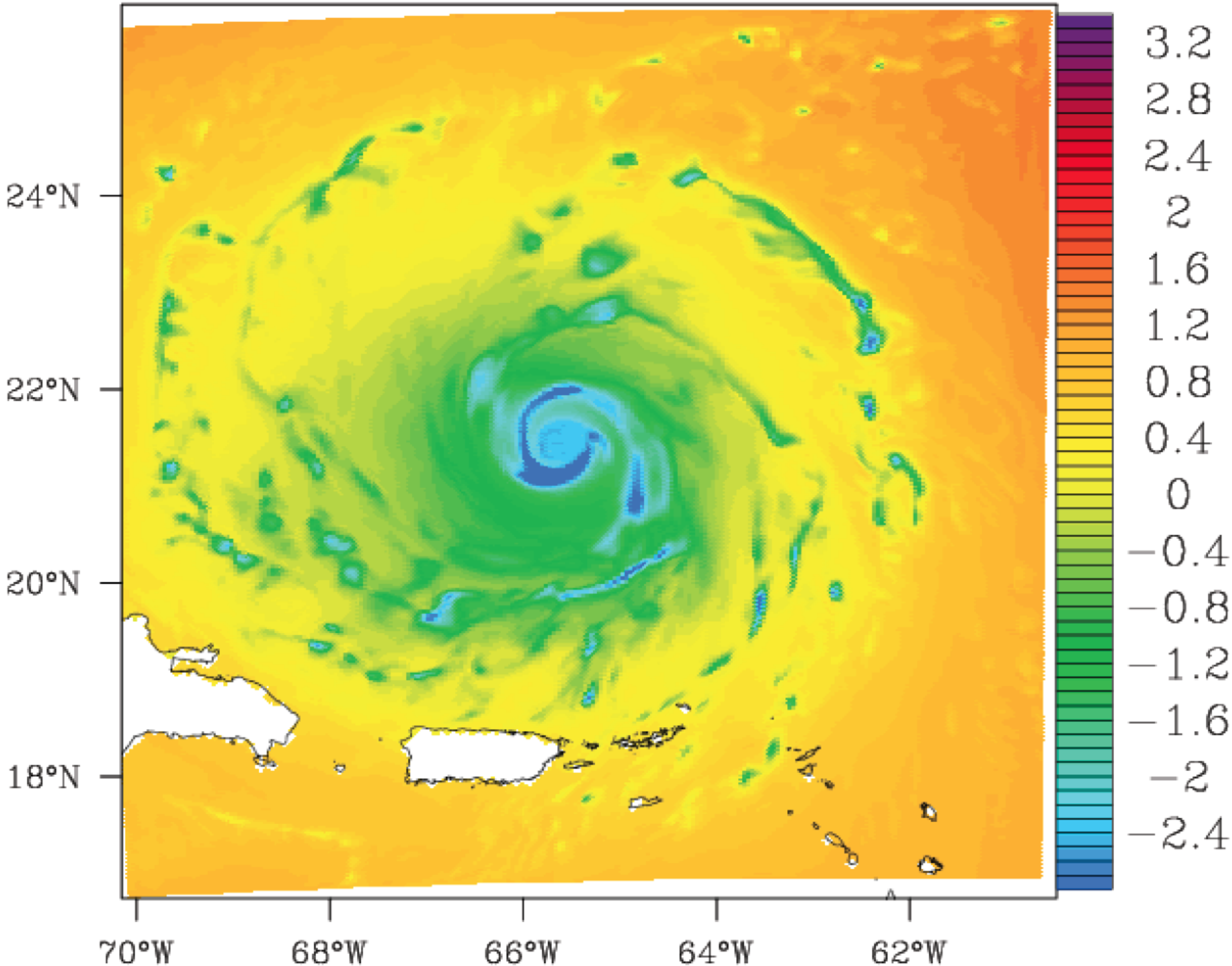
1) is small enough so that we don't need 504 x 10^3 x 10^3 unknowns
2) captures most of the variability of the model states
3) includes what the observations are sensitive to
4) allows the assimilation to adjust all the variables consistently

$\Rightarrow$ vertical principal components of the model variables

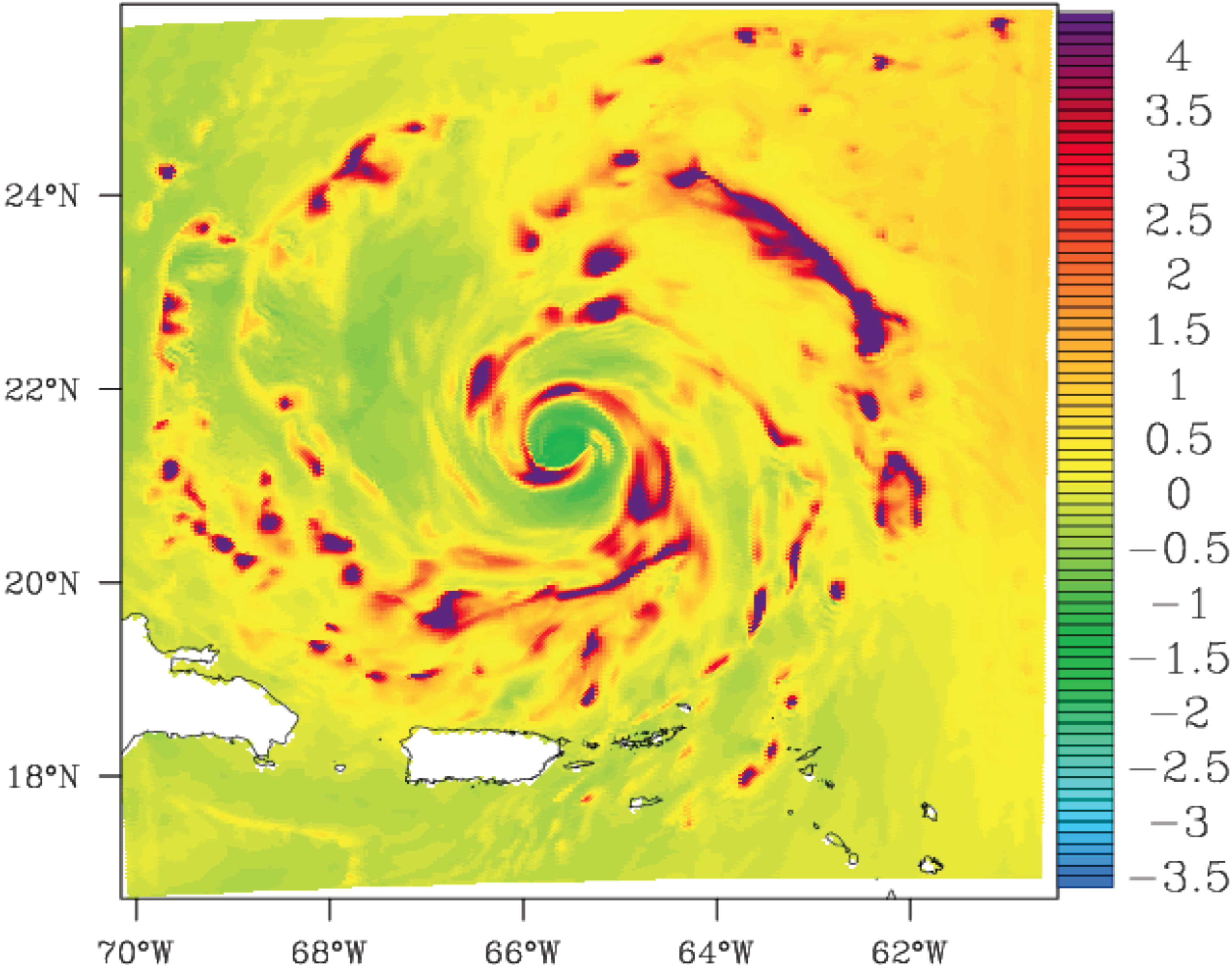
Analysis of HRD sims of Hurricane Earl: PC coefficients (504 variables)



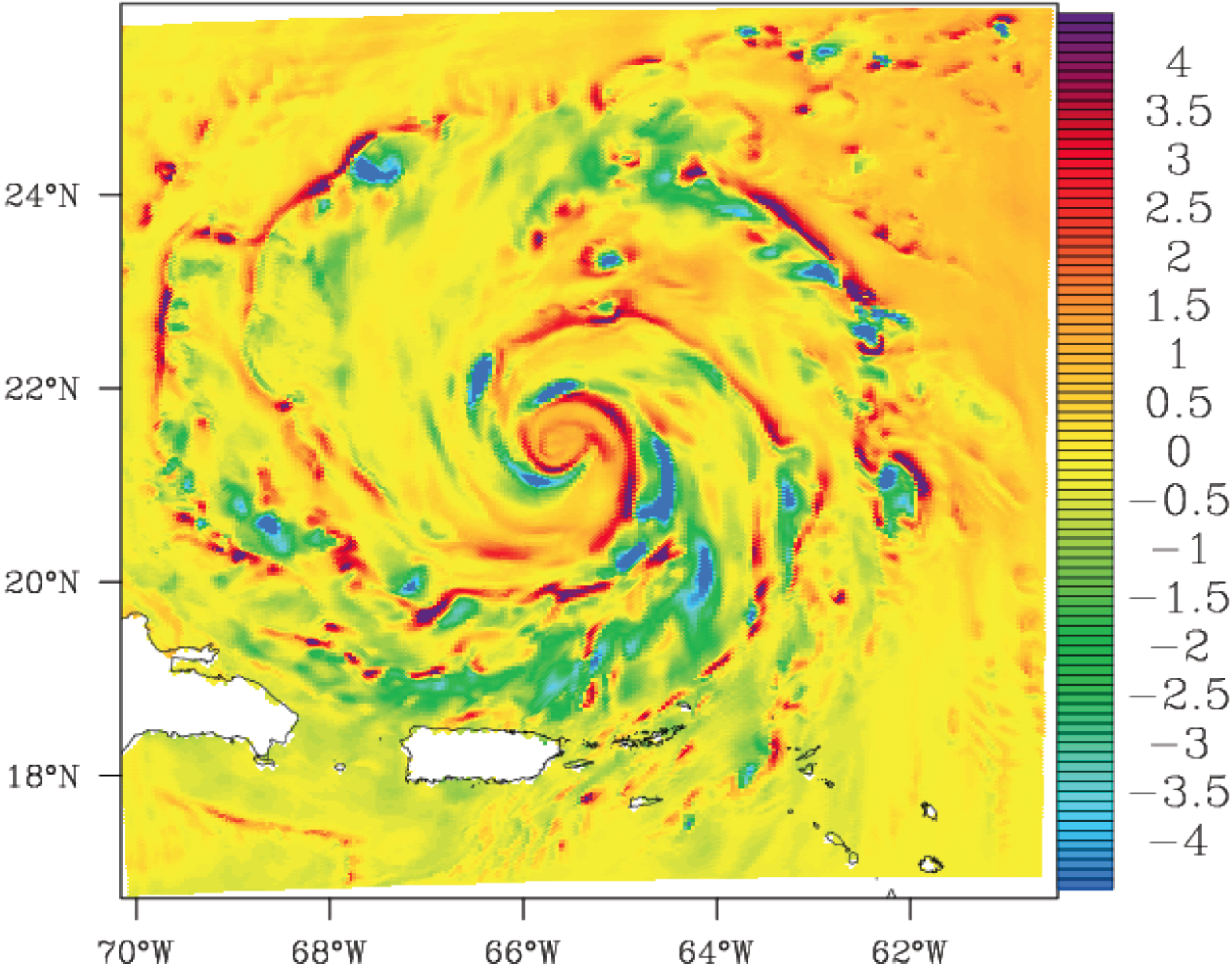
Analysis of HRD sims of Hurricane Earl: PC 1 (“P/T”)



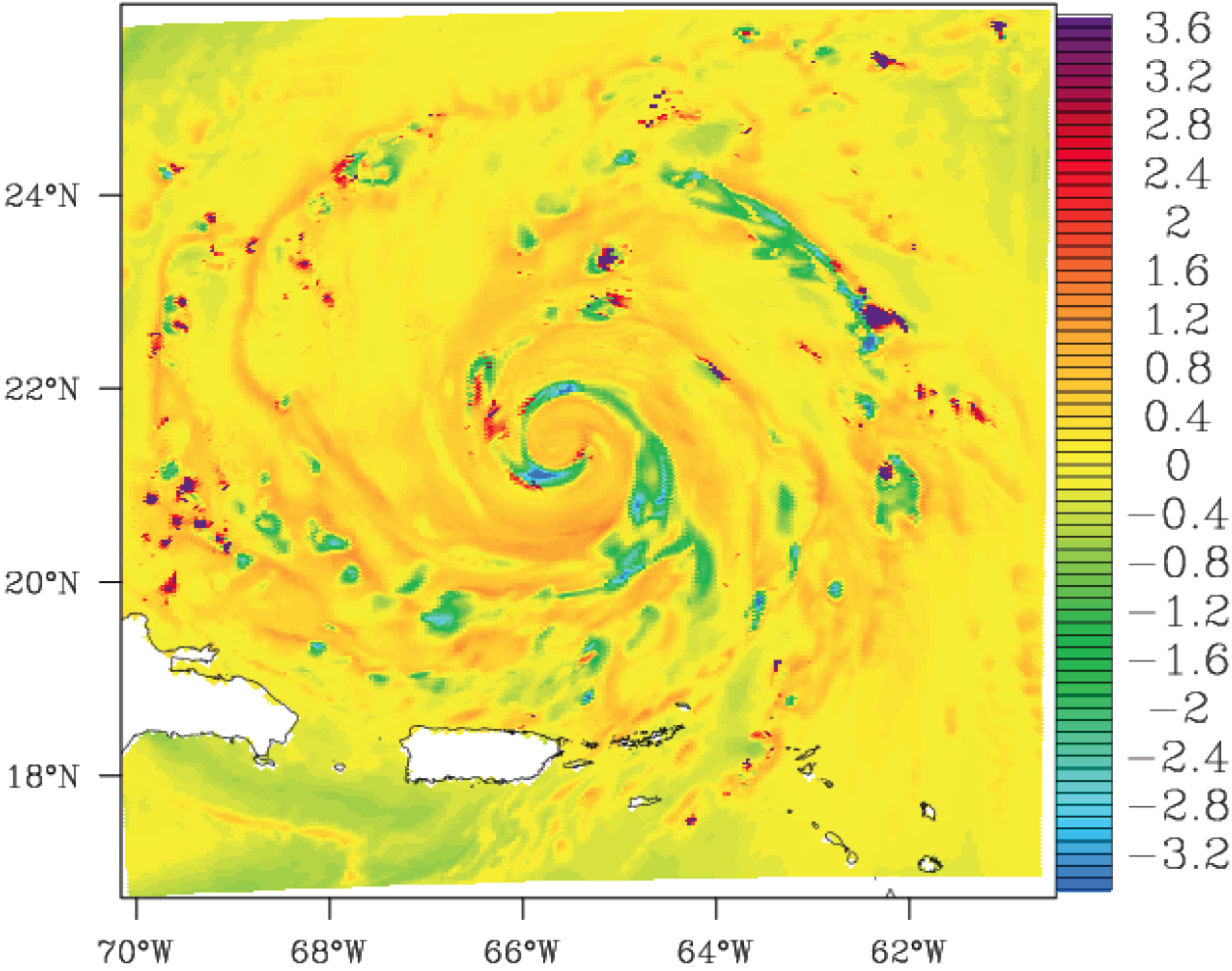
Analysis of HRD sims of Hurricane Earl: PC 2 (“rain”)



Analysis of HRD sims of Hurricane Earl: PC 4 ("ω")



Analysis of HRD sims of Hurricane Earl: PC 10 ("hail")



Observations:

$$T_b = \varepsilon(w_s) T_S \, e^{-\int_0^\infty k_{ext}} + \int k_{abs}(h)\; T(h)\; e^{-\int_h^\infty k_{ext}} \, dh + \left(\int k_{abs}(h)\; T(h)\; e^{-\int_0^h k_{ext}} \, dh \right) (1 - \varepsilon(w_s)) e^{-\int_0^\infty k_{ext}}$$

surface ∧ condensation ∧ condensation ∨, reflected ∧

$$= \varepsilon(w_s)\; T_S \; A(atmosphere) + B(atmosphere) \; + C(atmosphere)(1 - \varepsilon(w_s))$$

$$= \varepsilon(w_s) \left(\; T_S \; A(atmosphere) \; + \; F(atmosphere) \right) + \; G(atmosphere)$$

$$= H(a_1, a_2, \ldots, a_?)$$

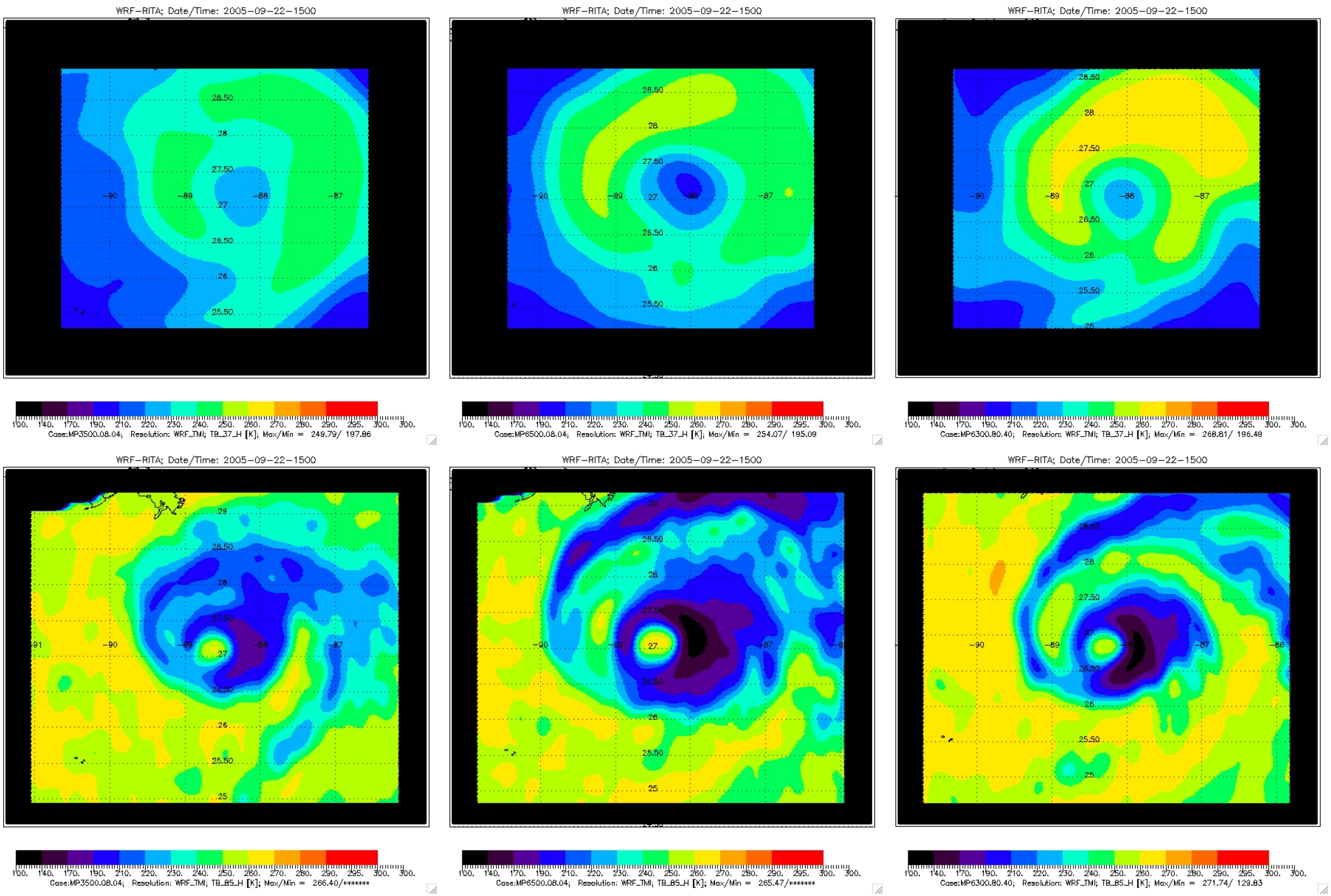
$\Rightarrow$ Our original idea was to assimilate the first two T_b principal components **PC_1** and **PC_2** , expressed in terms of combinations a_1, a_2 and a_3 of the vertical principal components of the model variables with which they are most correlated

Alternative: forward-calculated Tb (3 different parametrizations)

M3-500.08.04 | M6-500.08.04 | M6-300.80.40

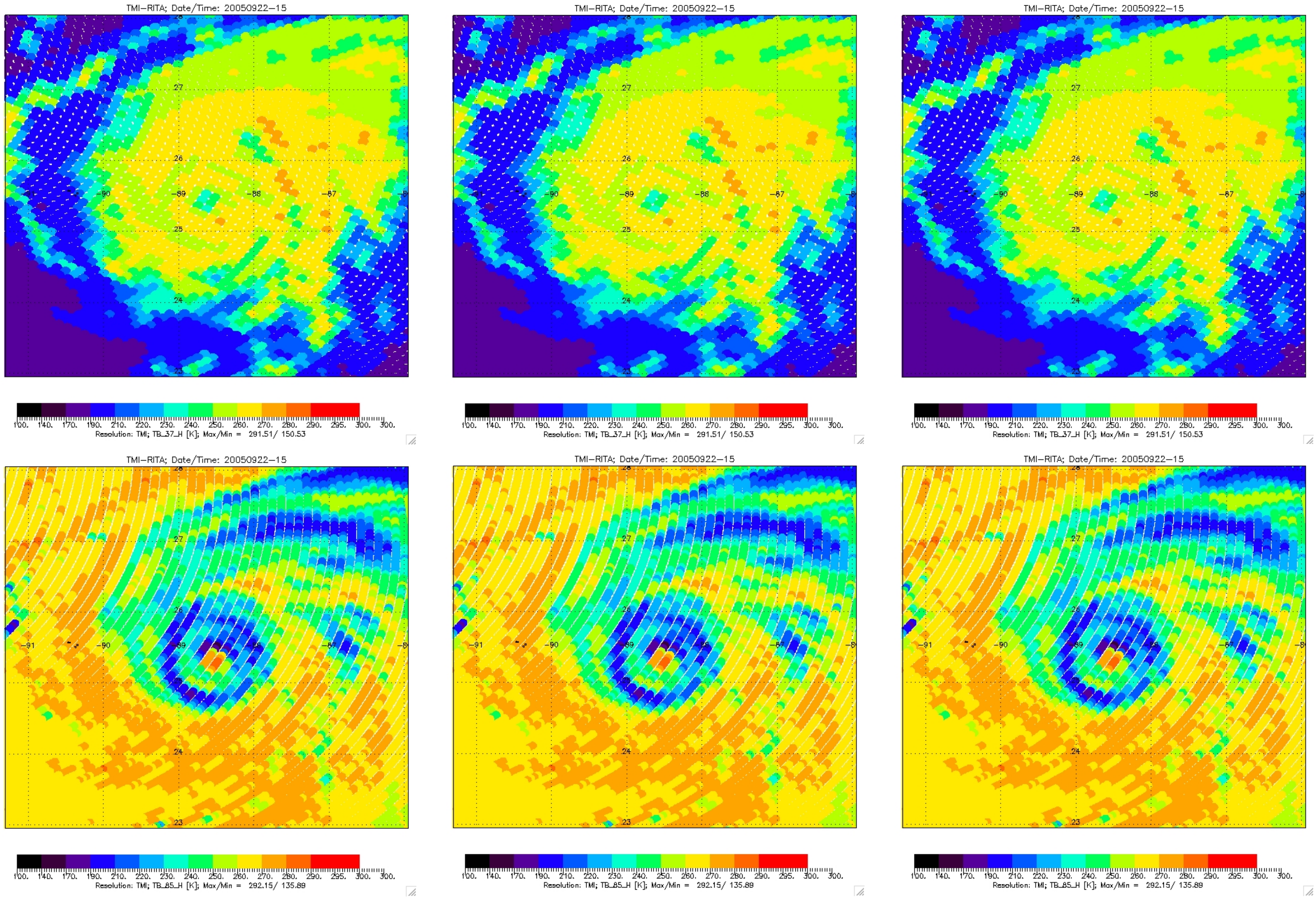
37H

85H



Alternative: TMI T_b (observed)

Quite Different!

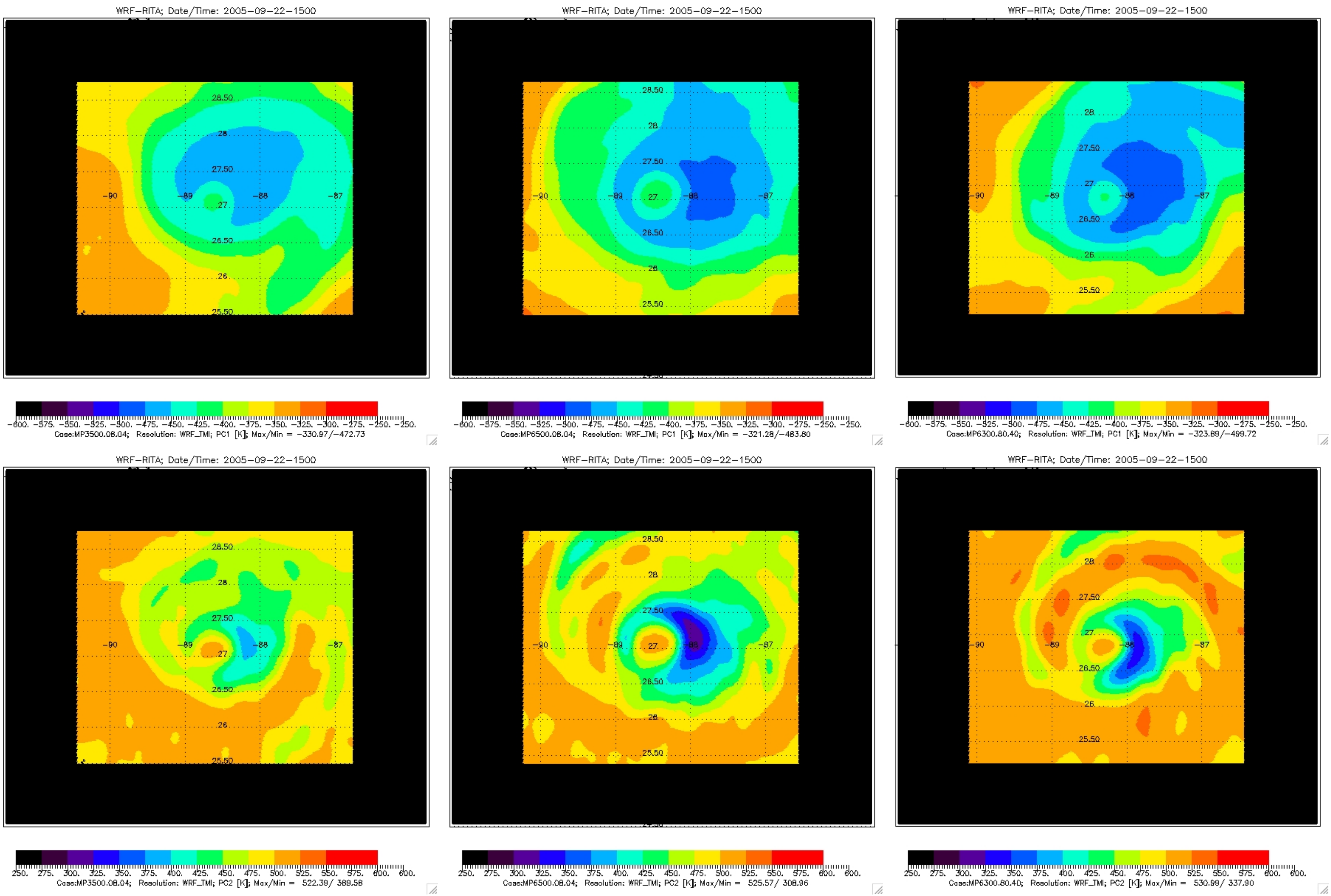


37H

85H

Alternative: PCs of forward-calculated Tb (same 3 parametrizations)

M3-500.08.04 | **M6-500.08.04** | **M6-300.80.40**

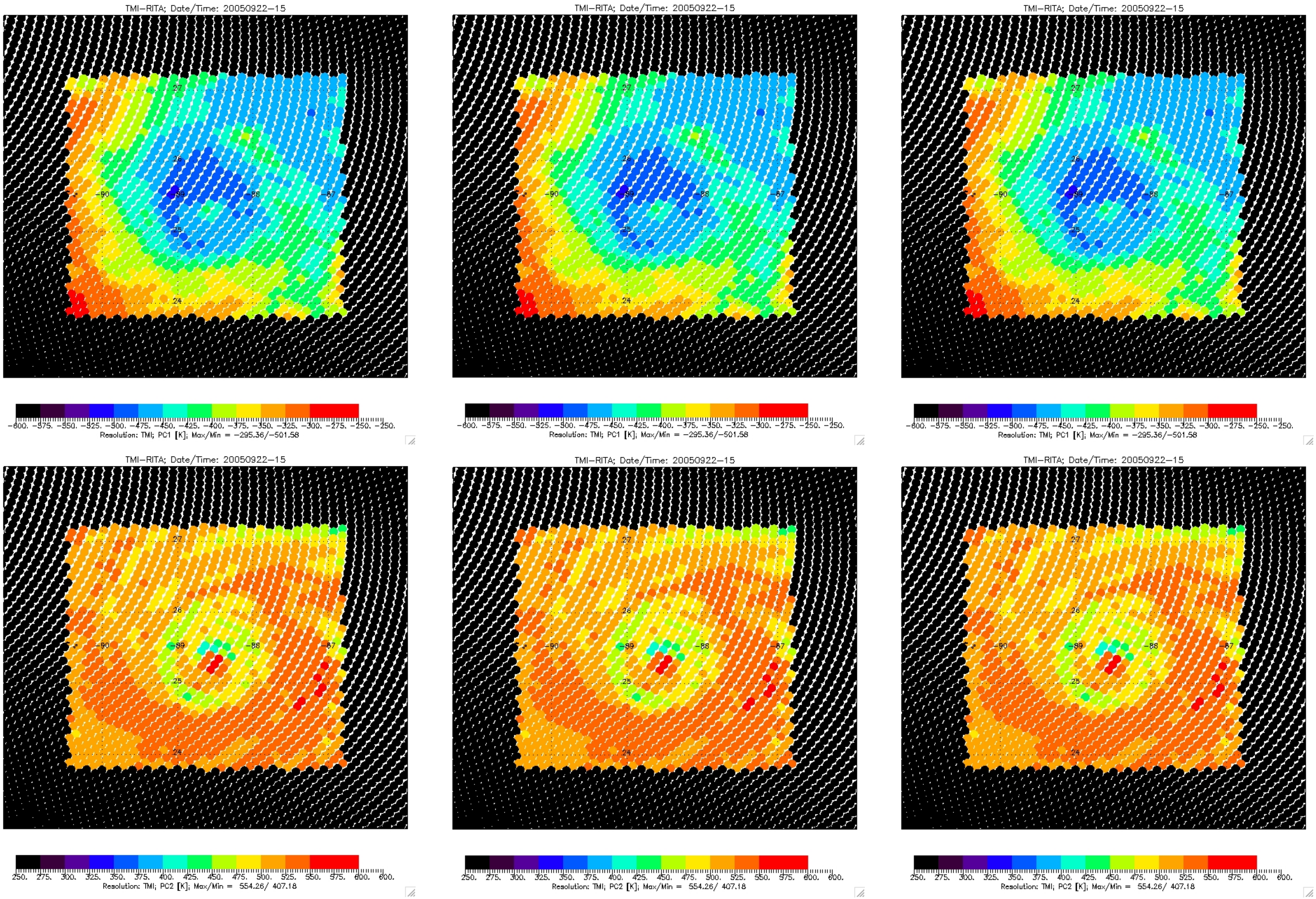


PC_1

PC_2

Alternative: PCs of TMI T_b (observed)

PC$_1$ not so Different!



PC$_1$

PC$_2$

Alternative:

$\Rightarrow$ which combination(s) of T_b are "optimal" to assimilate?

linear answer:

$-0.12\ T_{10.7V}\ -0.41\ T_{10.7H}\ -0.05\ T_{19.3V}\ -0.36\ T_{19.3H}\ +0.05\ T_{23V}\ +0.26\ T_{37V}\ -0.19\ T_{37H}\ +0.61\ T_{89V}\ +0.46\ T_{89H}$
(atmospheric scattering index)

$-0.21\ T_{10.7V}\ +0.16\ T_{10.7H}\ +0.18\ T_{19.3V}\ +0.36\ T_{19.3H}\ +0.19\ T_{23V}\ +0.66\ T_{37V}\ +0.48\ T_{37H}\ +0.25\ T_{89V}\ +0.09\ T_{89H}$
(atmospheric emission index)

$+0.12\ T_{10.7V}\ +0.12\ T_{10.7H}\ +0.12\ T_{19.3V}\ +0.26\ T_{19.3H}\ +0.70\ T_{23V}\ +0.05\ T_{37V}\ +0.43\ T_{37H}\ -0.35\ T_{89V}\ +0.29\ T_{89H}$
(surface wind + vapor)

$\Rightarrow$ More complete answer + observation operator + +
in the next installment