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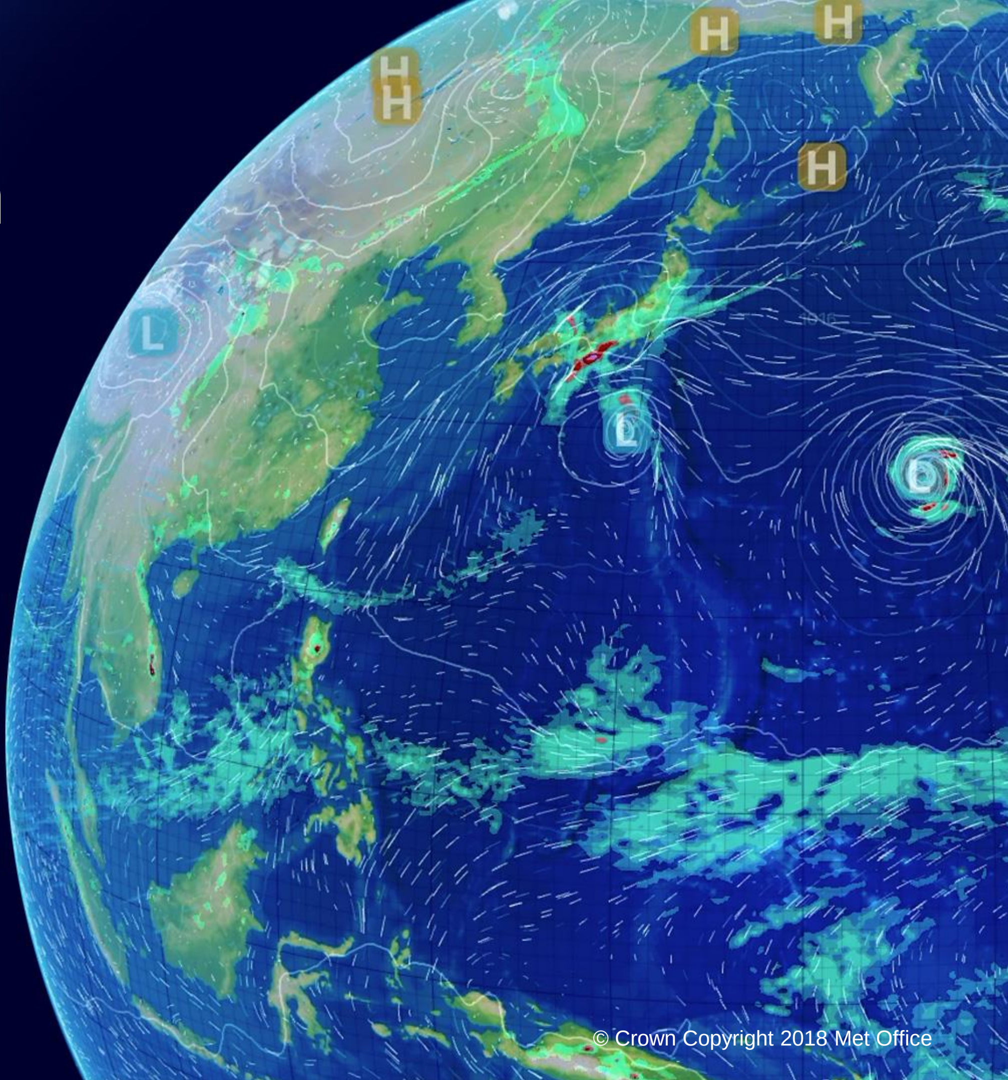
How to make changes in hydrometeors at the observation location - adjoints, incrementing operators and ensemble correlations

Stefano Migliorini

with contributions from Andrew Lorenc, Brett Candy, Byung-il Lee, Tim Payne, Bill Bell, James Hocking, Yanqui Zhu, Philippe Lopez



Outline

- The problem of estimating water in different phases from moisture-sensitive (satellite) observations
- Dynamical data assimilation: a powerful tool
- Moist control variable(s) and incrementing/simplification operators
- Humidity and cloud perts from forecast ensemble (and linearized physics)
- Design of the moisture incrementing operator
- Results and conclusions

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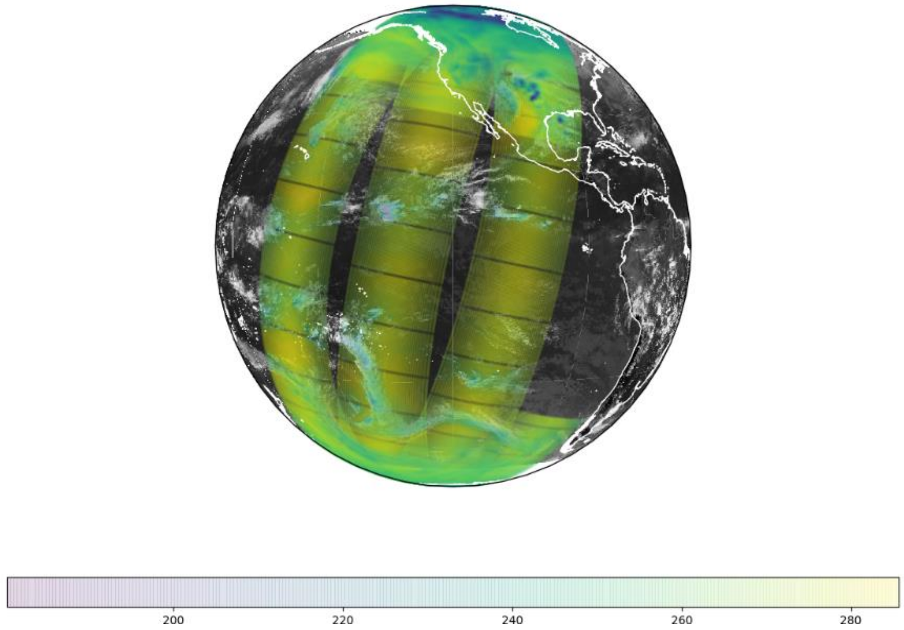
Observing water in the atmosphere

- Image of MHS ch5 rads and global composite of IR geostationary imagery



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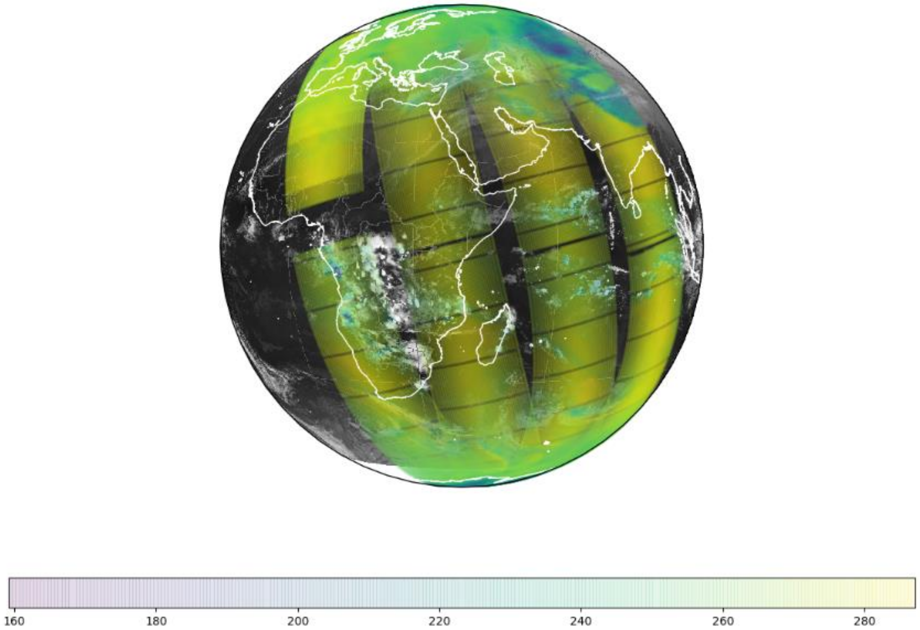
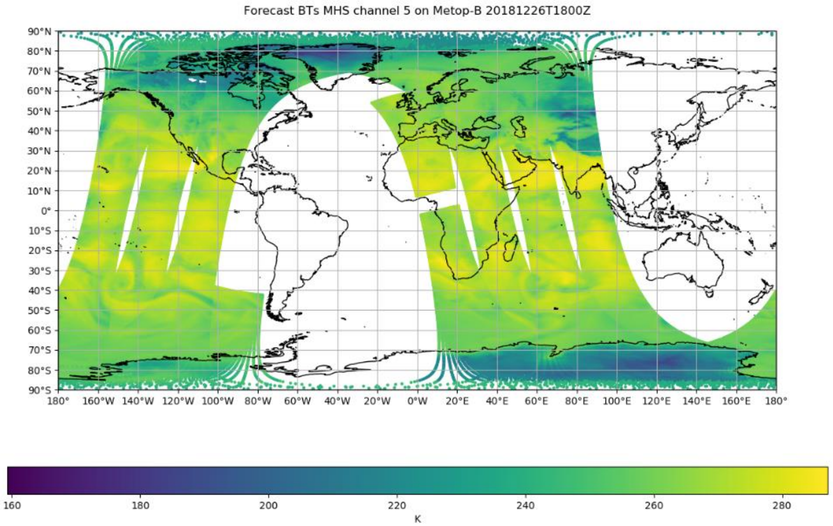


BT [K]

Observing water in the atmosphere

- Image of MHS ch5 rads and simulated rads



- Better agreement at large scale, smaller scale differences (need for QC)

How DA can create (better) cloud and precip

- Cloud (and precip) control variable(s): Thibaut Montmerle and Mayeul Destouches’s presentation
- Moisture incrementing operator
- Flow-dependent forecast errors (from previous cycle) including cloud and precip fields and their parametrization schemes
- Availability of *accurate* rad. trans. sensitivities to cloud and precip fields
- PF or TL physics schemes including cloud and precip
- Incremental 4D-Var (outer loop)
- Sequences of obs of tracer fields to infer winds (“tracer effect”): Frederic Fabry’s presentation

Linking obs and analysis increments

- $J(\delta \boldsymbol{x}_0) = \frac{1}{2}\left(\delta \boldsymbol{x}_0 + \boldsymbol{x}_0^g - \boldsymbol{x}_b\right)^T \boldsymbol{P}_b^{-1}\left(\delta \boldsymbol{x}_0 + \boldsymbol{x}_0^g - \boldsymbol{x}_b\right) + \frac{1}{2}\sum_{k=0}^{K}(\boldsymbol{d}_k - \boldsymbol{G}_k \delta \boldsymbol{x}_0)^T \boldsymbol{R}_k^{-1}(\boldsymbol{d}_k - \boldsymbol{G}_k \delta \boldsymbol{x}_0)$
- $\boldsymbol{G}_k = \boldsymbol{H}_k \boldsymbol{M}_{t_0 \to t_k} = \boldsymbol{H}_k \boldsymbol{M}_{t_{k-1} \to t_k} \boldsymbol{M}_{t_{k-2} \to t_{k-1}} \cdots \boldsymbol{M}_{t_1 \to t_2} \boldsymbol{M}_{t_0 \to t_1}$
- $\boldsymbol{d}_k = \boldsymbol{y}_k - G\left(\boldsymbol{x}_0^g\right) = \boldsymbol{y}_k - (H_k \circ M_{t_0 \to t_k})\left(\boldsymbol{x}_0^g\right)$

$\boldsymbol{x}_0^a$

$\boldsymbol{x}_0^g$

$\boldsymbol{y}_0 \quad \boldsymbol{y}_1 \quad \cdots \quad \boldsymbol{y}_{k-1} \quad \boldsymbol{y}_k \quad \cdots \quad \boldsymbol{y}_K$

$\boldsymbol{t}_0 \quad \boldsymbol{t}_1 \quad \cdots \quad \boldsymbol{t}_{k-1} \quad \boldsymbol{t}_k \quad \cdots \quad \boldsymbol{t}_K$

analysis window

Estimating the moisture components

- The moisture variables in the PF (or TL) model can be a reduced set of those in NL model
- Need for simplification operator $\boldsymbol{S}$ to relate the two sets of grids and variables: $\delta \boldsymbol{w}_0 = \boldsymbol{S}\delta \boldsymbol{x}_0$
- For affordability reasons we perform minimization of $J(\delta \boldsymbol{x}_0)$ on reduced set of "control" variables: $\boldsymbol{v} = \boldsymbol{T}\delta \boldsymbol{w}_0$
- Both $\boldsymbol{S}$ and $\boldsymbol{T}$ are non-square, hence not invertible
- But in DA we need transformations in the opposite direction: $\delta \boldsymbol{w}_0 = \boldsymbol{U}\boldsymbol{v}$ and $\delta \boldsymbol{x}_0 = \boldsymbol{S}^{-I}\delta \boldsymbol{w}_0$
- We can *design* the pseudo-inverse transformations $\boldsymbol{U}$ and $\boldsymbol{S}^{-I}$ based on dynamical/physical laws and/or statistical regressions
- $\boldsymbol{S}^{-I}$ is the moisture incrementing operator (MIO)

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Moisture variables (in the Met Office system)

- Model variables: $\boldsymbol{x} = (\cdots, q, q_{cl}, q_{cf}, C_l, C_f, C_t)$
- Perturb. forecast (PF) model vars: $\delta\boldsymbol{w} = (\cdots, q', q_c')$
- $\delta\boldsymbol{w}$ components not independent: we need uncorrelated $\boldsymbol{v}$ and transform $\boldsymbol{U}$ such that $\delta\boldsymbol{w}_0 = \boldsymbol{U}\boldsymbol{v}$
- Met Office CVs: $\boldsymbol{v} = (\psi', \chi', p_A', \mu')$ = stream function, velocity potential, unbalanced pressure, moist variable
- μ' proportional to RH_T' (q_T') close to (away from) saturation: moisture-insensitive obs preserve cloud when $\mu' = 0$
- Parameter transform $\boldsymbol{U}$ determines q_T' from μ'

Dealing with moisture in the minimization

- $J(\delta\boldsymbol{w}_0) = \frac{1}{2}\left(\delta\boldsymbol{w}_0 + \boldsymbol{w}_0^g - \boldsymbol{w}_b\right)^T \boldsymbol{B}^{-1}\left(\delta\boldsymbol{w}_0 + \boldsymbol{w}_0^g - \boldsymbol{w}_b\right) + \frac{1}{2}\sum_{k=0}^{K}\left(\boldsymbol{d}_k - \boldsymbol{H}_k\boldsymbol{S}^{-I}\boldsymbol{M}_{t_0\to t_k}\delta\boldsymbol{w}_0\right)^T \boldsymbol{R}_k^{-1}\left(\boldsymbol{d}_k - \boldsymbol{H}_k\boldsymbol{S}^{-I}\boldsymbol{M}_{t_0\to t_k}\delta\boldsymbol{w}_0\right)$

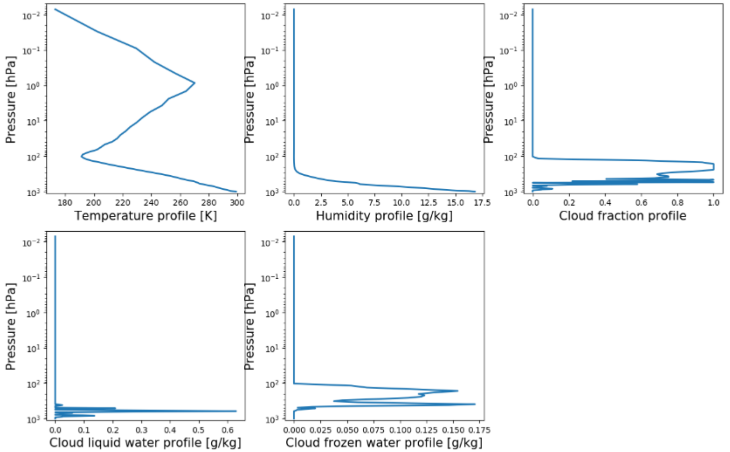
where $\widetilde{\boldsymbol{G}}_k = \boldsymbol{H}_k\boldsymbol{S}^{-I}\boldsymbol{M}_{t_0\to t_k}$. The gradient of J can be written as

- $\nabla J(\delta\boldsymbol{w}_0) = \boldsymbol{B}^{-1}\left(\delta\boldsymbol{w}_0 + \boldsymbol{w}_0^g - \boldsymbol{w}_b\right) + \sum_{k=0}^{K}\widetilde{\boldsymbol{G}}_k^T \boldsymbol{R}_k^{-1}\left(\boldsymbol{d}_k - \widetilde{\boldsymbol{G}}_k\delta\boldsymbol{x}_0\right) = \boldsymbol{B}^{-1}\left(\delta\boldsymbol{w}_0 + \boldsymbol{w}_0^g - \boldsymbol{w}_b\right) + \sum_{k=0}^{K}\boldsymbol{M}_{t_k\to t_0}^{\boldsymbol{T}}\,\boldsymbol{S}^{-T}\boldsymbol{H}_k^T\boldsymbol{R}_k^{-1}\left(\boldsymbol{d}_k - \widetilde{\boldsymbol{G}}_k\delta\boldsymbol{x}_0\right)$
- At the end of the minimization, the updated model state is calculated as
- $\boldsymbol{x}_0^a = \boldsymbol{x}_0^g + \boldsymbol{S}^{-I}\delta\boldsymbol{w}_0$
- For successive iterations, starting from the background:

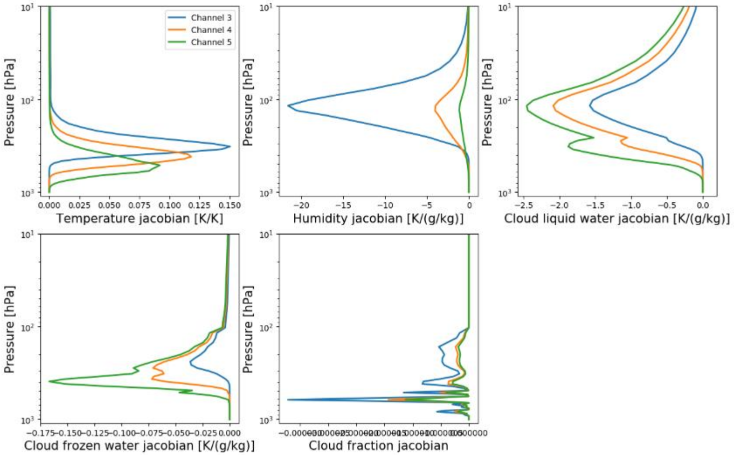
$$\boldsymbol{x}_0^{a(m)} = \boldsymbol{x}_0^b + \boldsymbol{S}^{-I}\sum_{j=0}^{m}\delta\boldsymbol{w}_0^{(j)}$$

Interface with obs: jacobians

- The MIO allows the DA method to interface directly with the obs operator for humidity-and-cloud-sensitive obs



MHS

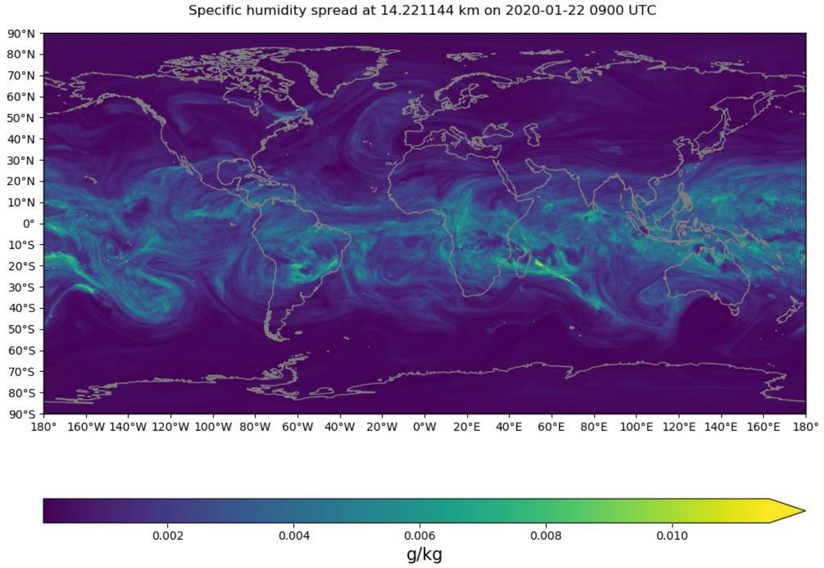


Hybrid methods

- From ensemble prediction system:
- $\boldsymbol{W} = \frac{1}{\sqrt{N-1}}(\boldsymbol{w}_1 - \overline{\boldsymbol{w}}, \boldsymbol{w}_2 - \overline{\boldsymbol{w}}, \cdots, \boldsymbol{w}_N - \overline{\boldsymbol{w}}) = (\boldsymbol{w}_1', \boldsymbol{w}_2', \cdots, \boldsymbol{w}_N')$
- Hybrid covariance: $\boldsymbol{B} = \beta_c^2 \boldsymbol{B_c} + \beta_e^2 \boldsymbol{W}\boldsymbol{W}^T \circ \boldsymbol{C}$
- $\delta\boldsymbol{w}_0 = \beta_c \boldsymbol{U}\boldsymbol{v} + \beta_e \sum_{i=1}^{N} \boldsymbol{w}_i' \circ \boldsymbol{\alpha}_i$
- The cost function now depends on $\boldsymbol{v}$ and on N $\boldsymbol{\alpha}_i$ variables
- When $\boldsymbol{w}_i'$ includes cloud and precip fields it is possible to determine cloud and precip DA increments by minimizing the extended $\delta\boldsymbol{w}_0$. Note that these increments need to be “simplified” if PF or TL cannot propagate them.

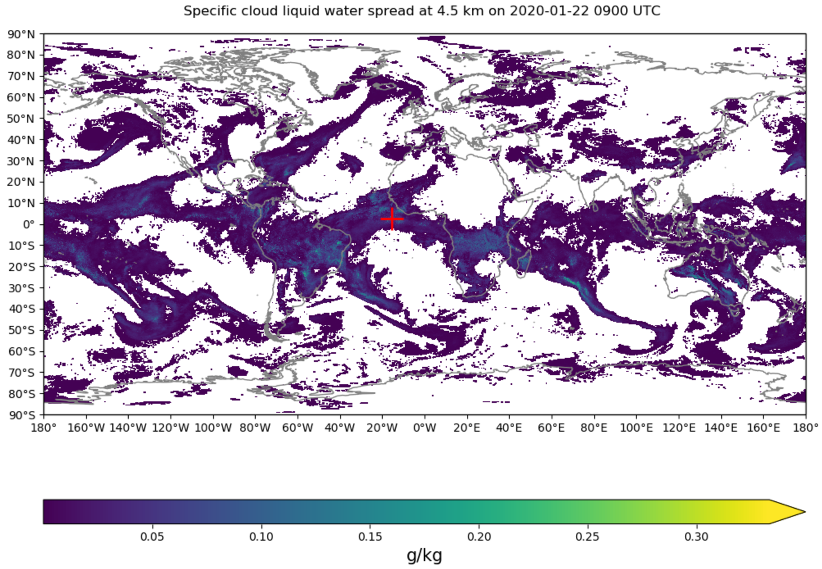
Specific humidity ensemble forecast spread

- From En-4DEnVar, model level 25 (4.5 km)



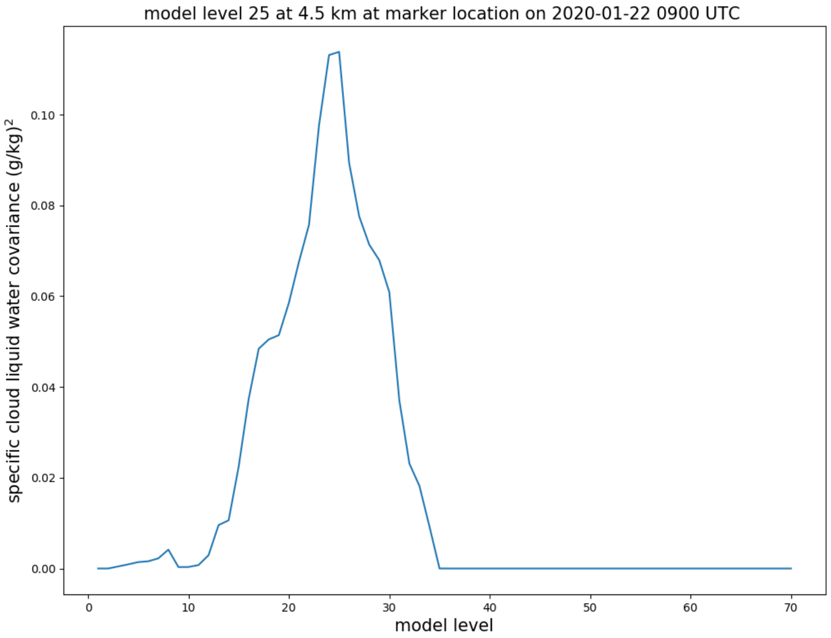
Cloud liquid water ensemble forecast spread

- From En-4DEnVar, model level 25 (4.5 km)



Cloud liquid water ensemble covariance

- From En-4DEnVar at marker location



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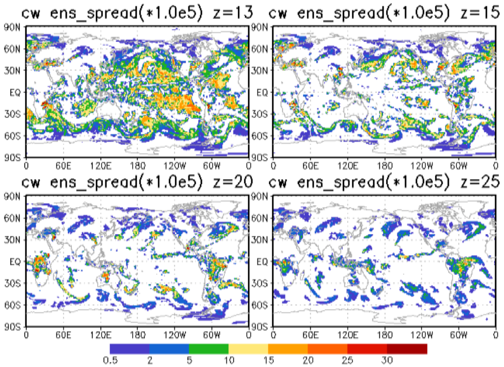
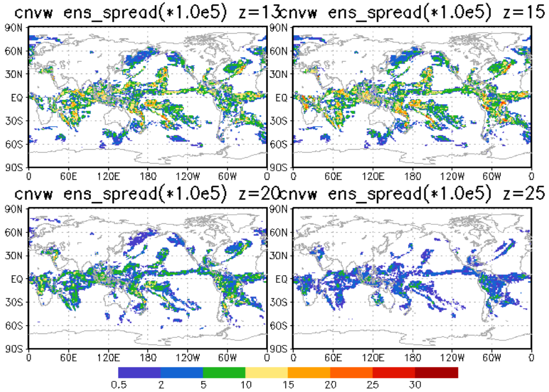
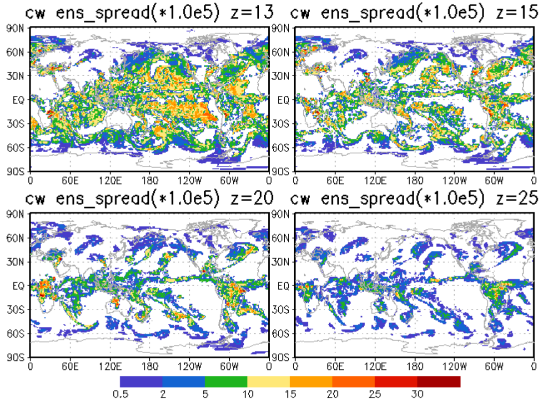
From Yanqui Zhu, NCEP

Accounting for convective cloud contributions

- Specific cloud water ensemble spread:
- grid-scale   subgrid-scale   Combined ensemble spread







- Combine subgrid & grid scale clouds in the GSI, remove subgrid-scale clouds from cloud analyses before passing them back to model, or do not feed back cloud to model;
- Treat convective clouds separately as additional control variable(s).

Moisture increments from linearized physics

- The physical tendencies of temperature and specific humidity produced by moist processes (at ECMWF, see Tompkins and Janisková, 2004):
- $\frac{\partial q}{\partial t} = -C_{ce} + E_{prec} + D_{conv}$; $\frac{\partial T}{\partial t} = L\left(C_{ce} - E_{prec} - D_{conv}\right) + L_f\left(F_{rain} - M_{snow}\right)$
- C_{ce} large-scale condensation/evaporation
- E_{prec} is the moistening due to the evaporation of precipitation
- D_{conv} is the detrainment of cloud water from convective clouds.
- F_{rain} and M_{snow} freezing of rain and melting of snow
- L and L_f latent heats of vaporisation/sublimation and fusion.

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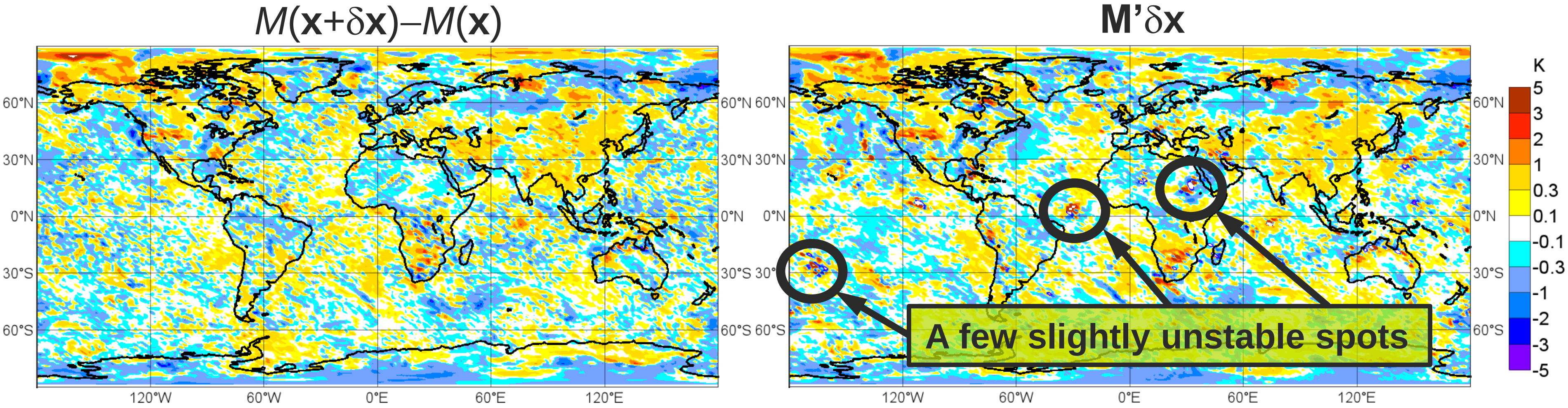
From Philippe Lopez, ECMWF

Linearization tests

- Assessment of TL approximation at high resolution (TCo1279, ~9 km, 12h)
- Comparison of non-linear difference $M(x+\delta x)-M(x)$ with perturbation evolved using the tangent-linear model $M'\delta x$ after 12h of integration.



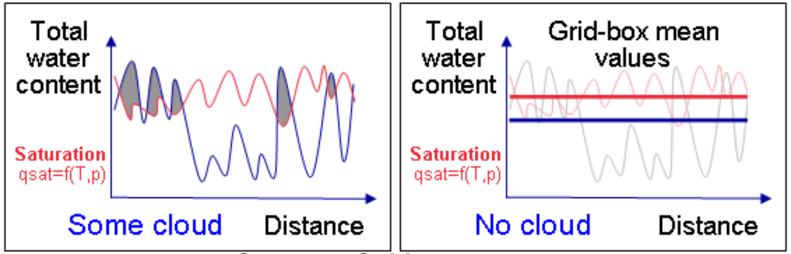
Temperature at level 129 (~980 hPa) on 20140105 at 12Z

Designing a moisture incrementing operator

Diagnosing cloud

- Gridbox-mean and local values (Mellor, 1977; Sommeria and Deardorf, 1977; Smith, 1990)
- Condensation due to CCN keeps local supersaturation close to zero:

$$q_c^* = 0 \text{ for } q^* < q_s^*;\ q_c^* = q_T^* - q_s^* \text{ for } q^* \geq q_s^*$$



Courtesy C. Morcrette

- Grid-box-mean specific cloud water $q_c = \int_0^\infty q_c^* \psi(q_c^*) dq_c^*$

The ‘s’ distribution

- $q_c^* = q_T - q_s + \mathrm{s} \equiv Q_c + s$

$$q_c = \int_{-Q_c}^{\infty} (Q_c + s)\, G(s) ds \qquad C = \int_{-Q_c}^{\infty} G(s) ds \qquad \int_{-\infty}^{\infty} G(s) ds = 1 \qquad \int_{-\infty}^{\infty} sG(s) ds = 0$$

$$q_c = C(Q_c) Q_c + \int_{-Q_c}^{\infty} sG(s) ds$$

- Using differentiation under the integral sign rule: $\frac{dq_c}{dQ_c} = C$
- Note this relation holds for any $G(s)$
- Consistent with prognostic cloud scheme

Moisture increments

- By neglecting higher order terms we can write the TL as

$$q'_c = CQ'_c = C(q'_T - q'_s(T,p))$$

- From $q_s = \epsilon e_s(T)/p$ we get

$$q'_c = C\left(q'_T - \left(\frac{dq_s}{dT}\right)_p T' - \left(\frac{dq_s}{dp}\right)_T p'\right) = C\left(q'_T - q_s\frac{d\ln e_s(T)}{dT}T' + q_s\frac{p'}{p}\right)$$

- We can neglect the p’ term leading to

$$q'_c \cong C\left(q'_T - q_s\frac{d\ln e_s(T)}{dT}T'\right) \qquad C' = \frac{dC}{dQ_c}Q'_c \cong G(-Q_c)\left(q'_T - q_s\frac{d\ln e_s(T)}{dT}T'\right)$$

- $s = -Q_c$ defines the boundary between the saturated and unsaturated parts of the distribution
- It is possible to find $G(-Q_c)$ closure in terms of q_c and C
- Water vapour increments are found from $\boldsymbol{S}\boldsymbol{S}^{-I} = \boldsymbol{I}$:

$$q' = q'_T - q'_c \cong (1-C)q'_T + Cq_s\frac{d\ln e_s(T)}{dT}T'$$

- Sum of specific humidity incr. in clear and of evaporated cloud incr. in cloudy portion

Critical points

- For $C = 0$ the cloud water increments are zero
- For $C = 0$ and $C = 1$ the cloud fraction increments are zero ($G(-Q_c) = 0$)
- With this formulation it is not possible to create cloud when there is no cloud in the forecast
- Not possible to reduce cloud when cloud fills the entire grid box
- In cloud-free conditions the adjoint of the MIO $\boldsymbol{S}^{-\boldsymbol{T}}$ cannot change the gradient of the obs cost function even when $\left\|\boldsymbol{H}_k^T \boldsymbol{R}_k^{-1}\left(\boldsymbol{d}_k - \widetilde{\boldsymbol{G}}_k \delta \boldsymbol{x}_0\right)\right\| > \mathbf{0}$
- Outer loop can be used to change from cloud-free to cloud

Liquid and frozen cloud

- When $q_c = q_{cl} + q_{cf}$ we can write

$$q'_{cl} = C_l\left(q'_T - q'_{cf} - q'_s\right) \qquad C'_l = G_l(-Q_{cl})\left(q'_T - q'_{cf} - q'_s\right)$$
$$q'_{cf} = C_f(q'_T - q'_{cl} - q'_s) \qquad C'_f = G_f(-Q_{cf})(q'_T - q'_{cl} - q'_s)$$

- If we define $C_l^{eff} = \frac{C_l(1-C_f)}{1-C_lC_f}$ and $C_f^{eff} = \frac{C_f(1-C_l)}{1-C_lC_f}$ we have

$$q'_{cl} \cong C_l^{eff}\left(q'_T - q_s\frac{d\ln e_s(T)}{dT}T'\right) \qquad C'_l \cong G_l(-Q_{cl})(1 - C_f^{eff})\left(q'_T - q_s\frac{d\ln e_s(T)}{dT}T'\right)$$
$$q'_{cf} \cong C_f^{eff}\left(q'_T - q_s\frac{d\ln e_s(T)}{dT}T'\right) \qquad C'_f \cong G_f(-Q_{cf})(1 - C_l^{eff})\left(q'_T - q_s\frac{d\ln e_s(T)}{dT}T'\right)$$

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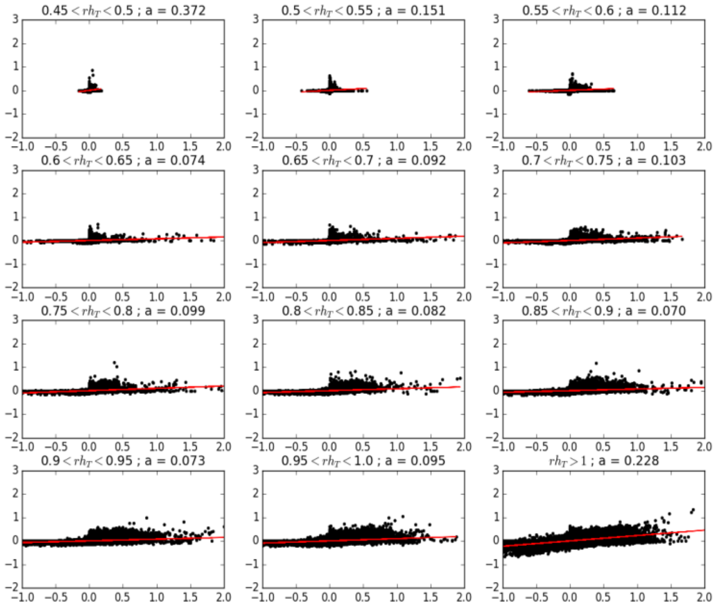
Cloud liquid water increments: regressions

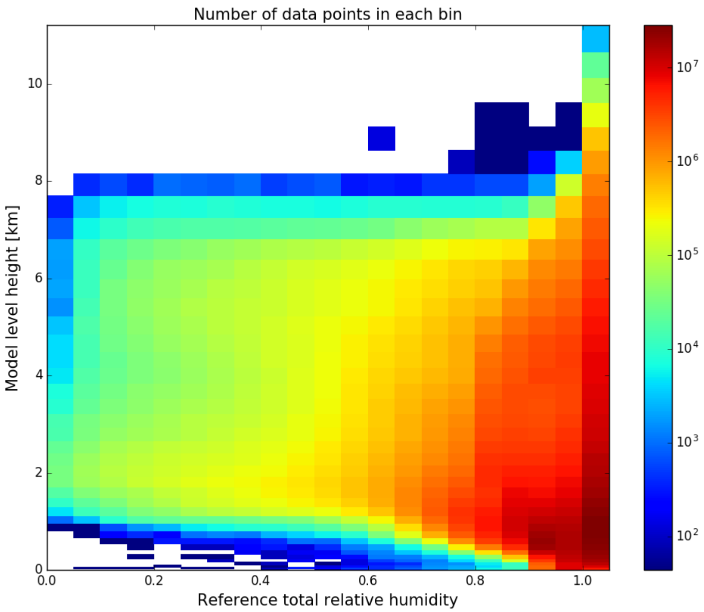
- Ensemble of 5 T+6 perturbed forecasts (20190110T0000Z, 20190115T0000Z, 20190224T1800Z, 20190225T0000Z, 20190227T0000Z)
- Model level 25 (4.33 km over MSL)
- Linear regression at different rh_T bins
- Following results from Byung-il Lee (KMA, visiting scientist at the Met Office)

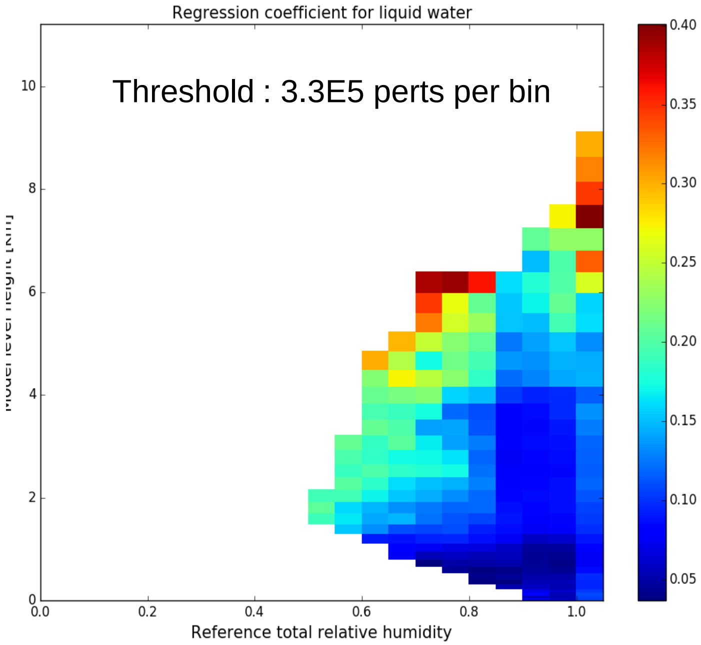
q'_{cl}



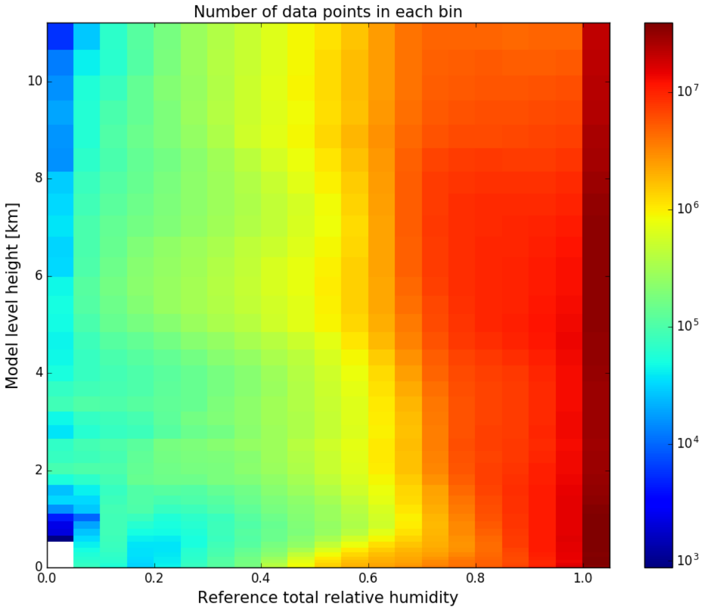
$$C_l^{eff}\left(q'_T - q_s\frac{d\ln e_s(T)}{dT}T'\right)$$

Cloud frozen water increments: regressions

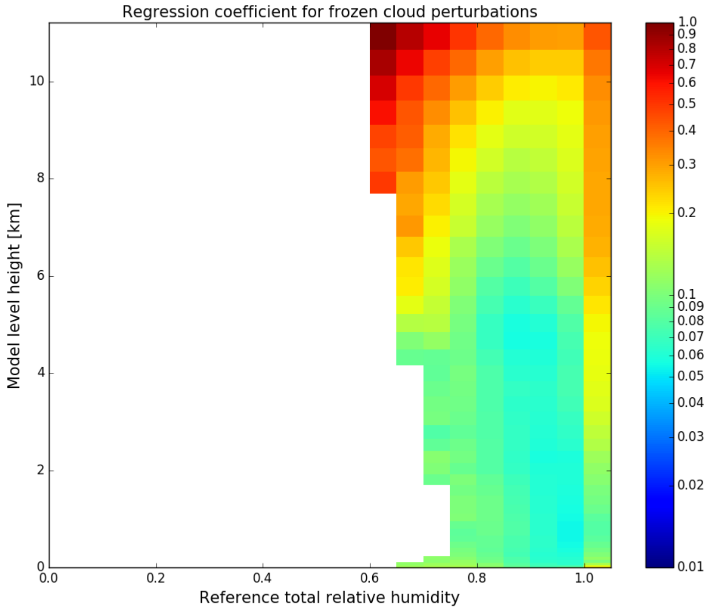




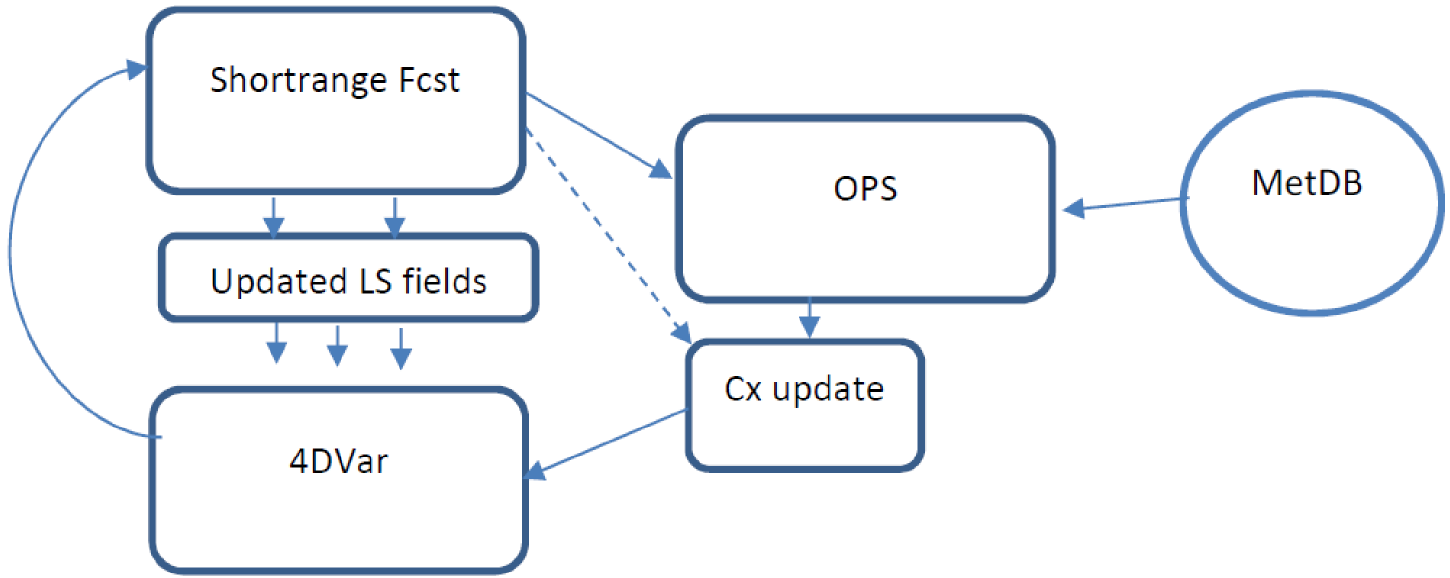
Cloud frozen water increments: regressions



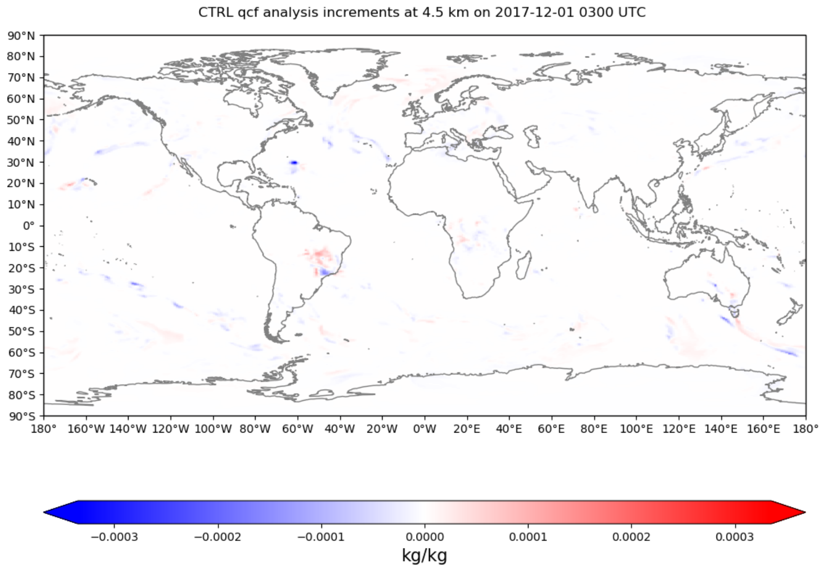
Threshold : 2.5E6 perts per bin



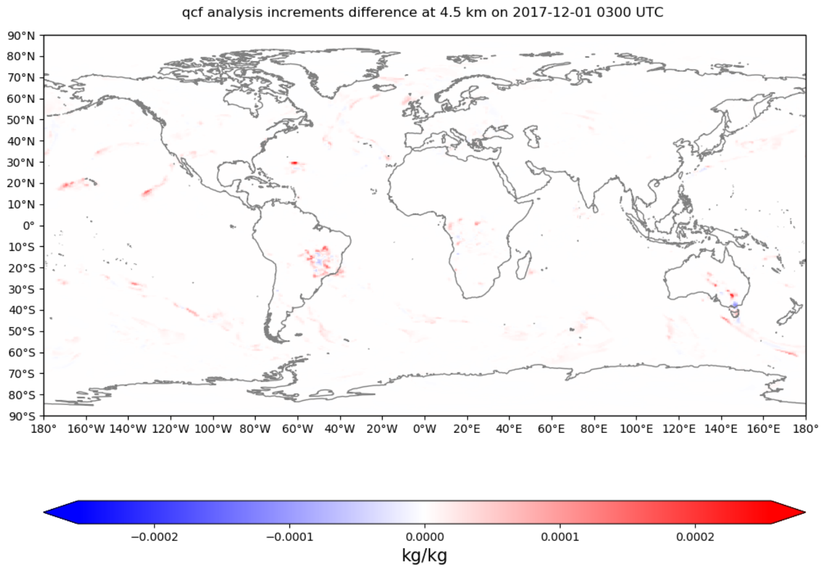
Results with experimental outer-loop suite



Analysis increments (first outer iter)



Analysis increments diff (third minus first outer iter)



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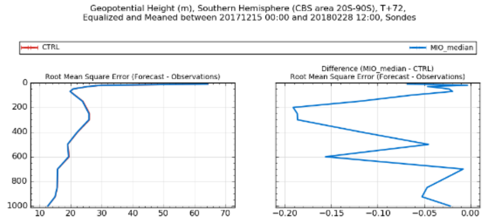
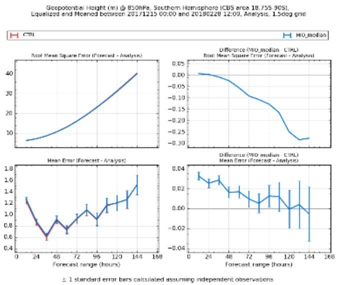
Evaluation results (v. operational-like config)

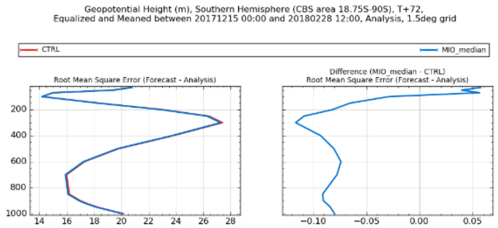
- Median regress coeff where zero



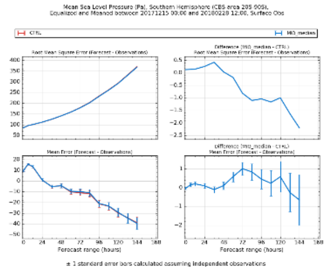
SH_Z T+72 v sondes



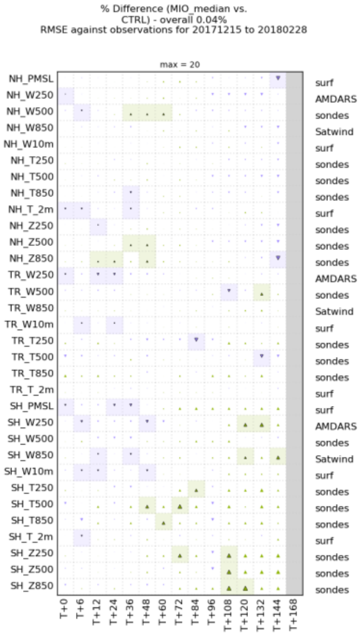
SH_Z 850 hPa v EC

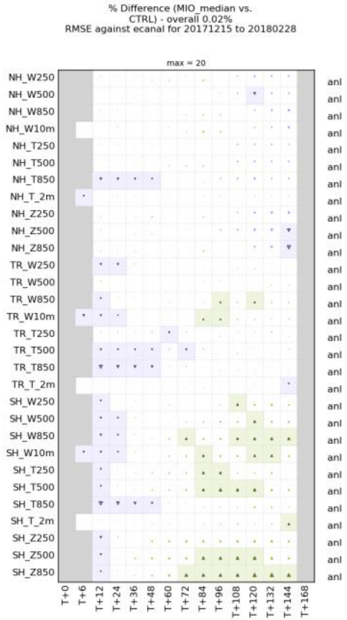


SH_Z T+72 v EC



SH_PMSL v surf obs





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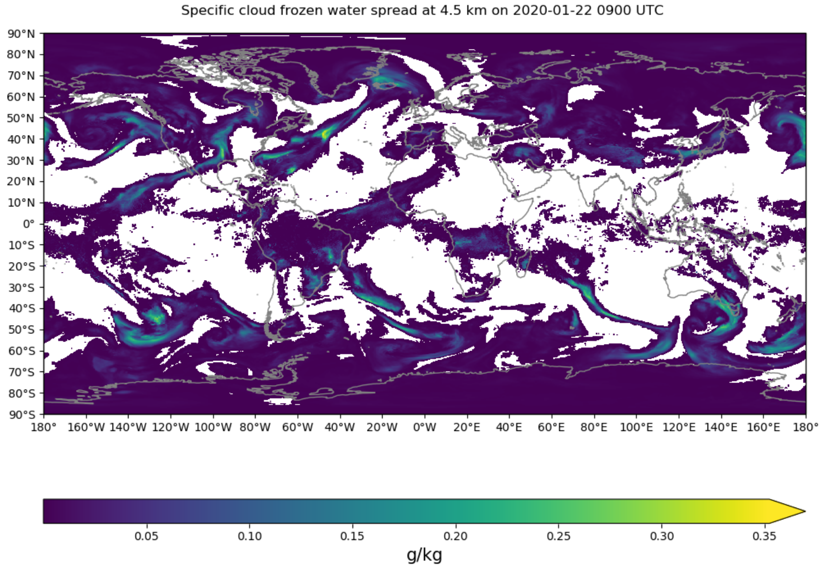
Summary and conclusions

- Satellite data provide an invaluable source of information on water in the atmosphere
- Ability to modify the forecast moisture content using obs depend on number of factors: cloud and precip control vars, MIOs, RTM jacobians, flow-dep forecast errors, linearized and non-lin parametriz. schemes, wind adjustments
- Results critically depend on approx. and known unknowns (e.g. particle shapes or habits)
- Advances in data assim and radiative transfer techniques, improved scattering databases, better physical representation of large scale and convective moist processes and increased avail of obs can lead to significant improvements in forecast skill

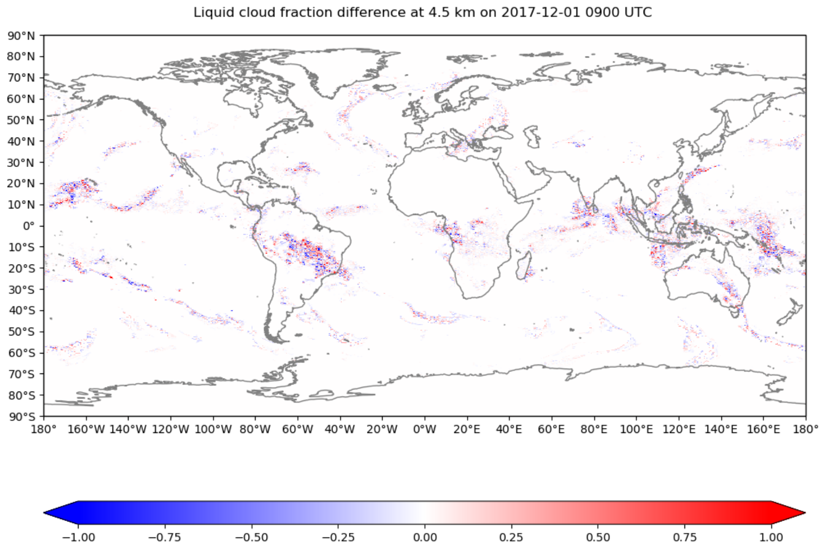
Additional slides

Cloud frozen water ensemble forecast spread

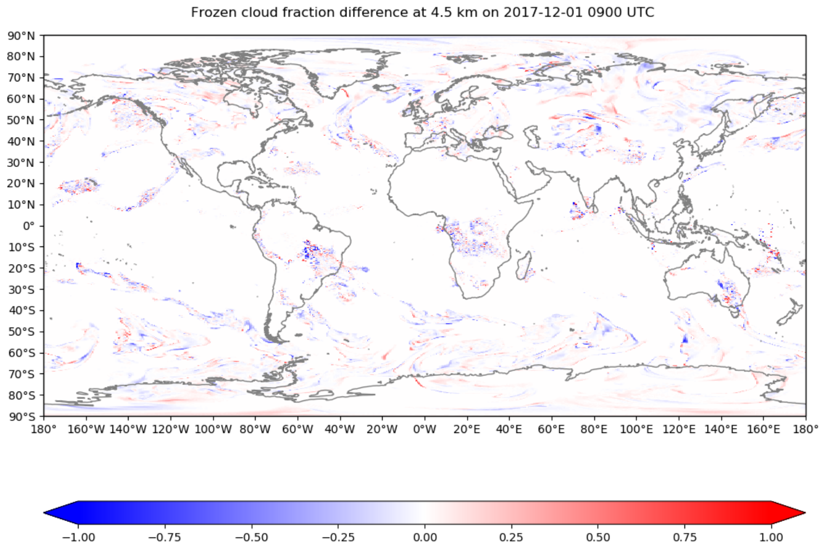
- From En-4DEnVar, model level 25 (4.5 km)



Liquid cloud fraction forecasts



Frozen cloud fraction forecasts



Sub-grid cloud water distribution

From Smith 1990

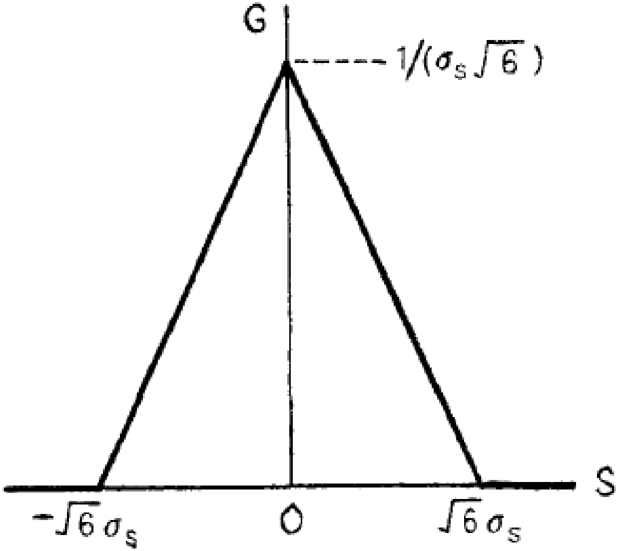
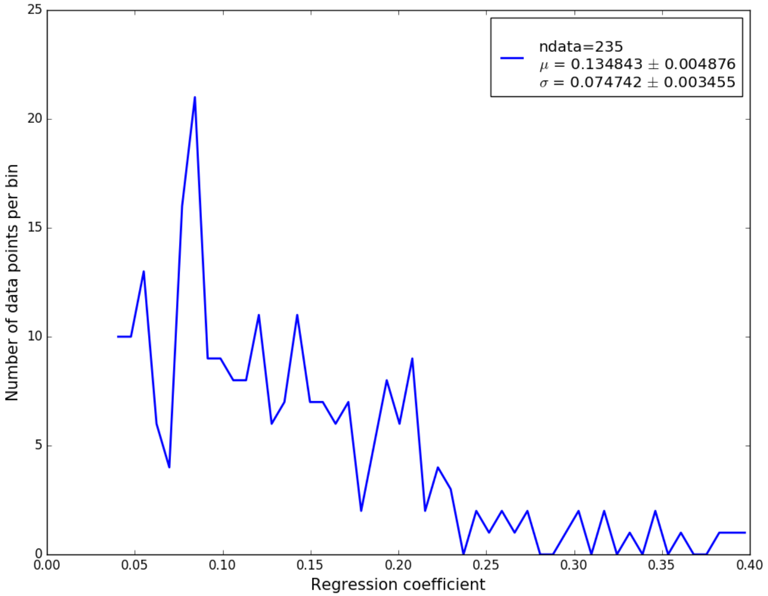
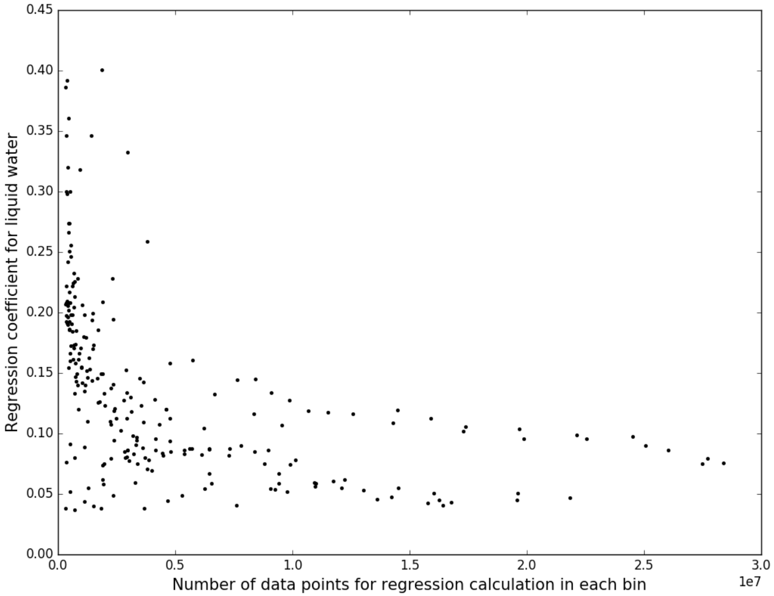


Figure 1. The symmetric triangular probability distribution function with standard deviation σ_s used in the cloud model.

Cloud liquid water increments: regressions

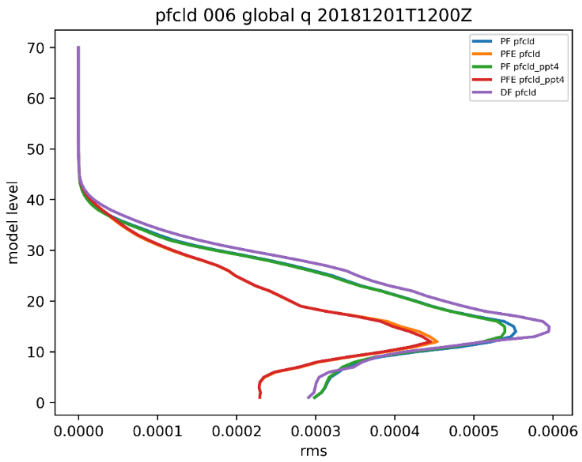
Threshold : 3.3E5 perts per bin

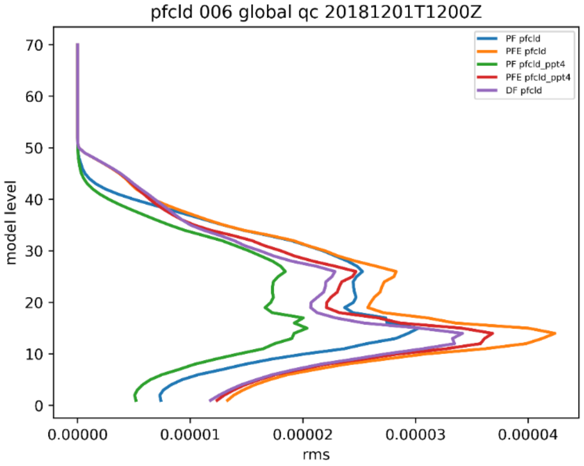




Linearization tests

- Initial increment difference between T+12 and T+6 forecasts valid at the same time: only acceptable for first outer-loop iteration
- $PF = \|\boldsymbol{S}^{-I}\delta\boldsymbol{w}_t\|$; $DF = \|\boldsymbol{P}(\boldsymbol{x}_2(t)) - \boldsymbol{P}(\boldsymbol{x}_1(t))\|$; $PFE = \|\boldsymbol{S}^{-I}\delta\boldsymbol{w}_t - (\boldsymbol{P}(\boldsymbol{x}_2(t)) - \boldsymbol{P}(\boldsymbol{x}_1(t)))\|$ where $\boldsymbol{P}$ is the reconfiguration at lower resolution





Linearization tests

- $PFEoDF = \|\boldsymbol{S}^{-I}\delta \boldsymbol{w}_t - (\boldsymbol{P}(\boldsymbol{x}_2(t)) - \boldsymbol{P}(\boldsymbol{x}_1(t)))\| / \| \boldsymbol{P}(\boldsymbol{x}_2(t)) - \boldsymbol{P}(\boldsymbol{x}_1(t))\|$