Use of cloud condensate in the background error formulation

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Outline

1. Cloud nonlinear model, tangent linear model and control variables
2. Cloud link with the humidity control variable
3. Cloud condensate control variable
4. Summary and recommendations

Control variables - how they relate to model variables

- Nonlinear prognostic model variables: $(\ldots, T, q_v, q_l, q_i, N, q_r, q_s)$
- Tangent linear prognostic model variables - a subset of perturbations in the nonlinear variables: $(\ldots, \delta T, \delta q_v, \delta q_l, \delta q_i)$
- Control variables for the background error term - a linear combination of the tangent linear variables, chosen to reduce/eliminate cross-correlations between different control variables: $(\ldots, \delta T_u, (\delta q_v / q_{sat}^b)_u, (\delta q_c / f^b)_u)$
- Strategy for adding tangent linear and control variables
  - Try to add new variables without needing to change the existing ones, e. g. for the control variable add cloud condensate, not total water.
  - Add new tangent linear prognostic variables if they help to extract observational information: model/observation operator sensitivity and linearity decisive.
  - New control variables to describe errors for new tangent linear variables - can be a linear combination of TL variables.

Adding more cloud related variables: ECMWF example

- At ECMWF blue variables above are the current operational configuration:
  - There is only δq_v in the tangent linear model - diagnostic physics parameterization give cloud and precipitation variables for use in linear physics and observation operators. The adjoint model only uses cloud/rain observation information projected on $\delta T, \delta q_v$.
  - There is only $(\delta q_v / q^b_{sat})_u$ in the control variable - no prognostic cloud variables available in the TL/AD model.
- The variables in red are current developments at ECMWF:
  - Rain and snow (q_r, q_s) have been added to the nonlinear model.
  - Cloud liquid water and ice $(\delta q_l, \delta q_i)$ under development for the tangent linear model. With this development information from observations also projects onto the prognostic cloud variables.
  - Cloud condensate $\delta q_c = \delta q_l + \delta q_i$ under development for the control variable - liquid and ice available in the TL/AD model, and an accurate diagnostic split can be used, $\delta q_l = \alpha(T^b)\delta q_c$ and $\delta q_i = (1 - \alpha(T^b))\delta q_c$.

Humidity-temperature background error correlations: connection to clouds I

- Humidity-temperature background errors as a function of relative humidity is close to 1 at saturation and reduces to zero at about 85% relative humidity.
- It appears the correlation mainly describes large scale condensation in clouds: the correlation coefficient looks very similar to cloud cover versus relative humidity for stratiform clouds.
- A simple cloud scheme describing instantaneous condensation conserves total in-cloud and gridpoint mean water in the absense of precipitation,

$$\delta q_t^c = \delta q_s(T^b) + \frac{\delta q_l + \delta q_i}{N} = \delta q_s(T^b) - \frac{\delta q_v}{N} = 0$$

Humidity-temperature background error correlations: connection to clouds II

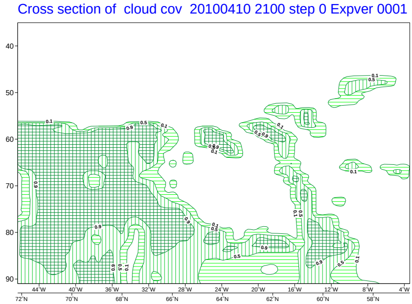
- This gives the gridpoint mean humidity change in response to a temperature change as

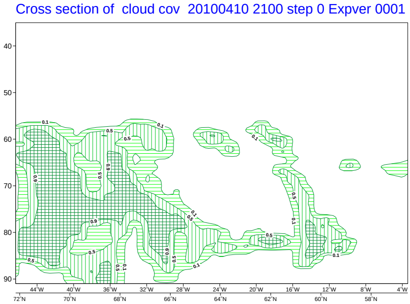
$$\delta q_v = N \delta q_s(T^b) = N \left. \frac{\partial q_s}{\partial T} \right|_{T^b} \delta T$$

- The humidity control variable definition contains a similar relationship, after multiplying with $q_s(T^b)$

$$\delta q_v = (\delta q_v)_u + Q_v(rh^b) \frac{q_v^b}{q_s(T^b)} \left. \frac{\partial q_s}{\partial T} \right|_{T^b} \delta T$$

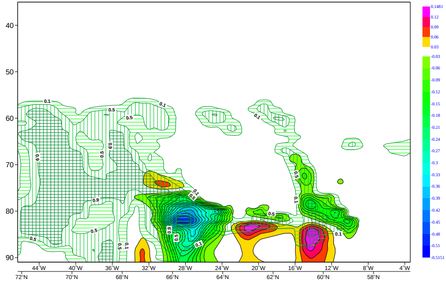
Humidity-temperature background error correlations: connection to clouds III

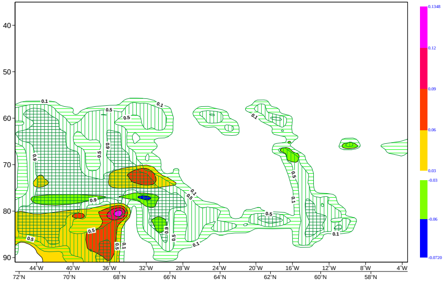




- Cross section Greenland-Iceland of
  - (left) Humidity-temperature correlation $Q_v(rh^b)$ in terms of $N_{eff} = \frac{q_v^b}{q_s(T^b)} Q_v(rh^b)$.
  - (right) Model first guess cloud cover N.
- Similarities, but the correlation also picks up additional processes, so $N_{eff} > N$.

Humidity-temperature background error correlations: connection to clouds IV





- Cross section Greenland-Iceland (model first guess errors in green)
  - (left) 'Balanced' δq_l increments implied by $Q_v(rh^b)$.
  - (right) 'Balanced' δq_i increments implied by $Q_v(rh^b)$.
- Too large increments here, but could use first guess N instead.
- Can this be used? Add cloud increments to nonlinear model at outer loop level, even if no clouds in TL?

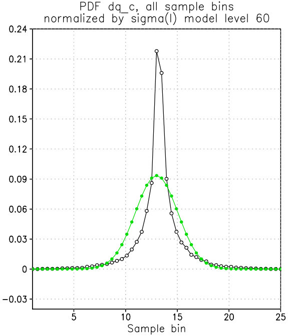
Cloud control variable - where to begin?

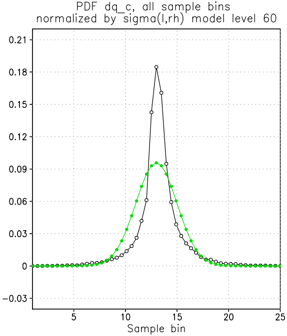
- Cloud condensate forms from humidity, and precipitation forms from cloud condensate, so one needs to include accurate cloud condensate before considering precipitation.
- Cloud condensate also more linear than cloud cover and precipitation, which is why cloud condensate $(\delta q_l, \delta q_i)$ chosen for extending the TL model at ECMWF.
- Humidity is (mostly) limited by condensation to $\frac{q_v}{q_{sat}} < 1$ (exception: supersaturation wrt ice).
- Similarly, cloud condensate is (mostly) limited by autoconversion (to precipitation) to $\frac{q_c}{Nq_c^{crit}} < 1 + \varepsilon < 2$ (exception: strong convection).
- Cloud condensate perturbations are (on average) accurately split into liquid and ice as a function of temperature $\alpha(T)$.
- Consider as control variable $(\delta q_c)_u$ or $(\frac{\delta q_c}{N^b q_c^{crit}})_u$.
- Always need to include the 'balance/correlation' with other variables, thus $(\cdot) = (\cdot)_u + (\cdot)_b$.

Study control variable candidates with ensemble forecast differences

- We use differences of 3-h forecasts from independent analyses using perturbed observations.
- We aim for a variable with homogeneous statistics, where the forecast difference pdf is close to Gaussian.
- Building on our humidity analysis work, this will be attempted by finding a flow-dependent variable transform $f(q_c)/\sigma(q_c, T, \ldots)$. The transform can even be nonlinear, with nonlinearities treated at outer loop level in 4D-Var.
- 'Balances' at later stage for the 'most Gaussian' variable: options open and range from total water conservation to linear cloud scheme operators.
- We start by plotting pdf histogram of a few candidate variables.

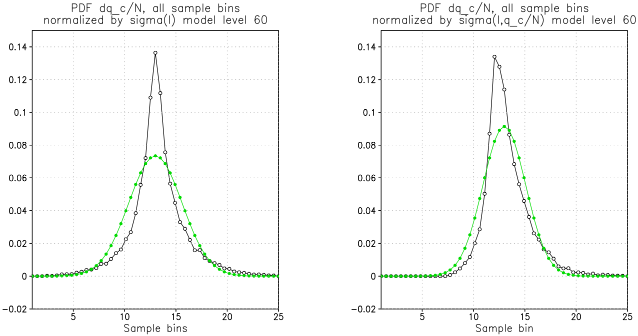
Cloud condensate δq_c: model level 60 ≈ ice





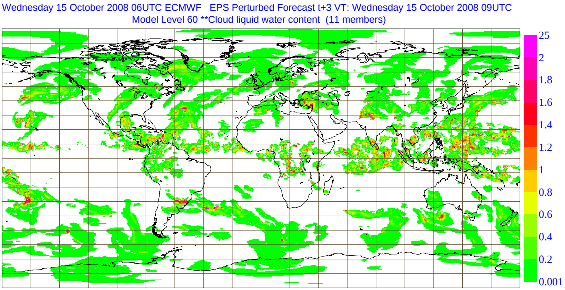
- Left: normalized by constant $\sigma(L)$ non-Gaussian, inhomogeneity causes relatively smaller values to accumulate close to zero.
- Right: normalized by flow dependent $\sigma(L, rh)$ still bad.

Normalized cloud condensate $\frac{\delta q_c}{N q_c^{crit}}$: level 60 $\approx$ ice

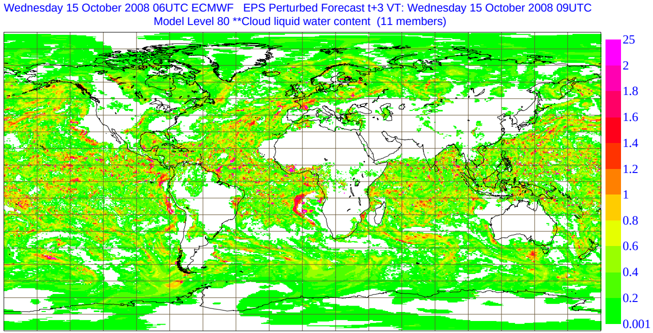


- Left: normalized by constant $\sigma(L)$
- Right: normalized by flow dependent $\sigma(L, \frac{q_c}{N q_c^{crit}})$.
- Both similar and better than δq_c.
- Only include samples for $N > 0.01$ and $\frac{q_c}{N q_c^{crit}} < 2$

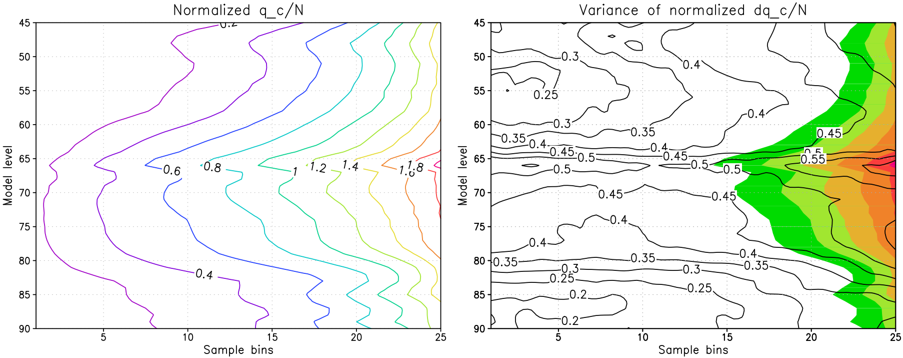
Normalized cloud condensate level 60



Normalized cloud condensate level 80

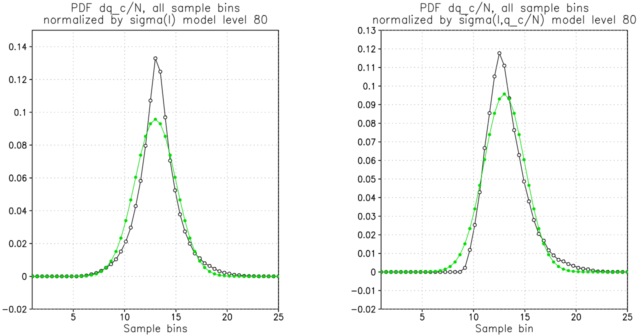


Normalized cloud condensate $\frac{\delta q_c}{N q_c^{crit}}$ variance



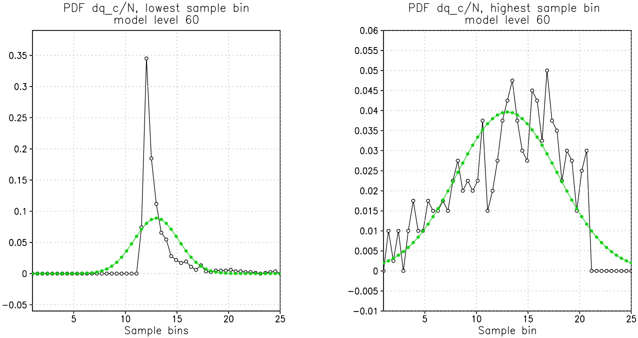
- Estimated flow-dependent error variance does not vary much, so not much extra gained by using it.
- We are still working to improve upon this formulation.

Normalized cloud condensate $\frac{\delta q_c}{N q_c^{crit}}$: level 80 ≈ water



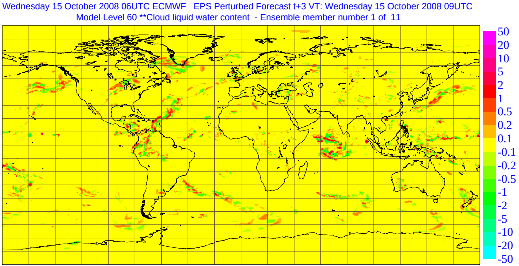
- Left: normalized by constant $\sigma(L)$
- Right: normalized by flow dependent $\sigma(L, \frac{q_c}{N q_c^{crit}})$.
- More Gaussian than upper (ice) levels.

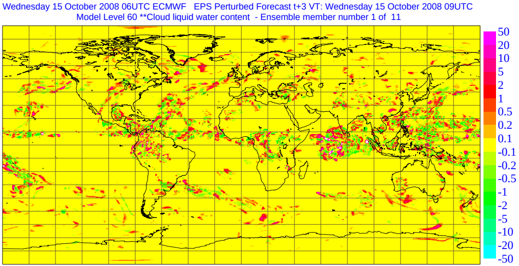
Extremes bins of the normalized cloud condensate $\frac{q_c}{Nq_c^{crit}}$



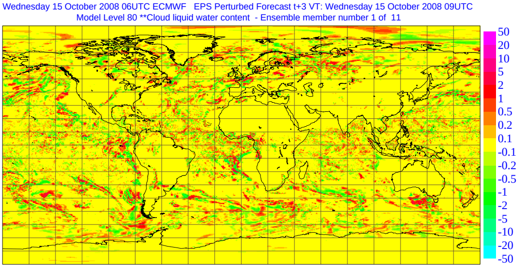
- Left: Samples with lowest background normalized cloud condensate.
- Right: Samples with highest background normalized cloud condensate.
- Asymmetry needs to be accounted for by a nonlinear transform of the control variable (at outer loop level) like for humidity.
- Note small sample size due to looking at one field - more samples smooth but do not change the picture.

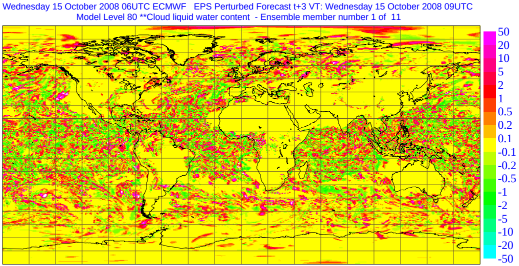
Cloud condensate differences $\times 1E4$ (upper) and normalized (lower): level 60





Cloud condensate differences $\times 1E4$ (upper) and normalized (lower): level 80





Summary and recommendations

- Adding cloud control variable(s) (in 4D-Var together with accurate TL evolution of cloud variables) will allow more detailed studies on the impact of cloud sensitive observations.
- Simplest approaches use total water variable (e. g. UK Met Office) or cloud condensate as planned at ECMWF.
- Precipitation control variables should probably only be attempted once cloud condensate has proven beneficial.
- Cloud analysis needs to address inhomogeneous variances and asymmetric pdf's through normalizations and non-linear symmetrization at outer loop level.
- The variable transforms developed to make the cloud condensate control variable more Gaussian can be applied both in variational and ensemble assimilation context.