Developments in ECMWF humidity background errors

Elías Hólm

ECMWF

March 9, 2018

Steps towards improved humidity analysis

1. Why we need improved humidity analysis
2. EDA humidity background error variances
3. Diabatic balance operator

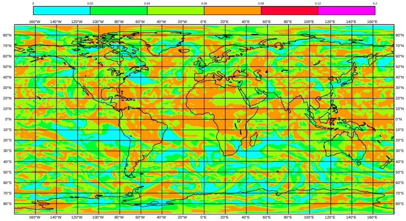
Motivation for current humidity analysis improvements

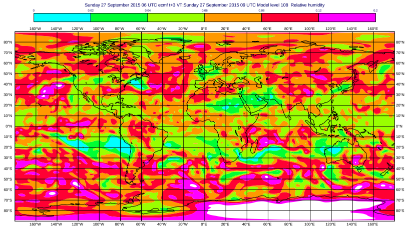
- Recent experiments with infrared radiances in particular indicated the humidity errors were too small, causing humidity signal to be aliased into temperature.
- Humidity variances were calculated differently from those of other variables due to our "gradual" approach to introduce ensemble information into the **B** calculation. Lets make it the same: filtered ensemble spread of the day.
- Humidity errors are correlated with temperature and dynamic variables in areas of high relative humidity. We already accounted for the correlation with temperature. Lets account for error correlation with the dynamics as well.
- Evidence from microwave data assimilation points to the need of cloud control variables for better use of these observations.
- Three steps of improvement, in order of impact:
  - Improve humidity variances (completed)
  - Improve humidity-temperature-dynamics balance operator (in progress)
  - Introduce cloud control variables (next step, feasibility OK)

Humidity background error variances from the EDA

- Pre-July 2017: Humidity background error variances were climatological average for given background relative humidity value and model level through a climatological statistically determined fit.
- Now: Use relative humidity background errors σ_{rh} from EDA like for other variables.
- Humidity sensitive data used better, in particular MW/IR where the radiance signal is more accurately apportioned between humidity and temperature.
- In the tropics in particular, where absolute humidity is highest, this leads to more accurate wind adjustments through the 4D-Var tracing effect.
- Results show improved O-B fits for wind and humidity sensitive observations and improved scores of wind in particular.

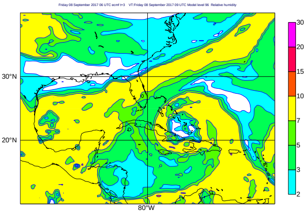
Relative humidity variances: background- vs. EDA-based

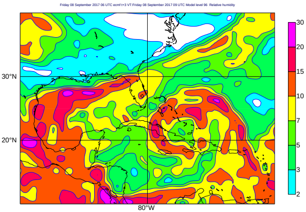




- Left: Old background-based RH stdev (750hPa, 2015092709)
- Right: New EDA-based RH stdev, about two times larger.

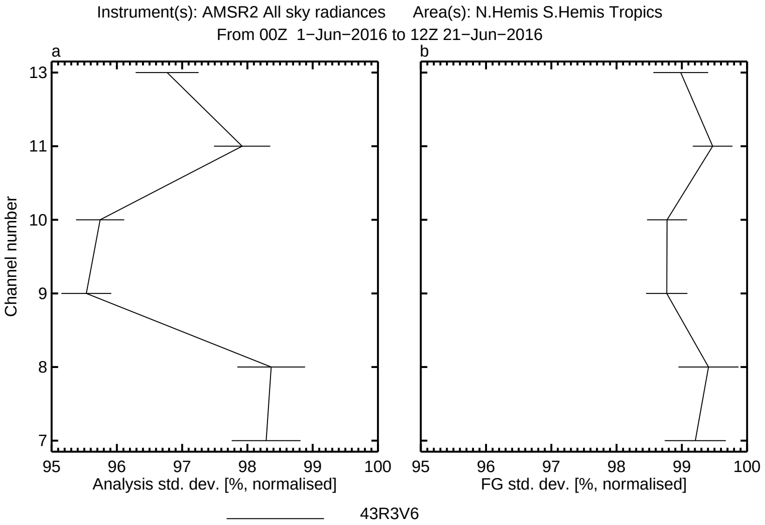
RH errors around TC's Jose and Irma 8 Sep 2017, 500hPa



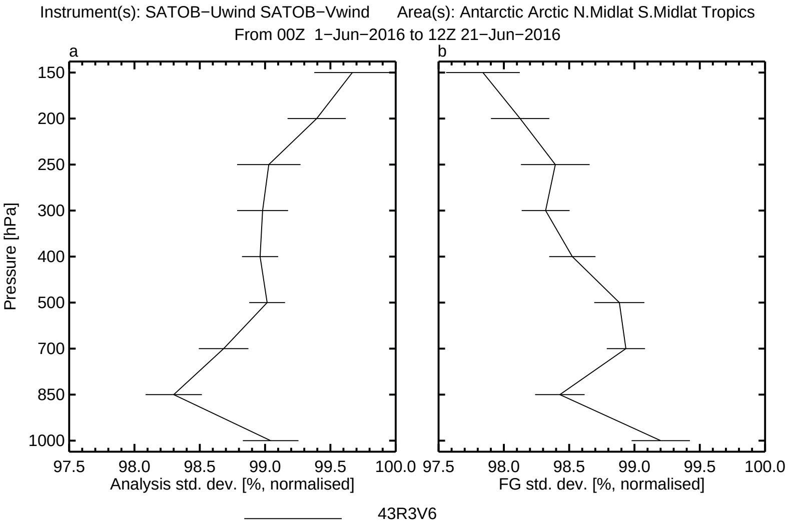


- Left: Old background-based RH stdev, “climatological average”.
- Right: New EDA-based RH stdev, captures extremes of the day.
- Below: VIIRS image from NOAA's Suomi NPP satellite.

Improving humidity **B** improves humidity: O-B for AMSR2



Improving humidity **B** improves wind: O-B for SATOB



RH dependent humidity-dynamics **B** correlations

- In the EnKF these correlations are explicit, but in variational assimilation balance operators are used to model these correlations.
- Several authors/Centres have explicitly/implicitly accounted for how the error correlation between humidity and other variables varies with relative humidity (*RH*), clouds and precipitation, including:
  - UKMO splitting operator for total water increments based on linearized Smith(1990) cloud scheme, and its new replacement by Migliorini, Lorenc and Bell (2018).
  - Environment Canada work on doing a few separate situation dependent regressions for part of the normal balance operator by Fillion et al. (2005) to account better for the coupling between vertical motion and diabatic heating.
  - Environment Canada diagnstic diabatic balance operator by Pagé, Fillion and Zwack (2007).
  - Meteo-France work on separate heterogeneous balance operators in high *RH* areas vs. outside these areas by Montmerle and Berre (2010).
- We try to merge the essence of all above into a simple linear formulation that automatically adjusts the balance as a function of *RH*, and thus cloudyness.

Diabatic balance through linear saturation adjustment

Use linear saturation adjustment (based on Asai 1965, Hólm et al. 2002 (operational ECMWF), Hólm 2015 (current/future development)),

$$\delta T = \delta T_n + C^b a \frac{L}{c_p}\left(\delta q_{vu} - \frac{L q_s(T^b)}{R_v (T^b)^2}\delta T_n\right)$$

$$\delta q_v = \delta q_{vu} - C^b a\left(\delta q_{vu} - \frac{L q_s(T^b)}{R_v (T^b)^2}\delta T_n\right)$$

$$\delta q_c = \delta q_{cu} + C^b a\left(\delta q_{vu} - \frac{L q_s(T^b)}{R_v (T^b)^2}\delta T_n\right)$$

In matrix from this becomes

$$\begin{pmatrix}\delta T\\ \delta q_v\\ \delta q_l\\ \delta q_i\end{pmatrix} = \begin{pmatrix} 1-\frac{L}{c_p}C^b a\gamma & \frac{L}{c_p}C^b a & 0 & 0\\ C^b a\gamma & 1-C^b a & 0 & 0\\ -\alpha C^b a\gamma & \alpha C^b a & 1 & 0\\ -(1-\alpha)C^b a\gamma & (1-\alpha)C^b a & 0 & 1\end{pmatrix}\begin{pmatrix}\delta T_n\\ \delta q_{vu}\\ \delta q_{lu}\\ \delta q_{iu}\end{pmatrix}$$

Details of linear saturation adjustment

- Increments δT_n and δq_{vu} assumed uniform over the gridcell.
- Saturation adjustment takes place in the in-cloud portion C^b of the gridcell, with C^b approximated by a regression formula as a function of rh^b and model level.
- $q^b = q_s(T^b)$ in the in-cloud part of the gridcell.
- Cloud condensate adjustment distributed by $\alpha(T^b)$ between δq_l and δq_i with $\alpha(T^b)$ varying between 0 and 1 according to mixed-phase formula.
- The adjustment conserves total water.
- The adjustment is unchanged for δT and δq_v whether δq_l and δq_i are included or not.
- Here $a = \frac{1}{1+\frac{L^2 q_s(T^b)}{c_p R_v \left(T^b\right)^2}}$ and $\gamma = \frac{L q_s(T^b)}{R_v \left(T^b\right)^2}$

Where does this fit in? Start from the dynamic balance

The balance operator consists of the dynamic horizontal simplified and linearized nonlinear balance (Fisher, 2003),
$\nabla^2 P_b = (f+\zeta)\times v_\psi + \frac{1}{2}\nabla(v_\psi \cdot v_\psi)$, combined with vertical balance operators (from statistical regression, Derber and Bouttier, 1999),

$$\begin{pmatrix} \delta\zeta \\ \delta\eta_n \\ \delta(T_n, p_s) \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ M & 1 & 0 \\ N & P & 1 \end{pmatrix} \begin{pmatrix} \delta\zeta \\ \delta\eta_u \\ \delta(T_u, p_{su}) \end{pmatrix}$$

and simplified and linearized version of quasi-geostropic ω-equation balance (Fisher, 2003), $\left(\sigma\nabla^2 + f_0^2\frac{\partial^2}{\partial p^2}\right)\omega' = -2\nabla\cdot\mathbf{Q}$,

$$\begin{pmatrix} \delta\zeta \\ \delta\eta \\ \delta T \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ Q_2 & 1 & Q_1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \delta\zeta \\ \delta\eta_n \\ \delta T \end{pmatrix}$$

Total balance operator

The total balance operator consists of the dynamic nonlinear and vertical balance, linear saturation adjustment and ω- equation balance,

$$\begin{pmatrix} \delta\zeta \\ \delta\eta_n \\ \delta T_n \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ M & 1 & 0 \\ N & P & 1 \end{pmatrix} \begin{pmatrix} \delta\zeta \\ \delta\eta_u \\ \delta T_u \end{pmatrix}$$

$$\begin{pmatrix} \delta T \\ \delta q_v \\ \delta q_c \end{pmatrix} = \begin{pmatrix} \beta_{tt} & \beta_{tv} & \beta_{tc} \\ \beta_{vt} & \beta_{vv} & \beta_{vc} \\ \beta_{ct} & \beta_{cv} & \beta_{cc} \end{pmatrix} \begin{pmatrix} \delta T_n \\ \delta q_{vu} \\ \delta q_{cu} \end{pmatrix}$$

$$\begin{pmatrix} \delta\zeta \\ \delta\eta \\ \delta T \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ Q_2 & 1 & Q_1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \delta\zeta \\ \delta\eta_n \\ \delta T \end{pmatrix}$$

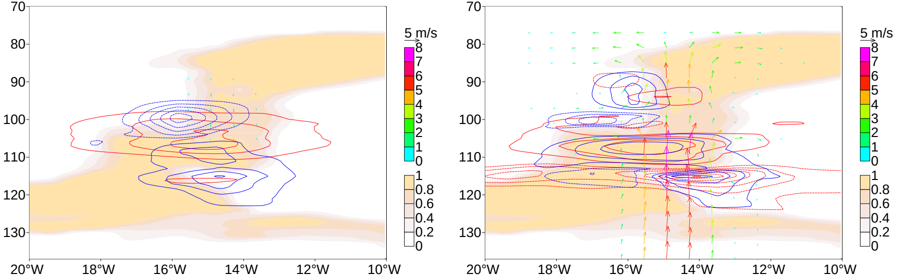
Apply saturation adjustment before ω-equation

- Apply saturation adjustment just before the ω-equation in the balance operator.
- Then the final divergence dynamically supports the water vapour and cloud condensate changes in an adaptive way without any special treatment:

$$\begin{pmatrix}\delta\zeta\\ \delta\eta\\ \delta T\\ \delta q_v\\ \delta q_c\end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0\\ Q_2+M+Q_1N(1-\frac{L}{c_p}C^b a\gamma) & 1+Q_1P(1-\frac{L}{c_p}C^b a\gamma) & Q_1(1-\frac{L}{c_p}C^b a\gamma) & Q_1\frac{L}{c_p}C^b a & 0\\ N(1-\frac{L}{c_p}C^b a\gamma) & P(1-\frac{L}{c_p}C^b a\gamma) & 1-\frac{L}{c_p}C^b a\gamma & \frac{L}{c_p}C^b a & 0\\ NC^b a\gamma & PC^b a\gamma & C^b a\gamma & 1-C^b a & 0\\ -NC^b a\gamma & -PC^b a\gamma & -C^b a\gamma & C^b a & 1 \end{pmatrix} \begin{pmatrix}\delta\zeta\\ \delta\eta_u\\ \delta T_u\\ \delta q_{vu}\\ \delta q_{cu}\end{pmatrix}$$

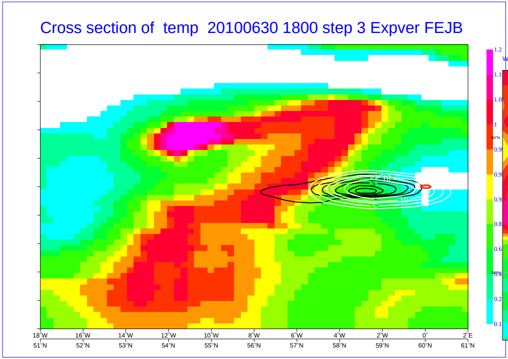
with $\delta q_c = \delta q_l + \delta q_i$ and $\delta T = \delta(T, p_s)$ and $\delta T_u = \delta(T, p_s)_u$.

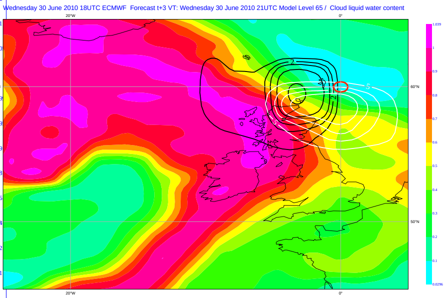
Diabatic balance for single all-sky observation profile



- Left: Current $q - T$ balance operator.
- Right: Diabatic balance operator before ω-equation (no δq_c).
- Increments of temperature (red lines), humidity (blue lines) and wind (arrows).

Feasibility of cloud control variable increments





- Single cloud liquid observation (bold red circle) at start of 6h 4D-Var window in very dry area with no background condensate: cloud condensate (black isolines) and specific humidity (white isolines) analysis increments [units 1E-6 kg/kg] and background relative humidity (colour).

Next: Add new cloud control variables

- Earlier study by Jiandong Gong, Philippe Lopez and Elías Hólm (unpublished manuscript) showed the feasibility of cloud control variables in the ECMWF system, using q_c with variance and balance based on RH-dependent climatological regressions and a TL model with prognostic cloudscheme and q_l, q_i.
- Add cloud liquid and ice to control variables. Treat just like humidity, using EDA variances and diabatic balance (no zero variances, always a minimum value).

References

- Asai, T. (1965): A numerical study of the air-mass transformation over the Japan Sea in winter. *J. Meteorol. Soc. Japan*, **Ser. II, Vol. 43**, 1–15.
- Derber, J., and F. Bouttier (1999): A reformulation of the backgroud error covariace in the ECMWFi global data assimilation system. *Tellus*, **51(2)**, 195–221.
- Fisher, M., (2003): Background error covariance modelling. *Proc. ECMWF Seminar on Recent Developments in Data Assimilation for Atmosphere and Ocean*, 8–12 September 2003, Reading, UK, pp.45–63.
- Hólm, E. V. (2015): Balance operator including linear saturation adjustment and cloud condensate. The 3rd Joint JCSDA-ECMWF Workshop on Assimilating Satellite Observations of Clouds and Precipitation into NWP Models. NCWCP, College Park, Maryland, December 1–3, 2015.
- Hólm, E., E. Andersson, A. Beljaars, P. Lopez, J-F. Mahfouf, A.J. Simmons and J.N. Thépaut, (2002): *Assimilation and Modelling of the Hydrological Cycle: ECMWF's Status and Plans*. ECMWF Tech. Memorandum No. **383**.