When observations confront highly nonlinear physical processes

Marta Janisková

Former ECMWF, Shinfield Park, Reading, UK

Thanks to: P. Lopez, F. Váňa & M. Fielding

Introduction

- An inclusion of the physical processes in the assimilating models is a necessary step to allow a consistent use of the observations and the dynamics of the model to obtain a better analysis and the subsequent forecast.
- A good model with physical parametrizations is needed to describe the time evolution of the model state over the assimilation window as accurately as possible.
- Physical parametrizations are also used during the assimilation to link the model's prognostic variables (typically temperature, wind, humidity and surface pressure) to the observed quantities (e.g., radiances, reflectivities, backscatters).
- Without the inclusion of physics, the assimilation of many satellite observations, such as all-sky radiances, precipitation and cloud-effected measurements would simply be impossible.

* However, assimilation of observations directly linked to the physical processes in a global numerical weather system comes with a lot of challenges to succeed

Most challenging – cloud and precipitation observations

- Despite the major influence of clouds and precipitation on atmospheric water and energy balance, most of the cloud-affected observations used to be discarded in data assimilation systems mainly because of:
  - discontinuous nature (in time and space) of clouds and precipitation

    → *irregular, small-scale and thus difficult to represent in global models*
  - spatial representativeness of satellite observations, especially from active instruments
  - non-Gaussian error characteristics of the cloud models
  - need to use linearized versions of these nonlinear processes (for variational assimilation)

- In the recent years, new approaches and developments are turning some of the most challenging cloud and rain related observations into some of the most valuable:
  - ECMWF's "all-sky" assimilation approach using satellite information in cloudy and rainy areas rather than discarding it. Including also radiances from microwave instruments.
  - New capabilities, including spaceborne radar and lidar systems such as those on the board of ESA-JAXA EarthCARE mission and the use of visible observations, continue to broaden what can be exploited.

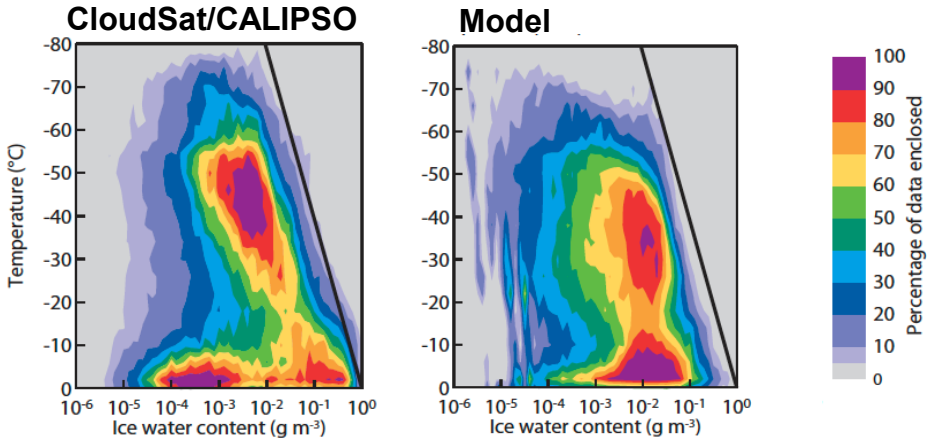
Requirements for data assimilation

- To succeed to assimilate observations in the presence of nonlinear physical processes requires:
  - reasonable representation of the physical processes related to the observations
  - observation operator being able to provide realistic model equivalents to the observations
  - linearity and regularity of the observation operator used in the variational assimilation framework
  - appropriate processing and screening of observations
  - removal of systematic biases via a bias correction scheme
  - characterizing the components of observation error including representativity issues

Reasonable representation of the physical processes, related to the observations, by the model

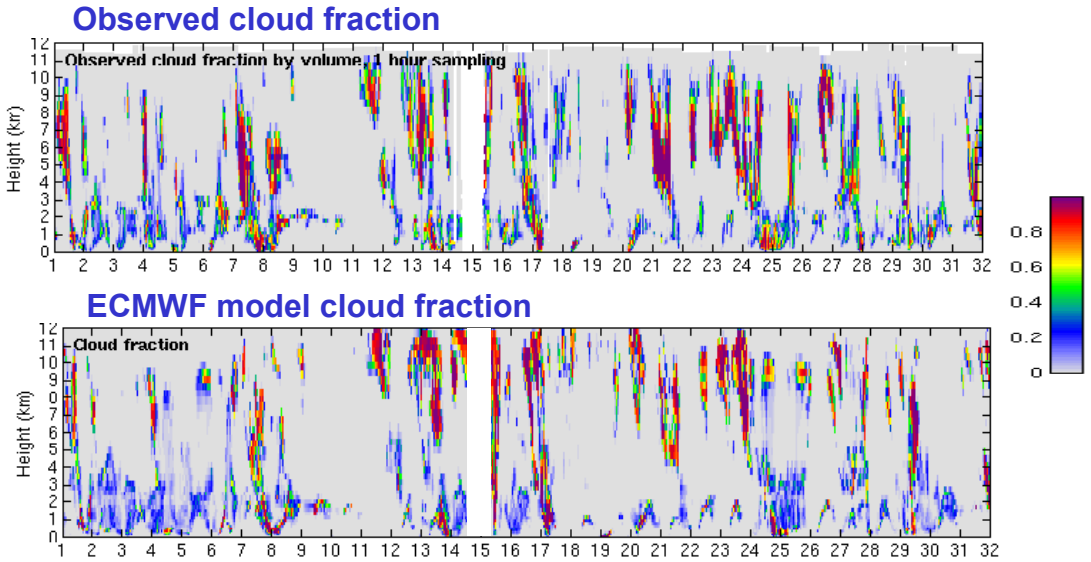
Performance of cloud scheme used in IFS forecast model

Comparison of IWC vs. temperature – July 2006, NH



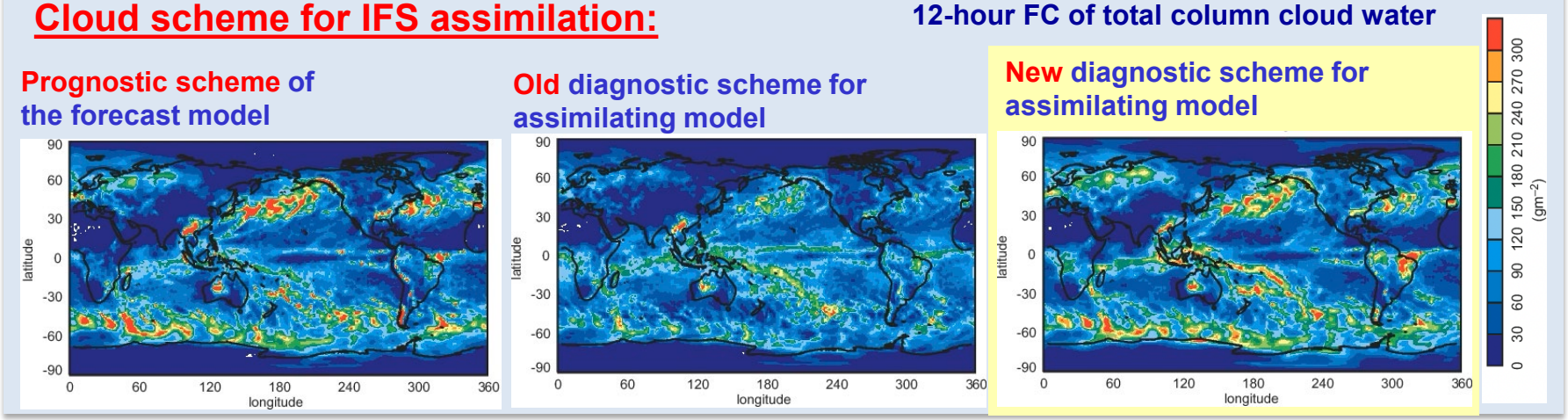
- Forecast model is able to correctly capture the major cloud events and hydrometeors, although errors in the details are clearly visible..

Comparison of the model cloudiness profiles against radar estimates at Chilbolton, August 2012



Cloud scheme for IFS assimilation:

12-hour FC of total column cloud water

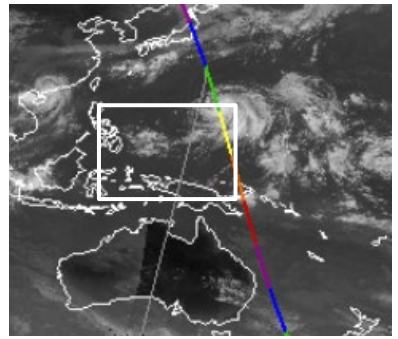


- Improved cloud scheme for assimilation model in a view of using space-borne cloud observations.

Accurate enough observation operators

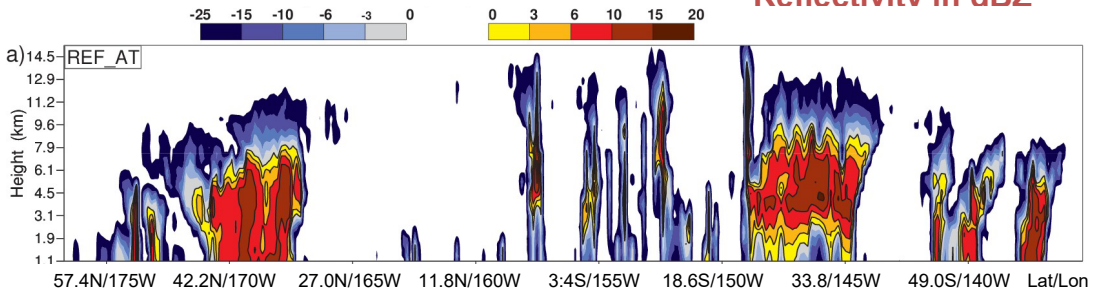
- Observation operator being able to provide realistic model equivalents to the observations

Typhoon Choi-wan
(Sept. 15th 2009)

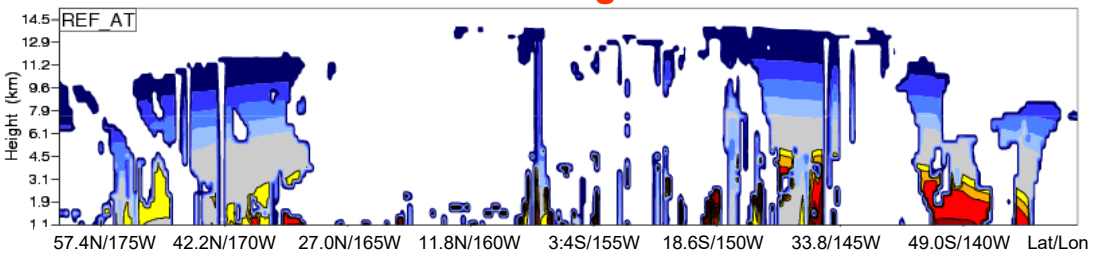


Observations

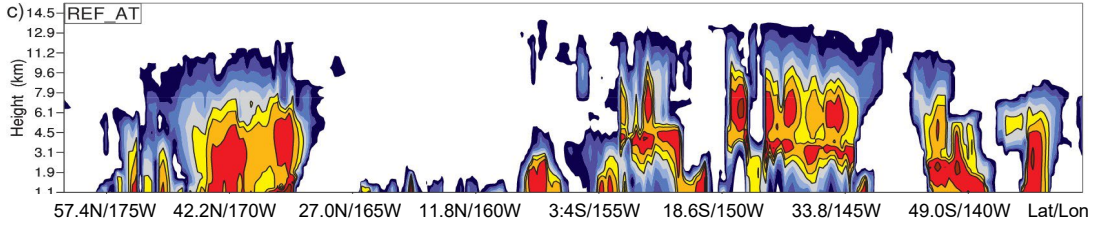
Reflectivity in dBZ



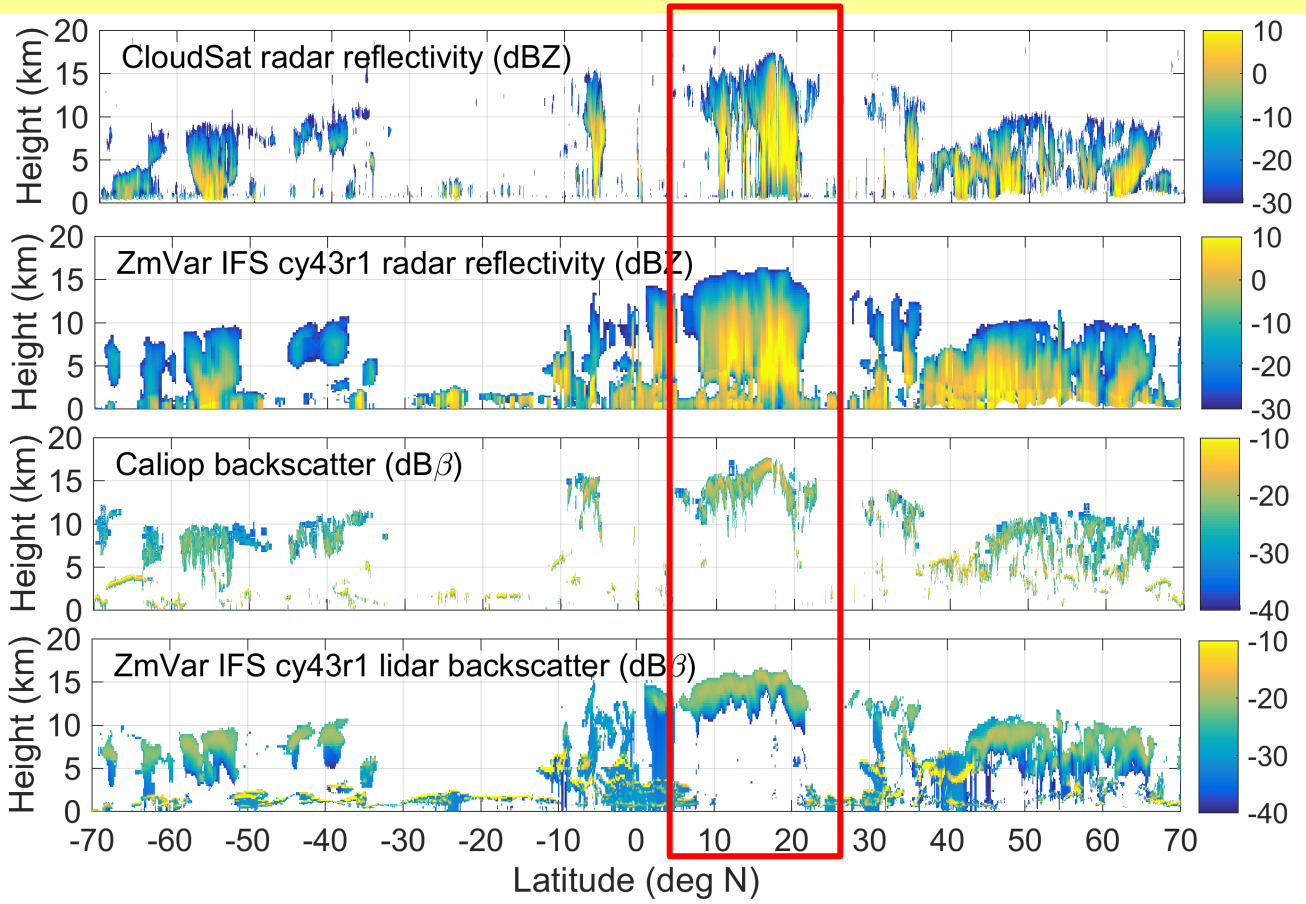
Model not accurate enough



ECMWF model used for 1D+4D-Var



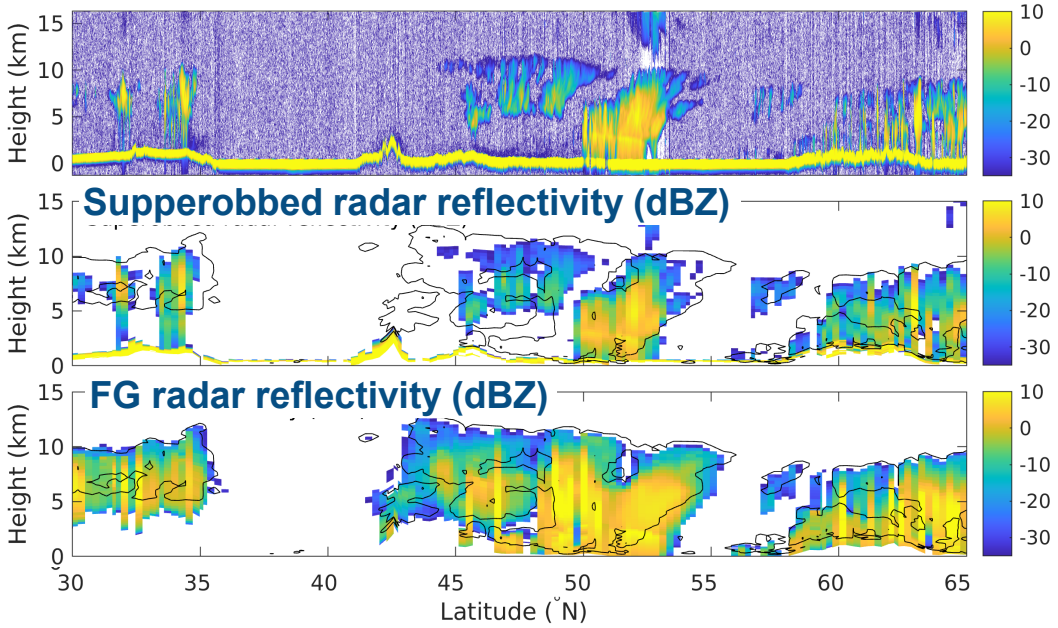
ECMWF cloud radar & lidar obs operators



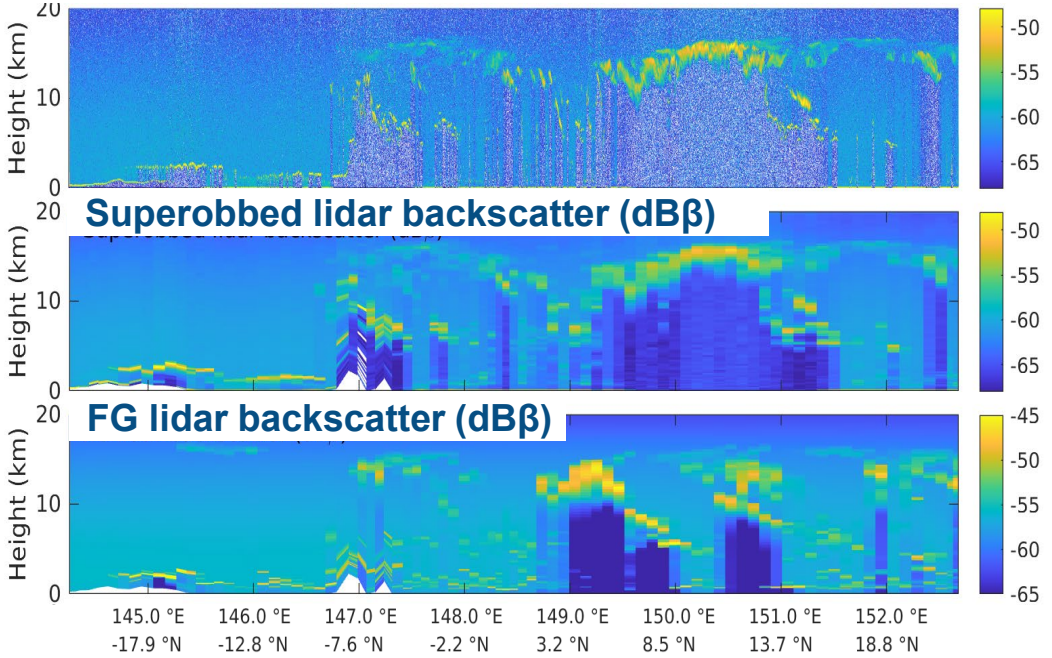
Smoothing observations

- High-resolution instruments (like satellite or ground based radars) provide massive volumes of information containing both micro-scale details and instrumental noise.
- Observations can be effectively smoothed by averaging them into "superobs" and thus making them vastly more compatible with the resolution of the models they are ingested into.
- By acting as a spatial low-pass filter, superobbing provides:
  - *smoother images, decreasing the effective sensor noise and thus the standard deviation of departures between model and observations*
  - *more representative and less noisy comparison & reducing the correlation in uncertainties between superobs*

EarthCARE radar reflectivity observations

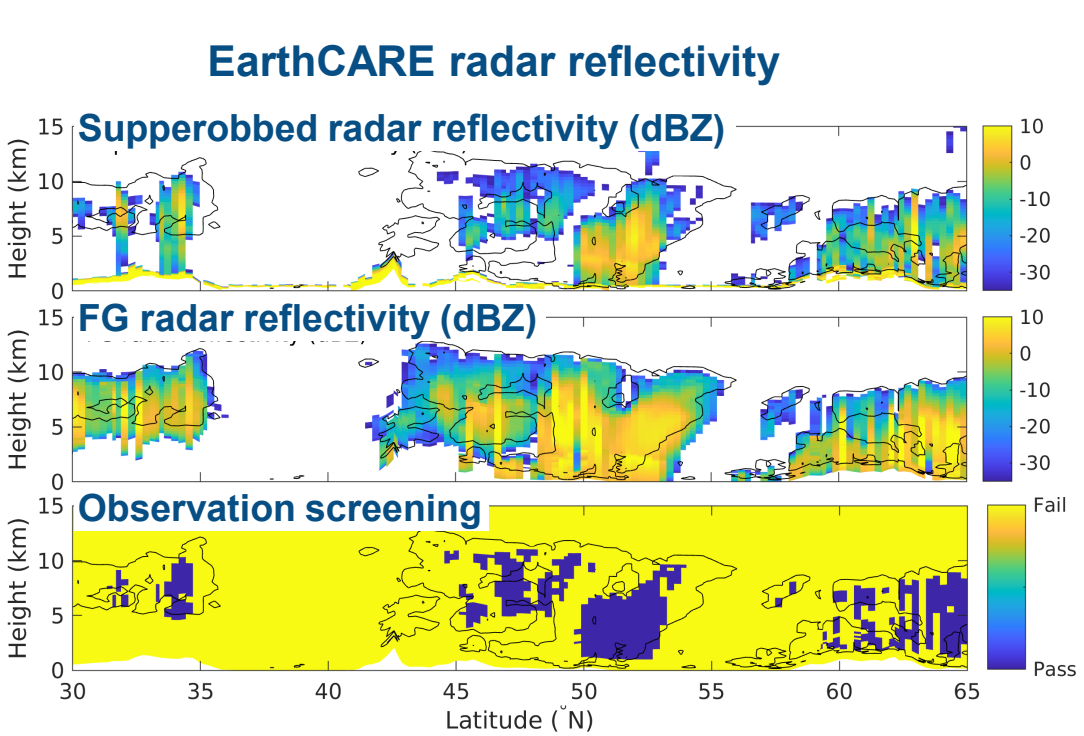


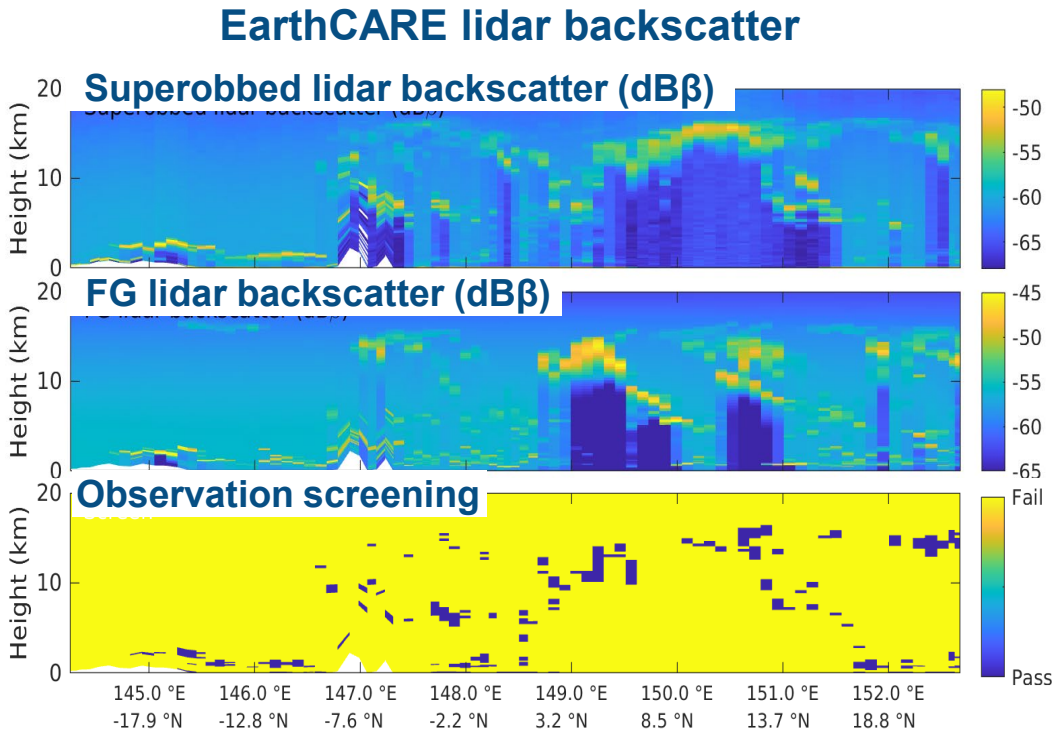
EarthCARE lidar backscatter observations



Screening and quality control

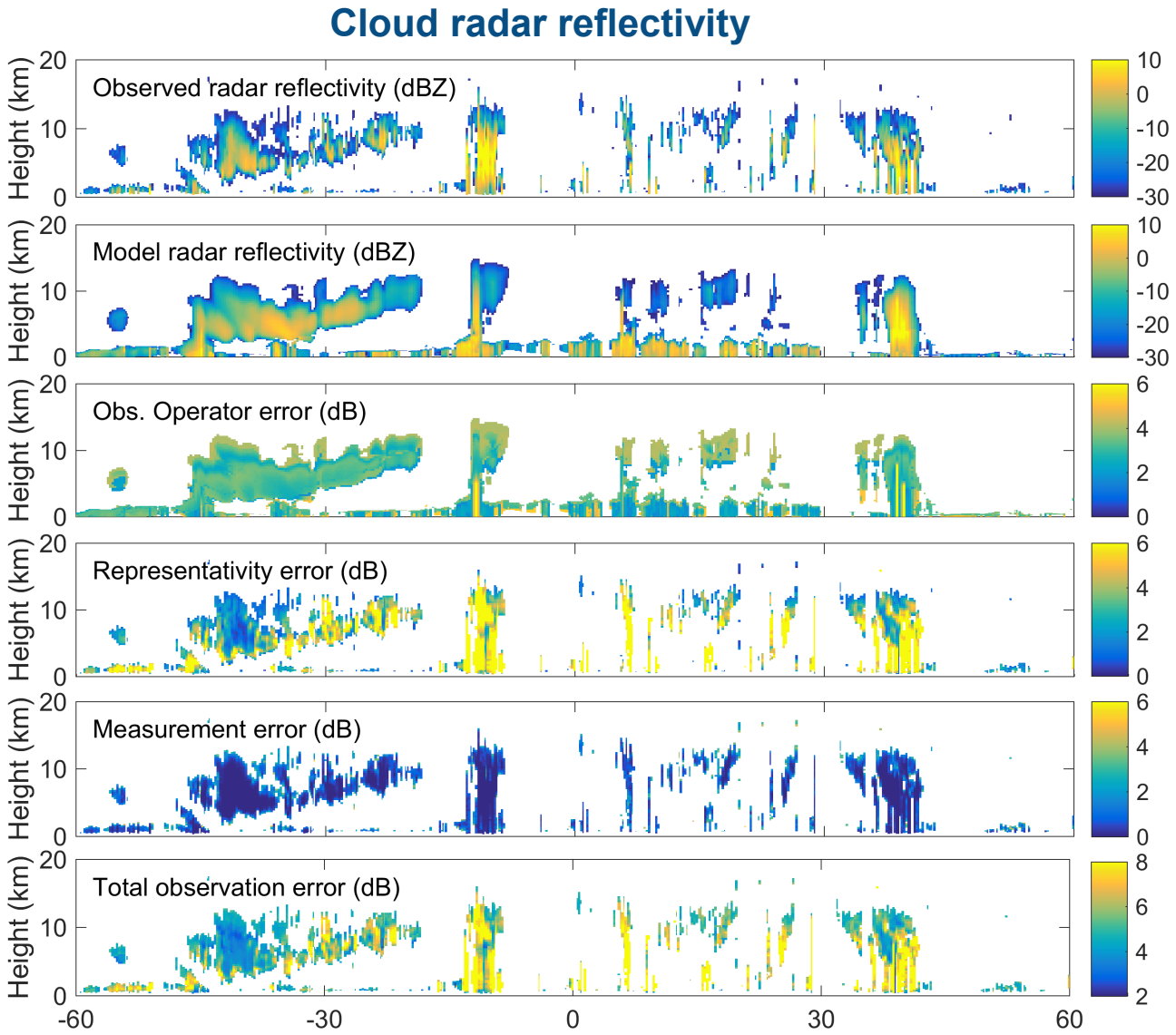
- Screening and quality control aim to provide a balance between including as much information from observations as possible whilst preventing ‘bad’ observations from degrading the analysis/forecast. This is important to:
  - reduce the volume of observations used by the assimilation system
  - ensure measurements are not assimilated:
    - where they are of poor quality
    - where the forward model is not capable of representing the observations.
    - where there is an excessive non-linear relationship between perturbations in the control variables and the corresponding simulated parameters





Characterizing the components of observation error including representativity issues

- Observation errors are a crucial component of a data assimilation system as, coupled with the background error, control the weight each observation is given.
- For observations related to the physical processes, especially for profiling observations, the true observation error likely to be highly situation dependent.
- Under the hypothesis of uncorrelated errors, observation errors defined as a combination of instrument error, observation operator error and representativity error.



Representativity error dominates total error

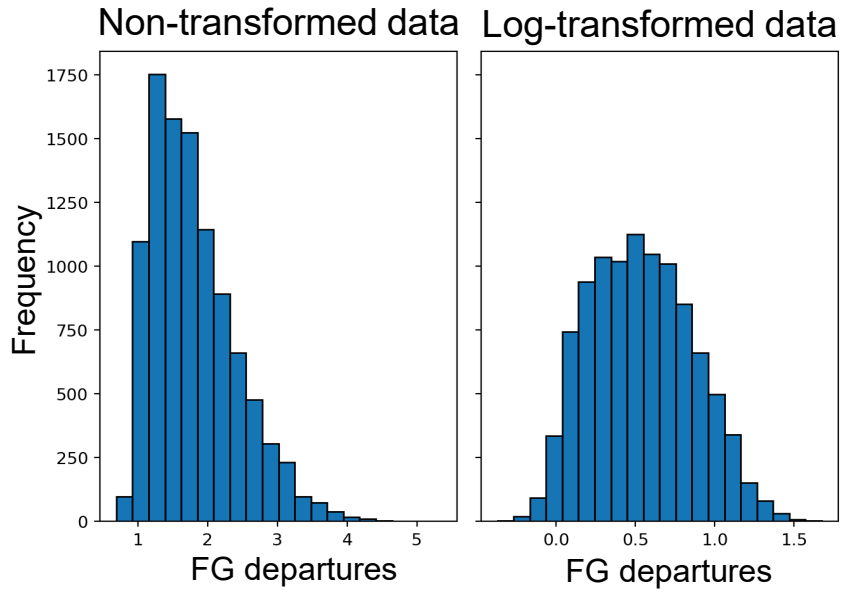
Other issues when assimilating observations linked to the physical processes

- For variables such as precipitation, clouds or optical depth, it is observed that error statistics for the background and observational errors diverge from the Gaussian shape and are often skewed

- Using the logarithmic change of variables helps the assimilation by making the observation error more Gaussian.
- Errors are then reassigned as:

$$r_{log} = \sqrt{\log_{10}(1 + \varepsilon_r^2)}$$

where r_{log} is the error variance of the logarithmic observation and ε_r is the relative error in physical obs



- When assimilating quantities such as rain rates (RR), for instance, how do we deal with the situations where $RR_{FG} = 0$ and $RR_{OBS} >> 0$ (→ *rain sensitivity to control variables is zero*).

- Issues for variational assimilation and incremental formulation:
  - resolution differences between inner and outer loops of 4D-Var:
    (e.g., at ECMWF: Tco1279 in main trajectory & T255, T319 and T399 in minimizations)
    → especially important for cloud and precipitation fields
  - linearized physics should not depart too much from nonlinear physics (*always on the run…*). .

Physical parameterizations in DA: historical background

- Physical parameterizations started to be used for data assimilation (DA) in methods such as physical initialization and nudging, but these applications would usually deal with a single type of observations at a time (e.g. precipitation from a radar).
- Work on linearised physics (LP) started in the mid-1990s, initially focusing on its potential usage in sensitivity studies as well as on non-differentiability issues.
- The development of LP packages really gathered pace at the turn of the century with the operational implementation of 4D-Var DA in both global and limited-area models.
- The ECMWF 4D-Var uses the most detailed LP package available at present:
  - comprehensive schemes implemented describing the whole set of physical processes and their interactions almost as in the non-linear model:
    - radiation
    - vertical diffusion
    - surface
    - orographic gravity wave drag
    - moist convection
    - large-scale condensation/precipitation
    - non-orographic gravity wave
  - with simplifications and/or regularization applied *(Janisková et al. 2002; Tompkins & Janisková 2004; Lopez & Moreau 2005; Janisková & Lopez 2013, 2023)*

Physical parametrizations in data assimilation (DA) needed:

- to convert the model state variables (as temperature, wind, humidity, surface pressure) into observed equivalents (e.g. radiances, reflectivities, precipitation, cloud, …)
- to describe the time evolution of the model state over the assimilation window as accurately as possible

- ***Using physics (full & simplified) in incremental 4D-Var system:***

4D-Var →

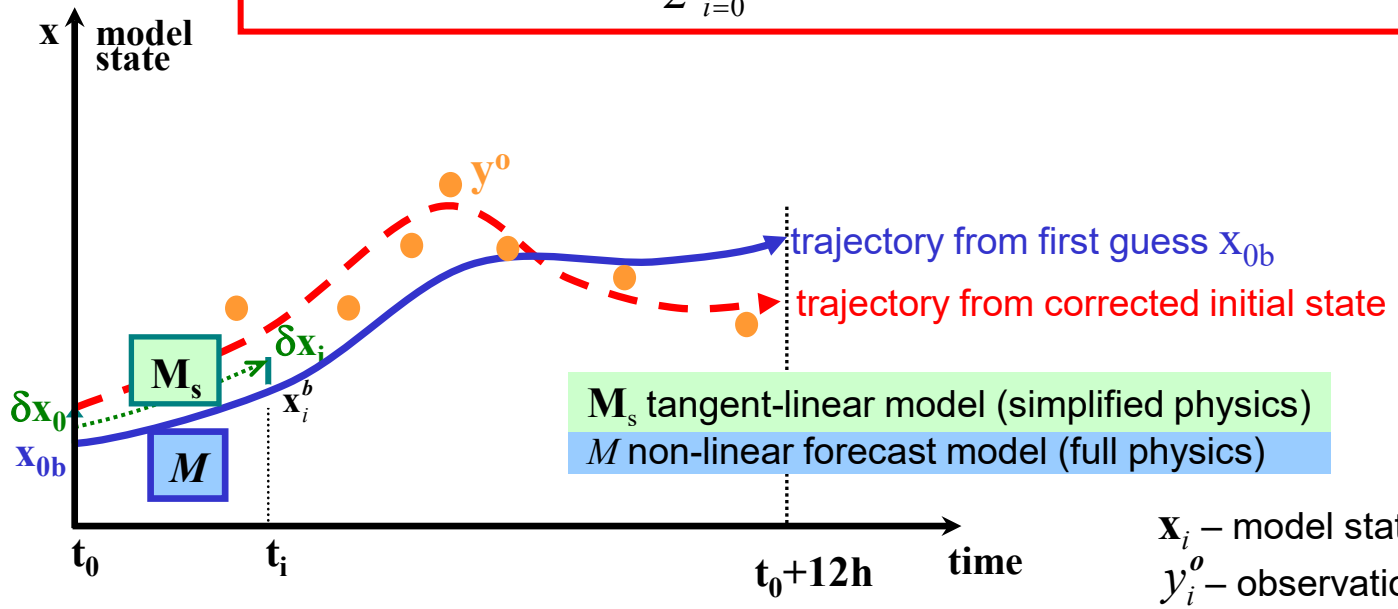
$$\min J(\delta\mathbf{x}_0) = \frac{1}{2}\delta\mathbf{x}_0^T\mathbf{B}^{-1}\delta\mathbf{x}_0 + \frac{1}{2}\sum_{i=0}^{n}\left(\mathbf{H}_i(\delta\mathbf{x}_i) - \mathbf{d}_i\right)^T\mathbf{R}_i^{-1}\left(\mathbf{H}_i(\delta\mathbf{x}_i) - \mathbf{d}_i\right)$$

$$\Leftrightarrow \nabla_{\delta\mathbf{x}_0} J = \mathbf{B}^{-1}\delta\mathbf{x}_0 + \frac{1}{2}\sum_{i=0}^{n}\mathbf{M}^T(t_i,t_0)\mathbf{H}_i^T\mathbf{R}_i^{-1}\left(\mathbf{H}_i(\delta\mathbf{x}_i) - \mathbf{d}_i\right) = 0$$

$\mathbf{d}_i = y_i^o - H_i(\mathbf{x}_i^b)$ - innovation vector

H_i non-linear observation operator

$\mathbf{H}_i$ tangent-linear observation operator



$\mathbf{M}_s$ tangent-linear model (simplified physics)

M non-linear forecast model (full physics)

$\mathbf{d}_i$ ← using non-linear model M at high resolution & full physics

$\delta\mathbf{x}_i$ ← using tangent-linear model $\mathbf{M}$ at low resolution & simplified physics

$\nabla_{\delta\mathbf{x}_0} J$ ← using a low resolution adjoint model $\mathbf{M}^T$ & simplified physics

$\mathbf{x}_i$ – model state at t_i

y_i^o – observations at t_i

Dealing with nonlinear and discontinues physical processes

- Physical processes being highly nonlinear and often discontinuous may cause serious problems for assimilating models.
  - *For instance, the models based on variational technique, like four-dimensional variational (4D-Var) assimilation, are using the minimization technique which is based on a linearization of the model equations*.

- The strong nonlinearities and thresholds can lead to the growth of spurious unstable perturbations
  - *without their proper treatment, the model can quickly become too inaccurate to be useful.*

- Therefore, it is important to apply a careful regularisation to smooth most significant nonlinearities and discontinuities inherent in the nonlinear parametrizations.

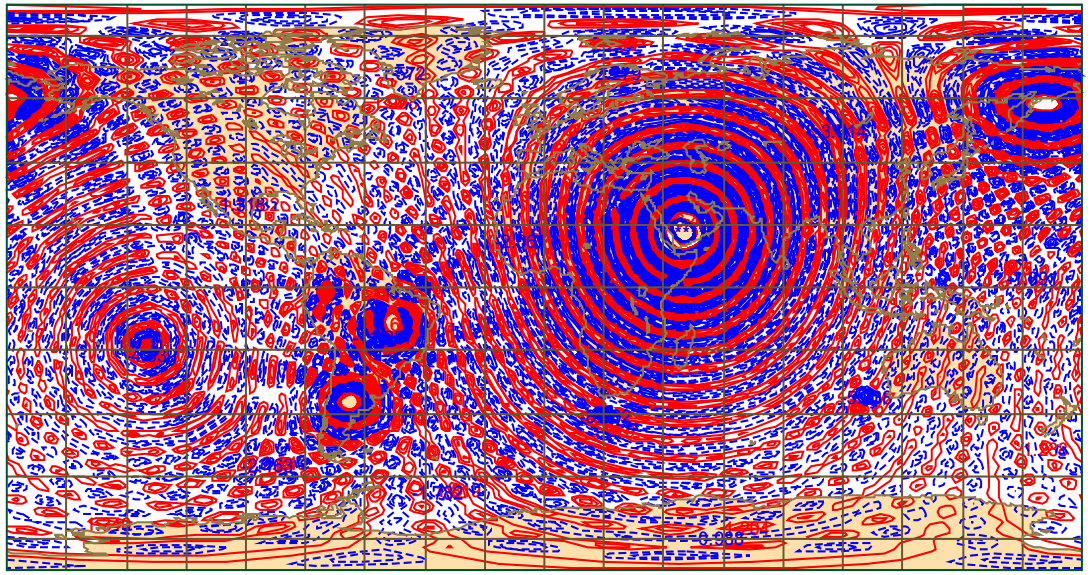
- Smoothing modifications and simplifications applied in physical parametrizations:
  - *Done with an aim to have the schemes as much differentiable as possible.*
  - *Finding a trade-off between a physically sound description of atmospheric processes and a linear physical parametrization is rather difficult.*

Regularization of the linearized physical parametrization

WHY REGULARIZATION IS SO IMPORTANT

Cont.int: 0.5e+07

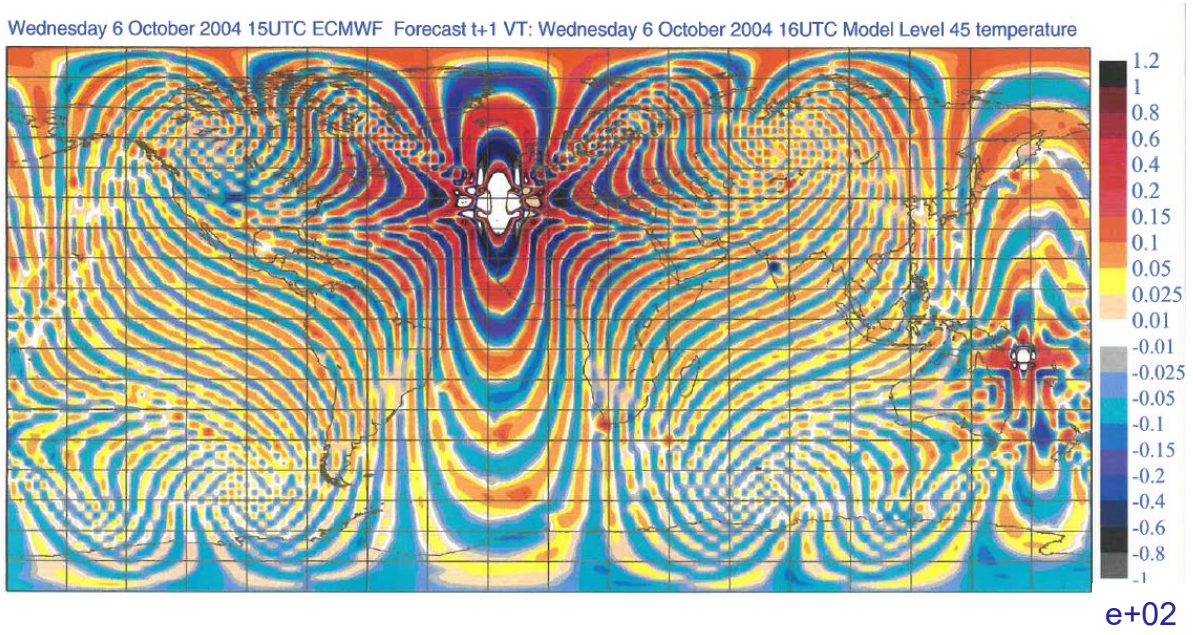
lv31 T* 1999-03-15 12h fc t+6 - TL with vdif (no regularization applied) [cont.int: 0.5e+07]



Without any treatment of most serious threshold processes, the TL approximation can become useless.

BAD NEWS !!!

Unless one wants to use model for generating modern art.



Importance of the regularization of TL model (1)

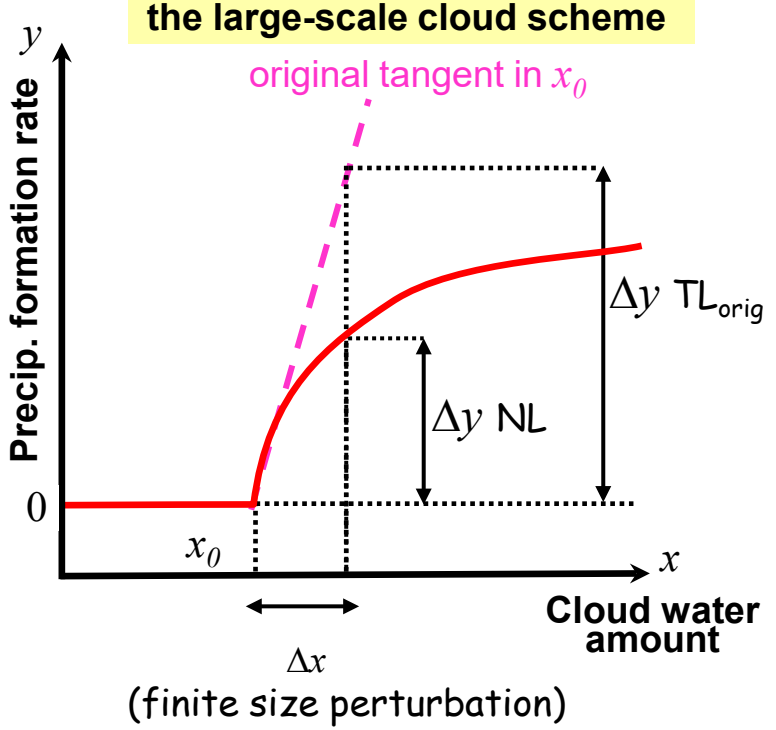
- In the case of physical processes, strong nonlinearities can occur sometimes in the presence of discontinuous/non-differentiable processes (e.g. switches or thresholds in cloud water and precipitation formation).

- An example of spurious TL noise caused by a threshold in the autoconversion formulation of the large-scale cloud scheme.

Nonlinear finite difference:
$M(\mathbf{x}+\delta\mathbf{x}) - M(\mathbf{x})$

Tangent-linear integration: Mδx

Autoconversion formulation of the large-scale cloud scheme



u-wind increments [m/s]
FC t+12, ~700 hPa

x 10^5

finite difference (FD)

TL integration without regularization

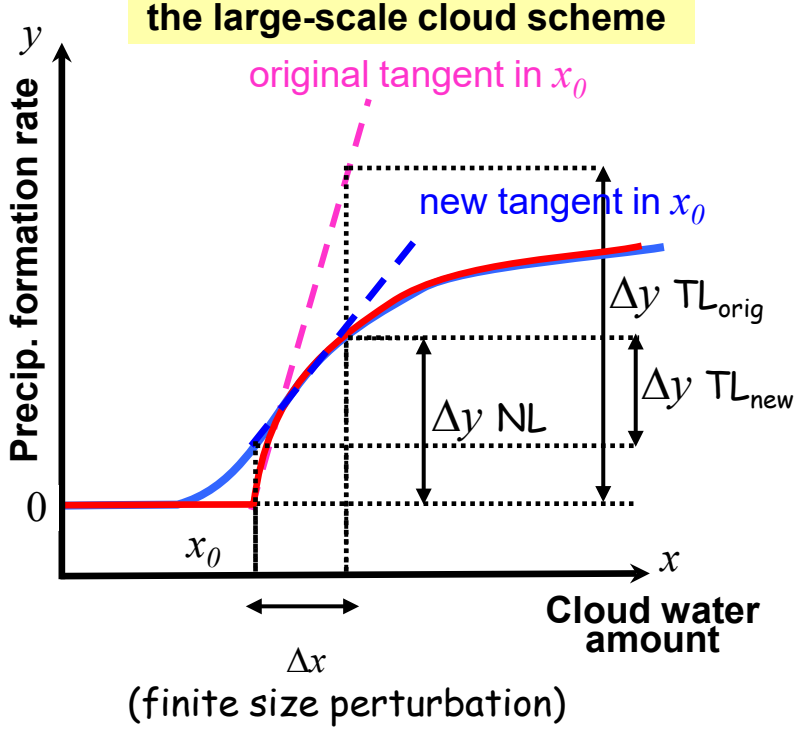
Importance of the regularization of TL model (2)

- Regularizations help to remove the most important threshold processes in physical parametrizations affecting the range of validity of TL approximation

Nonlinear finite difference:
$M(\mathbf{x}+\delta\mathbf{x}) - M(\mathbf{x})$

Tangent-linear integration: $M\delta\mathbf{x}$

Autoconversion formulation of the large-scale cloud scheme



u-wind increments [m/s]
FC t+12, ~700 hPa

finite difference (FD)

TL integration

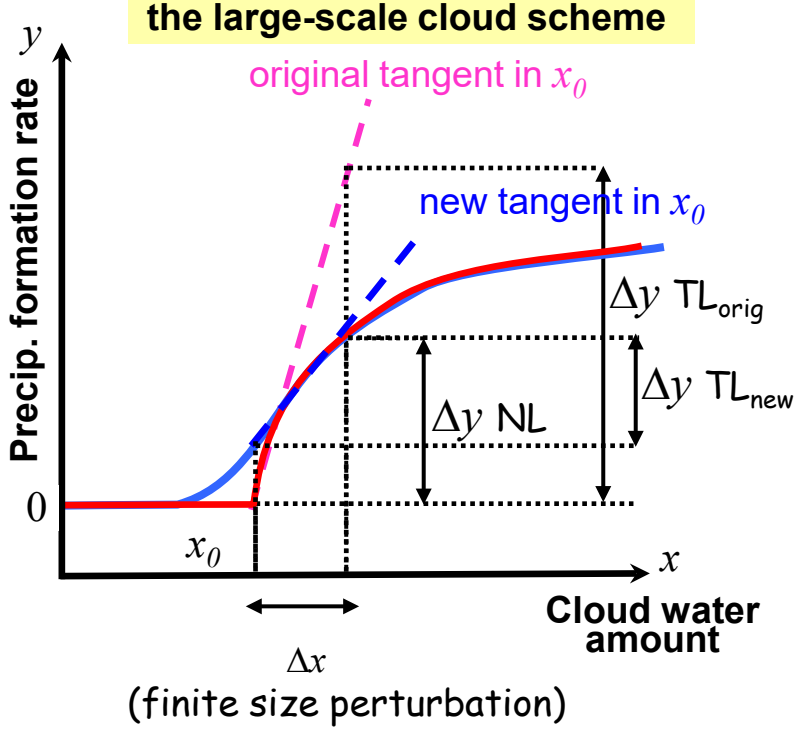
Importance of the regularization of TL model (2)

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Nonlinear finite difference:
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Autoconversion formulation of the large-scale cloud scheme



u-wind increments [m/s]
FC t+12, ~700 hPa

finite difference (FD)

TL integration without regularization

Tangent-linear (TL) approximation

Zonal wind increments at model level 31 (~ 1000 hPa)
24-hour integration

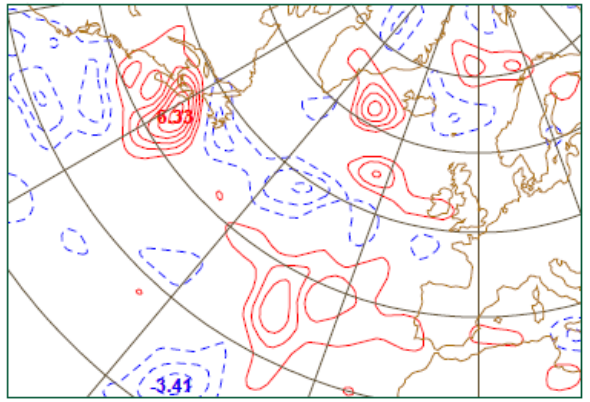
Comparison:

finite differences (FD) ↔ tangent-linear (TL) integration

$$M(\mathbf{x}_{an}) - M(\mathbf{x}_{fg}) \leftrightarrow M'(\mathbf{x}_{an} - \mathbf{x}_{fg})$$

$$(an = analysis, \quad fg = first\ guess)$$

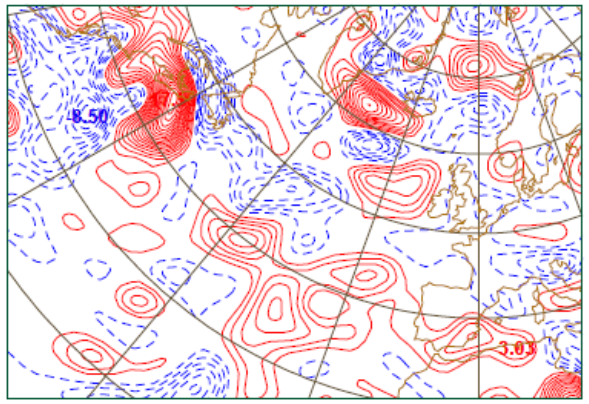
FD



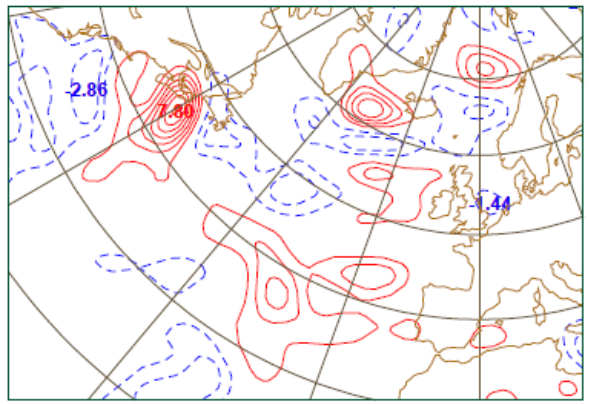
TL_{ADIAB} – **adiabatic TL model**

TL_{WSPHYS} – **TL model with the whole set of simplified physics**
(Mahfouf 1999, Janisková et al 1999)

TL_{ADIAB}



TL_{WSPHYS}



GREAT !!!

TL_{WSPHYS} better than TL_{ADIAB}

T63L31 run: 15/03/1999 T+24
T63 ~ 320 km

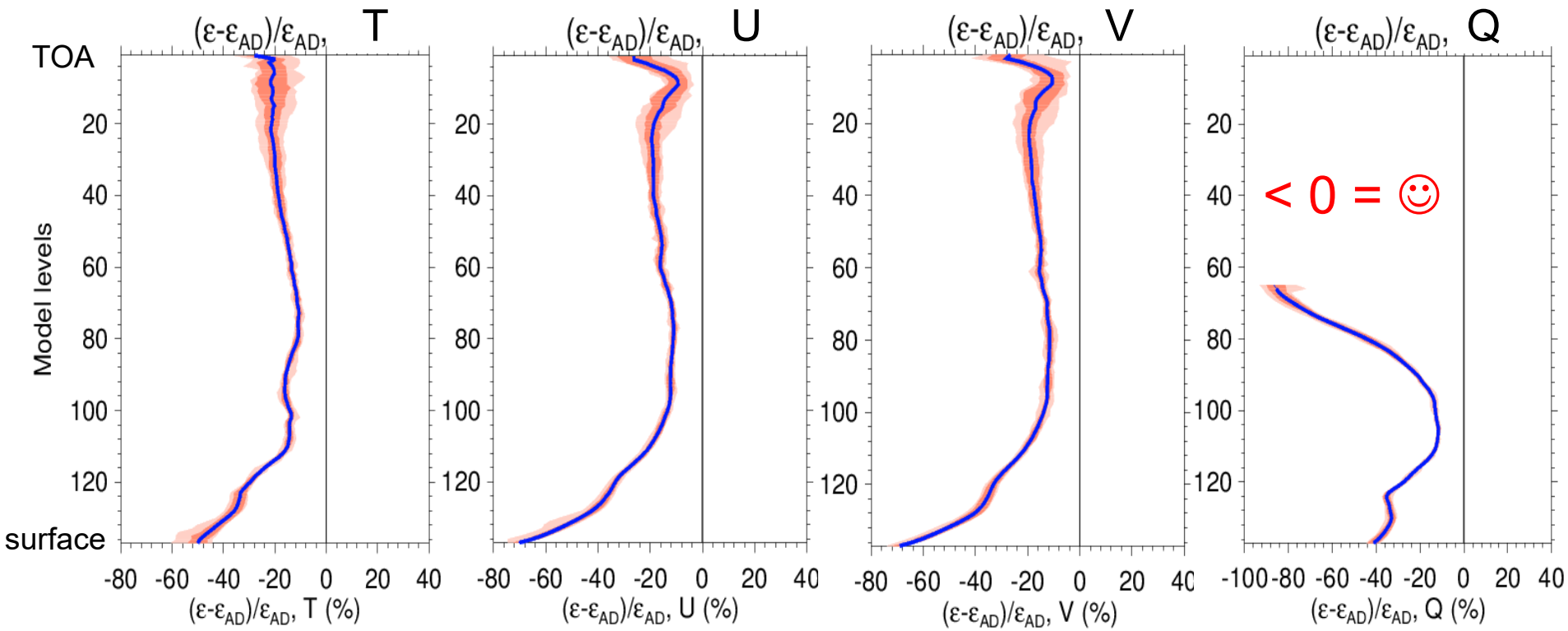
Impact of linearized physics on TL approximation

$$\frac{\varepsilon_{EXP} - \varepsilon_{REF}}{\varepsilon_{REF}}.100\%$$

where

$$\varepsilon = \overline{\left| \left[M(\mathbf{x}+\delta\mathbf{x}) - M(\mathbf{x}) \right] - M'(\delta\mathbf{x}) \right|}$$

non-linear (NL) difference ↔ tangent-linear (TL) integration



Mean vertical profile of change in TL error when full linearized physics included in TL.

Relative to adiabatic TL run (50-km resolution; 20 runs, 12h integ.)

Inclusion of linearized physics leads to better TL approximation.

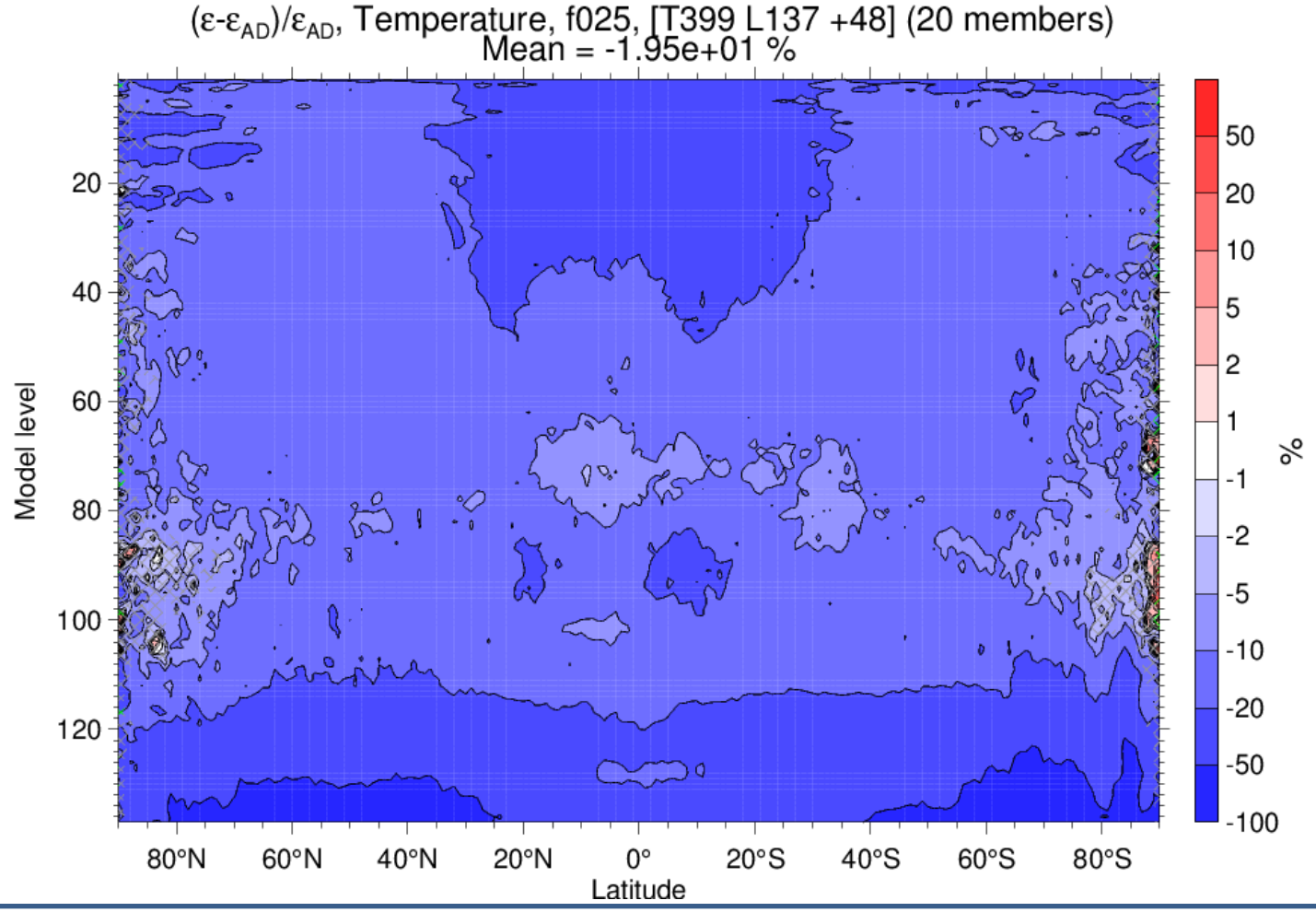
Impact of linearized physics on TL approximation – contribution from different processes

Zonal mean cross-section of change in TL error when TL includes:

VDIF + orog. GWD + SURF + RAD + non-orog GWD + moist physics

Blue = TL error reduction = ☺

Temperature



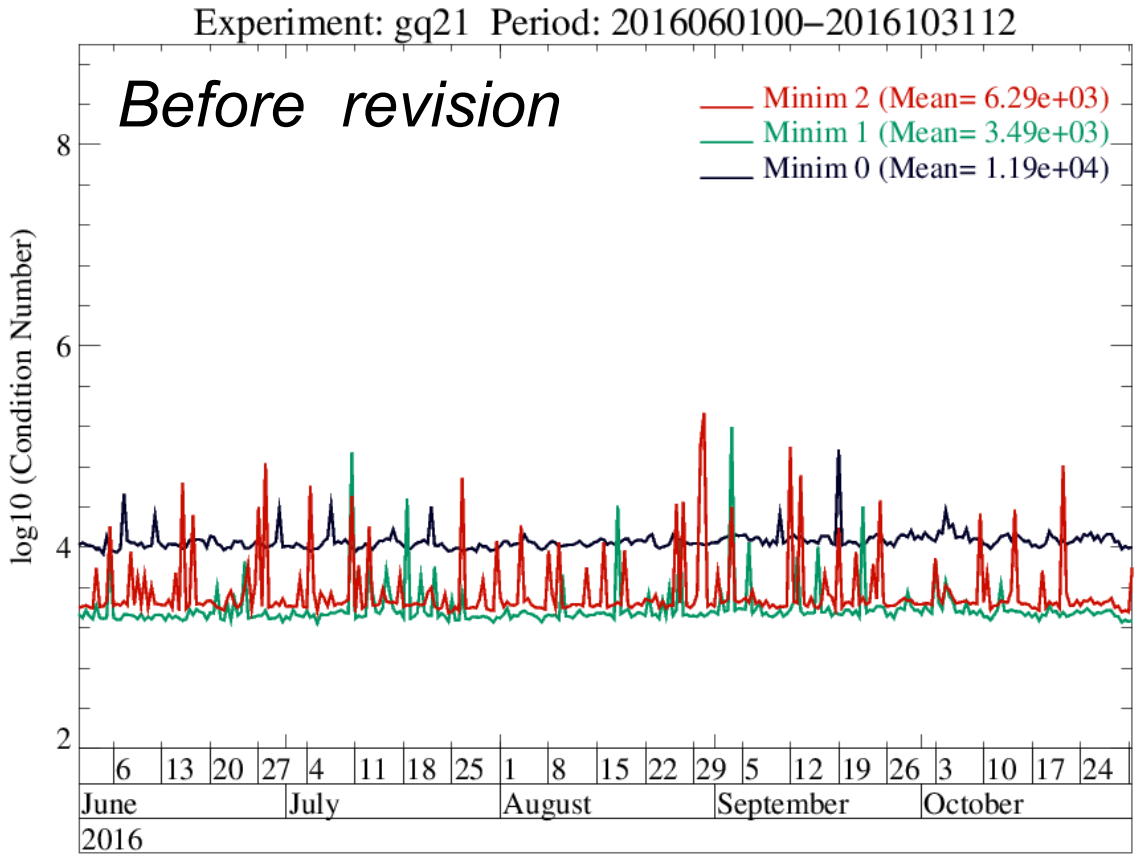
Relative to adiabatic TL run:

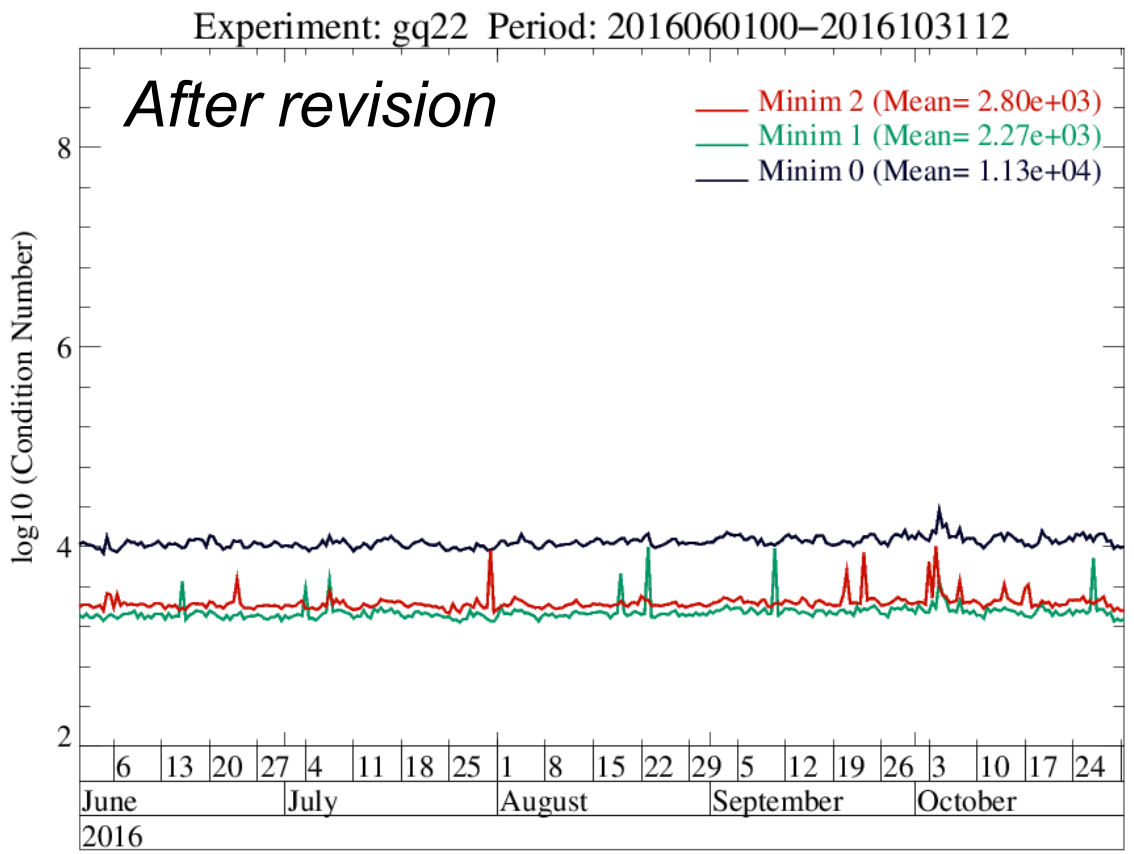
- 50-km resolution
- 20 runs
- after 12h integr.

Dealing with local spurious increments in 4D-Var

- Occurrences of high condition numbers (= ill-posed 4D-Var) increasing the risk of 4D-Var failures

- Modified linearized convection scheme (esp. downdraughts) dramatically reduced occurrences of high condition number



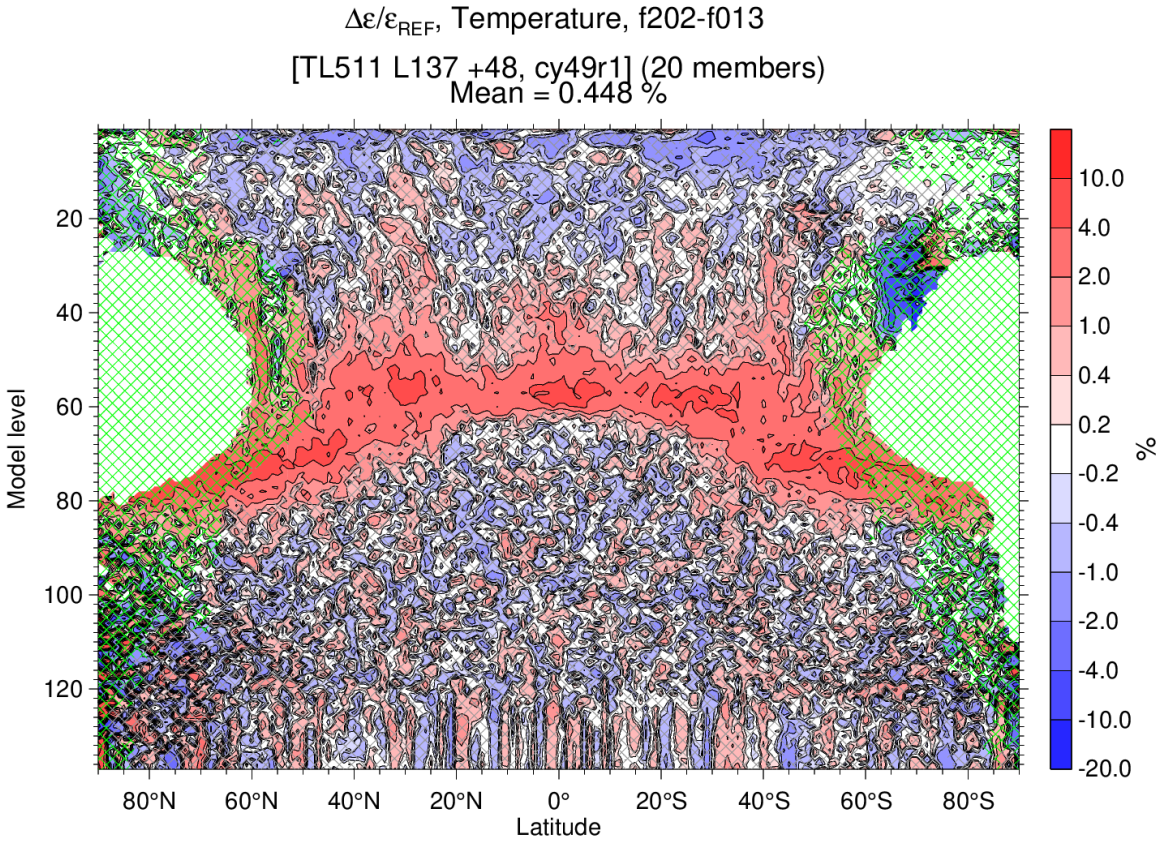


Time evolution of condition numbers in each minimization for 4D-Var analysis experiments (TCo399 L137, 5 months)

Courtesy of P. Lopez

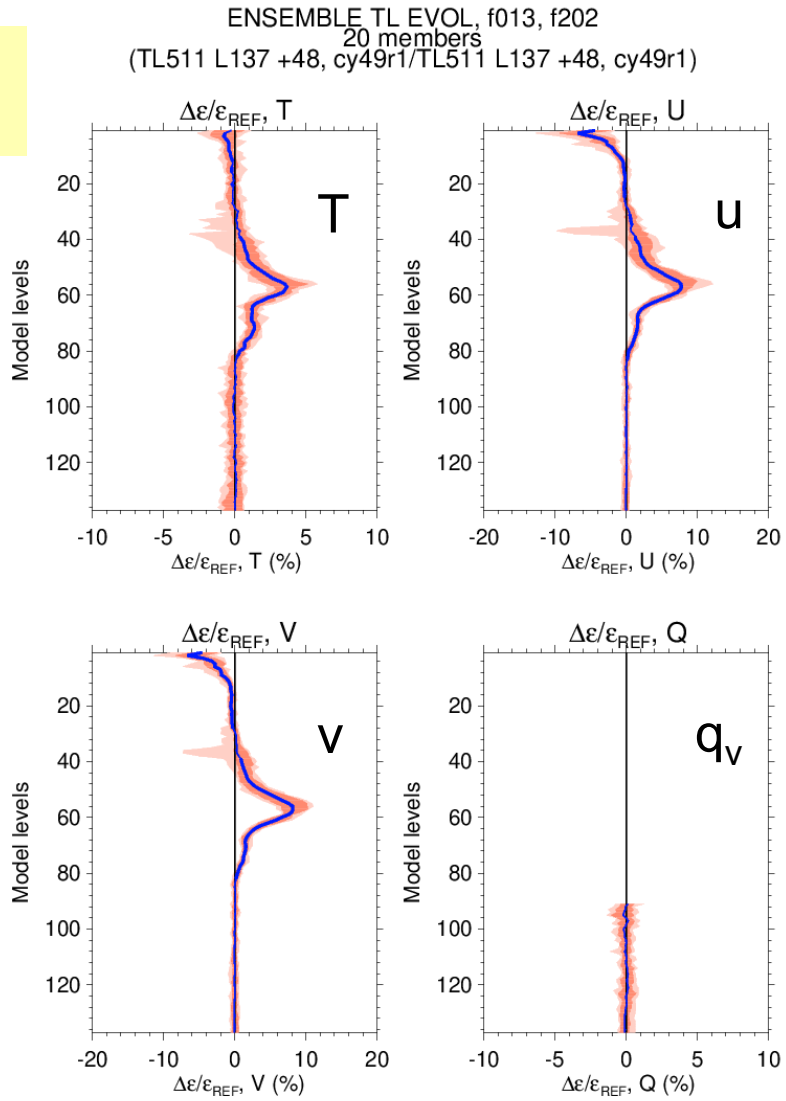
Dealing with degradation of TL approximation

- Example of TL approximation degradation due to changes in the NL vertical diffusion (mainly stratosphere), as proposed for CY50R1 of IFS model.



Zonal mean cross-section of TL error changes for temperature.

→ <u>Solution:</u> To include the same changes in the TL (& AD) vertical diffusion.



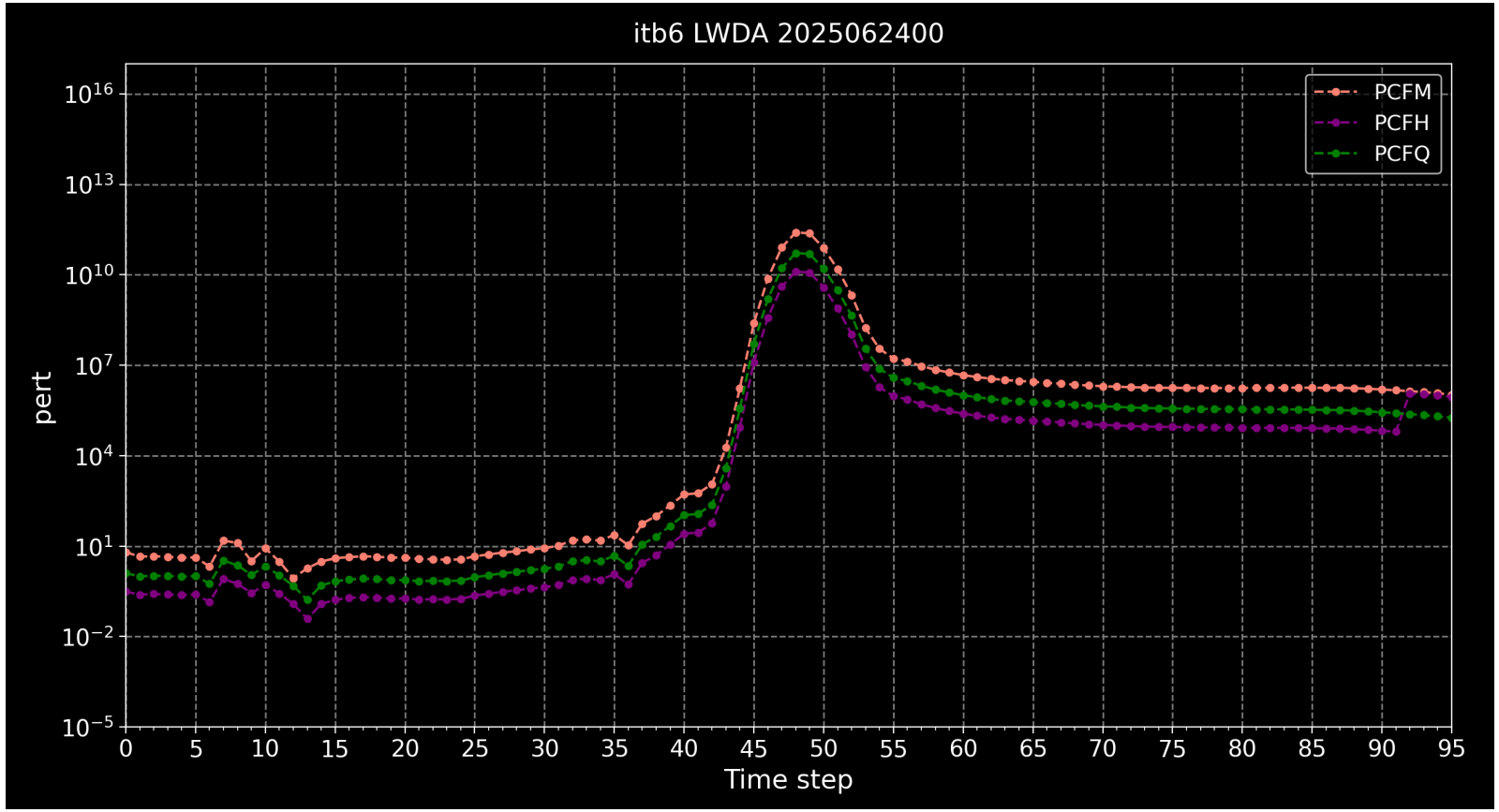
Mean vertical profiles of TL error changes.

Courtesy of P. Lopez

Dealing with TL instability causing failure in 4D-Var

- Example of TL instability that led to repeated failures of 4D-Var in CY50R1 e-suite of IFS model.

Perturbations (Log scale)



Time evolution of the perturbations of surface exchange coefficients for momentum, heat, and moisture at problematic ocean location.

→ <u>Solution:</u> Surface ocean currents had to be added in TL (& AD) of vertical diffusion.

Courtesy of P. Lopez

Source of noise in dynamics also possible

- SETTLST (*Stable Extrapolation Two-Time-Level Semi-Lagrangian*) scheme – to better digest a noise near the model top (above 50 hPa) → solving numerical instabilities or inaccuracies in regions of high wind shear or strong vertical velocities
- Instead of using two distinctively different regimes of vertical velocity extrapolation in time

$$\dot{\eta}^{t+\Delta t} = \dot{\eta}^{t} + \alpha(\dot{\eta}^{t} - \dot{\eta}^{t-\Delta t})$$

Original decision condition:

$$\alpha = \frac{1}{2}\left[1 - \mathrm{SIGN}\left(1, |\dot{\eta}^{t-\Delta t} - \dot{\eta}^{t}| - \beta(|\dot{\eta}^{t-\Delta t}| + |\dot{\eta}^{t}|)\right)\right]$$

when α would be 1 or 0

STEP function replaced by TANH function

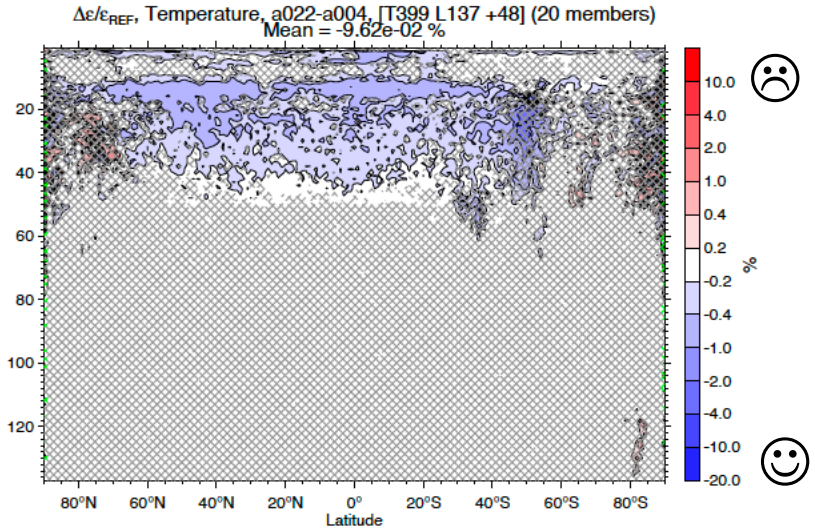
➔

Smooth transition between two regimes:

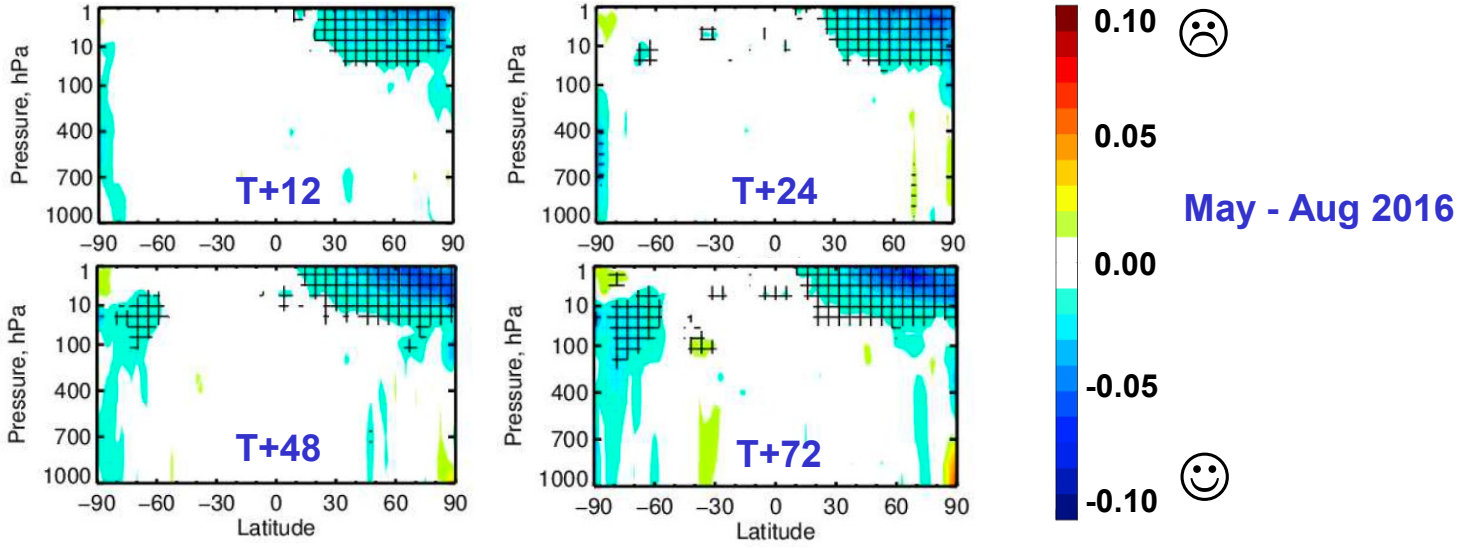
$$\alpha = \frac{1}{2}\left[1 + \tanh\left(RSCALE \cdot (\dot{\eta}^{t-\Delta t}\dot{\eta}^{t} + RSCALEOFF)\right)\right]$$

RSCALE : scaling factor for transition between cubic & linear interpolation

TL approximation for T – relative improvement



Difference in RMS error for geopotential normalized by RMS error of control



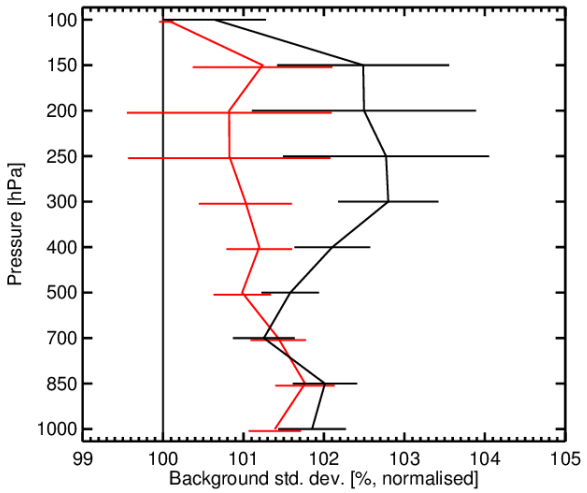
- Consistently improving tangent-linear approximation and forecast scores.

Courtesy of F. Váňa

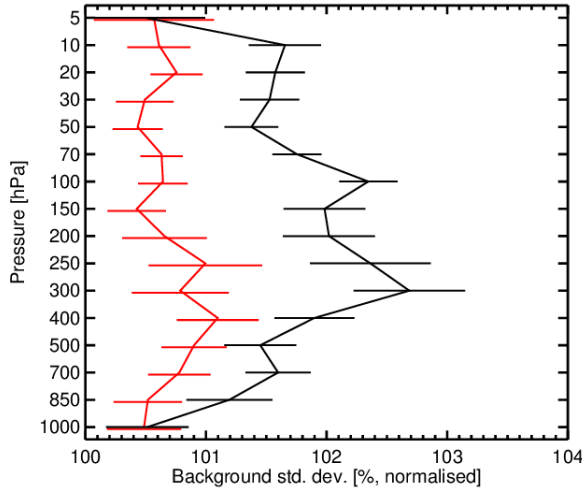
Improved fit to assimilated observations in analysis when using ECMWF linearized physics

adiab
nophysobs

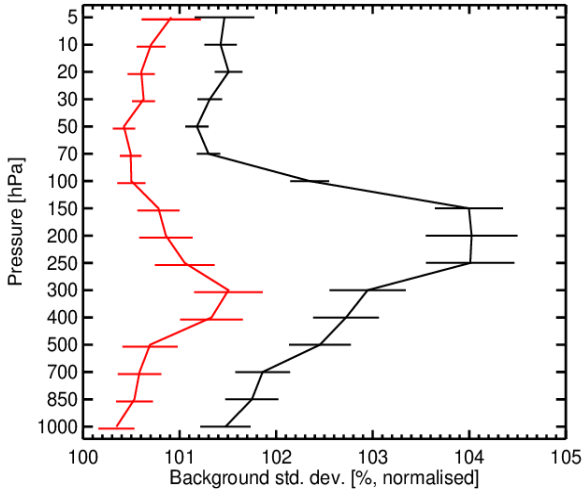
TEMP – q profiles



TEMP – T profiles



Conventional U/V wind profiles

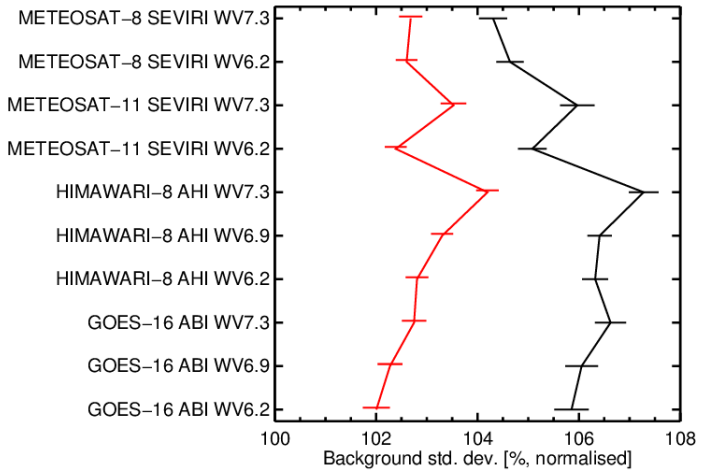


nophysobs
nophys
100 % = reference

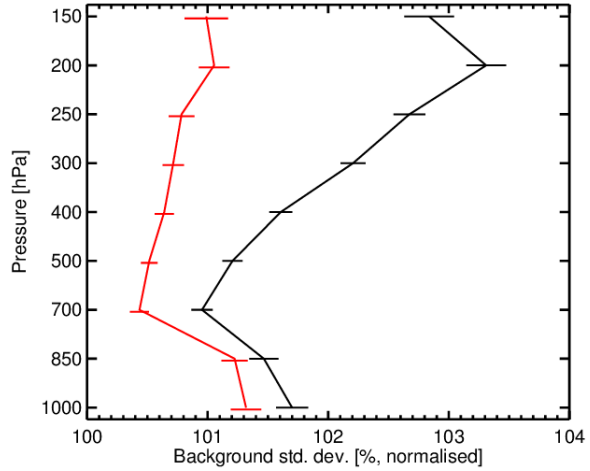
nophysobs = obs related to physical processes not assimilated

nophys = nophysobs + physics not included in the linearized model

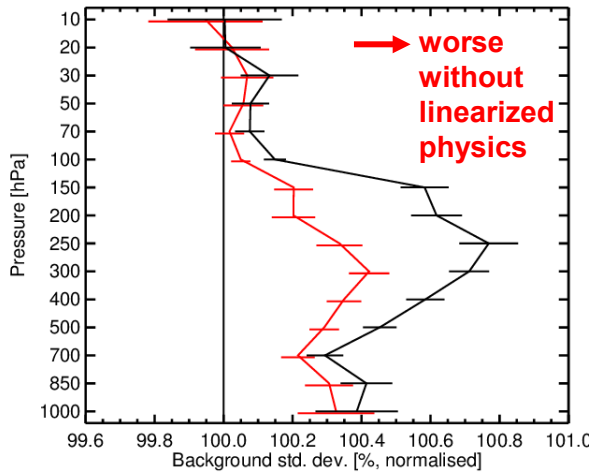
GOES



SATOB – U/V wind



AEOLUS – Mie cloudy, Rayleigh clear



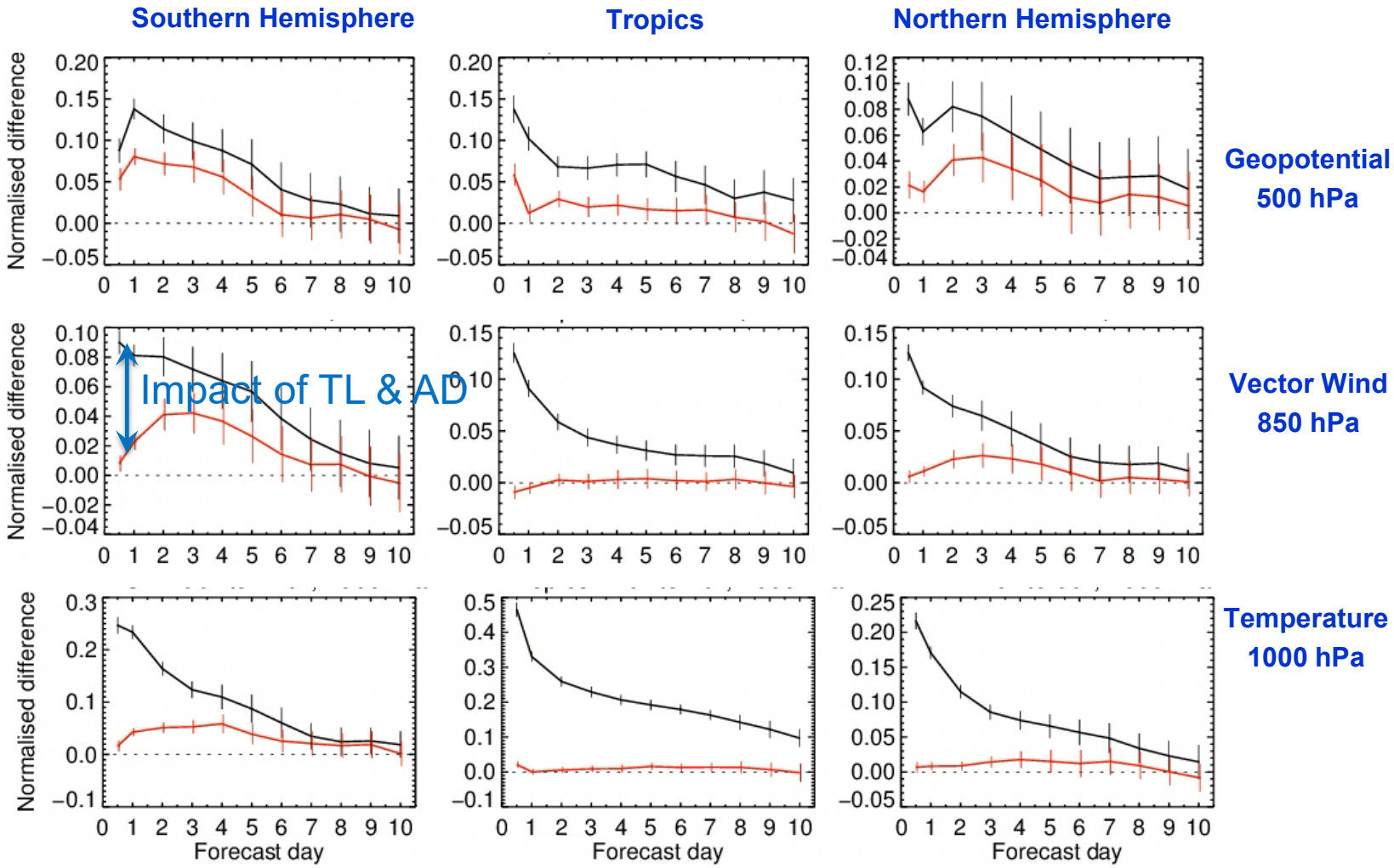
Run at:
TCo639 ~ 18 km, L137

- *Using linearized physics in data assimilation provides better model fit to observations*

3-month period: July – September 2021

Janisková and Lopez (2023)

Relative improvement of forecast scores from ECMWF linearized physics



Black line: impact of physics-related observations + linearized physics.
Red line: impact of physics-related observations alone.

Forecast scores against own analysis:

- RMS errors normalised by control
- bars indicate significance at 95% confidence level

3 months
$T_{CO}639$ L137
4D-Var LWDA
CY47R3

y > 0 → ☺

- *Including linearized physics in data assimilation improves forecast scores.*

Janisková and Lopez (2023)

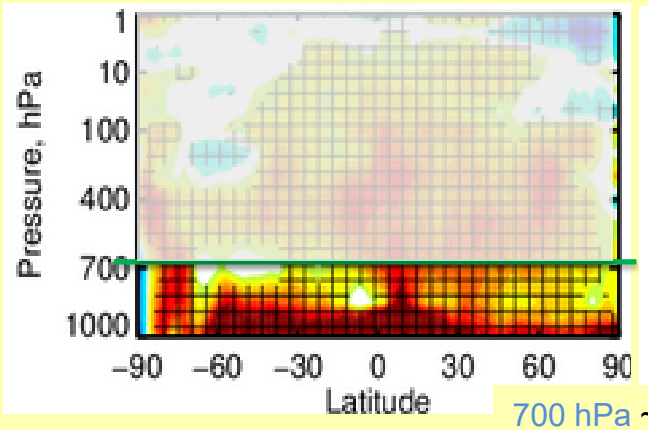
Relative improvement of forecast scores from ECMWF linearized physics – zonal means

Temperature

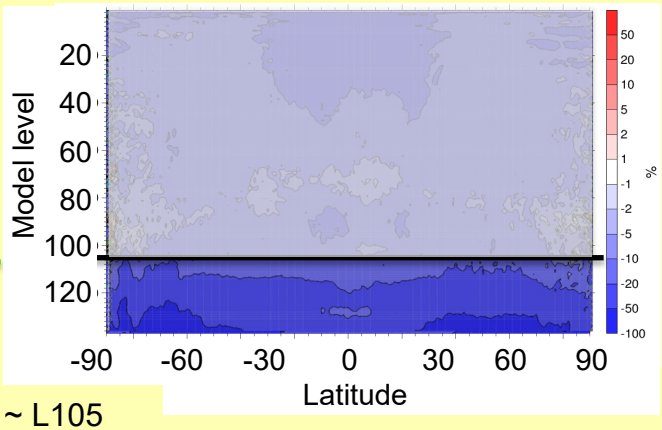
T+12

Maximum forecast improvement where TL error is the most reduced by linearized physics

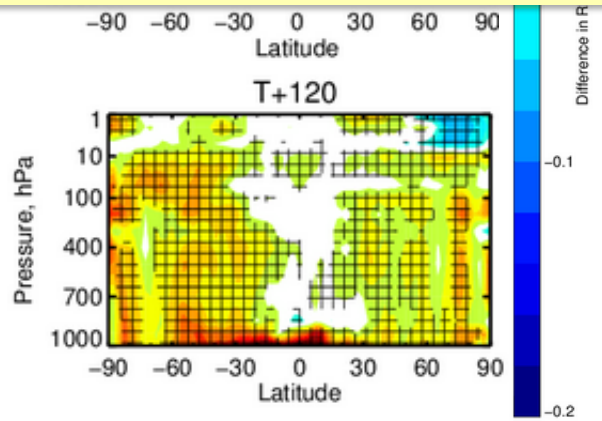
Forecast score



TL approximation



700 hPa ~ L105



Forecast scores:

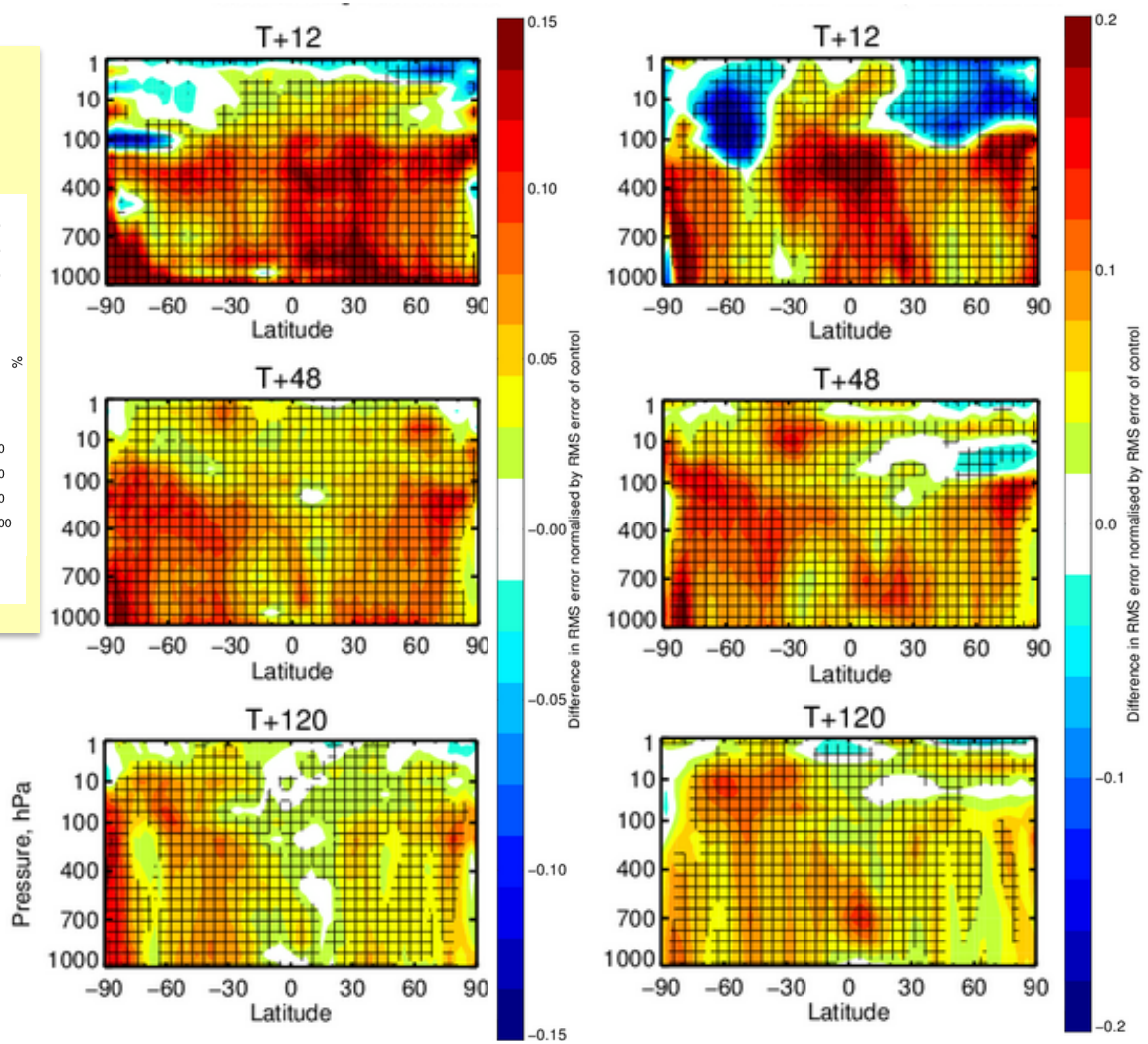
Positive values (red)

↓

Improvement when using linearized physics

Vector Wind

Geopotential

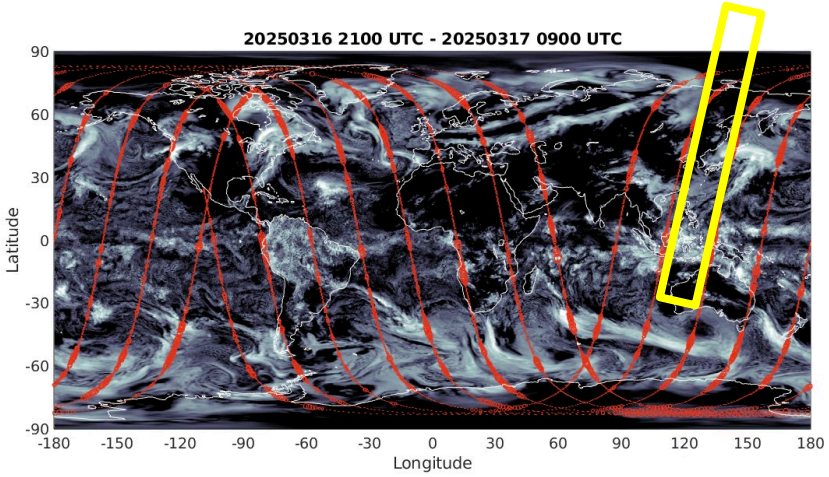


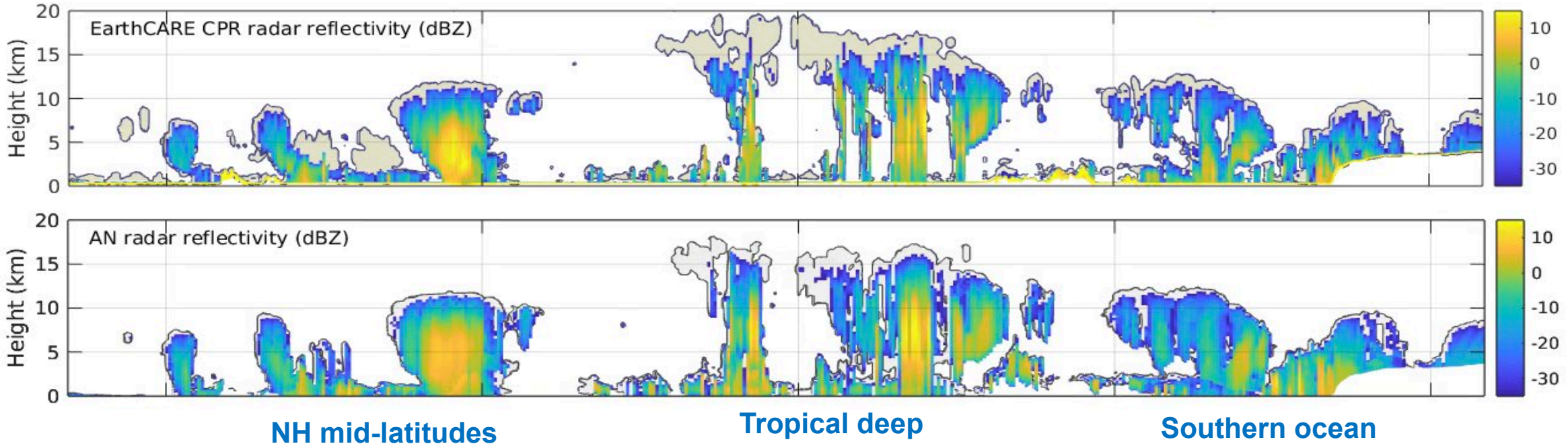
Difference in RMS error normalized by RMS error of control: July - September 2021

Benefit of assimilating new types of observations related to physics

- Using CloudSat cloud radar and CALIPSO cloud lidar observations *(Janisková 2015, Fielding & Janisková, Janisková & Fielding, 2020)* to prepare for assimilation of the vertical profiles of clouds from the current mission EarthCARE.

- Example: single-cycle 4D-Var assimilation experiment of EarthCARE cloud radar observations using TCo639 grid (~18 km) 17 March 2025.
- 4D-Var control variables (such as temperature and humidity) are adjusted during minimization to improve forward modelled fit to observations.



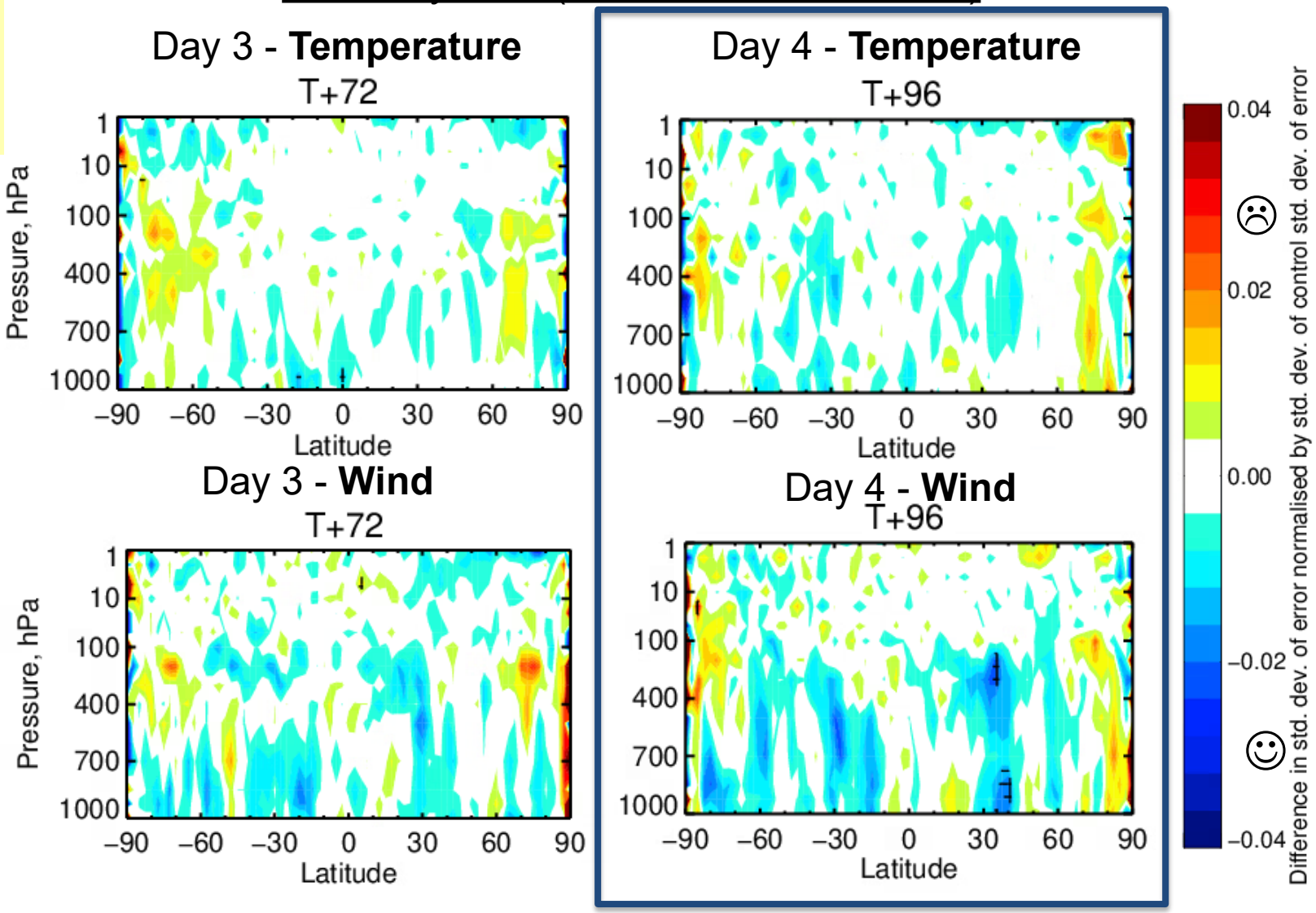


Courtesy of M. Fielding

Assimilation of EarthCARE cloud radar observations at ECMWF

- First-ever assimilation of cloud radar in an operational global NWP model began 10th June 2026!

- Improvements of 0.5 - 1 % in the forecat at day 3-4 in cloudy regions, consistent with CloudSat assimilation experiments.
- Smaller, positive impact on temperature scores.



Summary (1)

- **Positive impact from including physical parametrization schemes into the linearized model has been demonstrated.**

- **Physical parametrizations have become important components in current variational data assimilation systems:**
  - better representation of the evolution of the atmospheric state during the minimization of the cost function (via the adjoint model integration)
  - enabling to assimilate observations related to physical processes (rain, clouds, ...)
  - positive impact on analysis and subsequent forecast

- **First-ever assimilation of cloud radar in an operational global NWP model began 10th June 2026!**

- **Assimilation of EarthCARE CPR improves:**
  - cloud analysis globally
  - medium-range weather forecasts in cloudy (stormy?) regions

Summary (2)

- **For 4D-Var data assimilation system is crucial:**
  - Regularly check that the TL model is still a good approximation of the full NL model
  - Regularly check that the AD test is still correct
  - Warning: Permanently switching off some TL/AD physical parametrizations in 4D-Var could make the assimilation of many observation types impossible.

- **Optimizing the performance of linearized physics in 4D-Var requires finding the best compromise between:**

  linearity, computational cost $\Leftrightarrow$ realism (accuracy of representing physical processes)