Physical processes in adjoint models: potential pitfalls and benefits

Marta JANISKOVÁ

ECMWF

marta.janiskova@ecmwf.int

Thanks to: P.Lopez, F. Chevallier A. Benedetti, J.-N. Thépaut, M. Leutbecher

Linearized models in NWP

- **different applications:**
  - **variational data assimilation** ← *incremental 4D-Var at ECMWF*
  - **singular vector computations** ← *initial perturbations for EPS*
  - **sensitivity analysis** ← *forecast errors*

- **first applications with adiabatic linearized model**

- **nowadays, including the physical processes in the linearized model**

4D-Var – Four-dimensional Variational Data Assimilation
EPS – Ensemble Prediction System

Linearized model with physical processes

Including physical processes can:

- **in variational data assimilation:**
  - reduce spin-up
  - provide a better agreement between the model and data
  - produce an initial atmospheric state more consistent with physical processes
  - allow the use of new (satellite) observations *(rain, clouds, soil moisture, …)*

- **in singular vector computations:**
  - help to represent some atmospheric features

    (processes in PBL, tropical instabilities, development of baroclinic instabilities, …)

- **in sensitivity analysis:**
  - allow a reduction of forecast error

- **adjoint of physical processes can also be used for:**
  - model parameter estimation
  - sensitivity of the parametrization scheme to input parameters

Development of a physical package

- **for important applications:**
  - *incremental 4D-Var (ECMWF, Météo-France),*
  - *simplified gradients in 4D-Var (Zupanski 1993),*
  - *the initial perturbations computed for EPS (ECMWF),*

linearized versions of forecast models are run at lower resolution

⇓

the linear model can be "not tangent" to the full model

(different resolution and geometry, different physics)

⇓

simplified approaches as a way to include progressively physical processes in TL and AD models

- **simplifications done with the aim to have a physical package:**
  - **simple** – for the linearization of the model equations
  - **regular** – to avoid strong non-linearities and thresholds
  - **realistic enough**
  - **computationally affordable**

TL – tangent linear
AD – adjoint

Full nonlinear vs. simplified physical parametrizations

In NWP – a tendency to develop more and more sophisticated physical parametrizations → they may contain more discontinuities

⇓

For the "perturbation" model – more important to describe basic physical tendencies while avoiding the problem of discontinuities

Level of simplifications and/or required complexity depends on:

- **which level of improvement is expected** (for different variables, vertical and horizontal resolution, …)
- **which type of observations should be assimilated**
- **necessity to remove threshold processes**

Different ways of simplifications:

- **development of simplified physics** (for instance, gaining from experience with simpler parametrization schemes used in history)
- **applying only part of linearization**

Problems with including physics in adjoint models

- **Development** – requires substantial resources

- **Validation** – must be very thorough

  (for non-linear, tangent-linear and adjoint versions)

- **Computational cost** – may be very high

- **Non-linear and threshold nature** of physical processes

  (affecting the range of validity of the tangent-linear approximation)

Validation of the physical parametrizations

Non-linear model:

- Forecast runs with particular modified/simplified physical parametrization schemes

Tangent-linear (TL) and adjoint (AD) model:

- classical validation (TL - Taylor formula, AD - test of adjoint identity)
- examination of the accuracy of the linearization

Comparison:

finite differences (FD) $\leftrightarrow$ tangent-linear (TL) integration

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

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

Singular vectors:

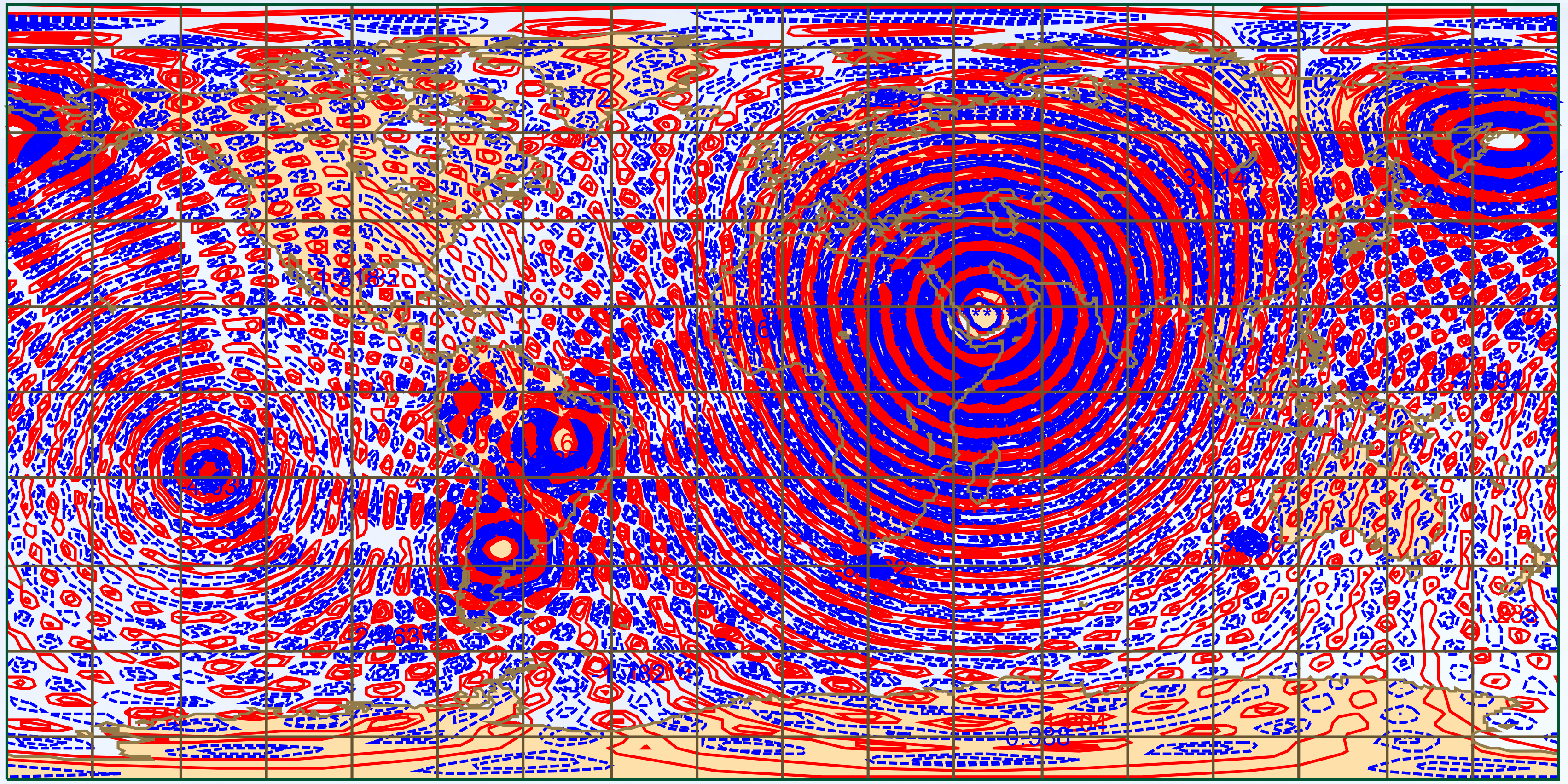
- Computation of singular vectors to find out whether the new schemes do not produce spurious unstable modes.

Importance of the regularization of TL model

- **physical processes are characterized by:**
  - * **threshold processes:**
    - discontinuities of some functions describing the physical processes *(some on/off processes)*
    - discontinuities of the derivative of a continuous function
  - * **strong nonlinearities**

WHY REGULARIZATION IS IMPORTANT

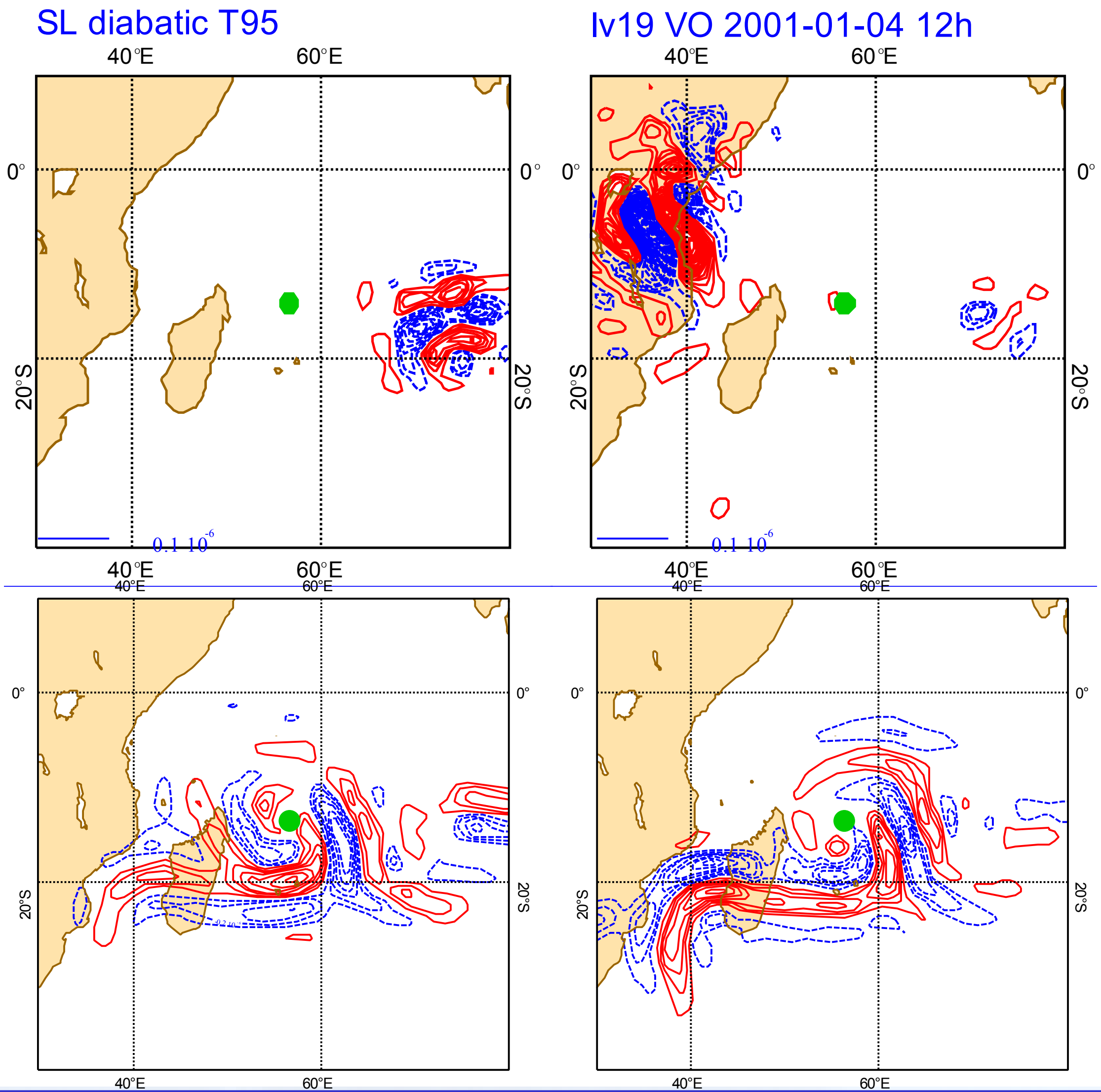
lv31 T* 1999-03-15 12h fc t+6 - TL with vdif (no regularization applied) [cont.int: 0.5e+07]



Without any treatment of most serious threshold processes, the TL approximation can turn to be useless.

SPURIOUS UNSTABLE MODES PRODUCED BY THE LINEARIZED PHYSICS

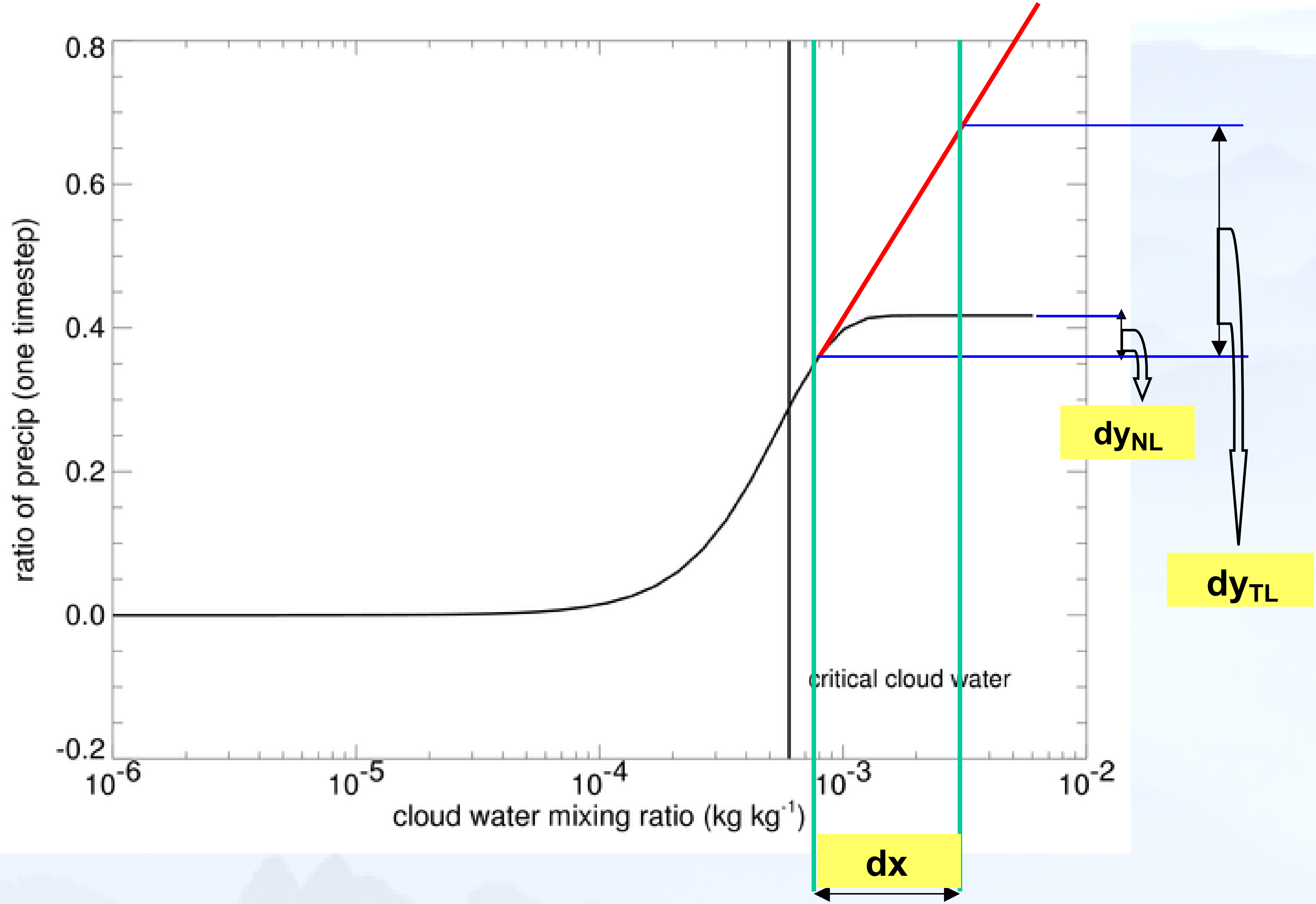
The first singular vectors located around the cyclone (58°E, 18°S) computed at the resolution T95 *(Barkmeijer, 2002)*



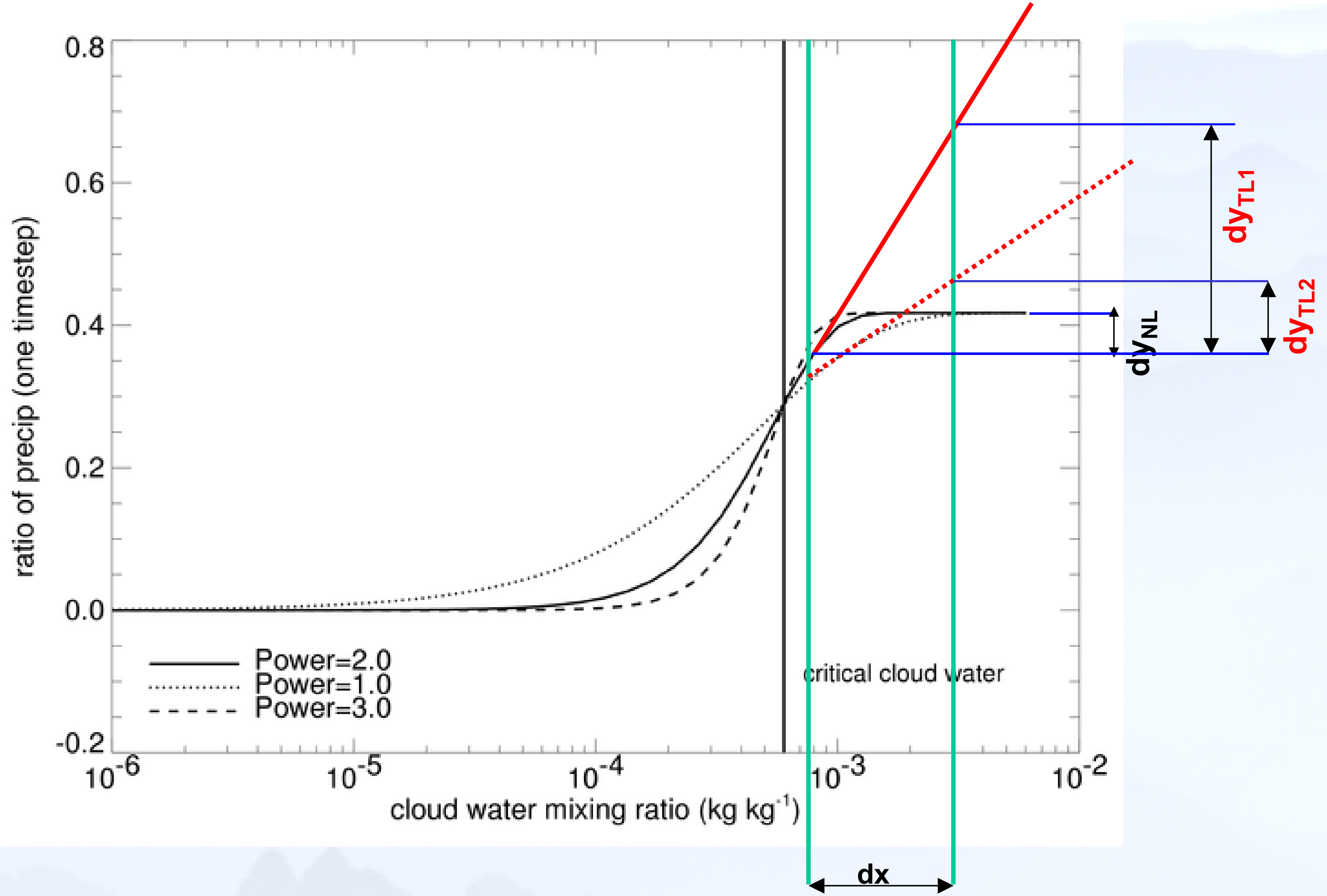
all linearized physical parametrization schemes

without the linearized large-scale precipitation scheme

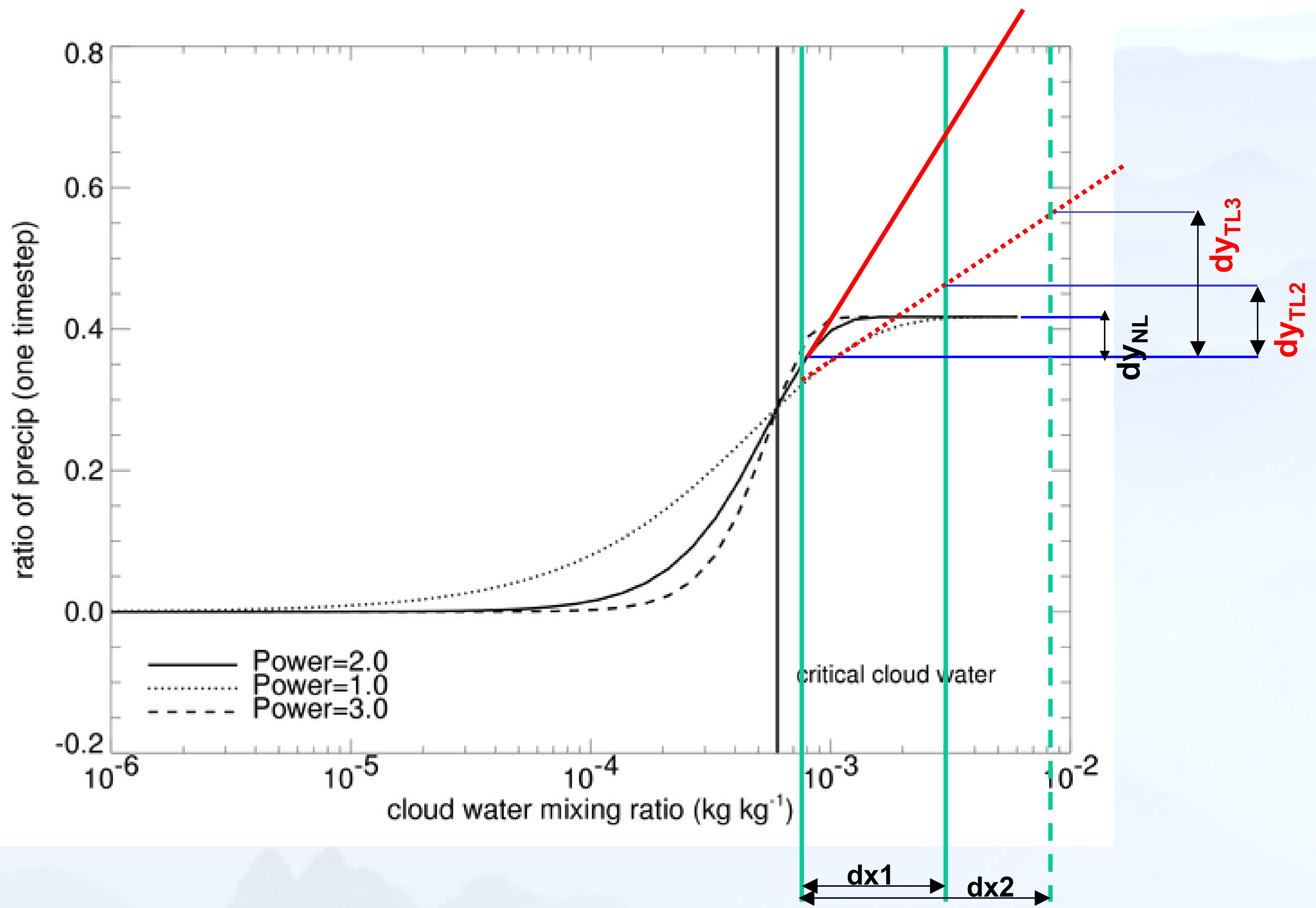
Potential source of problem



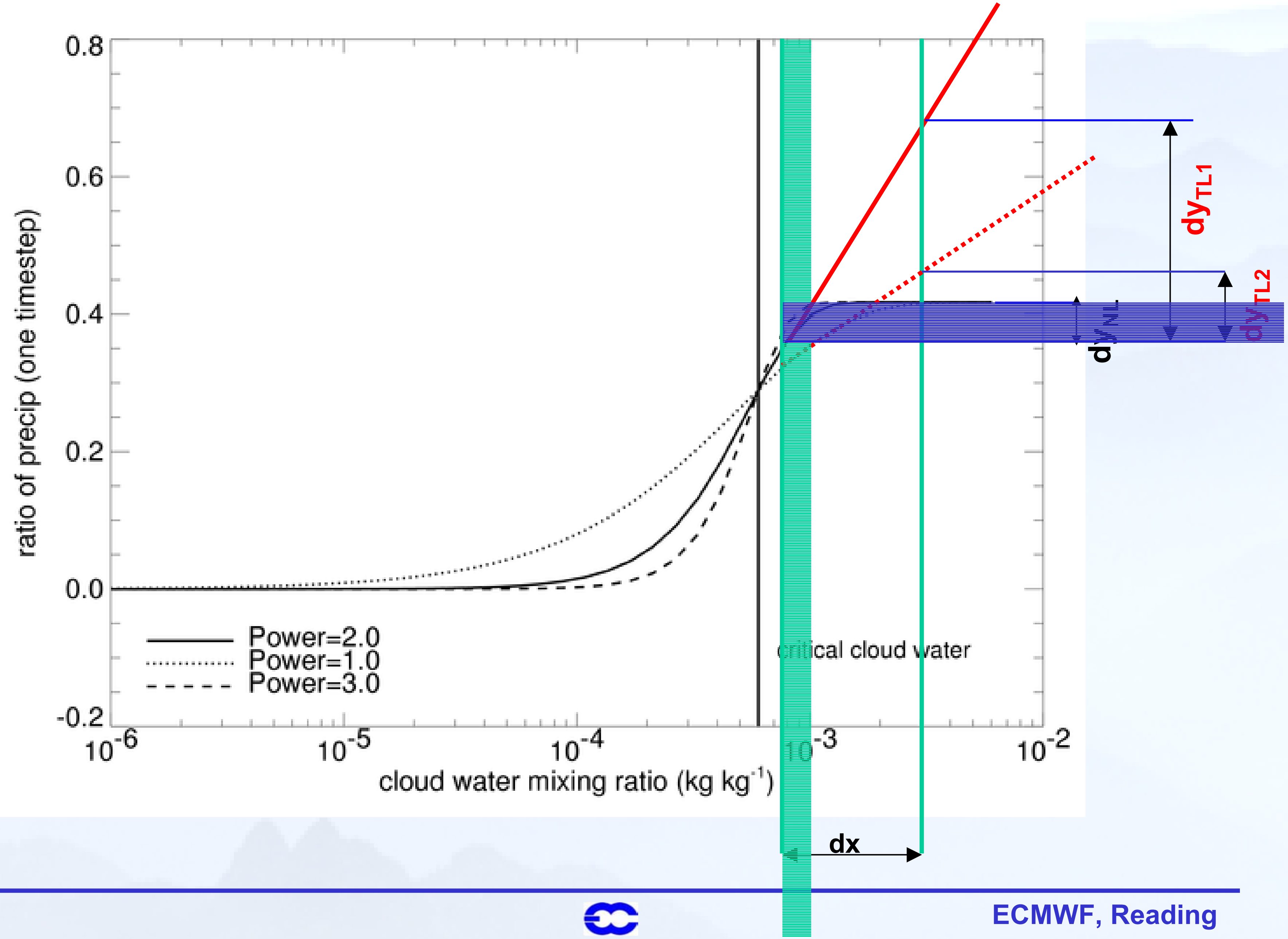
Possible solution, but …



… may just postpone the problem and influence the performance of NL scheme



However, the better the model → the smaller the increments

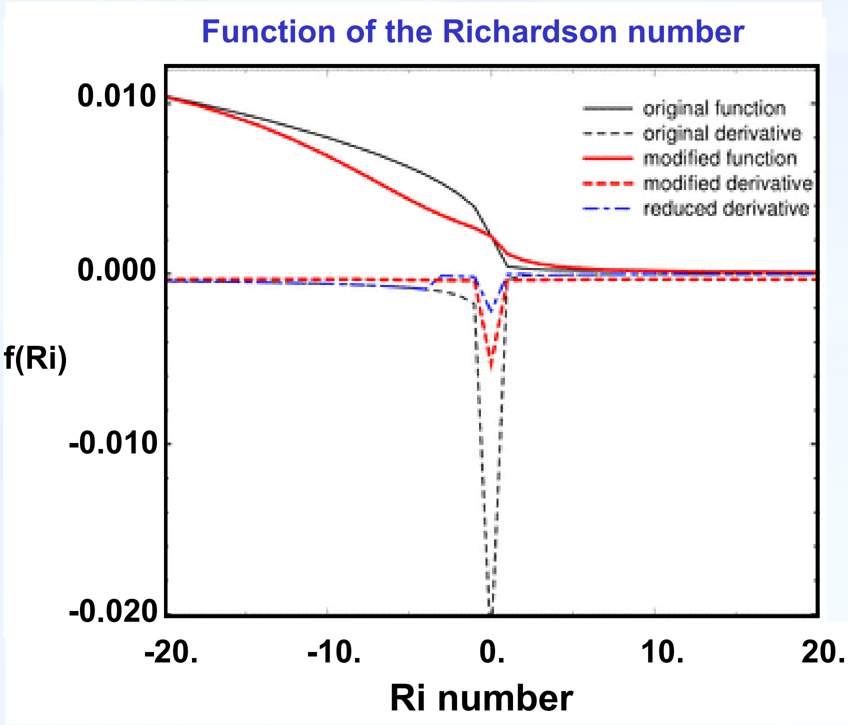


Examples of regularizations and simplifications (1)

Regularization of vertical diffusion scheme:

- **perturbation of the exchange coefficients** (which are function of the Richardson number Ri) **is neglected, K' = 0** *(Mahfouf, 1999)*

- **reduced perturbation of the exchange coefficients** *(Janisková et al., 1999)*:
  - **original computation of Ri modified in order to modify/reduce f'(Ri), or**
  - **reducing a derivative, f'(Ri), by factor 10 in the central part (around the point of singularity)**



Examples of regularizations and simplifications (2)

- **reduction of the time step to 10 seconds to guarantee stable time integrations of the associated TL model** *(Zhu and Kamachi, 2000)*

- **selective regularization of the exchange coefficients K based on the linearization error and a criterion for the numerical stability** *(Laroche et al., 2002)*

Comparison: FULL TL – K'=0 – reduced K' – selective K' *(Laroche et al.2002)*

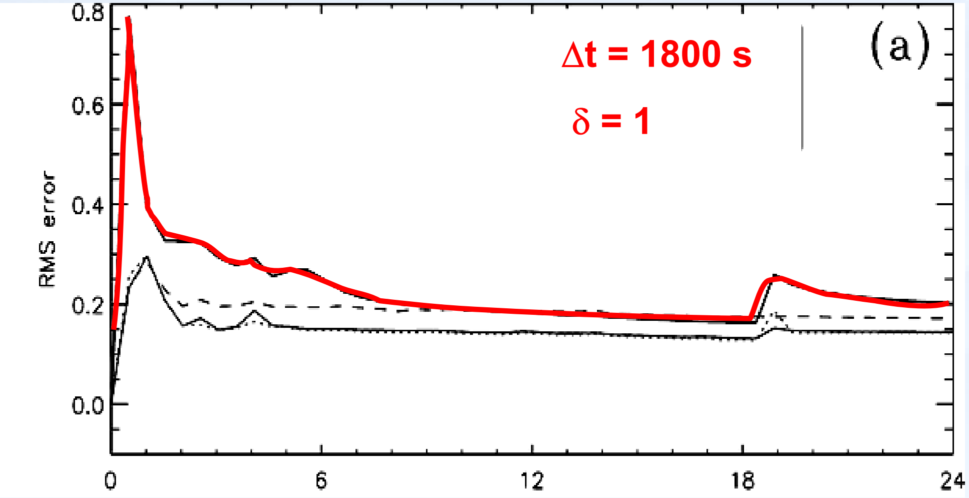
RMS linearization errors for the potential temperature perturbations at the 1st level above the surface

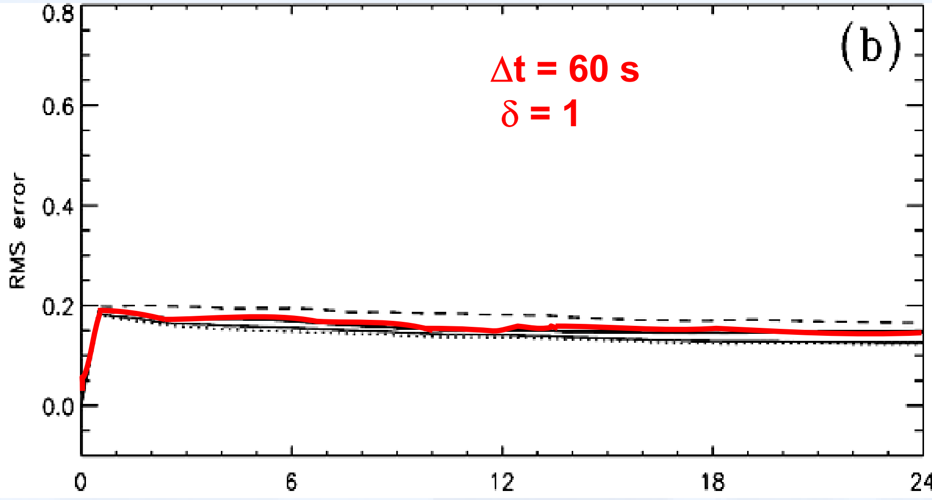
FULL TLM

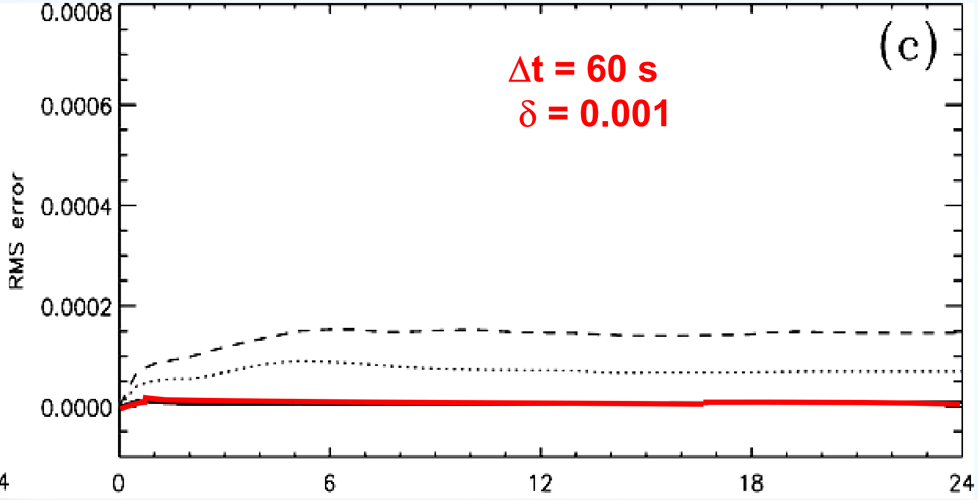
selective K'

reduced K'

K'=0







Importance of the regularization of TL model

- physical processes are characterized by:
  - * threshold processes:
    - discontinuities of some functions describing the physical processes *(some on/off processes)*
    - discontinuities of the derivative of a continuous function
  - * strong nonlinearities

- **regularizations help to remove the most important threshold processes in physical parametrizations which can effect the range of validity of the tangent linear approximation**

- **after solving the threshold problems**

⇓

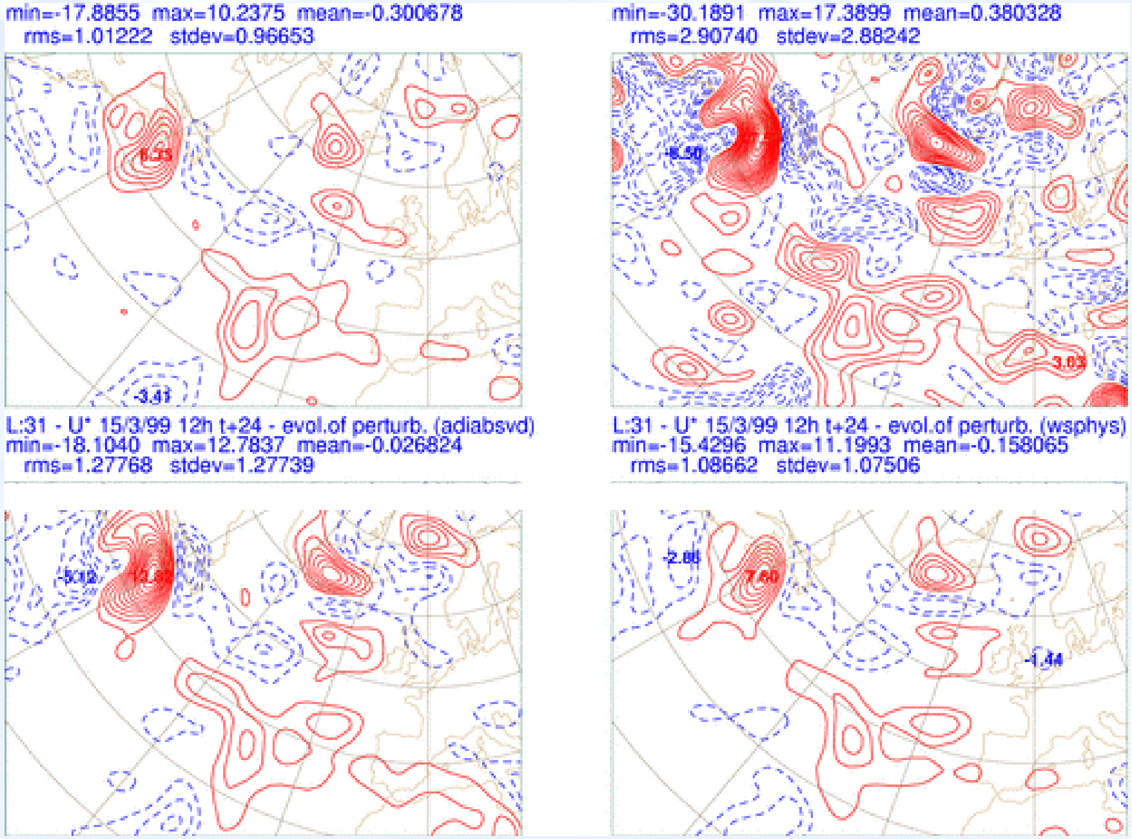
clear advantage of the diabatic TL evolution of errors compared to the adiabatic evolution

Zonal wind increments at model level ~ 1000 hPa

[24-hour integration]

FD | **TL_{ADIAB}**

$TL_{ADIABSVD}$ | **TL_{WSPHYS}**

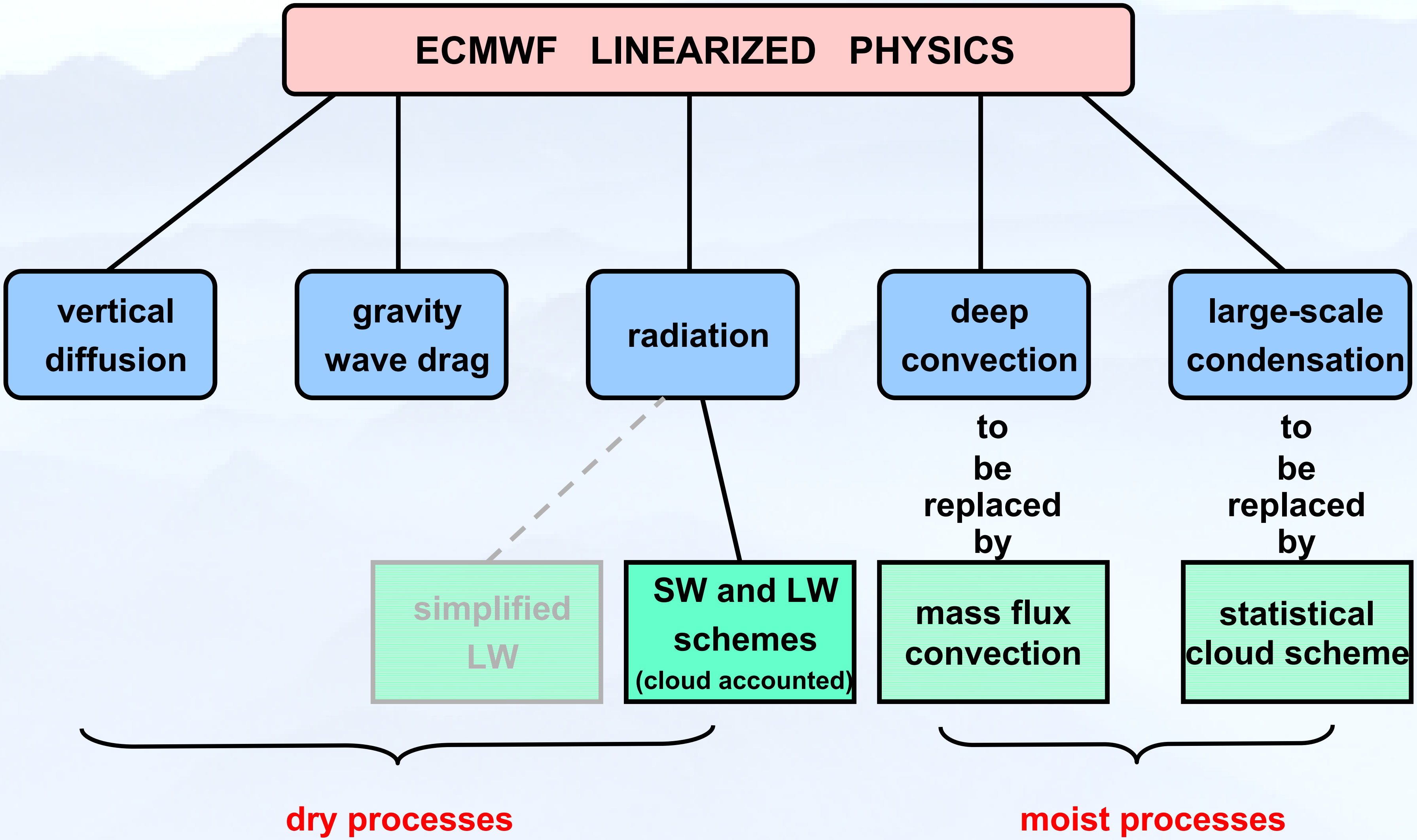


TL_{ADIAB} – adiabatic TL model

$TL_{ADIABSVD}$ – TL model with very simple vertical diffusion *(Buizza 1994)*

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

Simplified physical parametrizations



Tangent-linear diagnostics

Comparison:

finite differences (FD) $\leftrightarrow$ tangent-linear (TL) integration

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

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

Diagnostics:

- **mean absolute errors:**

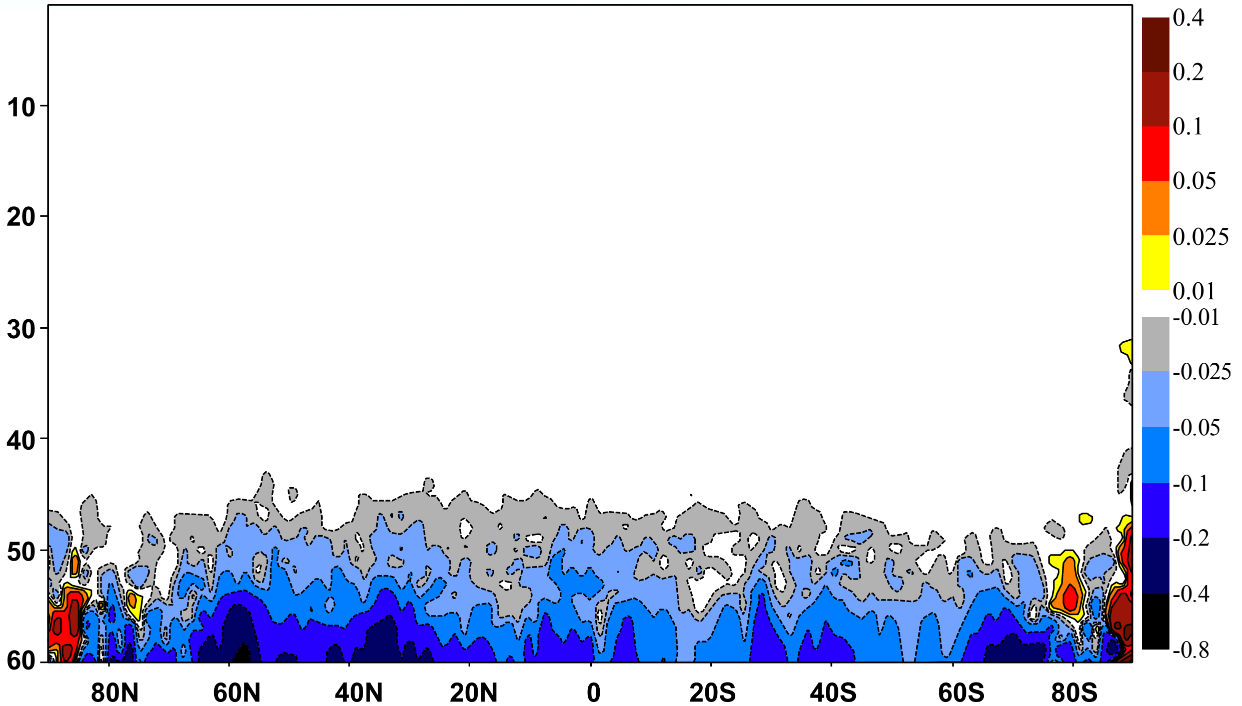
$$\varepsilon = \overline{\left| \left[M(\mathbf{x}_{an}) - M(\mathbf{x}_{fg}) \right] - M'(\mathbf{x}_{an} - \mathbf{x}_{fg}) \right|}$$

- **relative error**

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

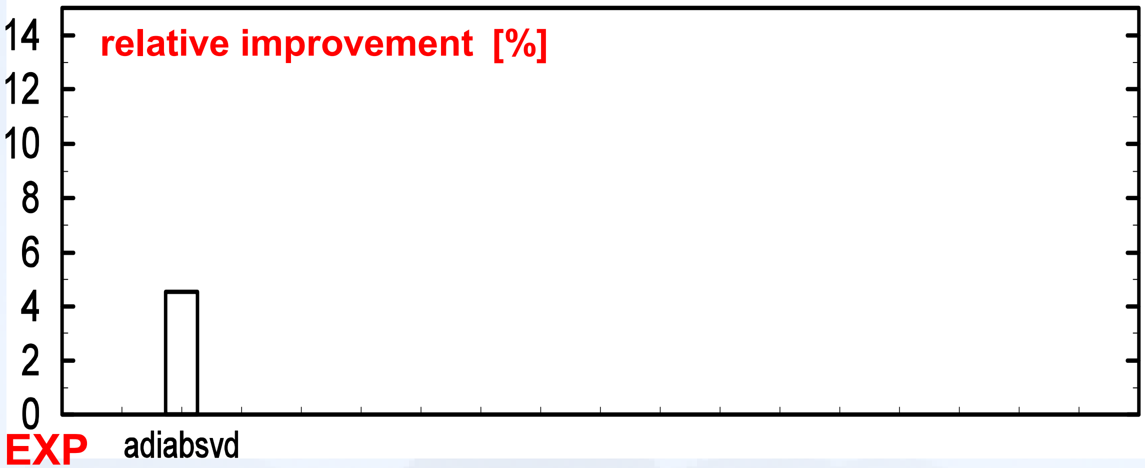
Impact of physical processes

Temperature



$\varepsilon_{EXP} - \varepsilon_{REF}$

REF = ADIAB

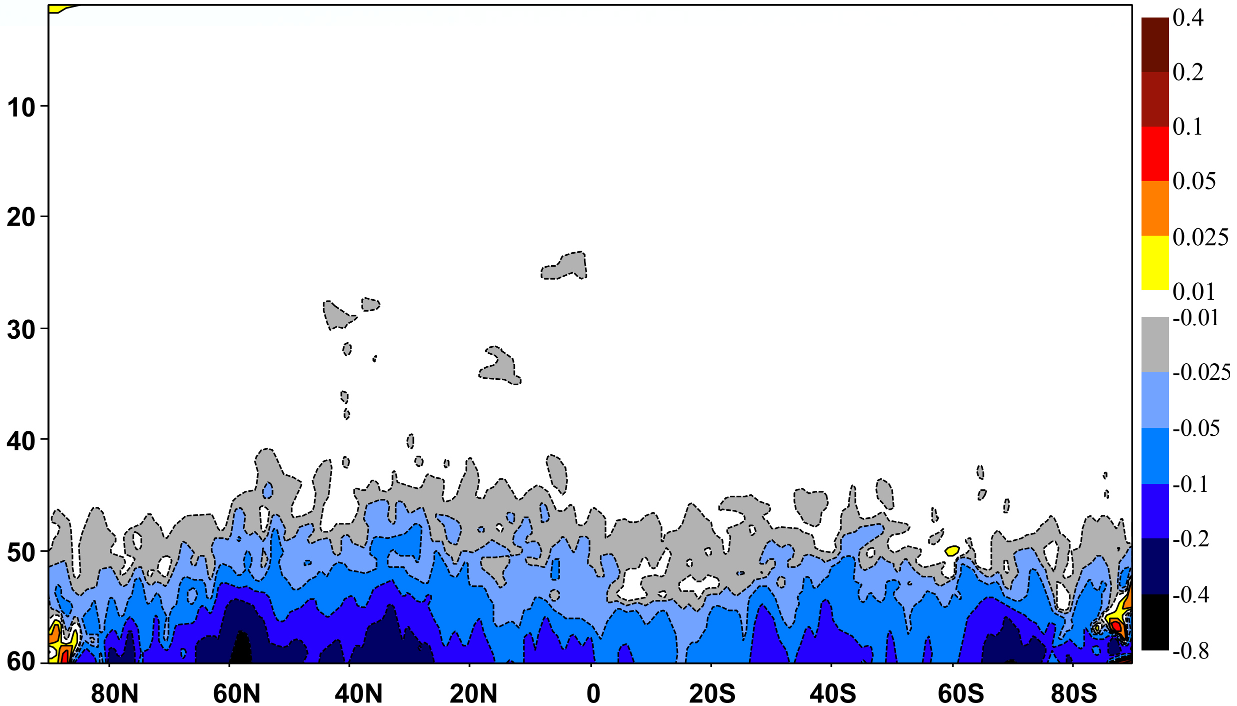


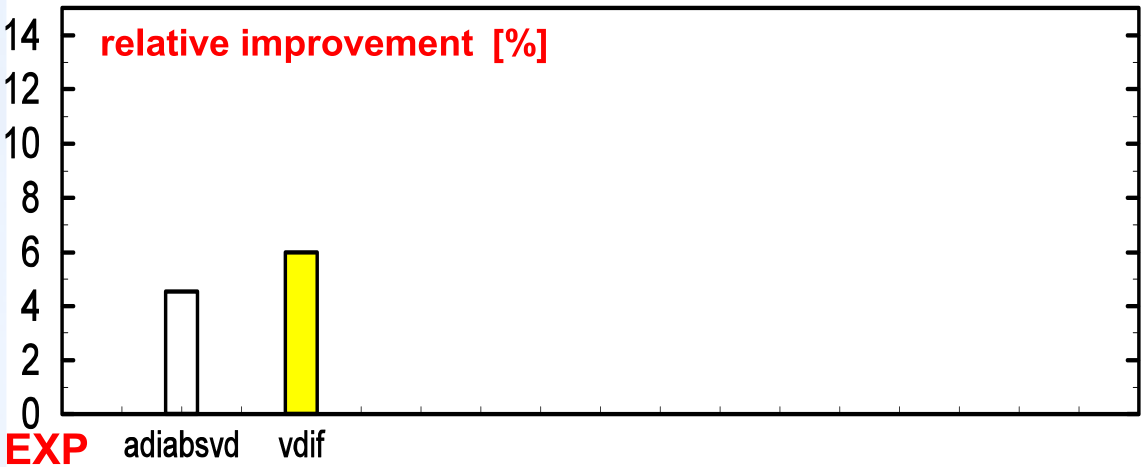
adiabsvd

Temperature

$\varepsilon_{EXP} - \varepsilon_{REF}$

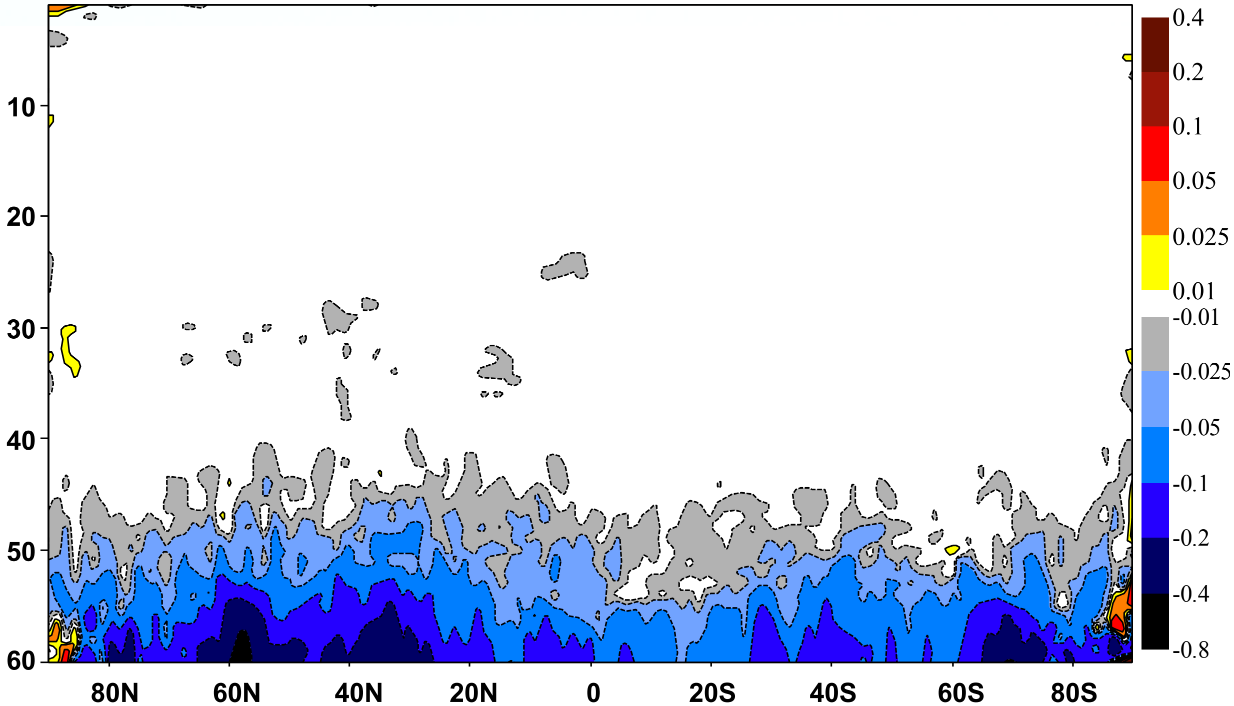
REF = ADIAB





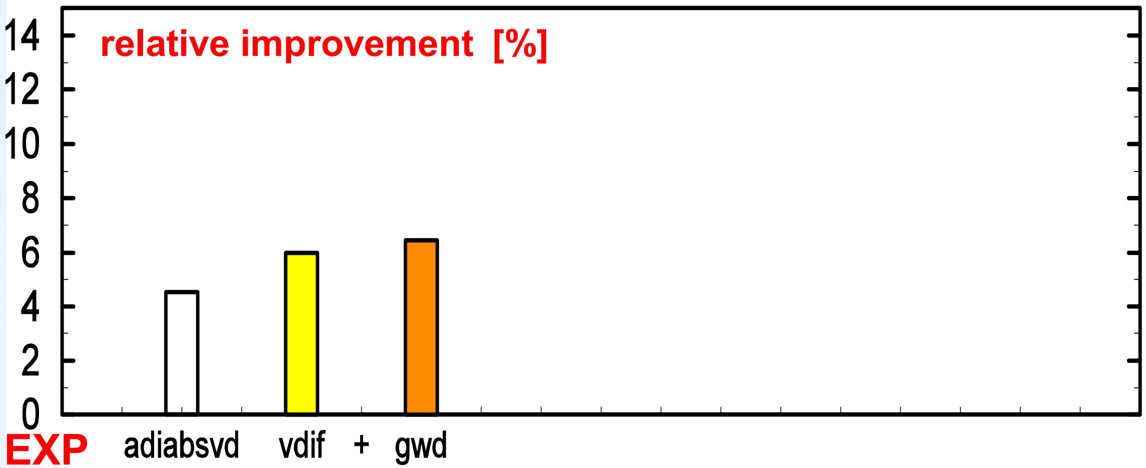
Impact of physical processes

Temperature



$\varepsilon_{EXP} - \varepsilon_{REF}$

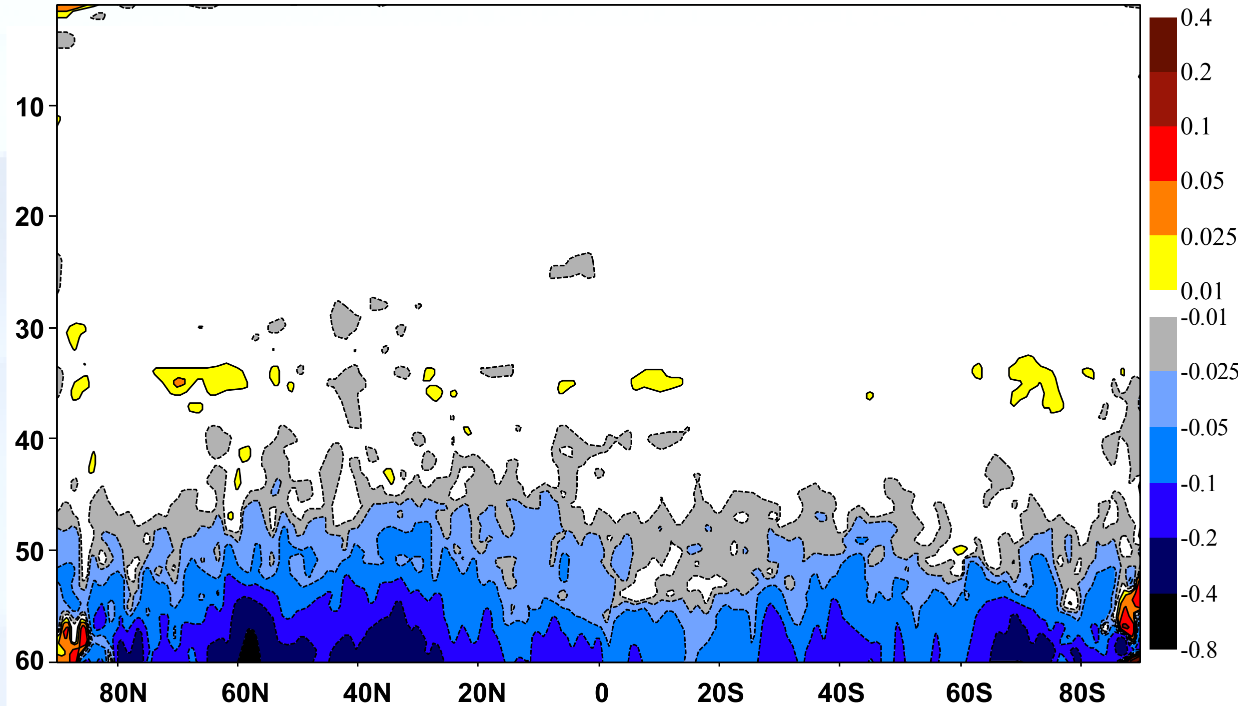
REF = ADIAB



adiabsvd || vdif + gwd

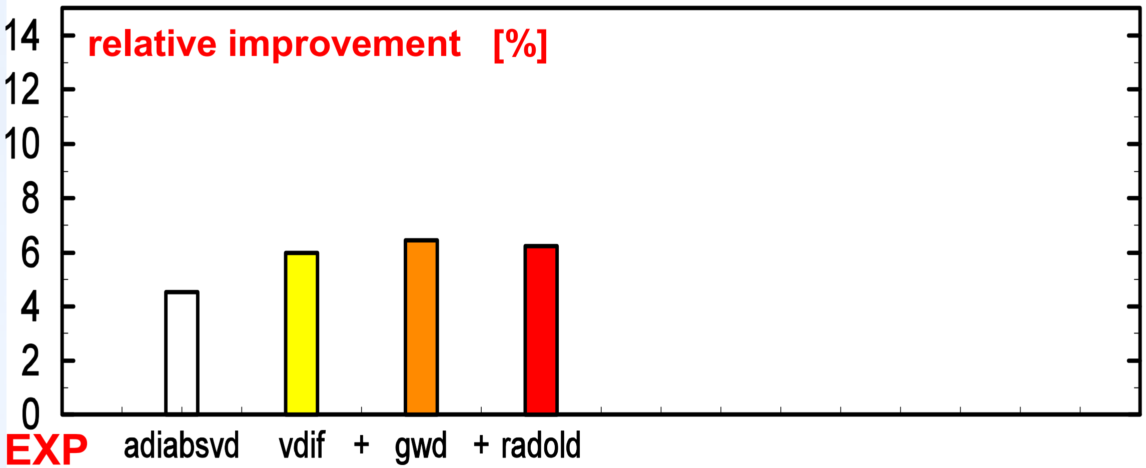
Impact of physical processes

Temperature



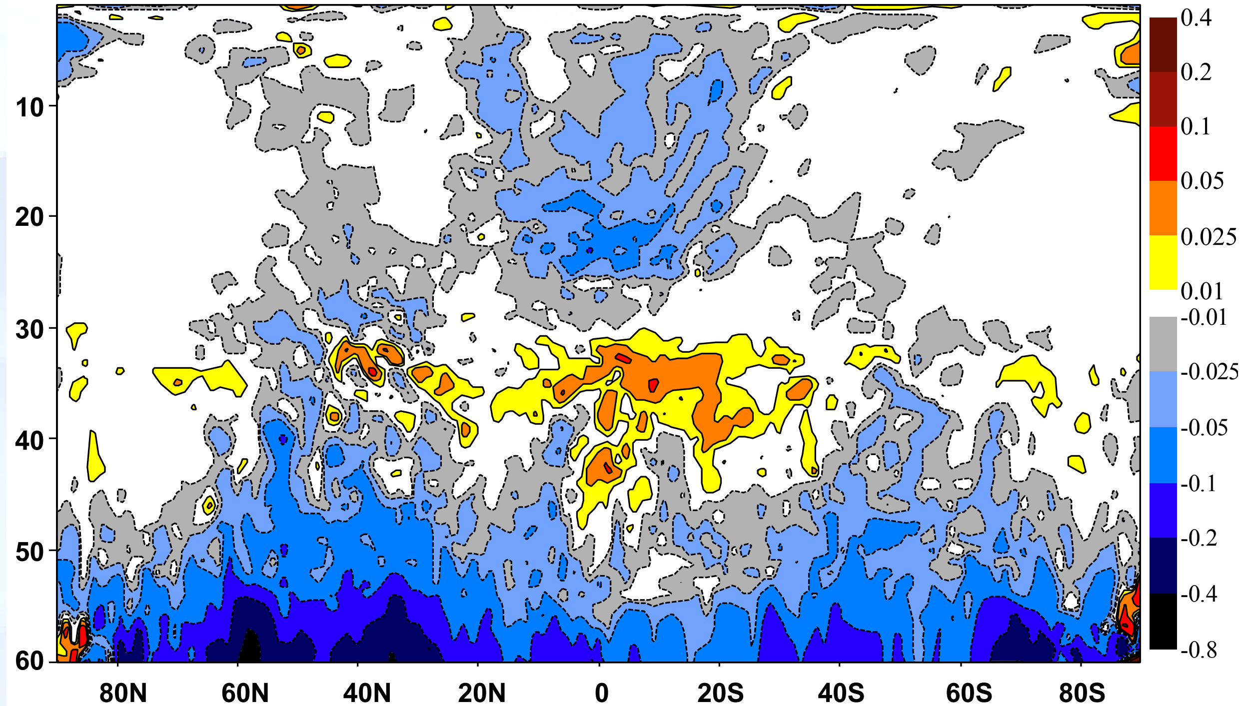
$\varepsilon_{EXP} - \varepsilon_{REF}$

REF = ADIAB



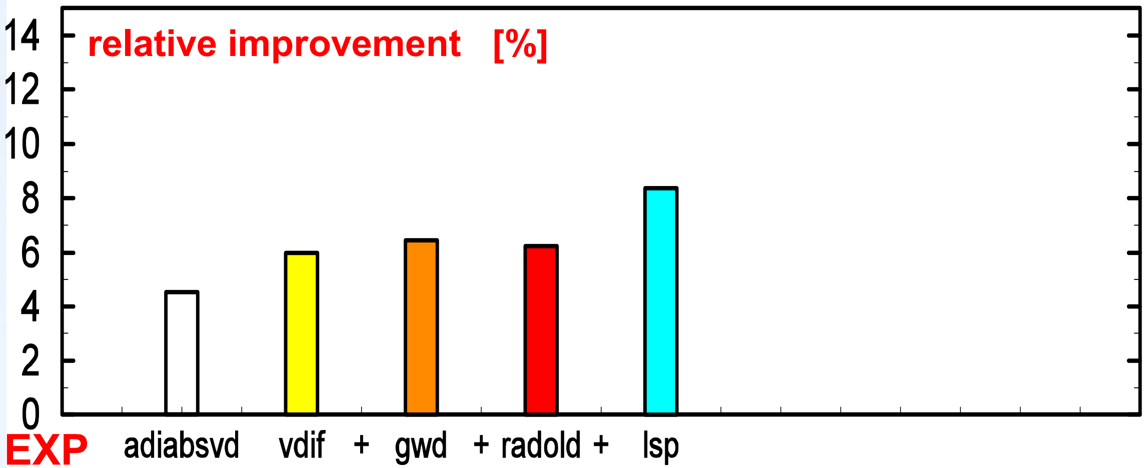
adiabsvd || vdif + gwd + radold

Temperature



$\varepsilon_{EXP} - \varepsilon_{REF}$

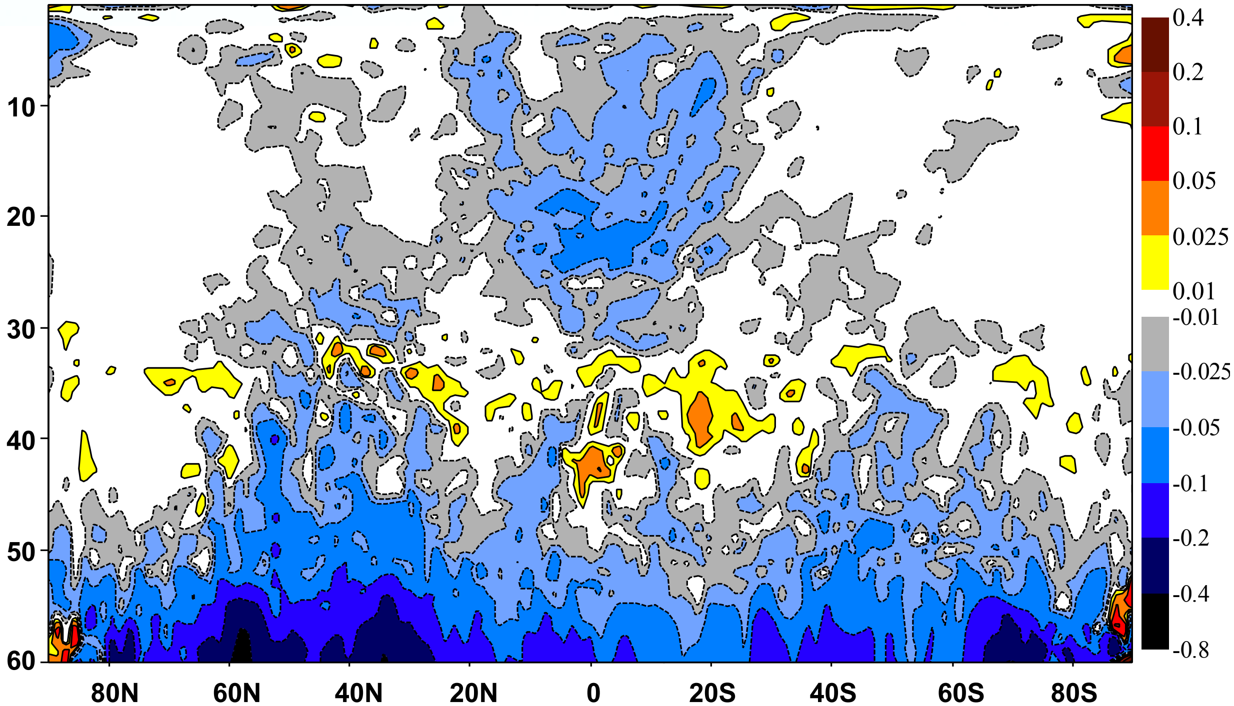
REF = ADIAB



adiabsvd || vdif + gwd + radold + lsp

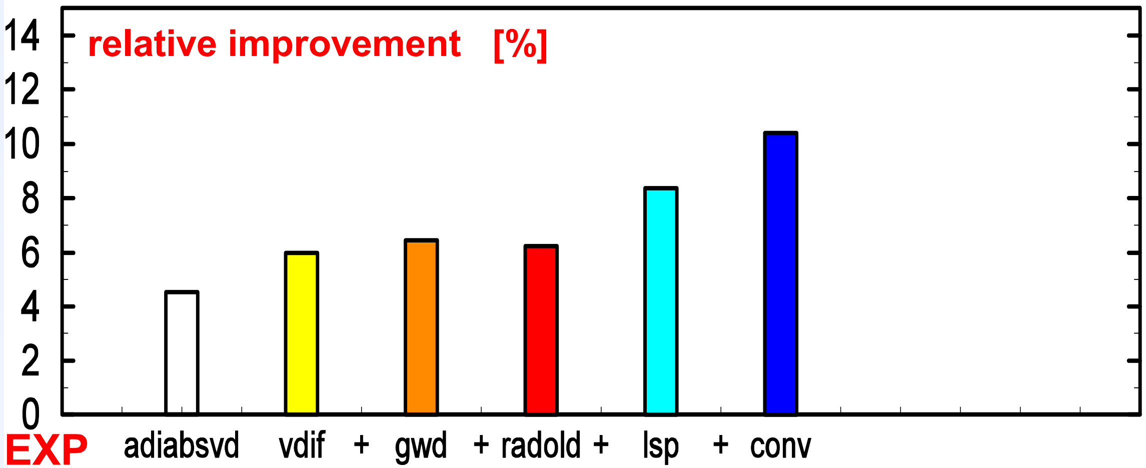
Impact of physical processes

Temperature



$\varepsilon_{EXP} - \varepsilon_{REF}$

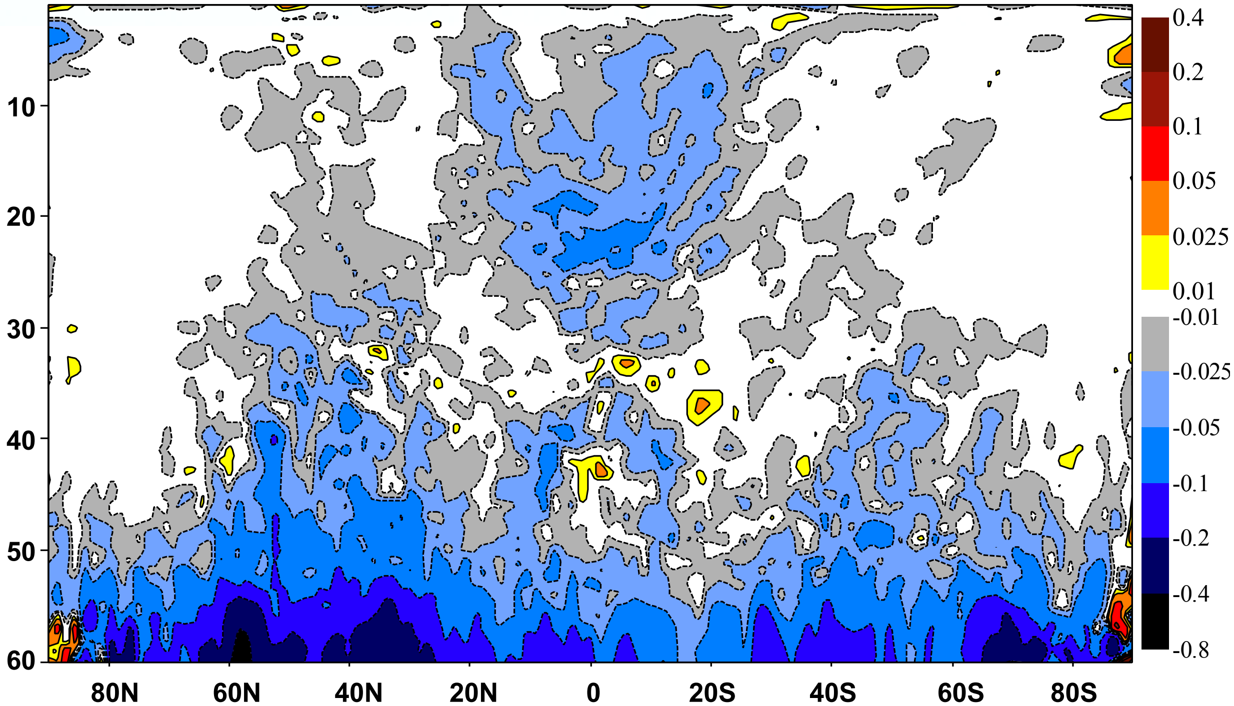
REF = ADIAB



adiabsvd || vdif + gwd + radold + lsp + conv

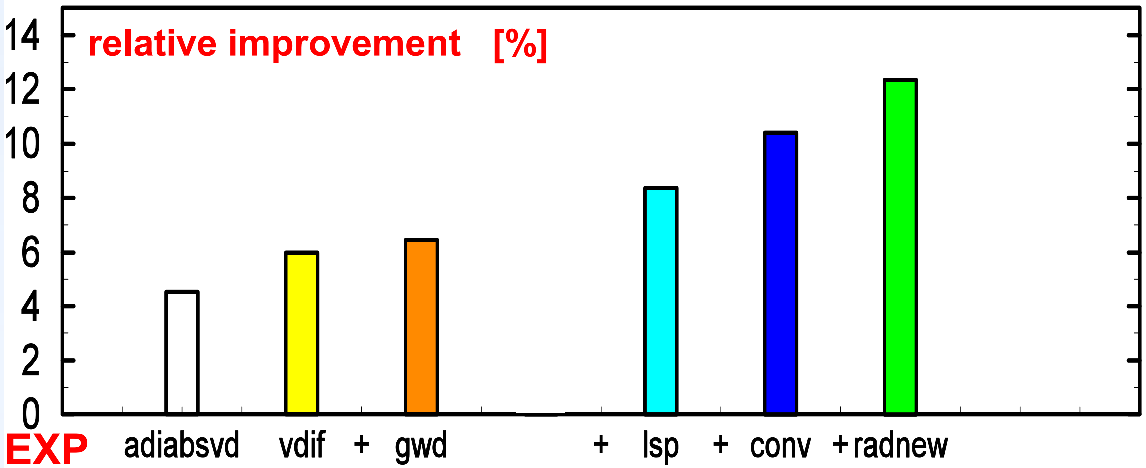
Impact of physical processes

Temperature



$\varepsilon_{EXP} - \varepsilon_{REF}$

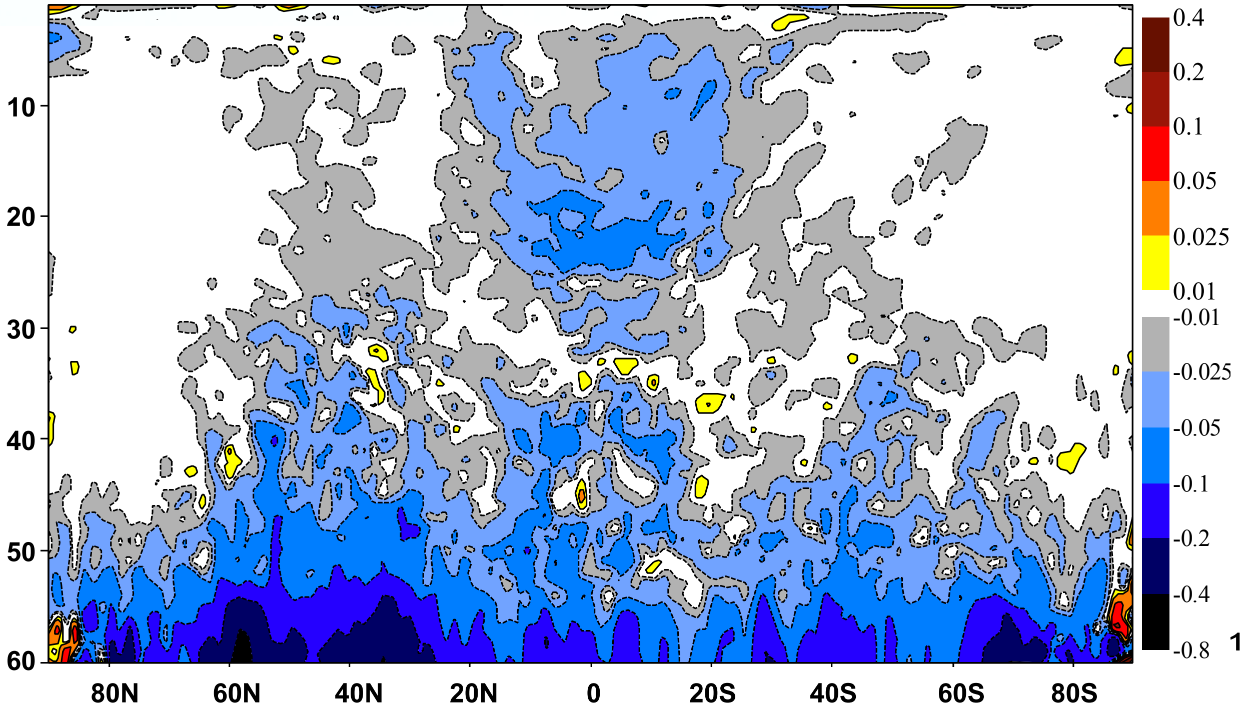
REF = ADIAB



adiabsvd || vdif + gwd + lsp + conv + radnew

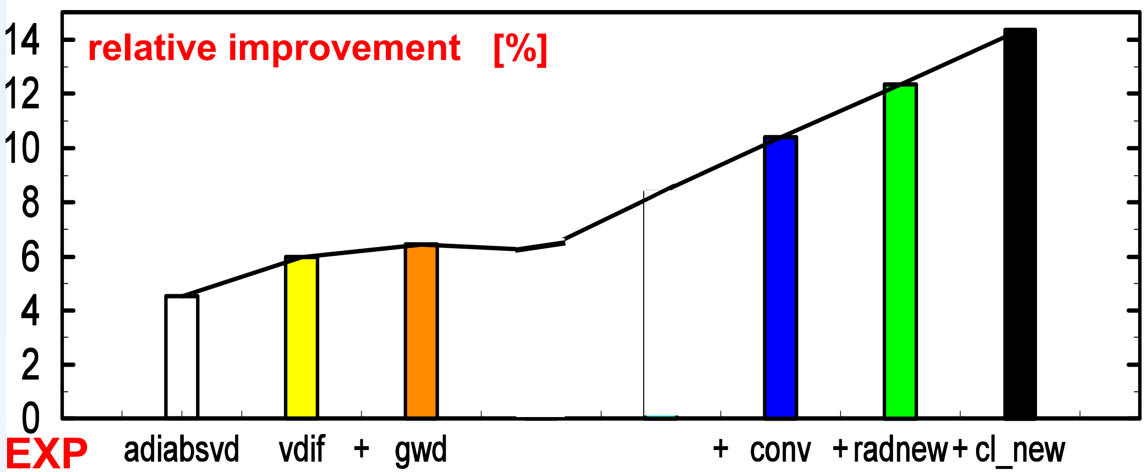
Impact of physical processes

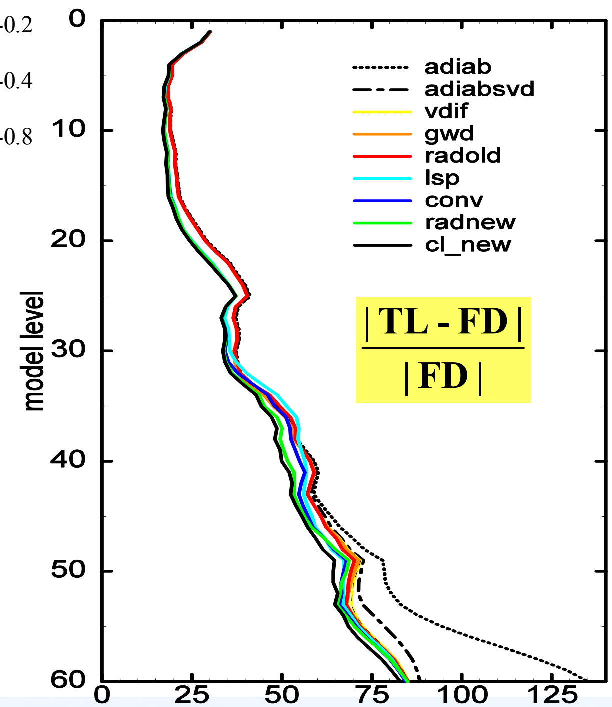
Temperature



$\varepsilon_{EXP} - \varepsilon_{REF}$

REF = ADIAB



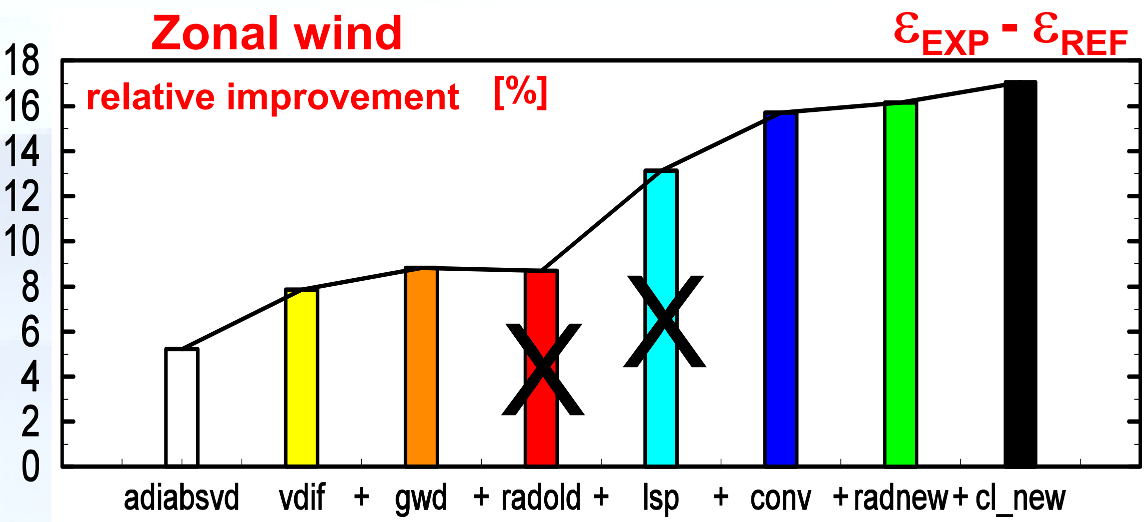


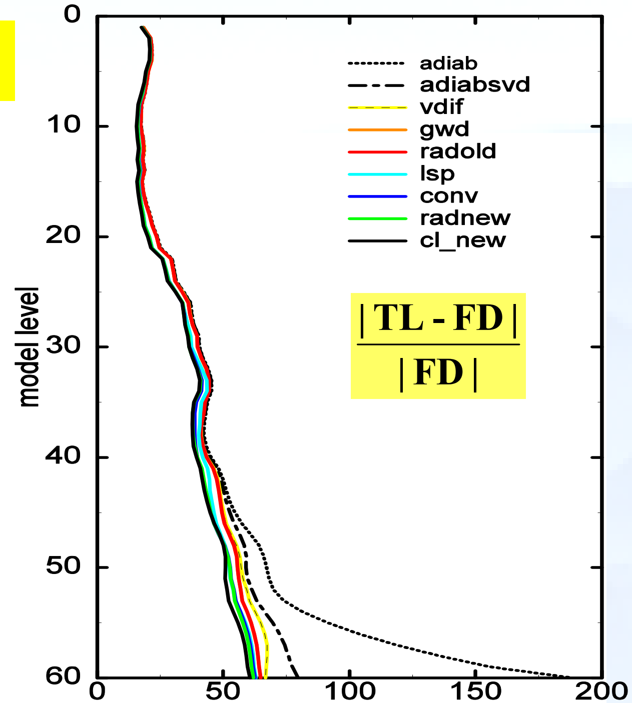
$$\frac{|TL - FD|}{|FD|}$$

adiabsvd || vdif + gwd + conv + radnew + cl_new

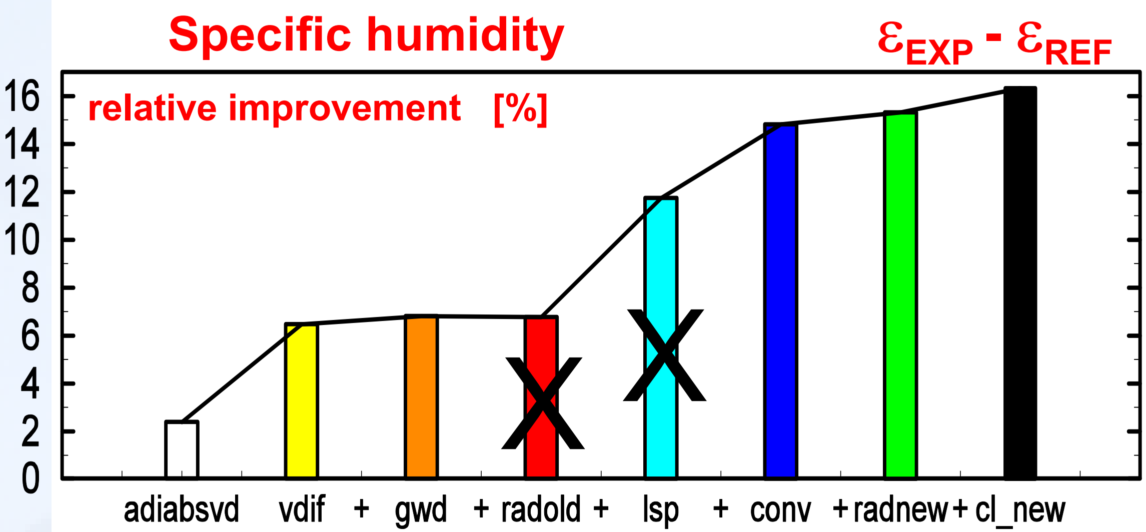
Impact of physical processes

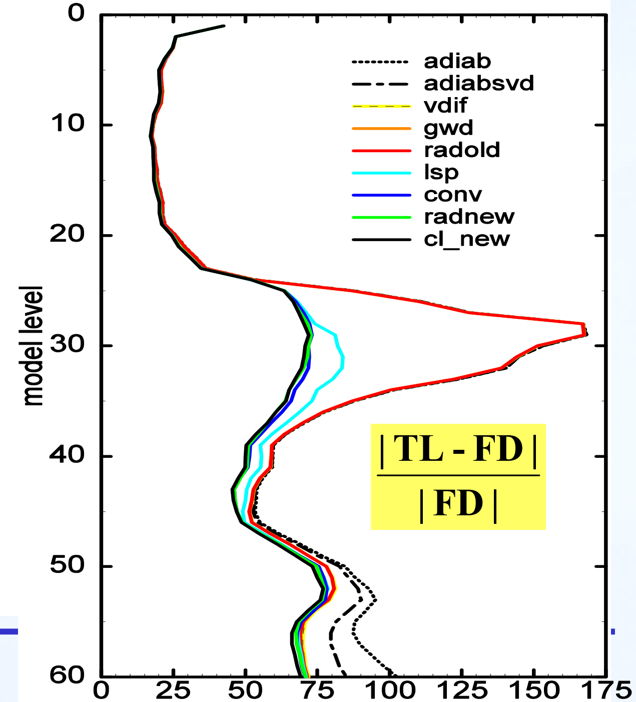
Zonal wind





Specific humidity

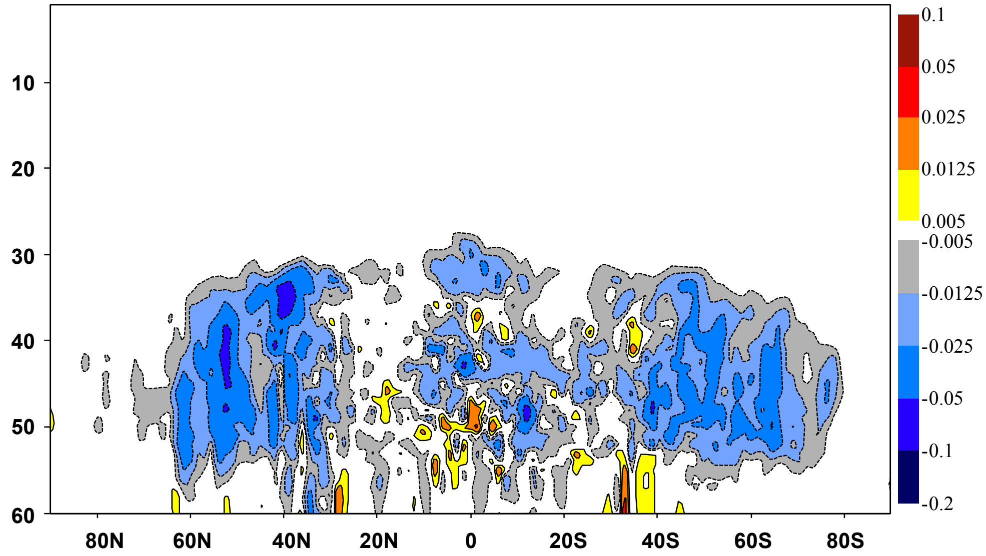




Impact of moist processes (lsp + conv)

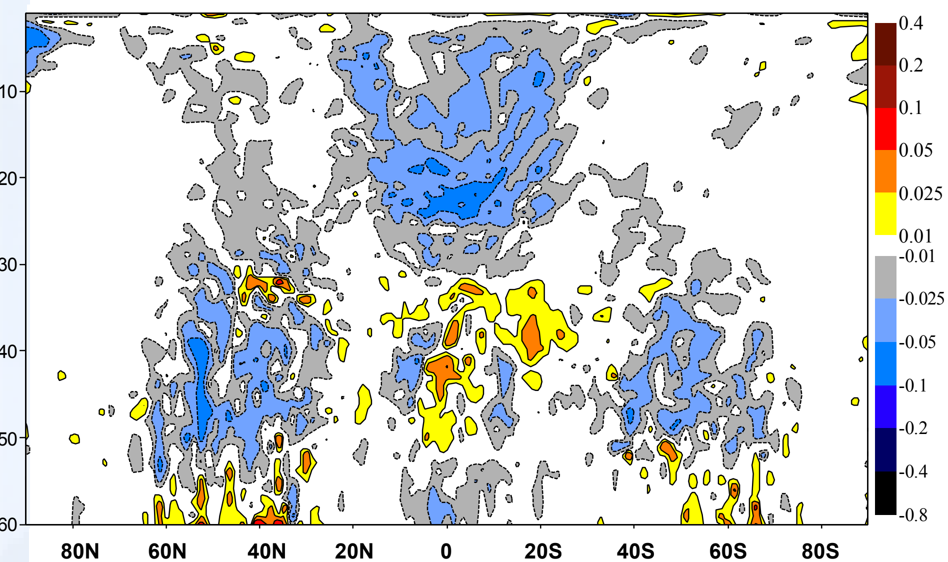
$\varepsilon_{EXP} - \varepsilon_{REF}$

REF = ADIAB

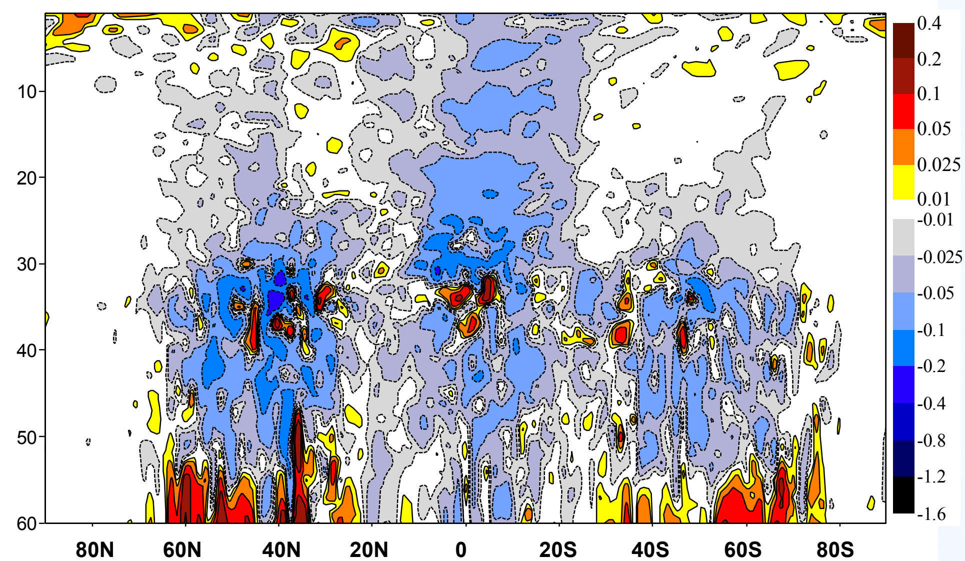


Specific humidity: 7.7 %

Temperature: 3.8 %



Zonal wind: 6.1 %



Physics in 4D-Var

- In incremental 4D-Var, the objective function is minimized in terms of increments:

$$\delta\mathbf{x}_i = M'(t_i, t_0)\,\delta\mathbf{x}_0 \qquad \leftarrow \quad \textit{tangent linear model}$$

with the model state defined at any time t_i as: $\mathbf{x}_i = \mathbf{x}_i^b + \delta\mathbf{x}_i \quad , \quad \mathbf{x}_i^b = M(t_i, t_0)\mathbf{x}_0^b$

- 4D-Var can be then approximated to the first order as minimizing:

$$\mathcal{J}(\delta\mathbf{x}_0) = \frac{1}{2}\delta\mathbf{x}_0^{\mathrm{T}}\mathbf{B}^{-1}\delta\mathbf{x}_0 + \frac{1}{2}\sum_{i=0}^{n}\left(H_i'(\delta\mathbf{x}_i) - \mathrm{d}_i\right)^{\mathrm{T}}\mathbf{R}_i^{-1}\left(H_i'(\delta\mathbf{x}_i) - \mathrm{d}_i\right)$$

where $\mathrm{d}_i = y_i^o - H_i(\mathbf{x}_i^b)$ is the *innovation vector*

Gradient of the objective function to be minimized:

$$\nabla_{\delta\mathbf{x}_0}\mathcal{J} = \mathbf{B}^{-1}\delta\mathbf{x}_0 + \frac{1}{2}\sum_{i=0}^{n}\mathbf{M}^{\mathrm{T}}(t_i, t_0)\mathbf{H}_i^{\mathrm{T}}\mathbf{R}_i^{-1}\left(H_i'(\delta\mathbf{x}_i) - \mathrm{d}_i\right)$$

d_i ← computed with the non-linear model at high resolution using full physics $\leftarrow M$

$\delta\mathbf{x}_i$ ← computed with the tangent-linear model at low resolution using simplified physics $\leftarrow M'$

$\nabla_{\delta\mathbf{x}_0}\mathcal{J}$ ← computed with a low resolution adjoint model using simplified physics $\leftarrow \mathbf{M}^{\mathrm{T}}$

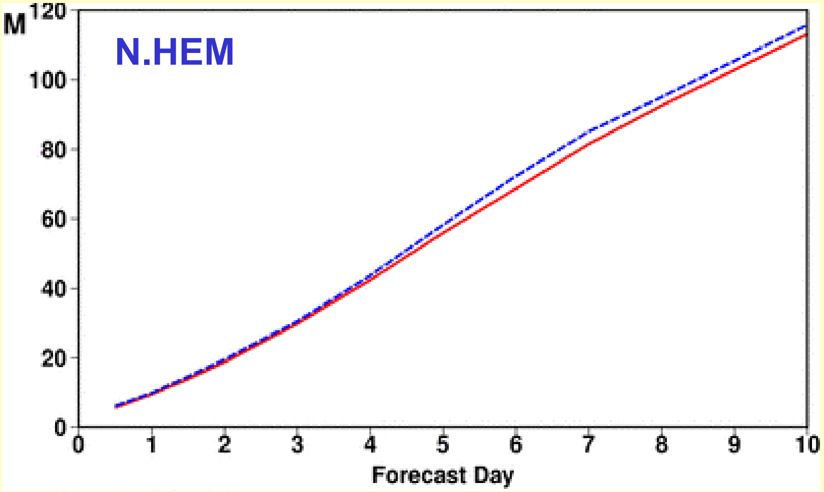
Impact of the linearized physics in 4D-Var (1)

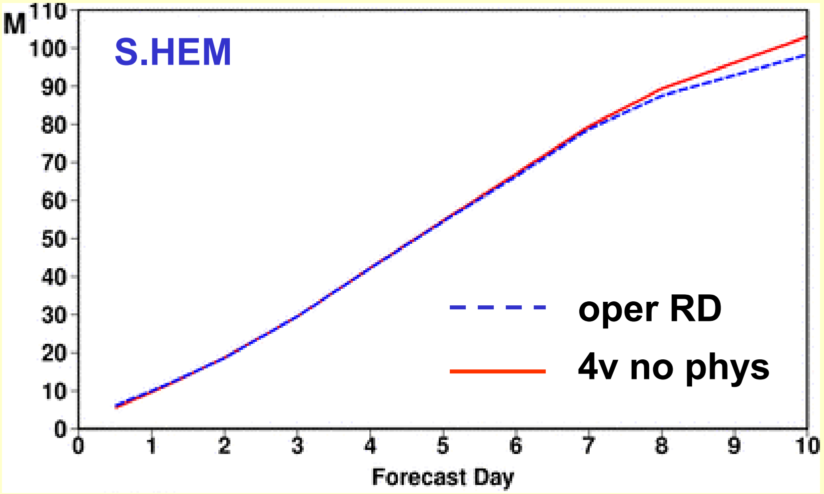
- **comparisons of the operational version of 4D-Var against the version without linearized physics included shows:**
  - *positive impact on analysis and forecast*

FORECAST VERIFICATION – 500 hPa GEOPOTENTIAL

period: 15/11/2000 – 13/12/2000

root mean square error – 29 cases

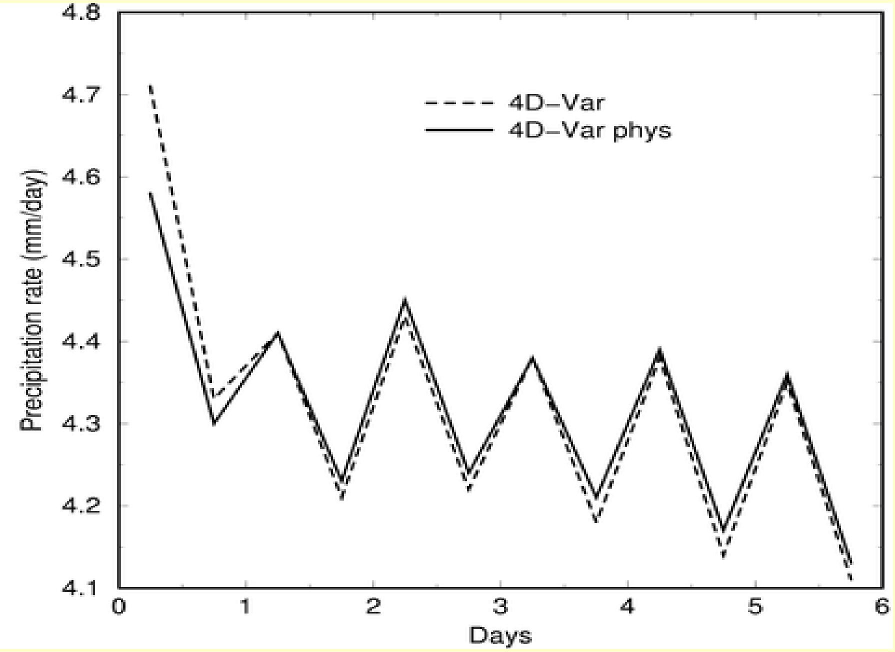




Impact of the linearized physics in 4D-Var (2)

– *reducing spin-up problem when using physical processes*

Time evolution of global precipitation in the tropical belt [30S, 30N] averaged over 14 forecasts issued from 4D-Var assimilation



Impact of the linearized physics in 4D-Var (3)

1-DAY FORECAST ERROR OF 500 hPa GEOPOTENTIAL HEIGHT

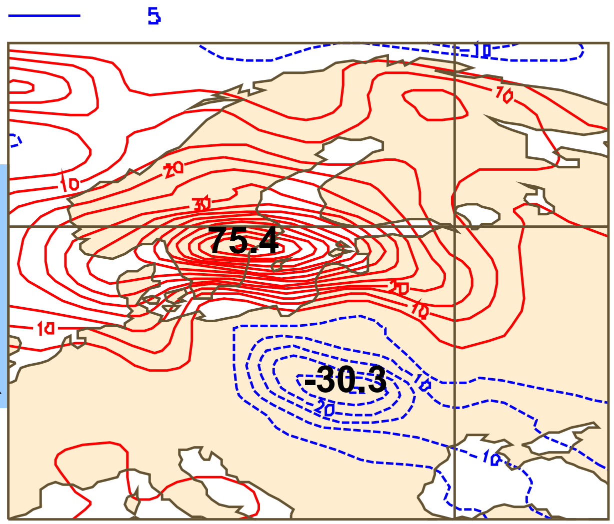
OPER vs. NEWRAD (27/08/2001 t+24)

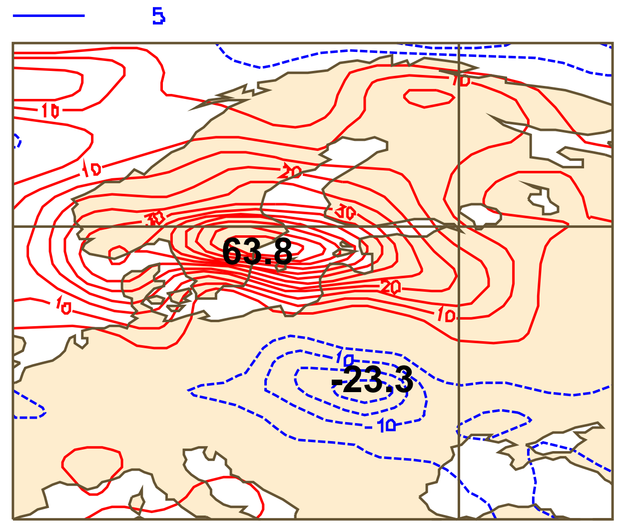
A1:

FC_OPER

–

ANAL_OPER



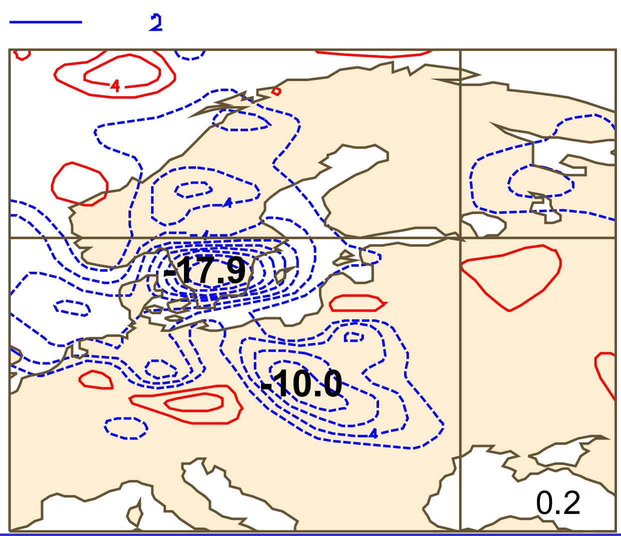


A2:

FC_NEWRAD

–

ANAL_OPER



A2 – A1

1D-Var assimilation of observations related to the physical processes

- **For a given observation y^o, 1D-Var searches for the model state $x=(T,q_v)$ that minimizes the objective function:**

$$\mathcal{J}(\mathbf{x}) = \underbrace{\frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b)}_{\text{Background term}} + \underbrace{\frac{1}{2}(H(\mathbf{x})-\mathbf{y}^o)^{\mathrm{T}}\mathbf{R}^{-1}(H(\mathbf{x})-\mathbf{y}^o)}_{\text{Observation term}}$$

B = **background error covariance matrix**

R = **observation and representativeness error covariance matrix**

H = **nonlinear observation operator (model space → observation space)**
(*physical parametrization schemes*, *microwave radiative transfer model*, *reflectivity model, …*)

- **The minimization requires an estimation of the gradient of the objective function:**

$$\nabla\mathcal{J}(\mathbf{x}) = \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \mathbf{H}^{\mathrm{T}}\mathbf{R}^{-1}(H(\mathbf{x})-\mathbf{y}^o)$$

- **The operator $\mathbf{H}^{\mathrm{T}}$ can be obtained:**
  - explicitly (Jacobian matrix)
  - using the adjoint technique

Precipitation assimilation at ECMWF

Goal: To assimilate observations related to precipitation and clouds in ECMWF's 4D-Var system including parameterizations of atmospheric moist processes.

A bit of history:

- Work on precipitation assimilation at ECMWF initiated by *Mahfouf* and *Marécal*.
- 1D-Var on TMI and SSM/I rainfall rates (RR) *(M&M 2000)*.
- Indirect '1D-Var + 4D-Var' assimilation of RR more robust than direct 4D-Var.
- '1D-Var + 4D-Var' assimilation of RR is able to improve humidity but also the dynamics in the forecasts *(M&M 2002)*.

More recent developments:

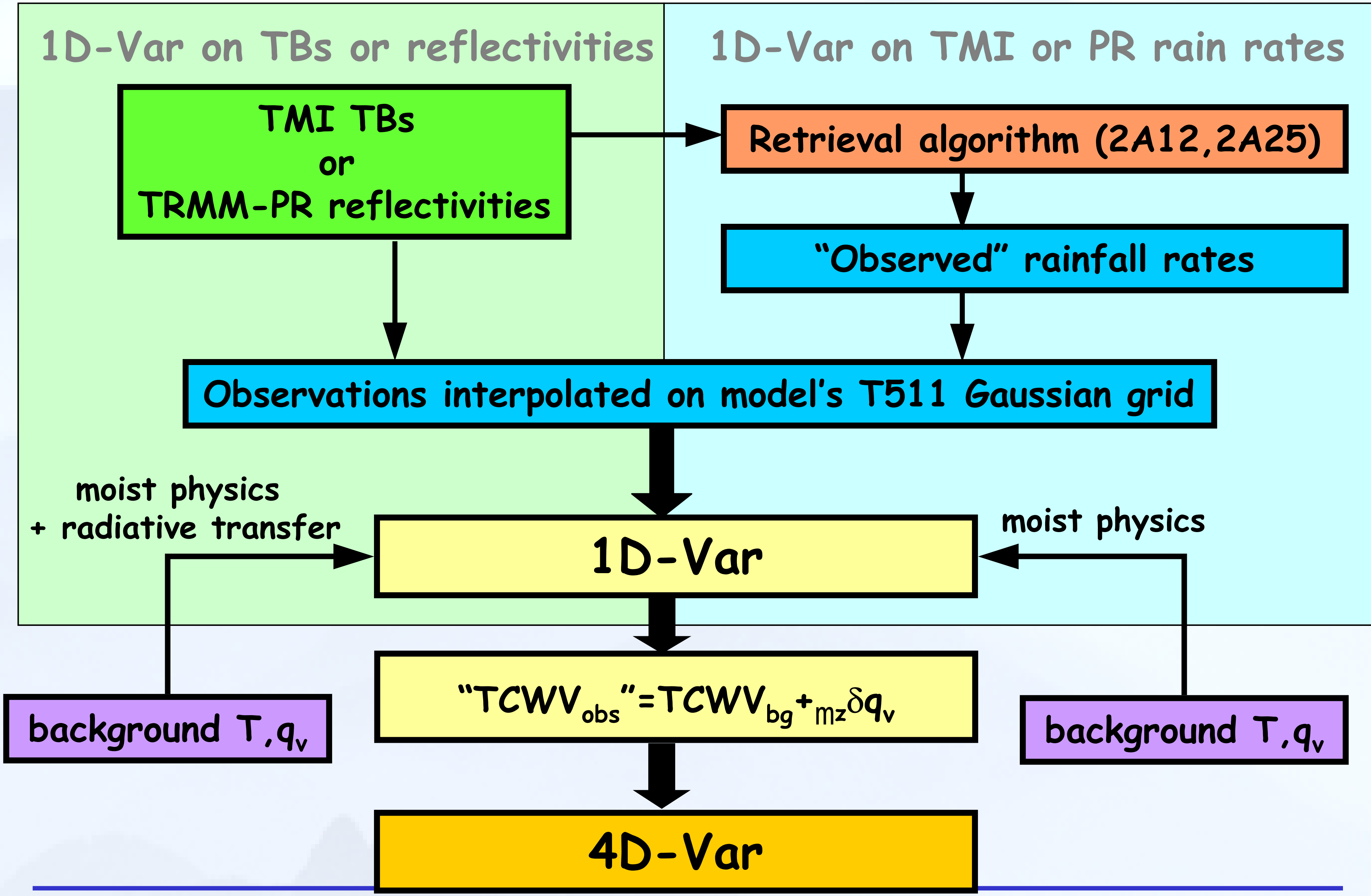
- **New simplified convection scheme** *(Lopez 2003)*
- **New simplified cloud scheme** *(Tompkins & Janisková 2003)*
- **Microwave Radiative Transfer Model** *(Bauer, Moreau 2002)*

} **used in 1D-Var**

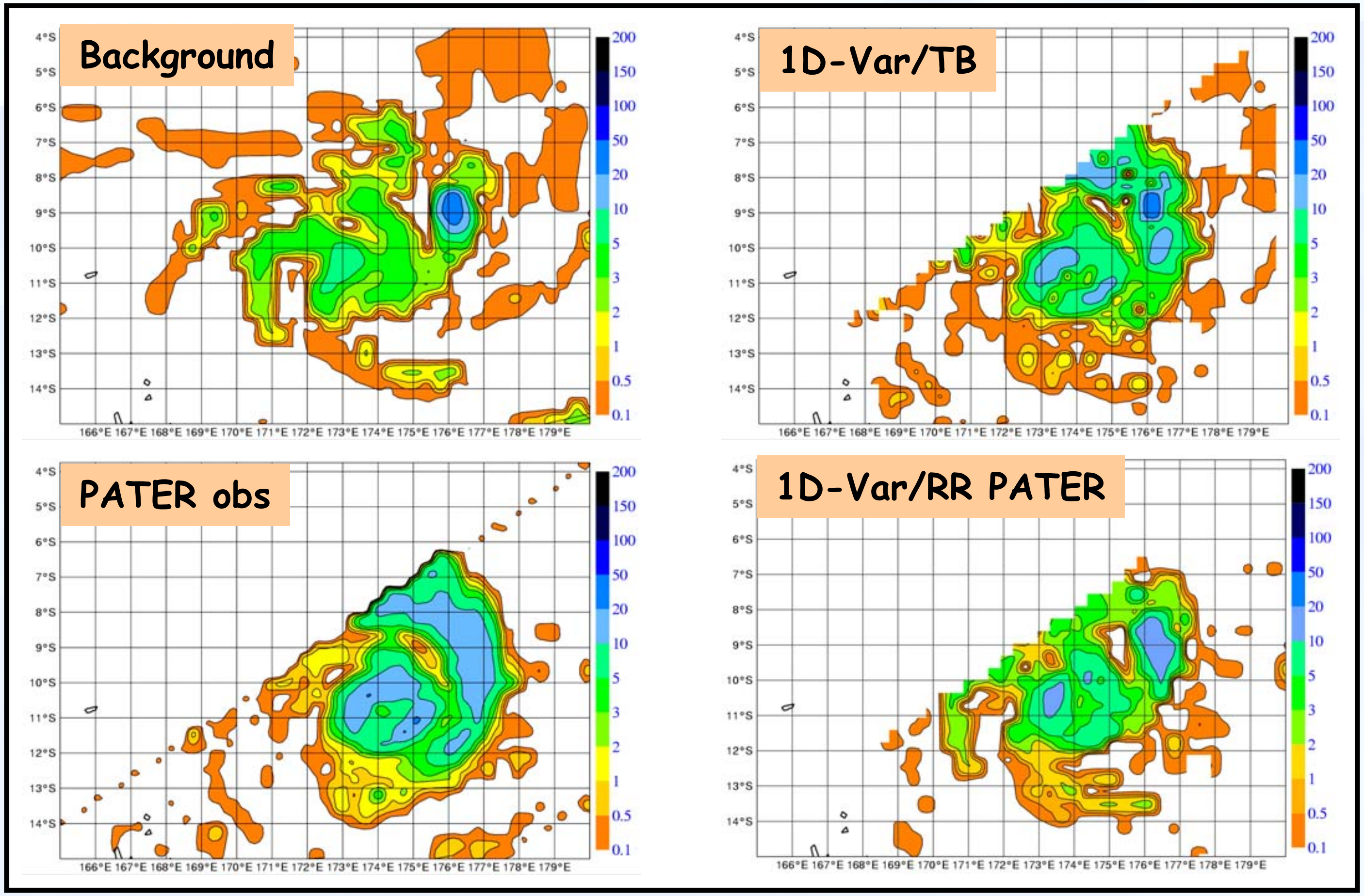
- **Assimilation experiments of direct measurements from TRMM and SSM/I (TB or Z) instead of indirect retrievals of rainfall rates, in a '1D-Var + 4D-Var' framework.**

TMI – TRMM Microwave Imager, TRMM – Tropical Rainfall Measuring Mission
SSM/I – Special Sensor Microwave/Imager

“1D-Var+4D-Var” assimilation of observations related to precipitation



1D-Var on TMI data *(Lopez and Moreau, 2003)*

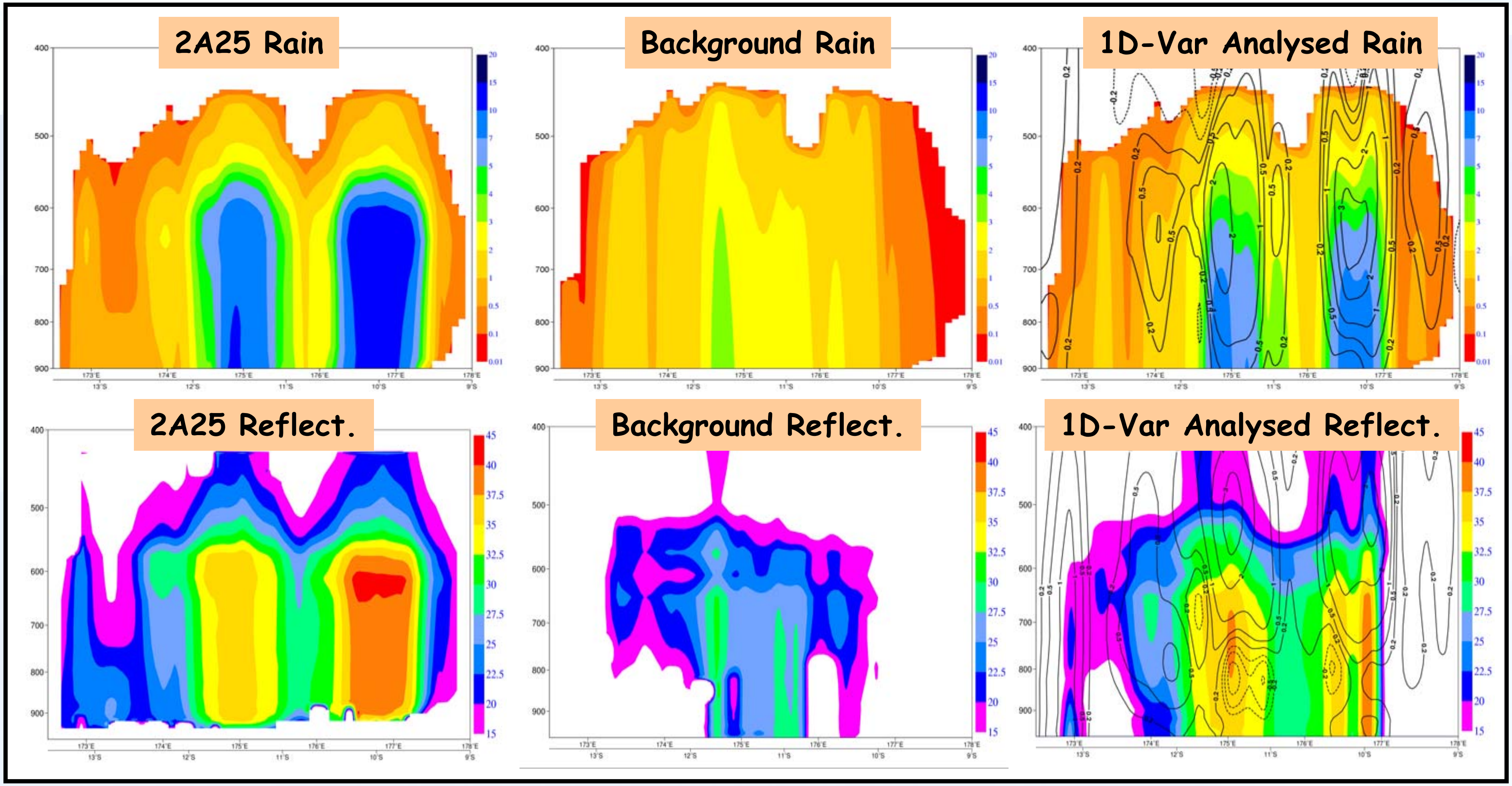


Tropical Cyclone Zoe (26 December 2002 @1200 UTC)

1D-Var on TMI Rain Rates / Brightness Temperatures

Surface rainfall rates (mm h^{-1})

1D-Var on TRMM/ Precipitation Radar data *(Benedetti, 2003)*



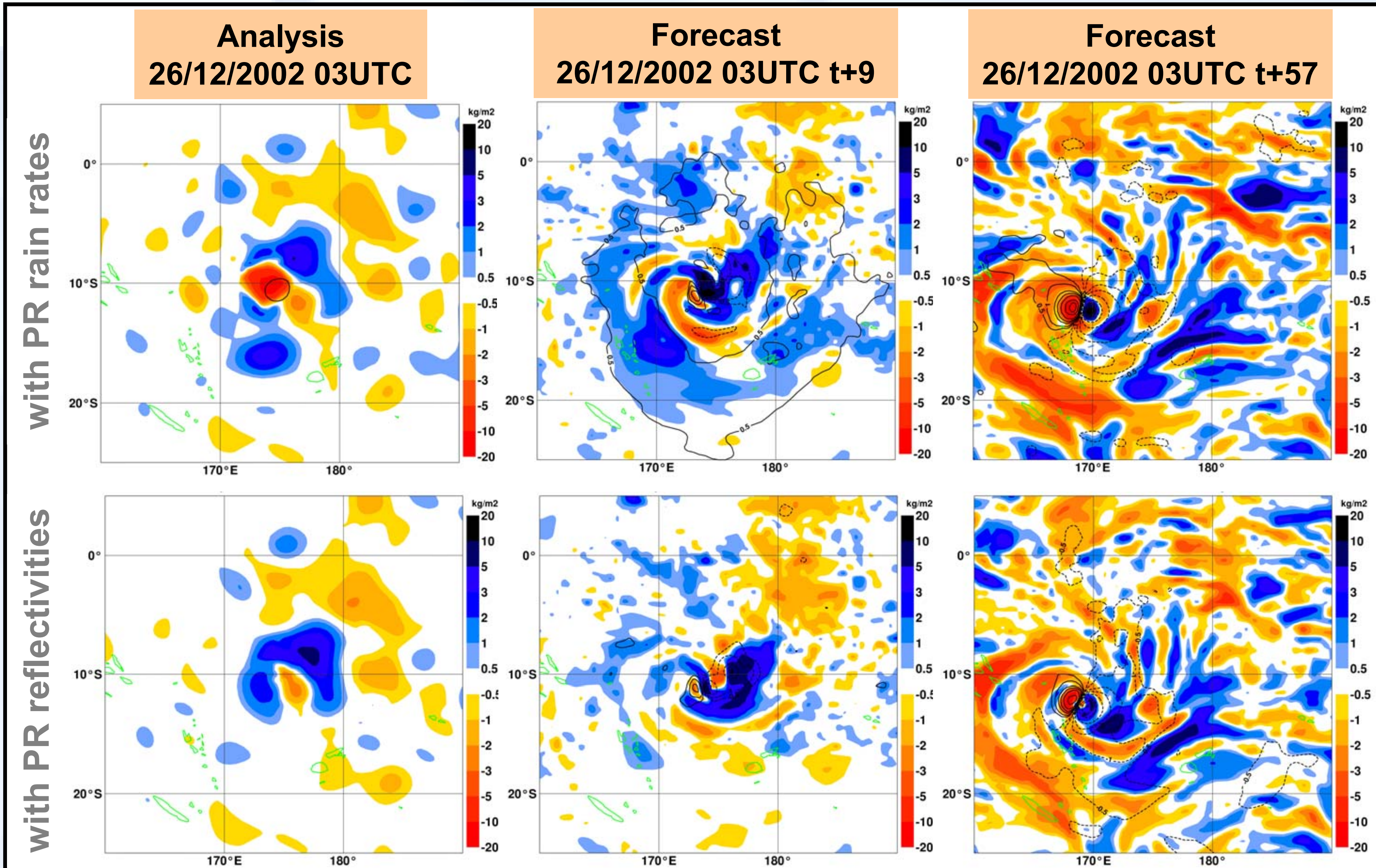
Tropical Cyclone Zoe (26 December 2002 @1200 UTC)

Vertical cross-section of rain rates (top, mm h^{-1}) and reflectivities (bottom, dBZ): observed (left), background (middle), and analysed (right).
Black isolines on right panels = 1D-Var specific humidity increments.

“1D-Var+4D-Var” assimilation of TRMM-PR rain rates/reflectivities:

Impact on analysed and forecast TCWV and MSLP (Experiment – Control)

(Tropical Cyclone Zoe, 26-28 December 2002)

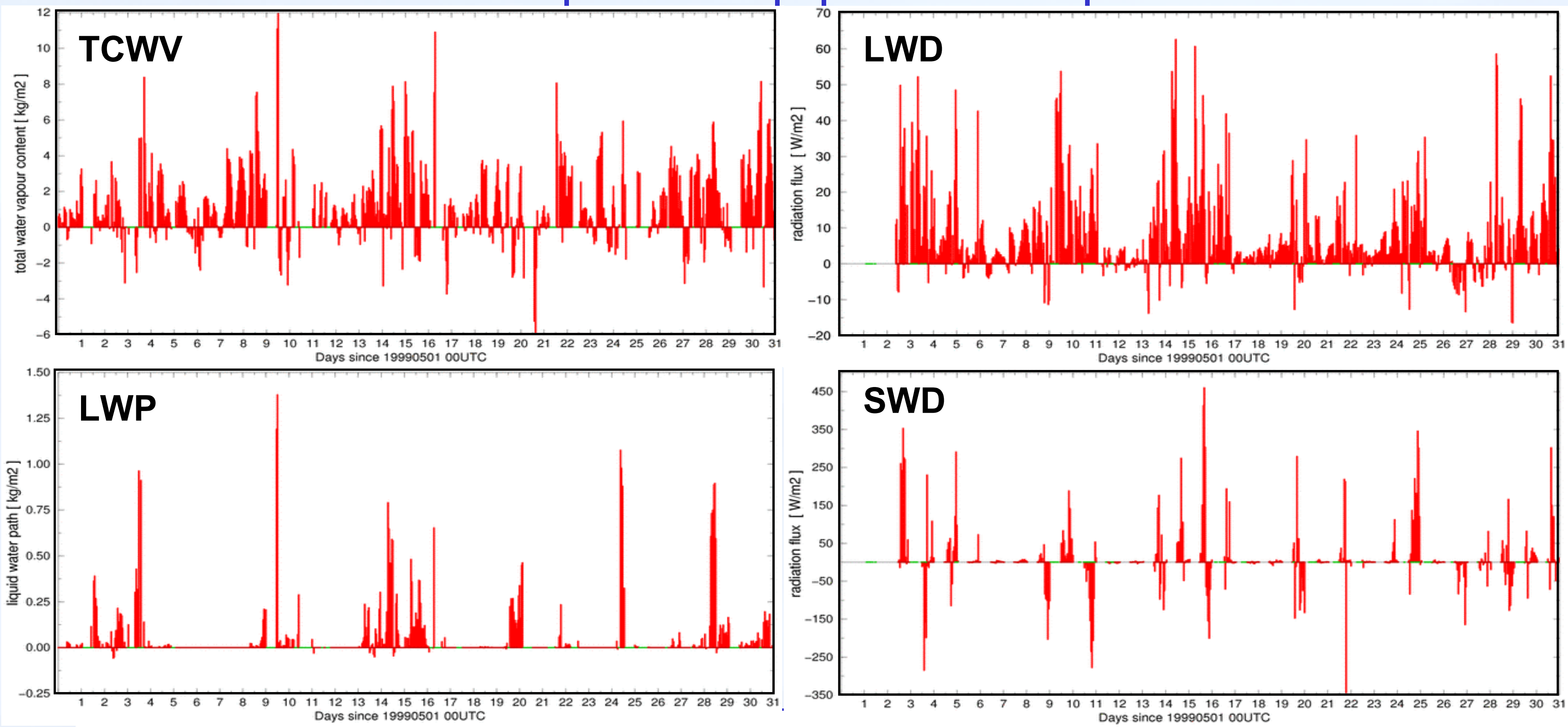


1D-Var assimilation of ARM observations (1)

ARM SGP, May 1999 - observations: - surface downward longwave radiation (LWD),
- total column water vapour (TCWV)
- cloud liquid water path (LWP)

Observation operator includes: - shortwave and longwave radiation schemes
- diagnostic cloud scheme

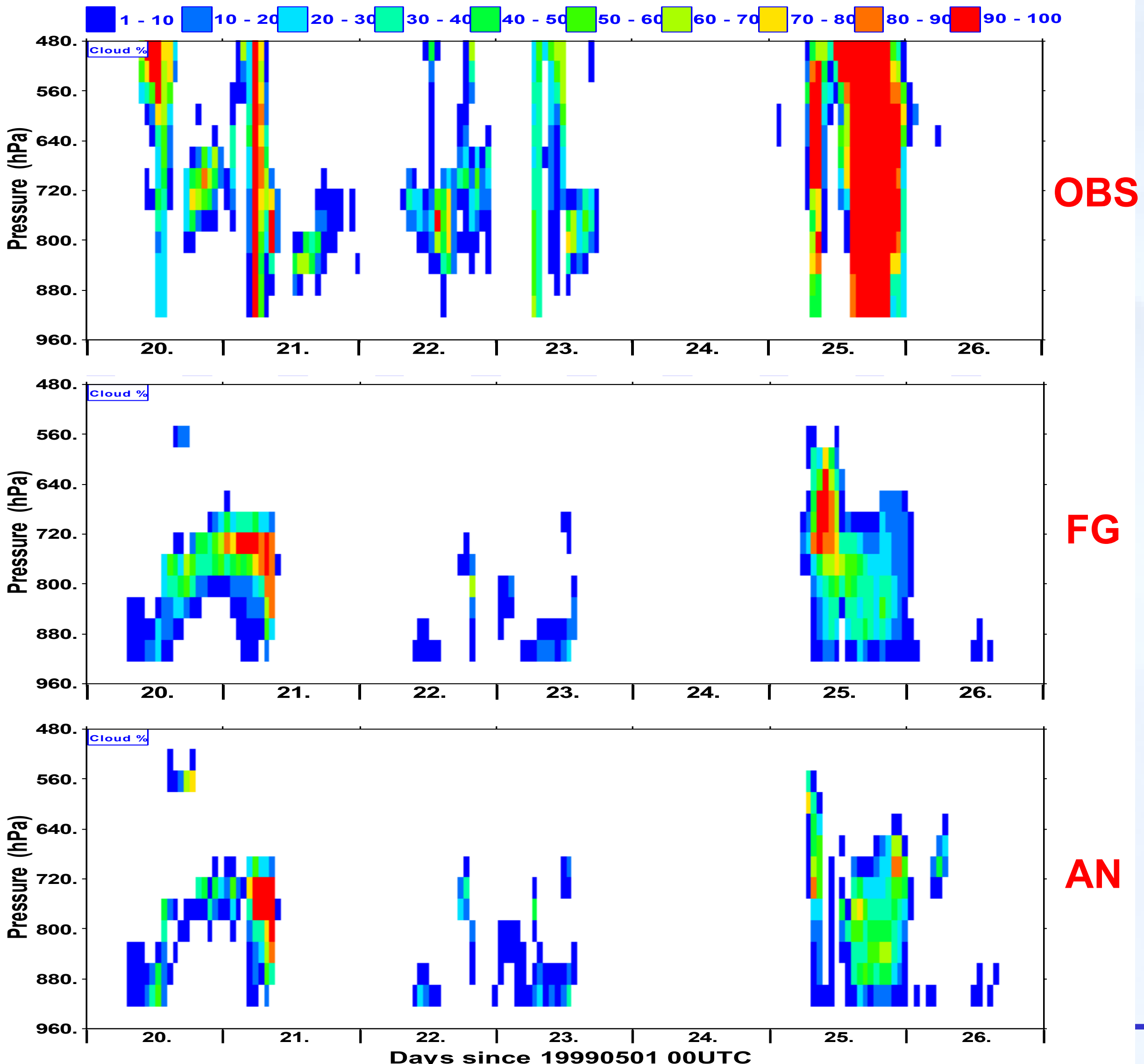
| FG - OBS | - | ANAL - OBS |



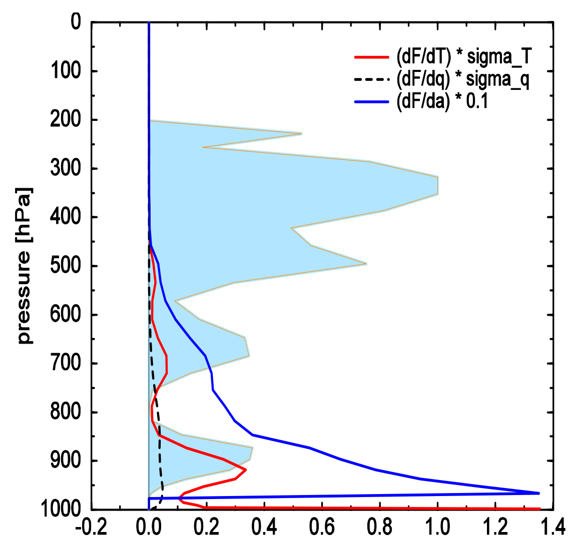
positive values = improvement

1D-Var assimilation of ARM observations (2)

Time series of the cloud fraction (%) for the period 20-26 May 1999.



Sensitivity of LWD to T, q and cloud fraction



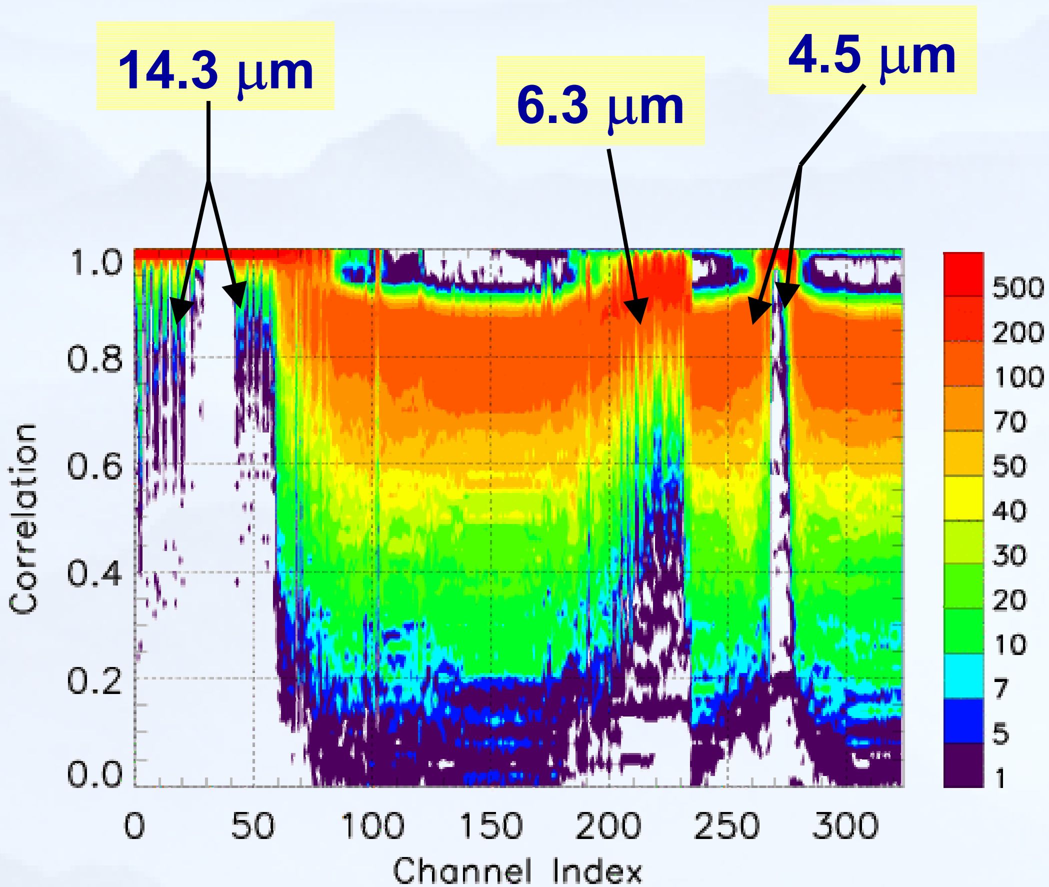
ARM – Atmospheric Radiation Measurement

Cloudy AIRS Tbs and 4D-Var *(Chevallier, 2003)*

- **4D-Var assumes that the forward operator is linear in the vicinity of the background**
  - ✓ **Fairly true for cloudy upper tropospheric channels**

PDF of correlations between **H.**δ**x** and *H*[**x**+δ**x**] – *H*[**x**]
Hemispheric data

- **x** = *T*, *q* profile
- *H* = cloud scheme + RTTOVCLD
- δ**x** = perturbation



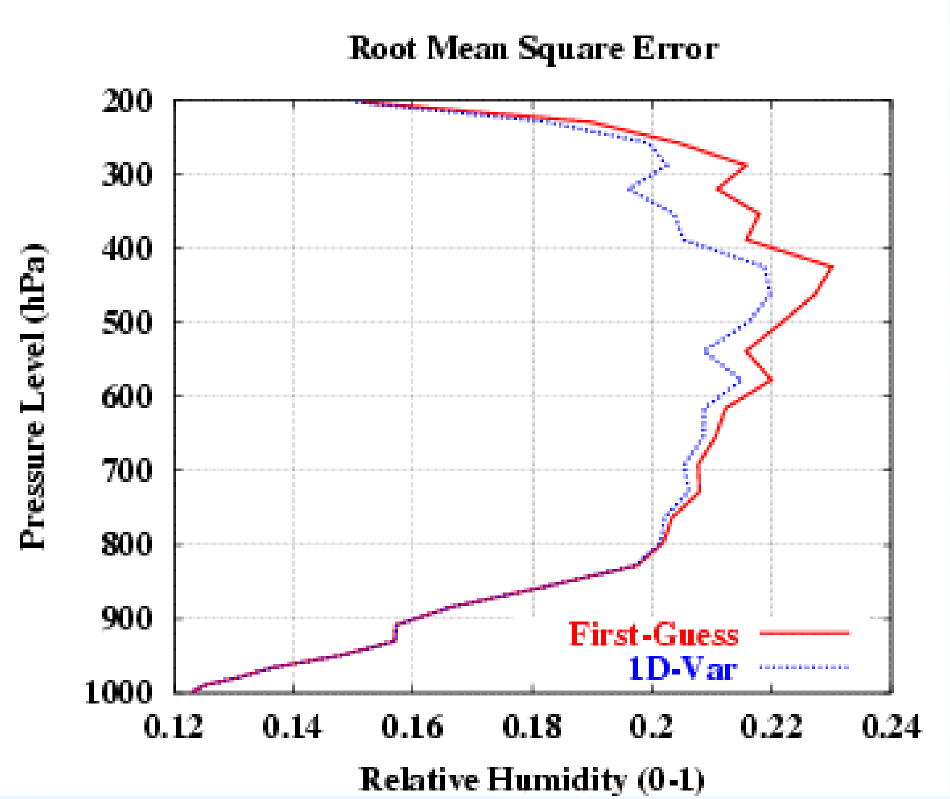
Cloudy AIRS Tbs and 1D-Var *(Chevallier, 2003)*

- **Linear 1D-Var retrievals**
  - ✓ **observations = 35 upper tropospheric AIRS channels**
  - ✓ **performed only if clouds are detected in more than 13 channels**

Validation:

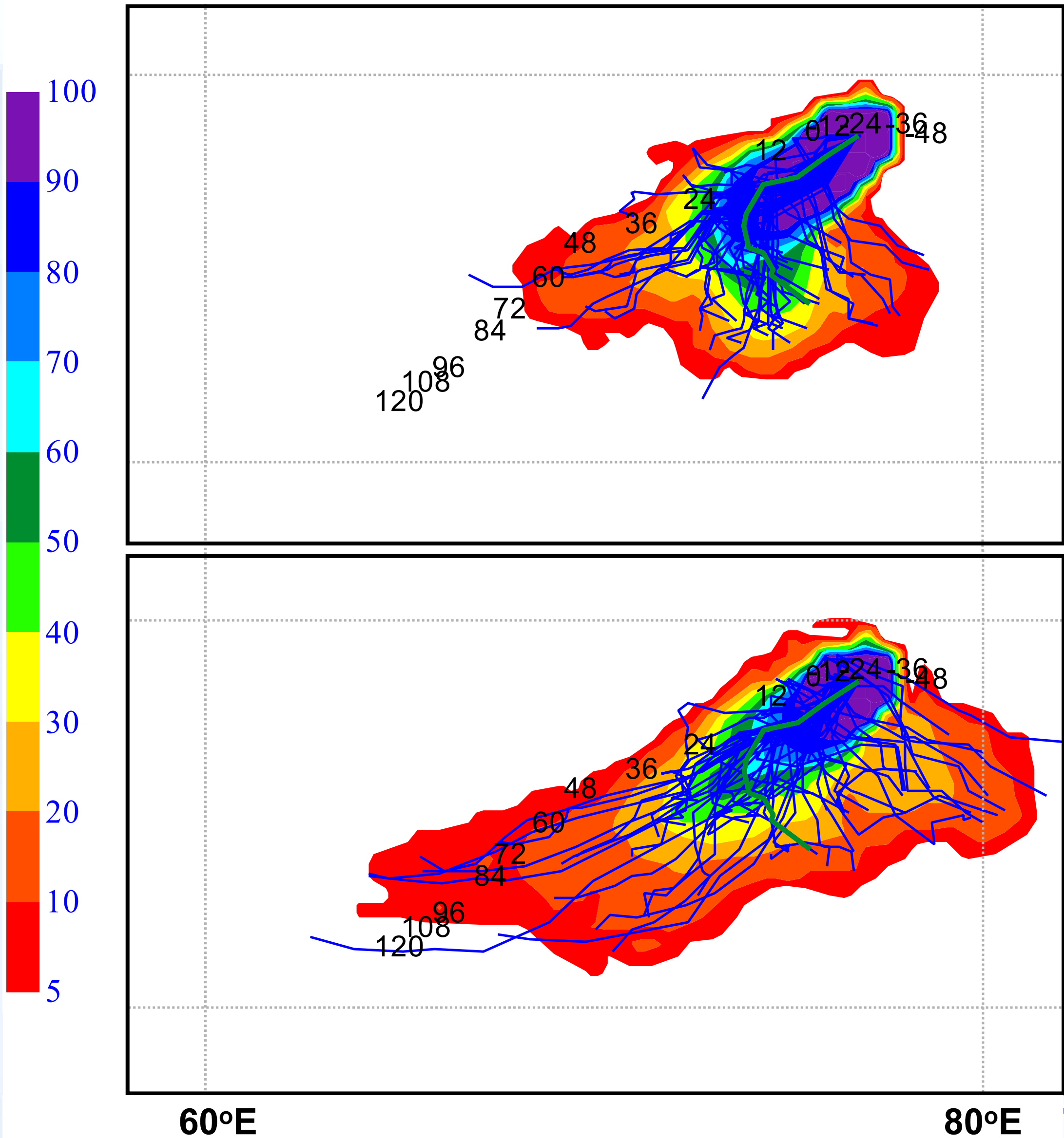
1D-Var vs
European radiosondes
Nov 2002 and Feb 2003

- If T<243K use Vaisala RS90 only
- ~ 250 matches in upper troposphere
- ~ 2300 matches in lower troposphere



Tropical singular vectors *(Leutbecher and Van Der Grijn, 2003)*

Probability that the cyclone KALUNDE will pass within 120 km radius during the next 120 hours



numbers – real position of the cyclone at the certain hour

green line – control T255 forecast (unperturbed member of ensemble)

Tropical SV with adiabsvd

(06/03/2003 12 UTC)

Tropical SV with wsphys

Sensitivity of the parametrization scheme to input variables

- **using the adjoint technique**

- adjoint $\mathbf{F}^T$ of the linear operator $\mathbf{F}$ provides the gradient of an objective function $\mathcal{J}$ with respect to $\mathbf{x}$ *(input variables)* given the gradient of $\mathcal{J}$ with respect to $\mathbf{y}$ *(output variables)*:

$$\frac{\partial \mathcal{J}}{\partial \mathbf{x}} = \mathbf{F}_{\mathbf{x}}^T \frac{\partial \mathcal{J}}{\partial \mathbf{x}} \quad \text{or} \quad \nabla_{\mathbf{x}} \mathcal{J} = \mathbf{F}_{\mathbf{x}}^T \nabla_{\mathbf{y}} \mathcal{J}$$

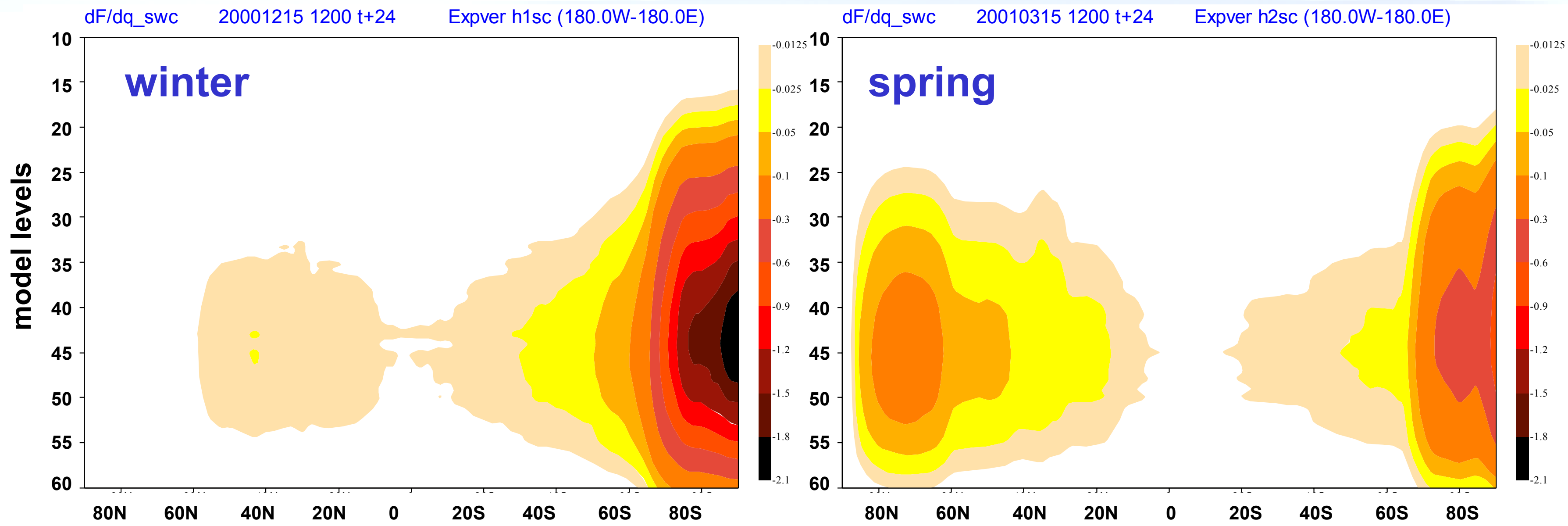
EXAMPLE: sensitivity of radiation scheme - the gradient with respect to **y** of unity size

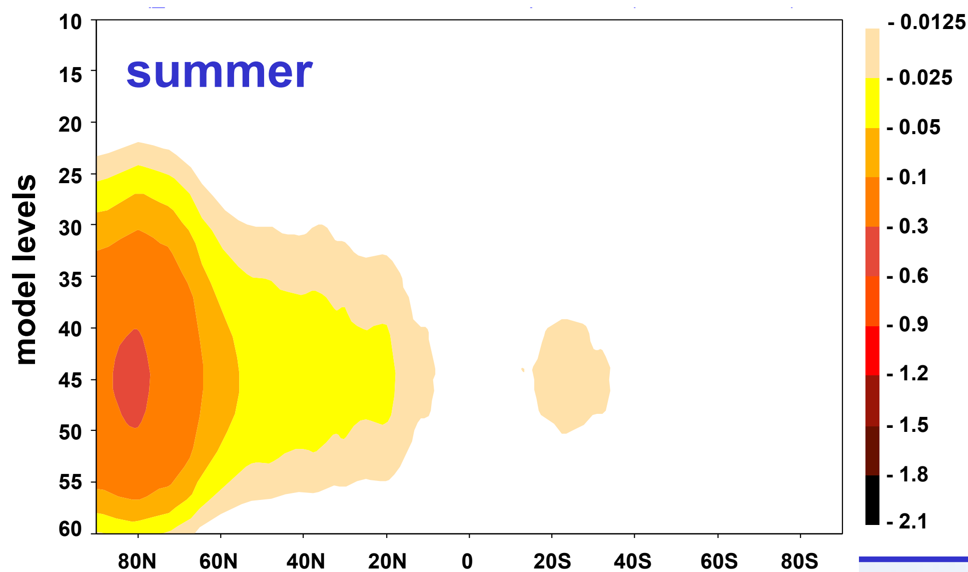
(i.e., perturbation of some of the radiation fluxes with $\pm 1\ W.m^{-2}$)

$$\nabla_{\mathbf{x}} \mathcal{J} = \frac{\partial F}{\partial \mathbf{x}} \begin{cases} \partial F / \partial T & \text{sensitivity to: temperature} \\ \partial F / \partial q & \text{spec.humidity} \\ \partial F / \partial a & \text{cloud cover} \\ \partial F / \partial q_{lw} & \text{cloud lwc} \\ \partial F / \partial q_{iw} & \text{cloud iwc} \end{cases}$$

- **experiments done in the global model:**
  - potential for a thorough evaluation of the relative importance of different variables for parametrization scheme
  - investigation of spatial and temporal patterns of sensitivity variations

Sensitivity of the shortwave upward radiation flux at the TOA with respect to specific humidity [$W.m^{-2}/g.kg^{-1}$] CLEAR SKY





$$\frac{dF}{dq} = 1\,W.m^{-2} / g.kg^{-1}$$

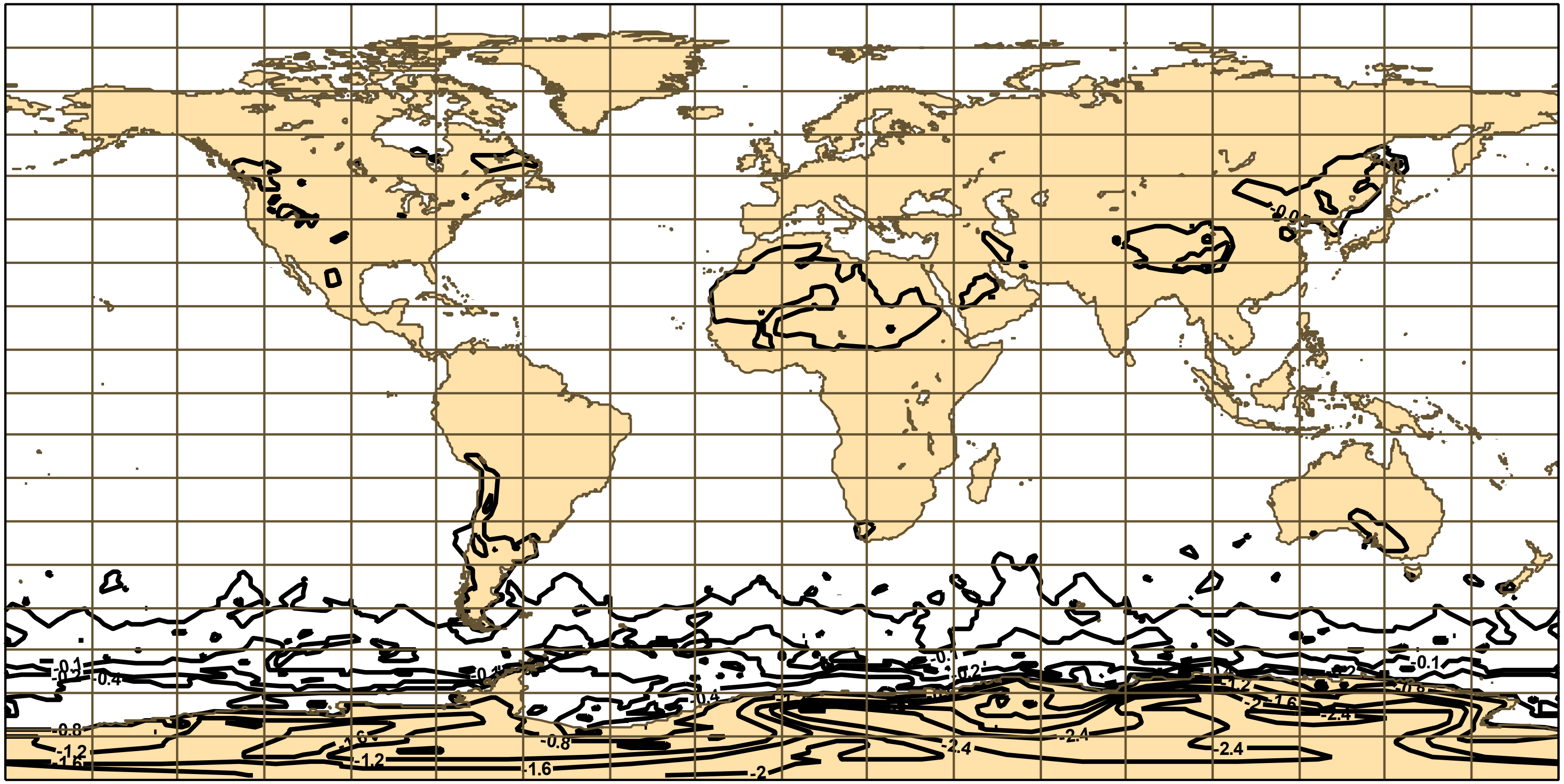
$$dq = 1\,g.kg^{-1} \rightarrow 1\,W.m^{-2}$$

Sensitivity of the shortwave upward radiation flux at the TOA with respect to specific humidity [W.m^{-2}/g.kg^{-1}] CLEAR SKY

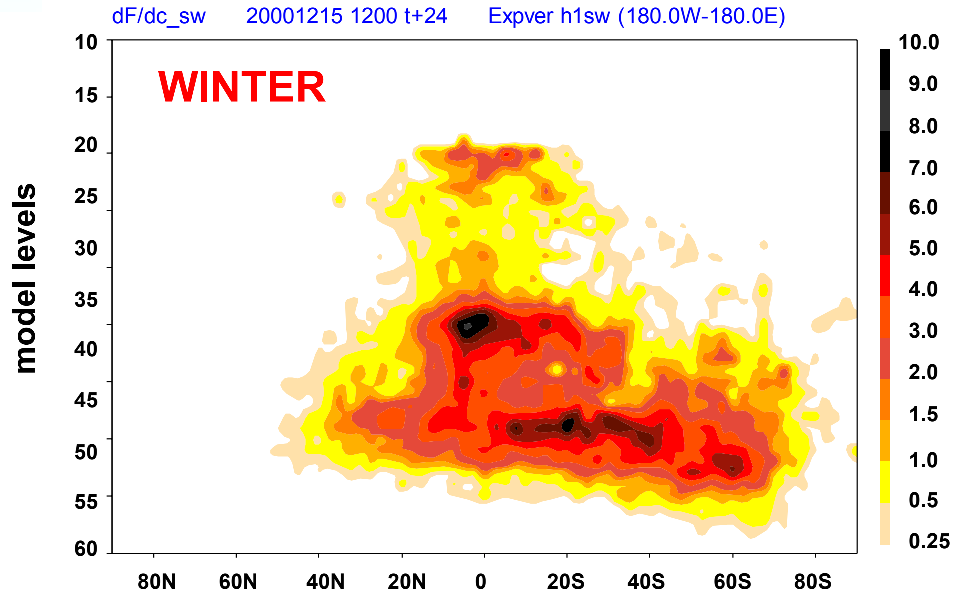
Level 44 ~ 700 hPa

WINTER

dF/dq_swc 15 December 2000 12UTC ECMWF t+24 Level 44



Sensitivity of the shortwave/longwave upward radiation flux at the TOA with respect to cloud fraction [W.m^{-2}/cloudfr]

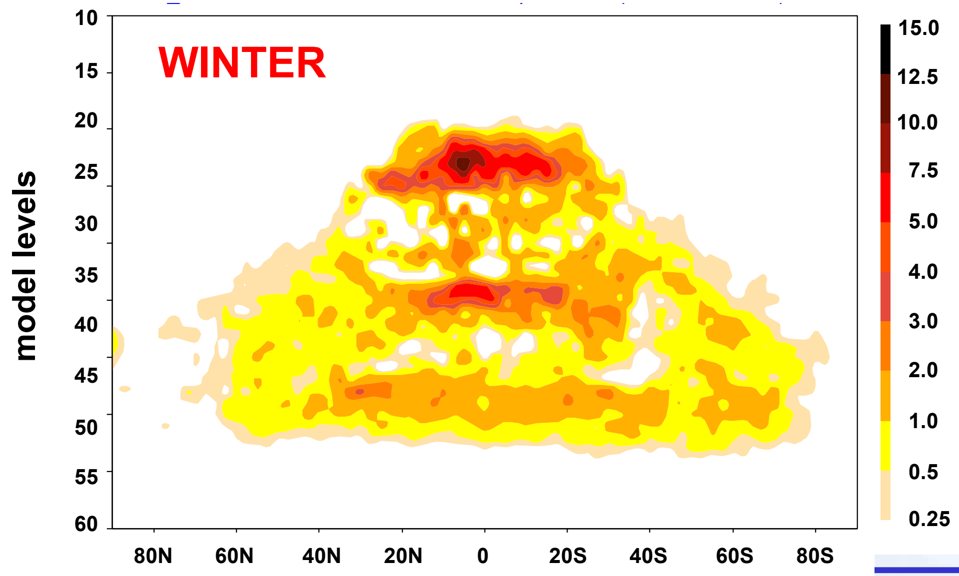


shortwave radiation

$$\frac{dF}{dc} = 5\,W.m^{-2} / cloudfr$$

$$dc = 1 \quad \rightarrow 5\,W.m^{-2}$$

$$dc = 0.2 \rightarrow 1\,W.m^{-2}$$



longwave radiation

Summary

- **Positive impact from including linearized physical parametrization schemes** *(into the assimilating model, singular vector computations used in EPS)* **has been demonstrated in experimental and operational runs.**

- **Adjoint of physical processes can also be used for sensitivity studies and model parameter estimation.**

- **Physical parametrizations become important components in recent variational data assimilation systems.**

- **Some care must be taken when deriving the linearized parametrization schemes** *(regularizations/simplifications)*.

- **This is particularly true for the assimilation of observations related to precipitation, clouds and soil moisture, to which a lot of effort is currently devoted.**

- **One cannot also forget technical difficulties and time-consuming adjoint development** $\rightarrow$ *reliable and efficient automatic tool for adjoint coding would be useful.*


ZERO BENEFIT


ZERO BENEFIT


ZERO BENEFIT


WE ARE
HERE
ZERO BENEFIT


MAXIMUM
POTENTIAL BENEFIT
WE ARE
HERE
ZERO BENEFIT

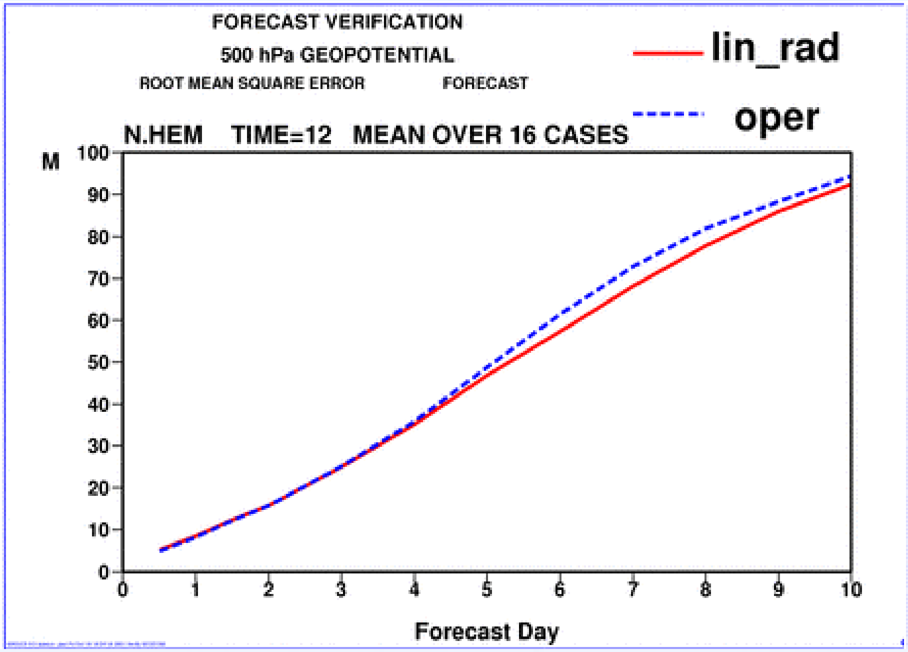
FORECAST VERIFICATION – 500 hPa GEOPOTENTIAL

period: 11/05/2001 – 26/05/2001

(4D- Var experiments with the new linearized radiation: lin_rad)

root mean square error – 16 cases

Northern Hemisphere



North America