Precipitation in NWP

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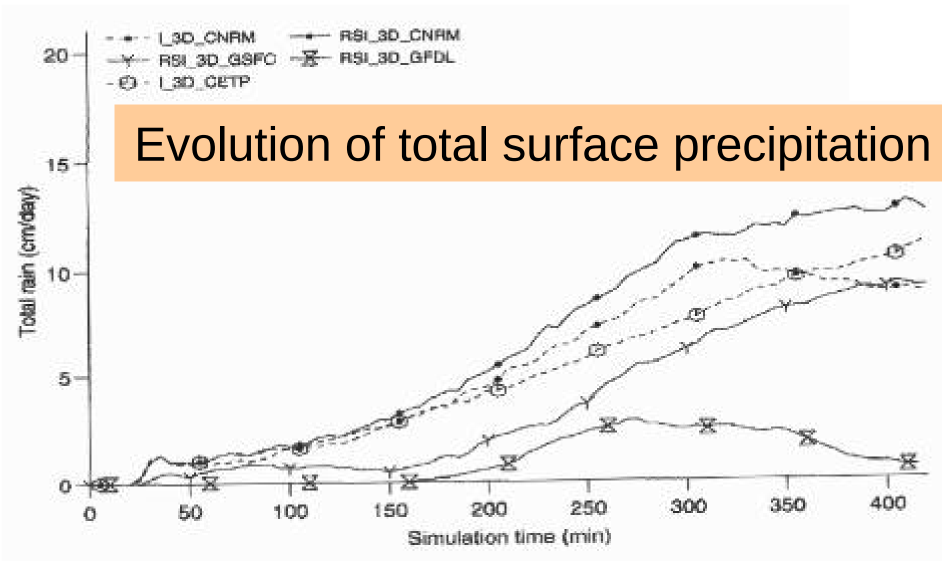
C. Vanbauce

Outline

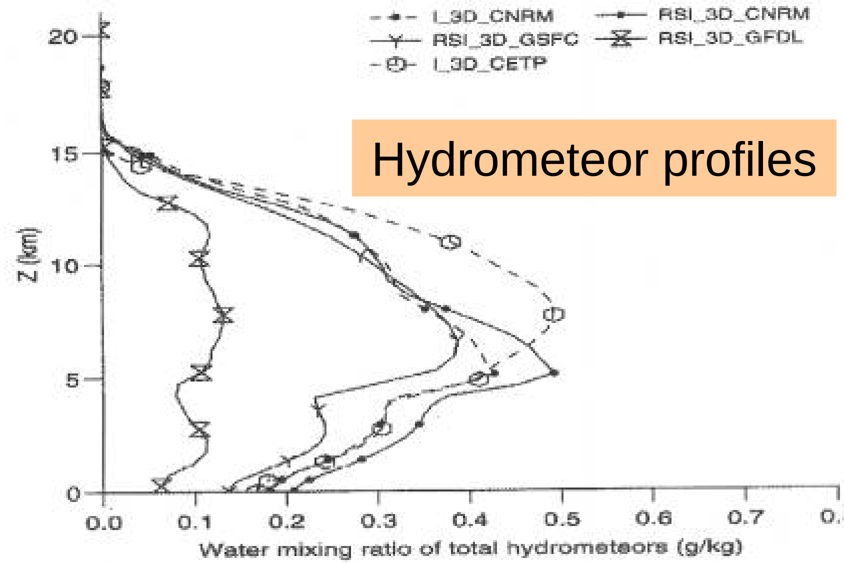
- How do we currently simulate precipitation?
  - Resolved/unresolved scales
  - Partitioning issues in DA
  - Prognostic/diagnostic treatment in FC model?
- How can we validate precipitation forecasts?
- Other important issues (incl. linearization)
- Importance of initialization
- Prognostic/diagnostic treatment in DA?
- How can we estimate model error statistics for DA?
- Time evolution of sensitivities of precipitation
- Summary and questions

Introduction

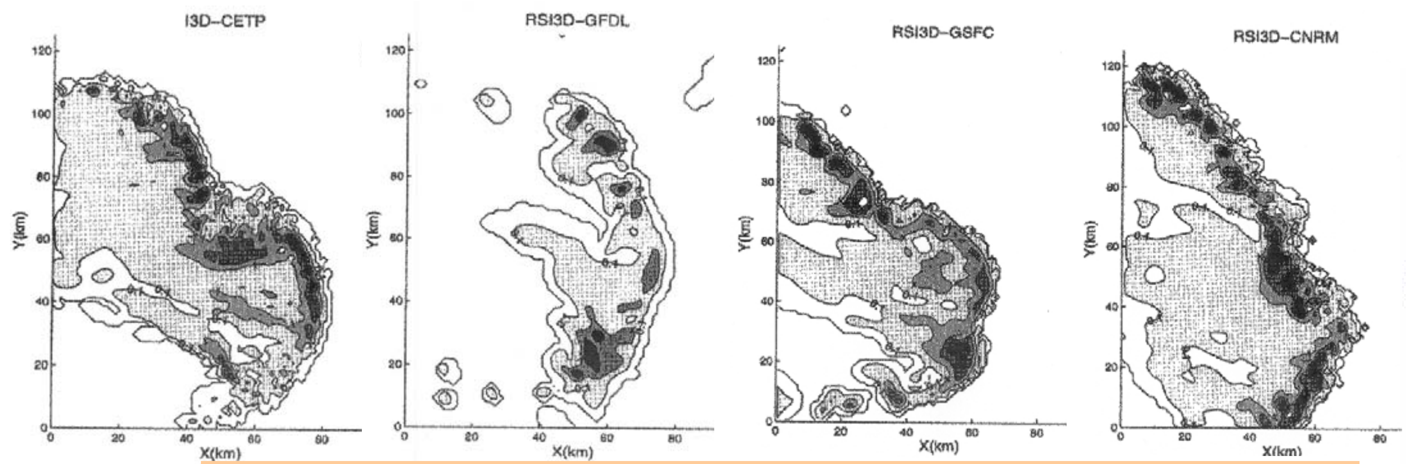
Comparison of forecasts from five CRMs (at ~1.25 km resolution) for a TOGA-COARE squall line (from Redelsperger *et al.* 2000).

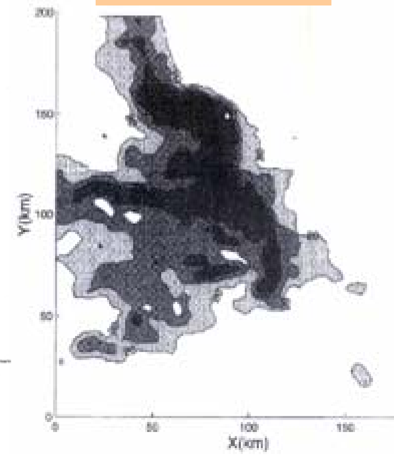


Evolution of total surface precipitation



Hydrometeor profiles





Radar obs

Maps of 6h-simulated total amounts of hydrometeors

Resolved/unresolved precipitation (1)

Subgrid-scale moist processes ('convection'): parameterizations are still far from perfect.

Various formulations: e.g.

- moisture budget:	Kuo (1965; CMC global)
- adjustment:	Betts-Miller-Janjic (1986, 1994; NCEP)
- mass-flux:	Arakawa-Schubert (1974; NCEP)
	Bougeault (1985; Météo-France)
	Kain-Fritsch (1990; CMC LAM, HIRLAM, MM5)
	Gregory and Rowntree (1991; Met. Office)
	Tiedtke (1993; BMRC, ECMWF)
	Donner (1993; GFDL)
	Bechtold *et al.* (2001; Méso-NH)

Various assumptions for:

- triggering of convection (deep, mid-level, shallow),
- bulk description of updraft properties,
- mixing between convective updrafts and environment,
- fraction of grid box covered by convective clouds/updrafts,
- closure assumption of the scheme (moisture convergence, CAPE),
- microphysics (incl. processes involving precipitation).

Resolved/unresolved precipitation (2)

Large-scale moist processes (resolved):

Various parameterizations:

e.g.: Sundqvist (1988; HIRLAM)
Smith (1990; Met. Office)
Tiedtke (1993; ECMWF)
Fowler et al. (1996; CSU)
Rotstayn (1997; BMRC)
Zhao-Carr (1997; NCEP Global)
Rasch-Kristjánsson (1998; HIRLAM)
Wilson and Ballard (1999; Met. Office)
Lopez (2002; under testing at Météo-France)

Various assumptions for:

- fraction of grid box with precipitation (different from cloud fraction),
- vertical overlap assumption (for evaporation and radiation, e.g. Jakob 2000),
- microphysics (precipitation processes: autoconversion, nucleation, collection, evaporation, melting,…).

Resolved/unresolved precipitation (3)

1) The partitioning between model's subgrid-scale and resolved precipitation depends on horizontal resolution.

2) In their 1D-Var rainfall assimilation experiments, Fillion and Mahfouf (2000) found that in saturated conditions the large-scale condensation scheme was more likely to become active during the minimization than any of the three convection schemes they tested, regardless of precipitation nature (due to stronger Jacobians).

→ How can we impose more constraint on this partitioning during the minimization?

e.g. assimilation of rain type from observations (Aonashi *et al.* 2004)?
or turn off the large-scale condensation scheme when convection expected?

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or turn off the large-scale condensation scheme when convection expected?

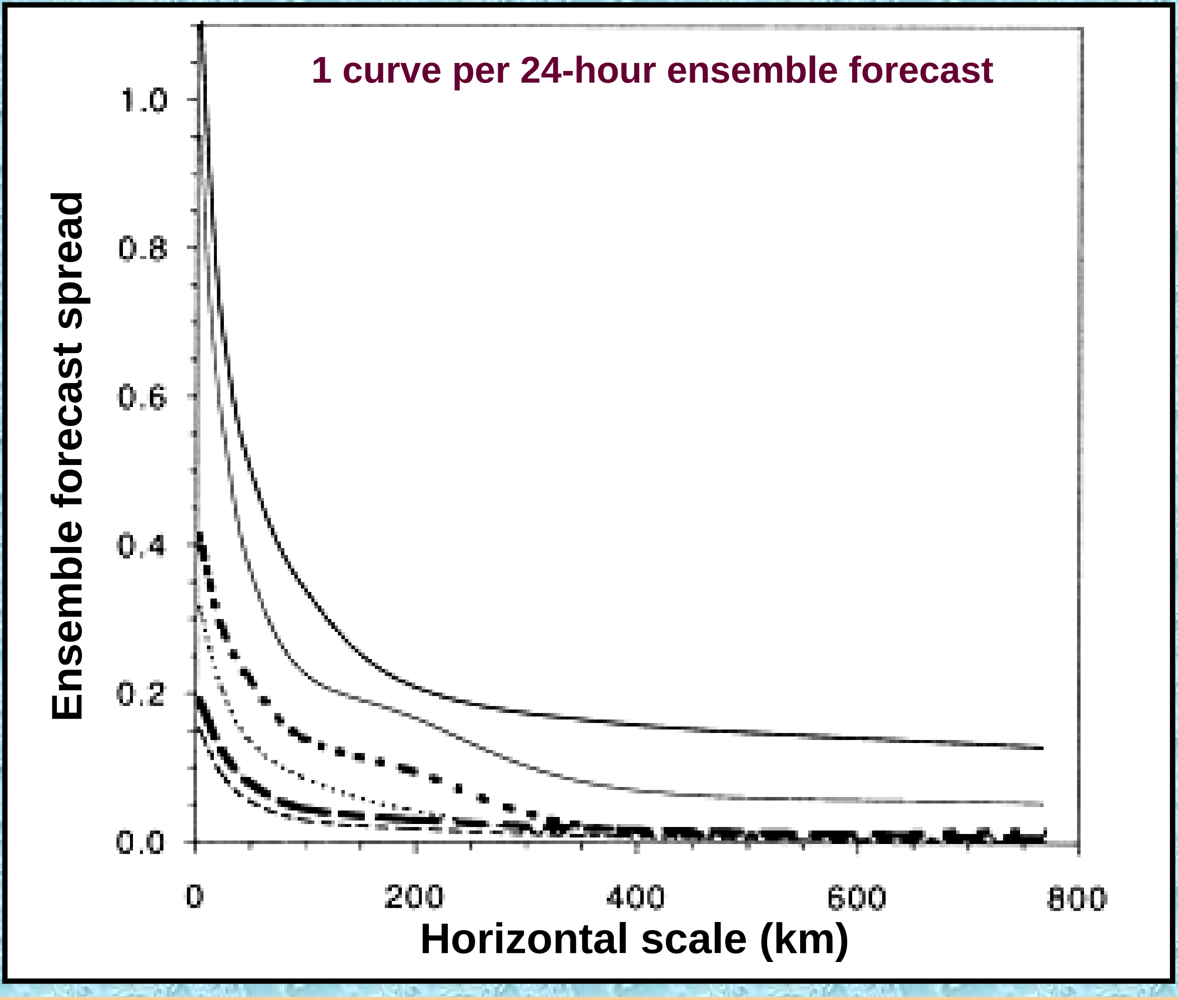
3) Increasing model resolution is certainly not the key to perfect simulations of precipitation, especially in cases of unorganized convection.

→ A statistical approach might be more suitable to address the problem of assimilation of precipitation at mesoscale (smoother assimilation).

e.g. take into account statistical information about spatial variability available from ground-based or space-borne radars.

Predictability issue for various horizontal scales

Results from ensemble runs with the MC2 model (3 km resolution) over the Alps, from Walser et al. (2004).



→ Predictability of precipitation decreases dramatically for horizontal scales smaller than a few tens of kilometers.

How must hydrometeors be treated in forecast models?

In the nonlinear forward model:

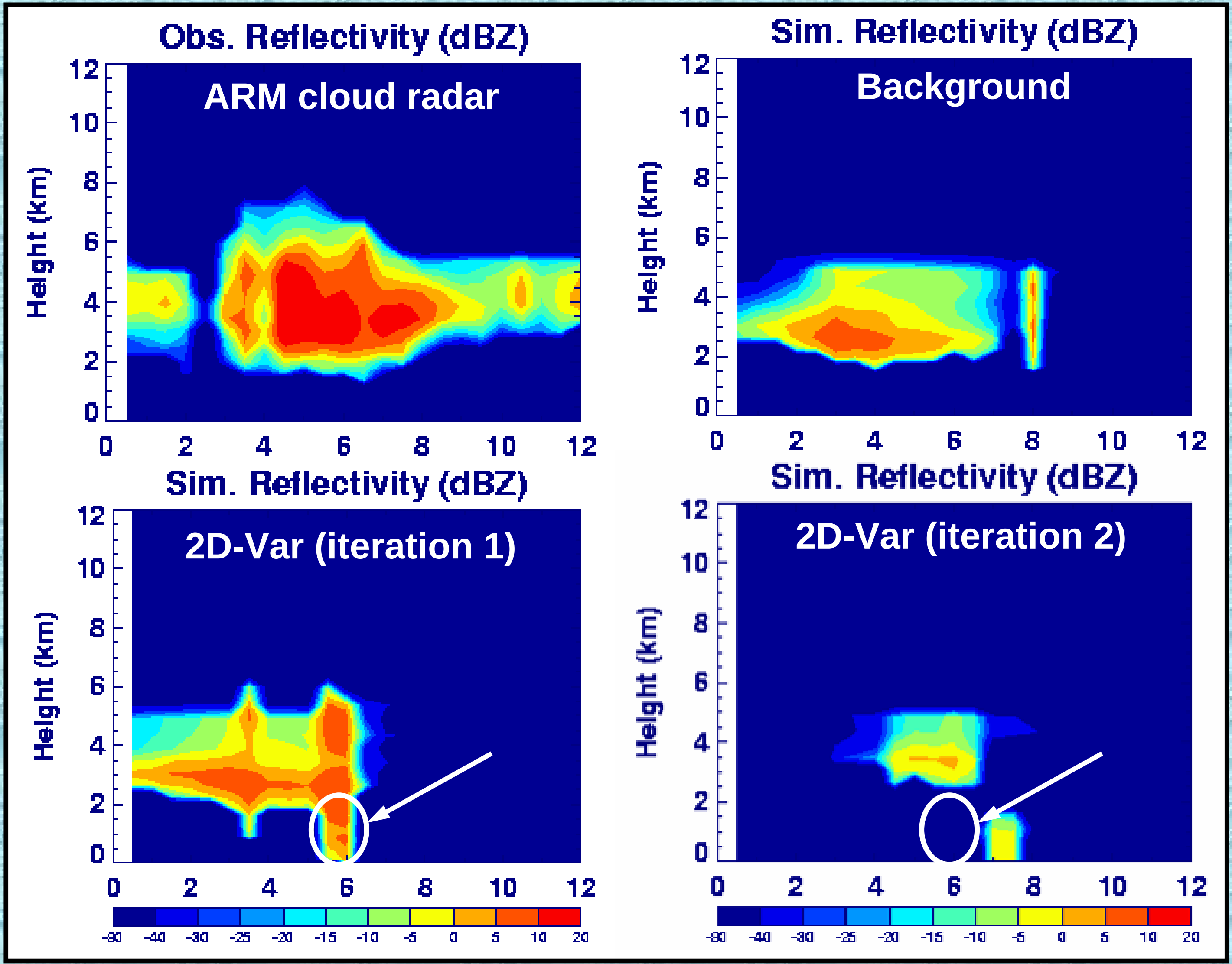
- Is it really necessary to include prognostic variables for precipitation in the nonlinear forward model for the purpose of data assimilation?
- Which prognostic variables should be considered?

  - amounts of particles for different categories (rain, snow, drizzle, graupel, hail)?
  - statistical moments of the PDF of bulk contents (mean, variance)?
  - particle size distributions?

- How detailed must the description of microphysical processes be?
- It is important to assume consistent hydrometeor size distributions in all radiative and microphysical calculations (incl. SW, LW, MW TBs and reflectivities).

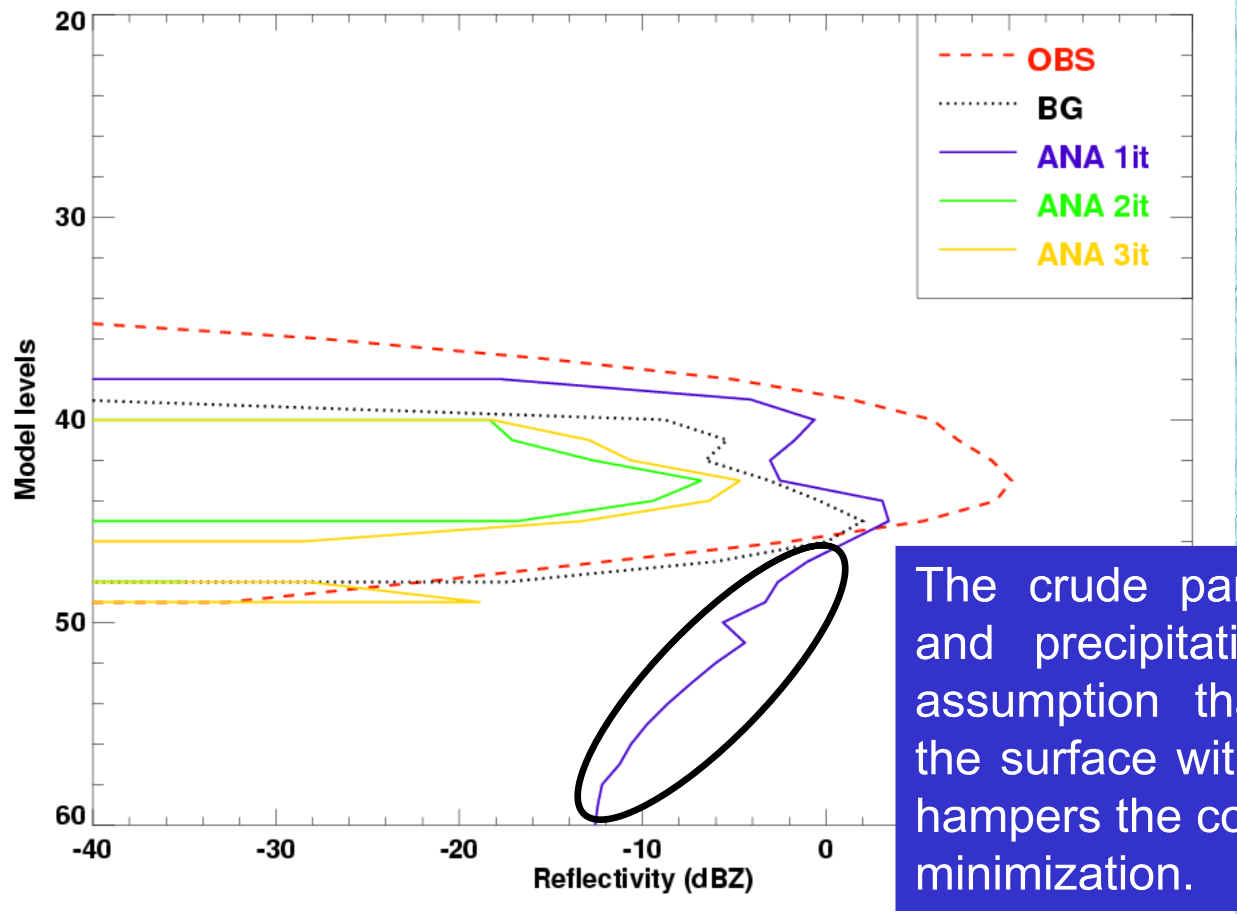
Diagnostic or prognostic treatment of precipitation? (1)

2D-Var assimilation of ARM Cloud Radar Reflectivities (12h-averaged profile)
Time evolution of reflectivity profiles from radar and single column model
(4 February 2001 00 UTC → 12 UTC).



Diagnostic or prognostic treatment of precipitation? (2)

2D-Var assimilation of ARM Cloud Radar Reflectivities: 12h-averaged profile from radar, model background and 2D-Var (4 February 2001 00 UTC → 12 UTC).



The crude partitioning between cloud and precipitation and the unrealistic assumption that precipitation reaches the surface within one time step (900s) hampers the convergence of the 2D-Var minimization.

The assimilation of vertical profiles of precipitation or reflectivity observations requires an accurate description of hydrometeor types and of their fall velocity in the forward nonlinear model.

How can we validate precipitation forecasts?

Available validation data sources include:

- Rain-gauge networks.

- Ground-based precipitation radar networks (US, Europe).

- Satellite microwave instruments
  (e.g. SSM/I, SSMI-S, TMI, TRMM-PR, Aqua):

  - Rainfall rates retrievals from microwave multi-channel measurements,

  - Microwave brightness temperatures (using a microwave radiative transfer model that includes scattering by precipitation),

  - Reflectivities from space-borne precipitation radar (using a reflectivity model).

- Lightning flash rates from satellites (TRMM-LIS, OTD):

  → indirect verification of convective precipitation occurrence, but mainly applicable over seasonal or longer timescales (sampling issue).

How can we validate precipitation forecasts?

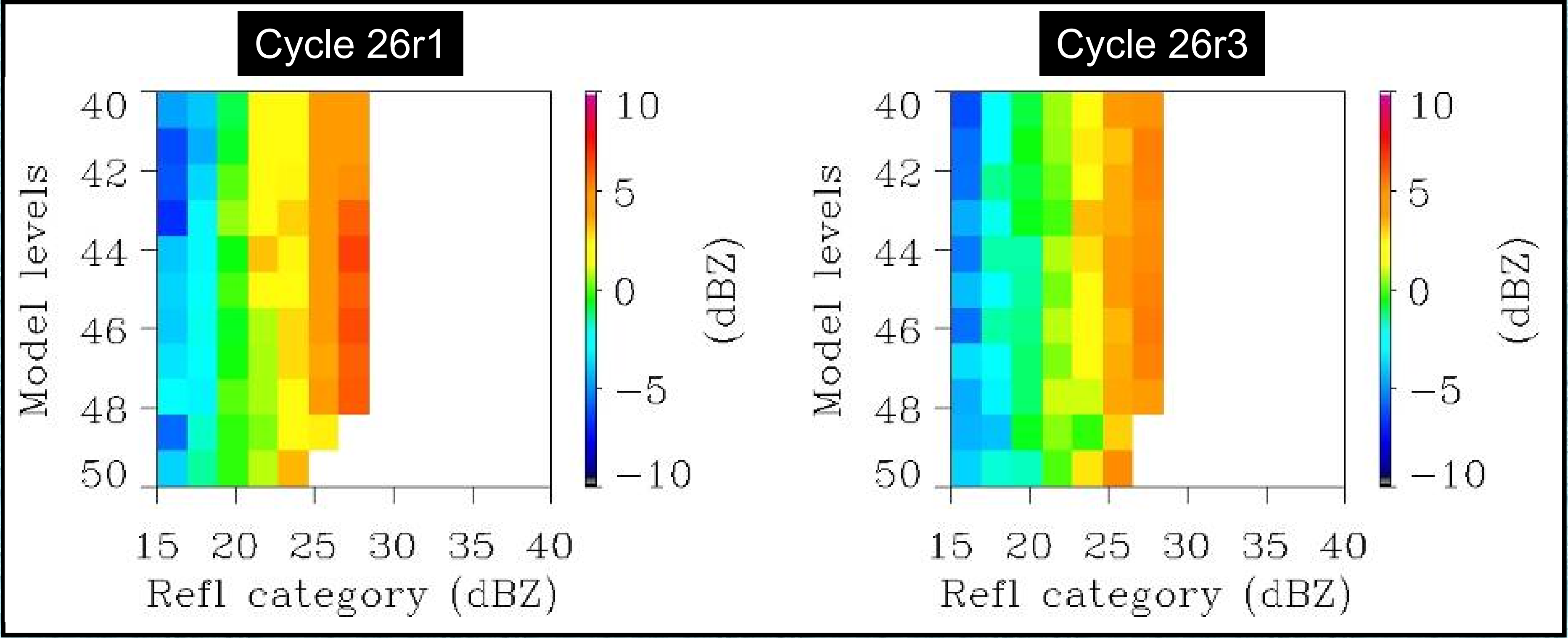
Some limitations:

- Satellite microwave instruments only provide instantaneous precipitation (unless some persistence is assumed or other pieces of information such as infrared geostationary imagery is added).
- Issue of spatial representativeness, especially when comparing model to rain-gauges.
- Complex geometry involved in radar measurements.
- How accurate are all these measurements?

Validation against TRMM Precipitation Radar

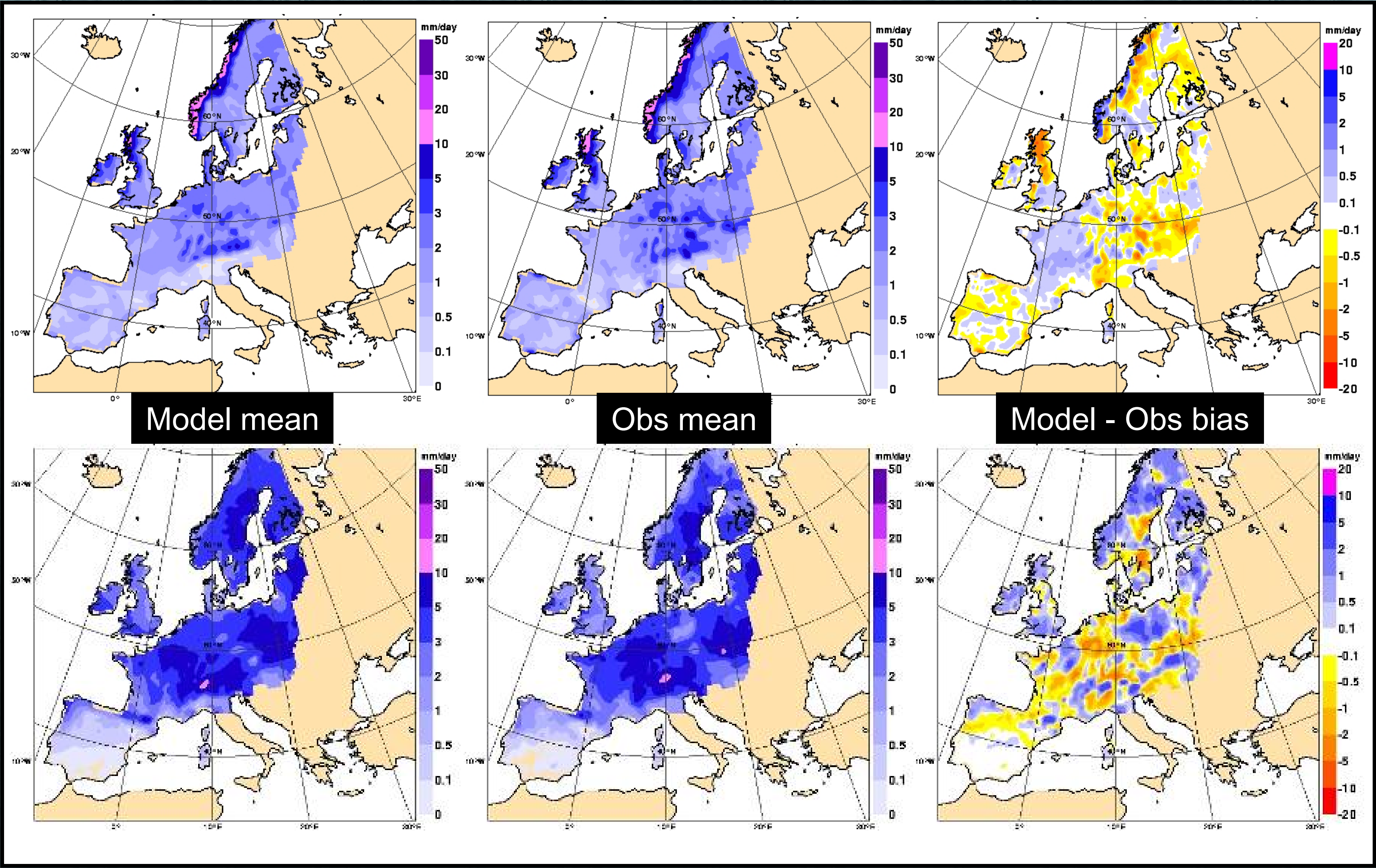
Distributions of reflectivity departures between TRMM-PR and ECMWF model (T511 L60) for 23 tropical cyclone cases (from A. Benedetti).

→ used here as a diagnostic tool for validating some changes in the convective parameterization.



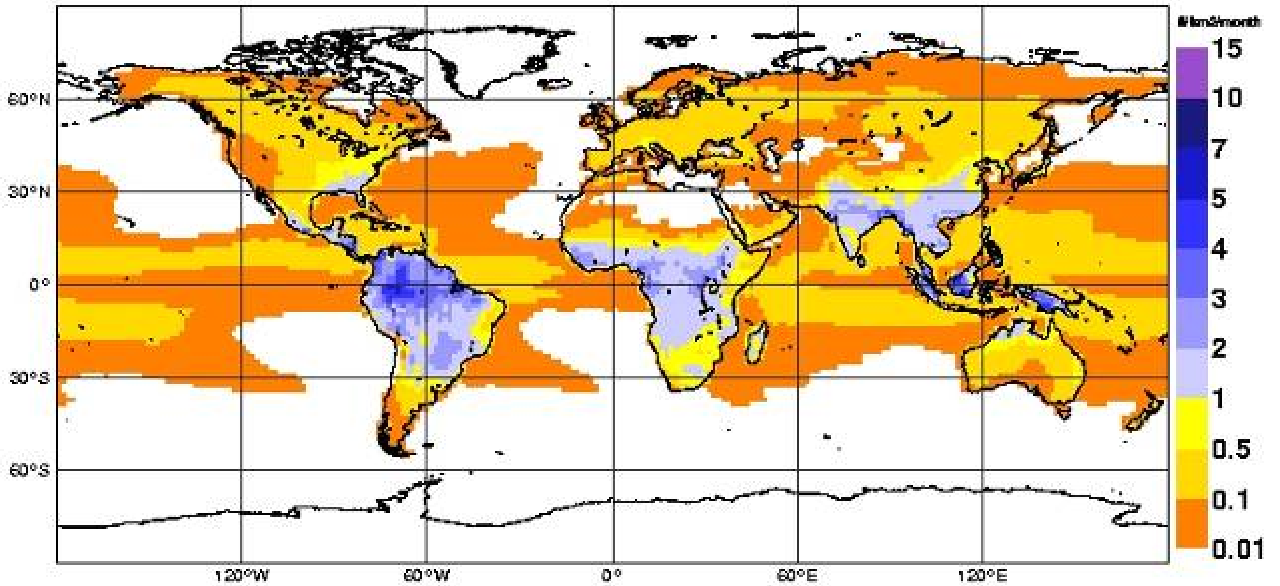
Validation against rain-gauge measurements (ELDAS)

Comparison of +6→+30h simulated precipitation with ELDAS rain-gauge gridded observations (0.2°): ECMWF T511L60 run over January (top) and July (bottom) 2000.



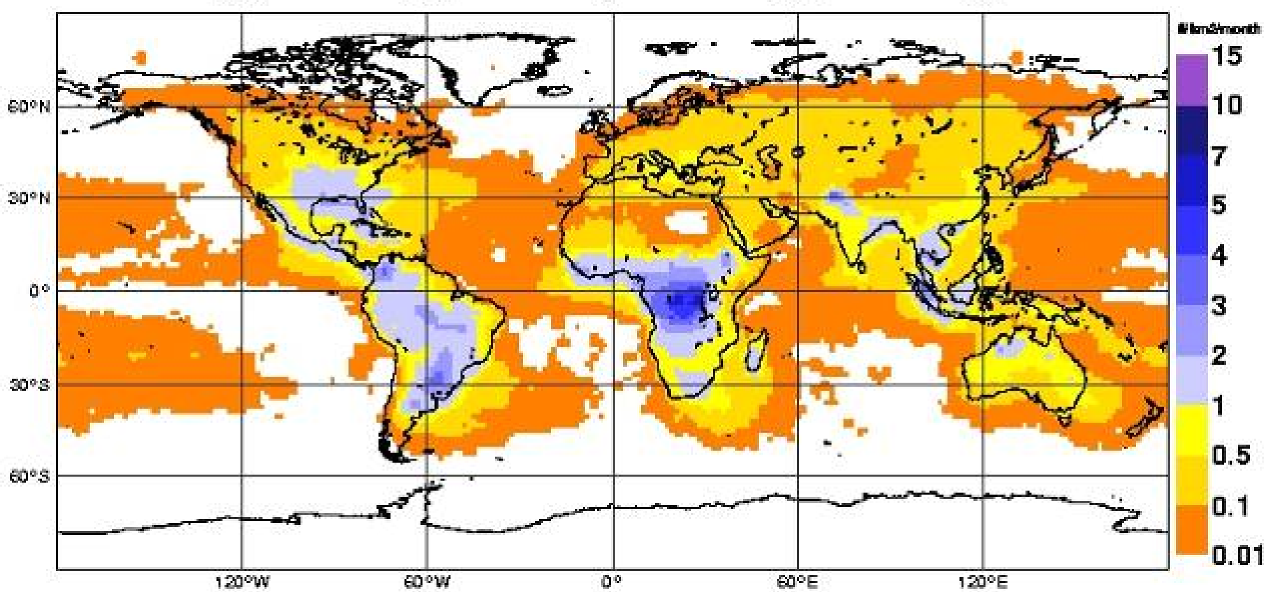
Tentative comparison of lightning flash rates from model and from LIS/OTD climatology → indirect validation of convective activity?

Model flash rates determined with a simple parameterization $f(w_u, M_{ice}, D_{cold})$



flashes/km^2/month

Mean of two 1-year ECMWF model runs T95 L60



5-year LIS/OTD climatology (Christian *et al.*, 2003)

Other important issues

- Simulation of precipitation over mountainous terrain is still problematic as a result of subgrid-scale orography.
- Imbalances present in models' initial conditions can lead to spin-up/spin-down problems.
  Can we expect DA in precipitation areas to improve on those?
- In limited area models, issue of boundary conditions.

Other important issues

- Simulation of precipitation over mountainous terrain is still problematic as a result of subgrid-scale orography.

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- In limited area models, issue of boundary conditions.

Linearization issues in DA:

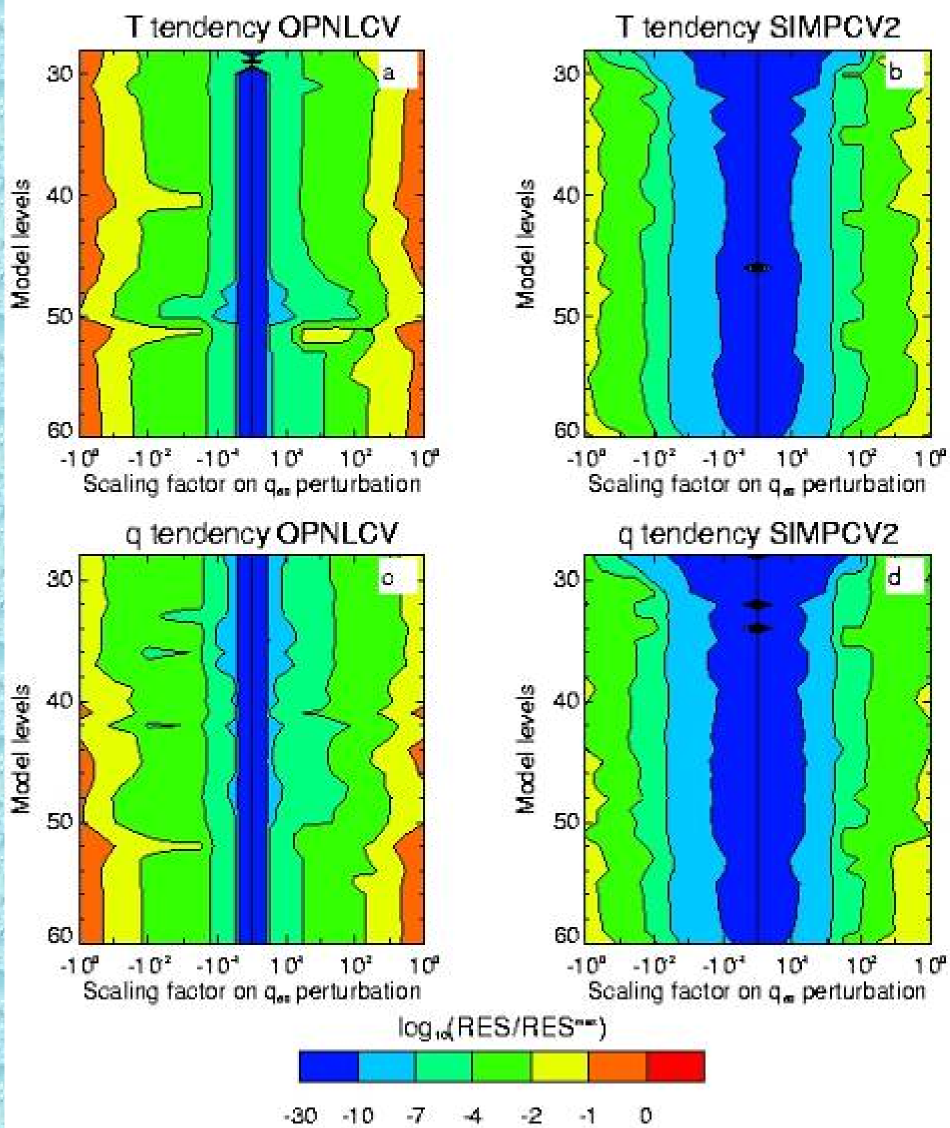
- Parameterizations of moist physical processes need to be simplified, linearized and regularized before being use in TL and AD calculations.

- However, they should also remain close enough to the nonlinear parameterizations used in the trajectory.

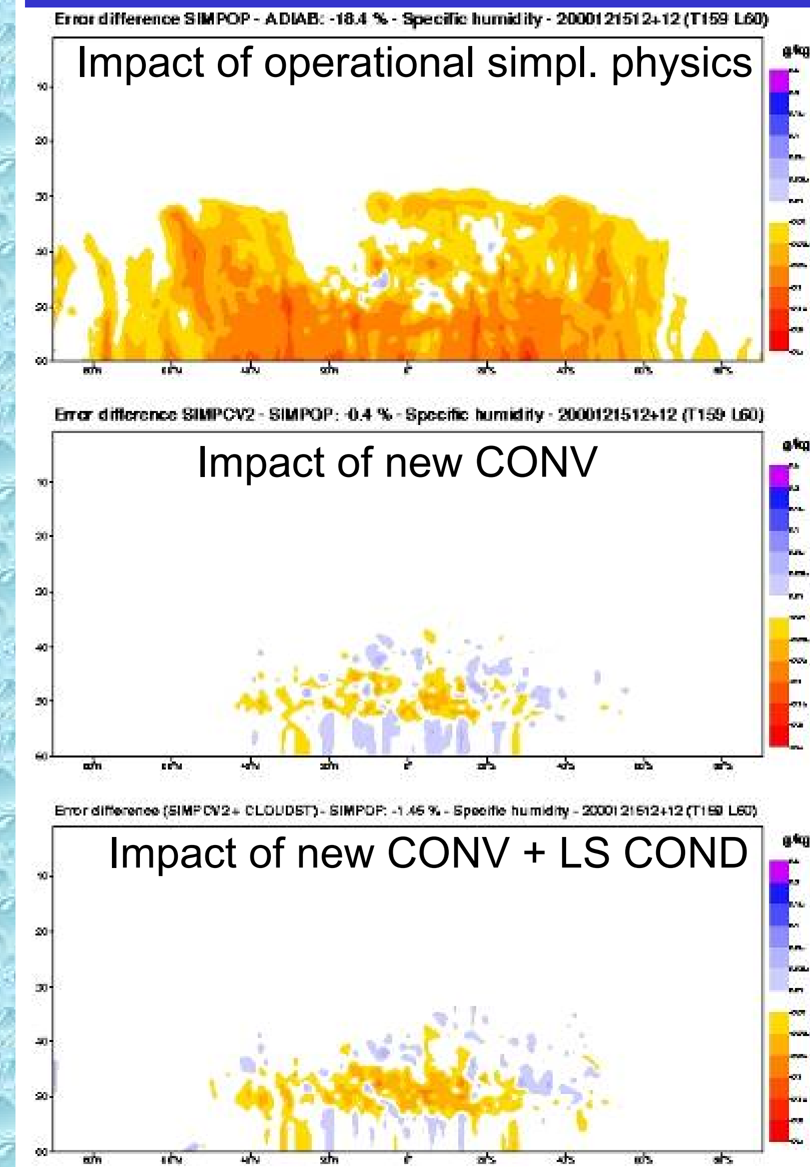
- Difficult and yet necessary to find a compromise between linearity and realism.

Linearization issues

Nonlinear residuals from two convection schemes:
left: Tiedtke (1989),
right: Lopez and Moreau (2005).

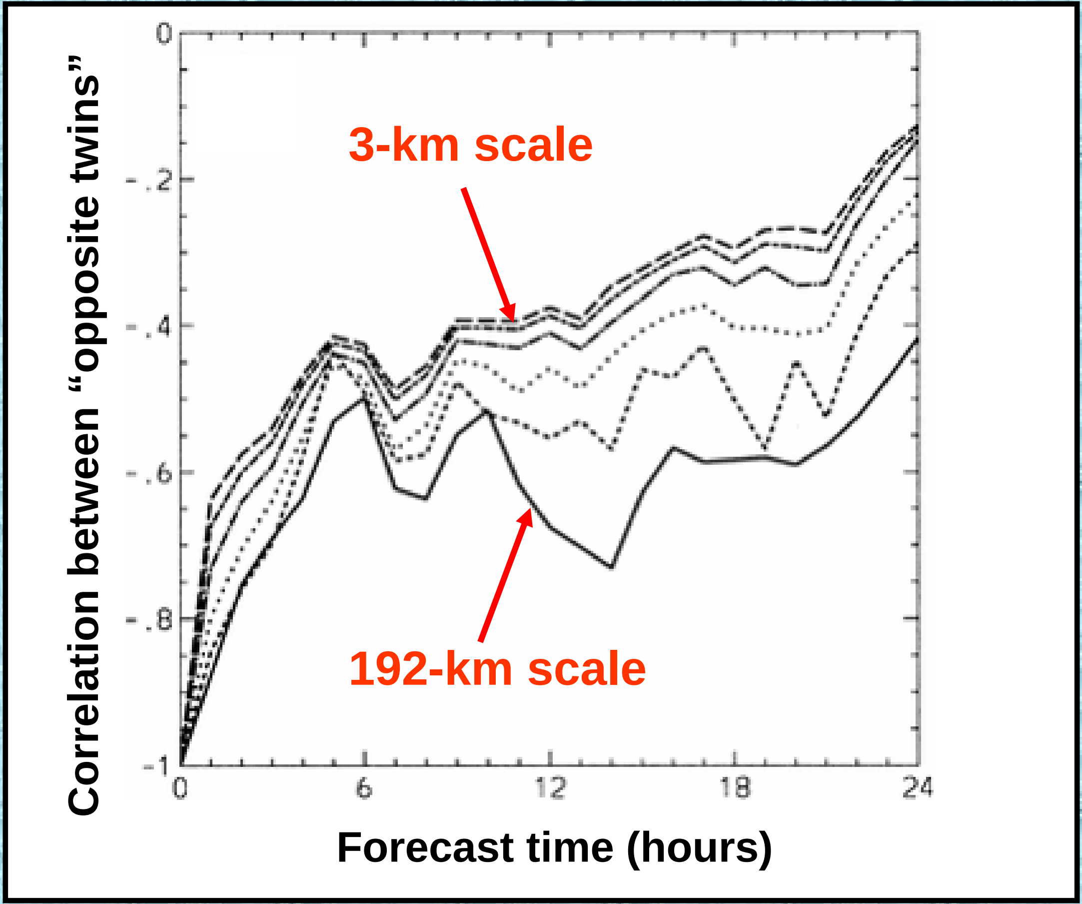


Relative change in linearity error on q due to simplified physics vs adiabatic TL run (ECMWF model, T159 L60).



Linearity issue for various time and horizontal scales

Results from ensemble runs with the MC2 model (3 km resolution) over the Alps, from Walser et al. (2004).



→ The validity of the linear assumption for precipitation quickly drops in the first hours of the forecast, especially for smaller scales.

Importance of initialization

Mesoscale initialization (Ducrocq *et al.* 2000)

guess = very short range forecast
from ALADIN or ARPEGE analysis

<u>Mesoscale analysis of mesonet surface observations</u>
(DIAGPACK/ALADIN OI scheme)

⇒ meso-β description of the low levels (cold pool, convergence line, low-level moisture flow,…)

Domains 1 & 2

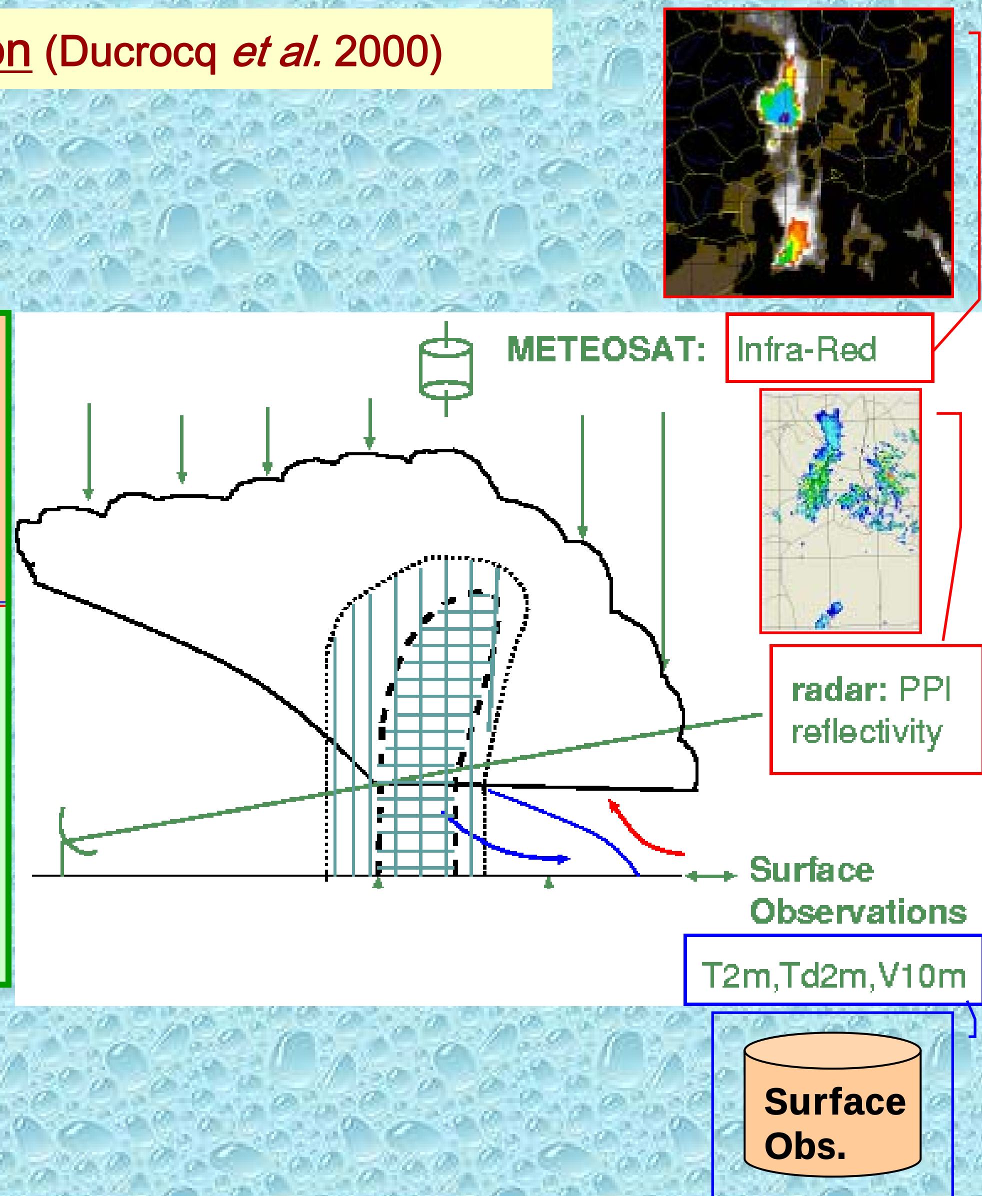
<u>Moisture and hydrometeors adjustment</u> based on the identification of cloudy and rainy areas from radar reflectivities and IR METEOSAT brightness temperatures.

⇒ introduce at meso-γ scale the convective system in development.

Domain 2

Modified initial state

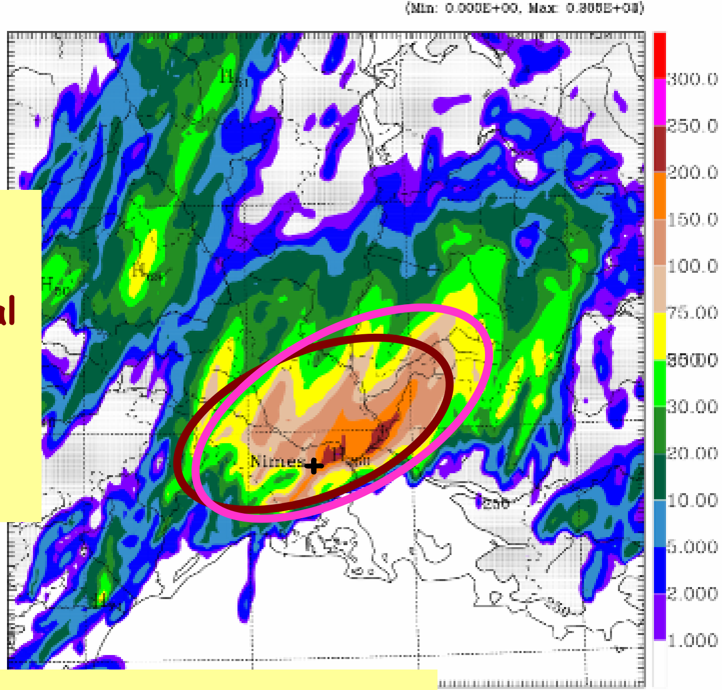
MESO-NH simulation



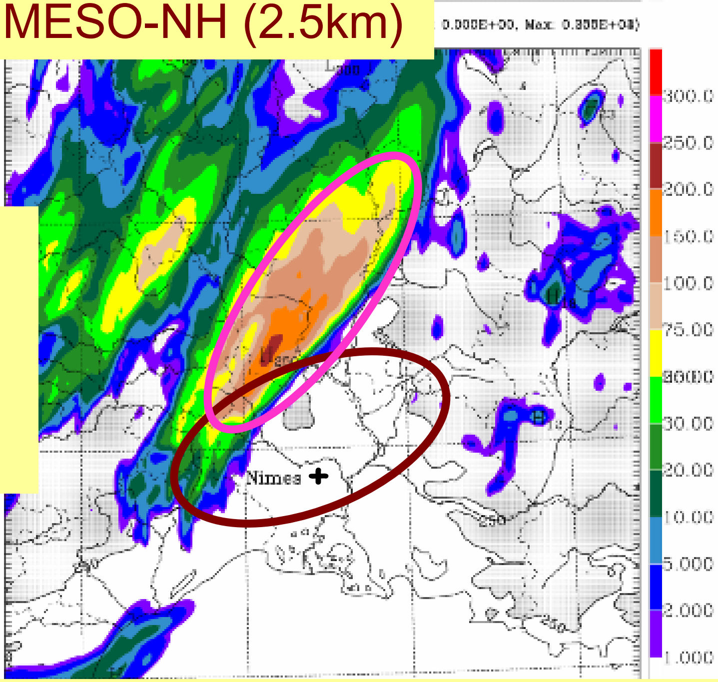
Impor

Gard flash-flood (8-9 Sept.2002)

Initial Conditions
Ducrocq et al (2000) Initialisation
12UTC 08/09/02

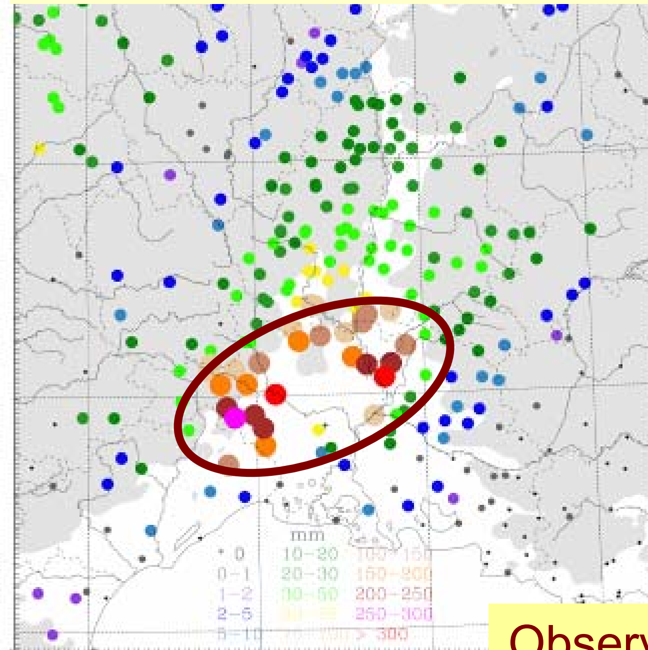


MESO-NH (2.5km)

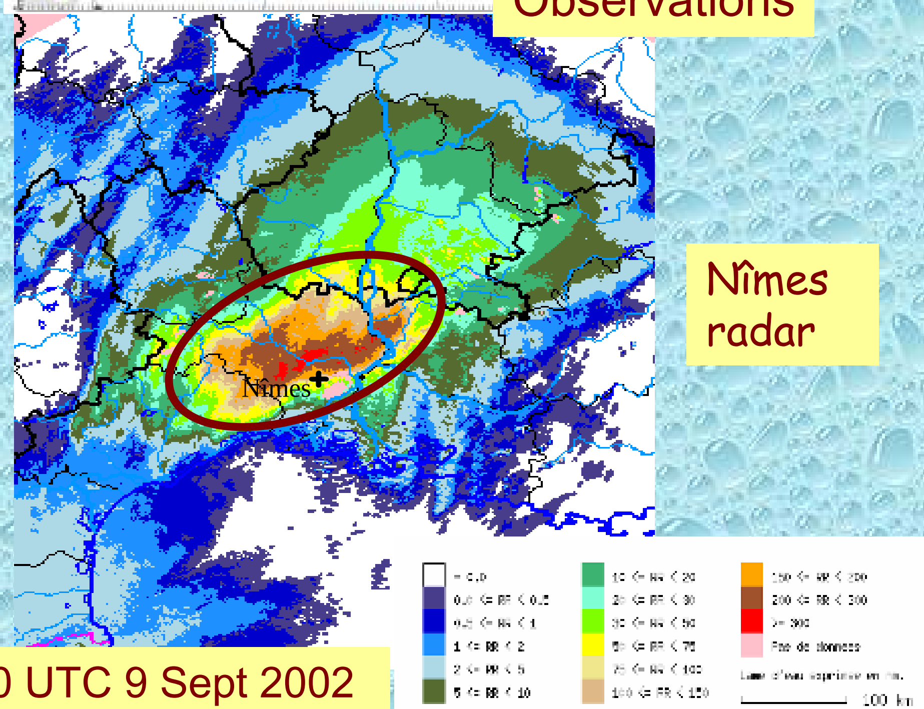


Initial Conditions :
ARPEGE analysis
12UTC 08/09/02

Raingauges



Observations



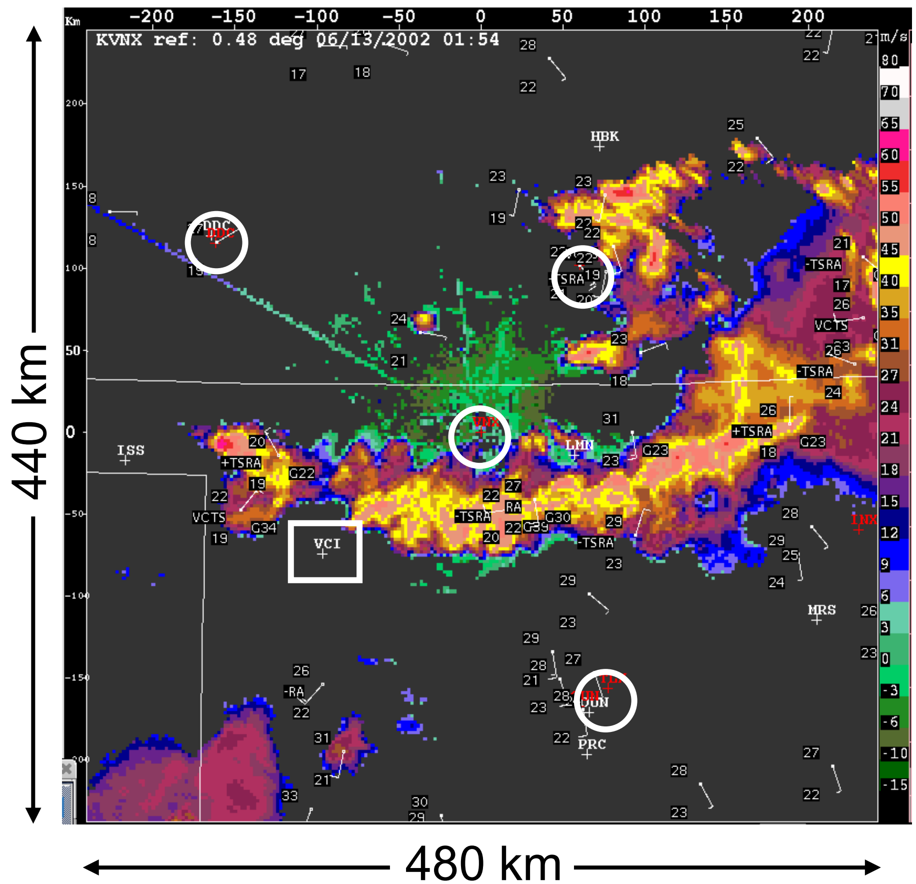
Nîmes radar

12h accumulated precipitation: 12 UTC 8 Sept → 00 UTC 9 Sept 2002

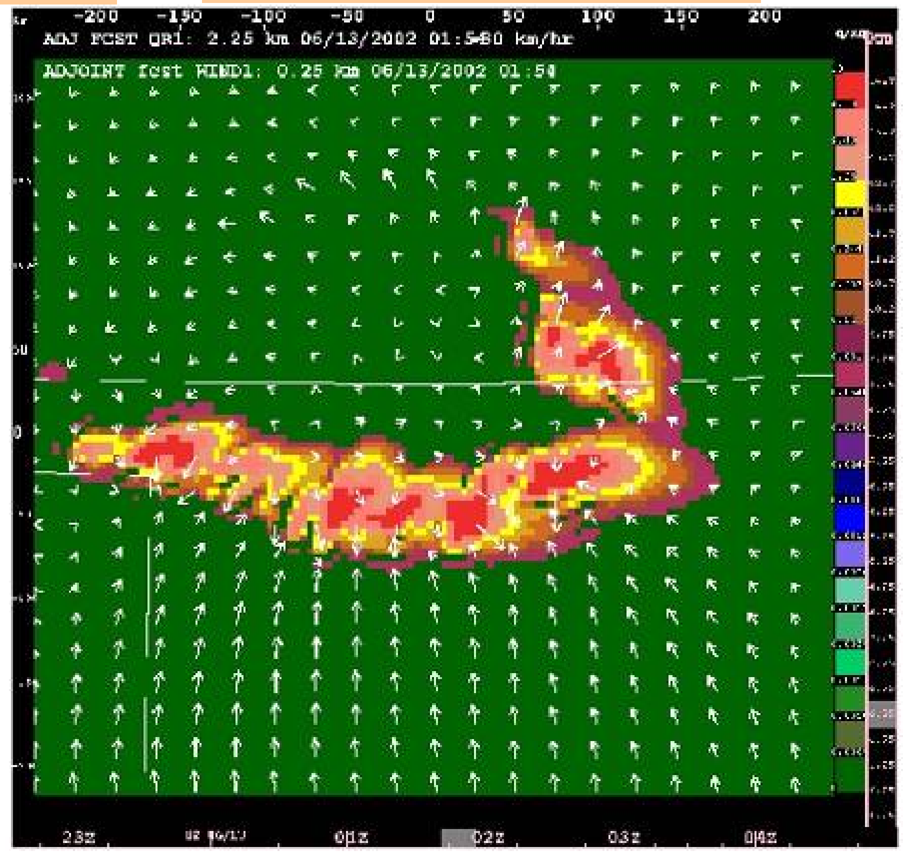
4D-Var assimilation of Doppler-radar radial velocities and reflectivities with VDRAS for a squall line case over Oklahoma (courtesy of Sun *et al.* 2005):

- 4-km resolution,
- Kessler-type warm microphysics and diffusion in AD,
- Three 12-mn 4D-Var assimilation cycles prior to 3h forecast,
- 4 NEXRAD radars (O), 30 METAR surface stations, 1 radio-sounding (☐).

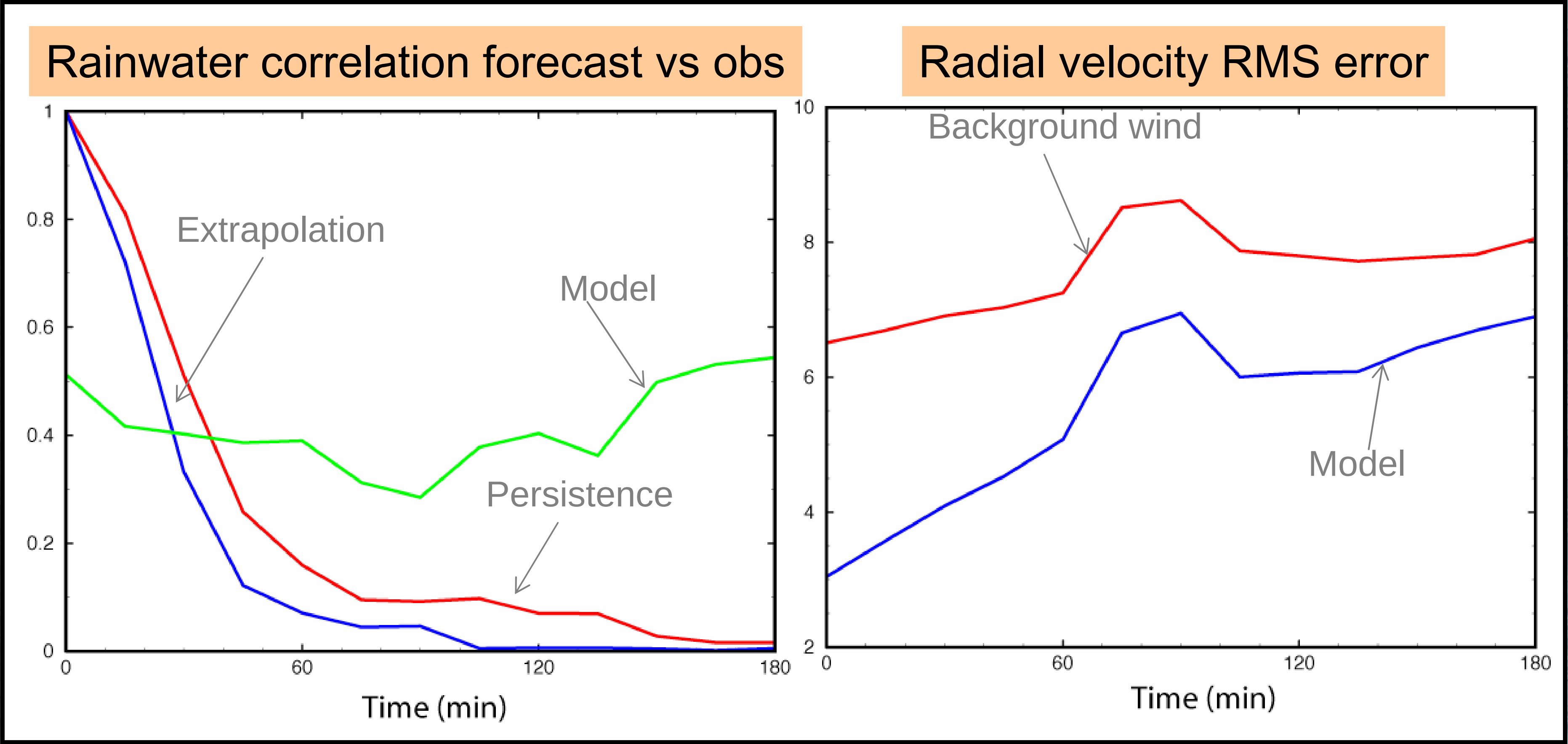
Radar observations (13 June 2002 01:54 UTC)



3h Forecast (same time)



4D-Var assimilation of Doppler-radar radial velocities and reflectivities with VDRAS for a squall line case over Oklahoma (courtesy of Sun *et al.* 2005):



- The rain forecast from the model started from 4D-Var analysis becomes better than both extrapolation and persistence after 40 mn.
- Best results are obtained when assimilating both reflectivities and radial velocities.
- They find it is crucial to initialize T, u, v and q_v, but not necessarily q_c and q_p.

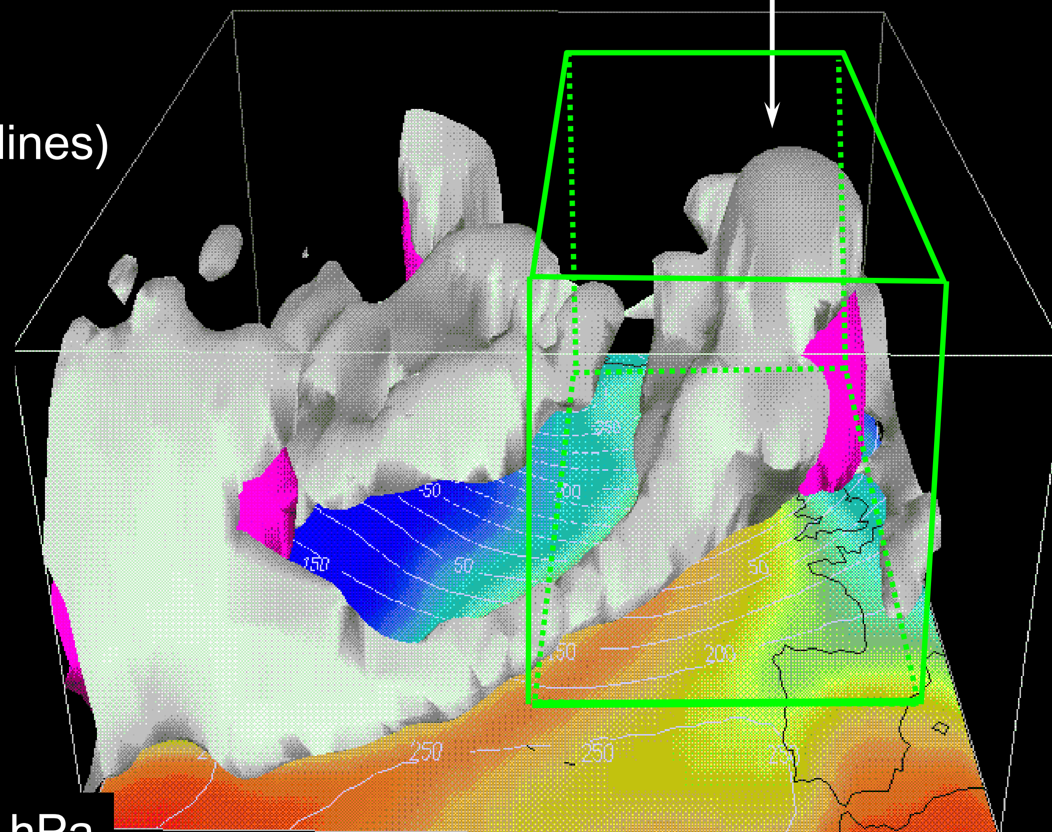
Hydrometeors as control variables in data assimilation?

In Data Assimilation:

- Is it really necessary to include control variables for precipitation in the DA system?
- Which control variables should be considered?
  - amounts of particles for different categories (rain, snow, drizzle, graupel, hail,…)?
  - statistical moments of the PDF of bulk contents (mean, variance)?
  - particle size distributions?
- How detailed must the description of microphysical processes be?

Sensitivity experiment including prognostic variables for large-scale clouds and precipitation in adjoint (T95 L31).

12h ARPEGE forecast valid at 1200 UTC 17 February 1997:
Cloud condensate (grey)
Precipitation (purple)
1000 hPa temperature (rainbow)
1000 hPa geopotential (white isolines)

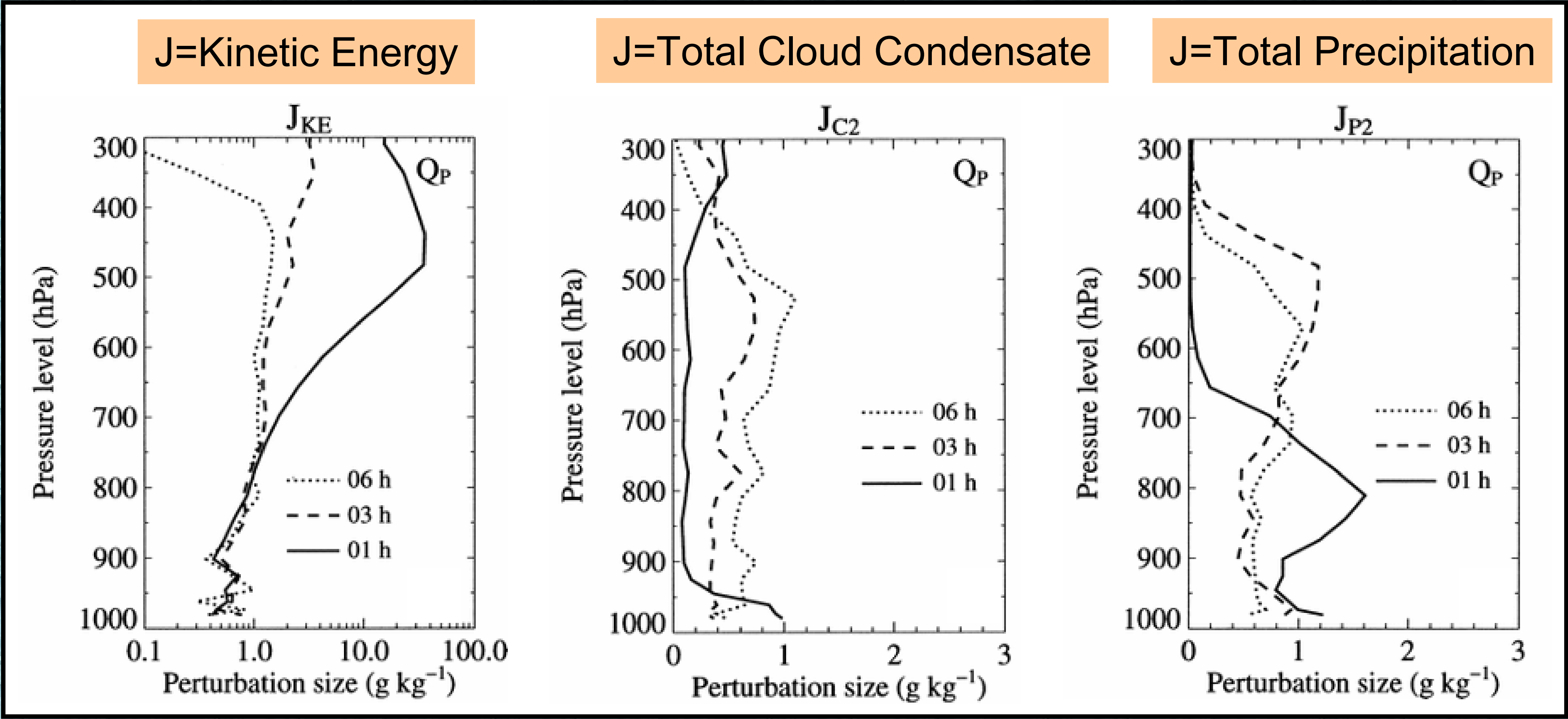


Three functionals are defined as spatial integrals inside green box:

J_{KE} = Kinetic energy
J_{C2} = Cloud condensate
J_{P2} = Precipitation

Hydrometeors as control variables in data assimilation?

Norm of optimal perturbations of precipitation content that are required to obtain a change of three functionals equal to that obtained when a 0.5 K perturbation is applied with a lead time of 6 hours (T95 L31 adjoint integration).



The inclusion of a precipitation prognostic variable in adjoint calculations is not expected to bring a substantial contribution, at least for resolutions coarser than 100 km. Conclusions might be different for the mesoscale over short timescales (~ 1 h).

Hydrometeors as control variables in data assimilation?

In Data Assimilation:

- Is it really necessary to include control variables for precipitation in the data assimilation system?

- Which control variables should be considered?

  - amounts of particles for different categories (rain, snow, drizzle, graupel, hail,…)?

  - statistical moments of the PDF of bulk contents (mean, variance)?

  - particle size distributions?

- How detailed must the description of microphysical processes be?

- The specification of model error statistics (in B and R) for precipitation variables is not straightforward (positive field):

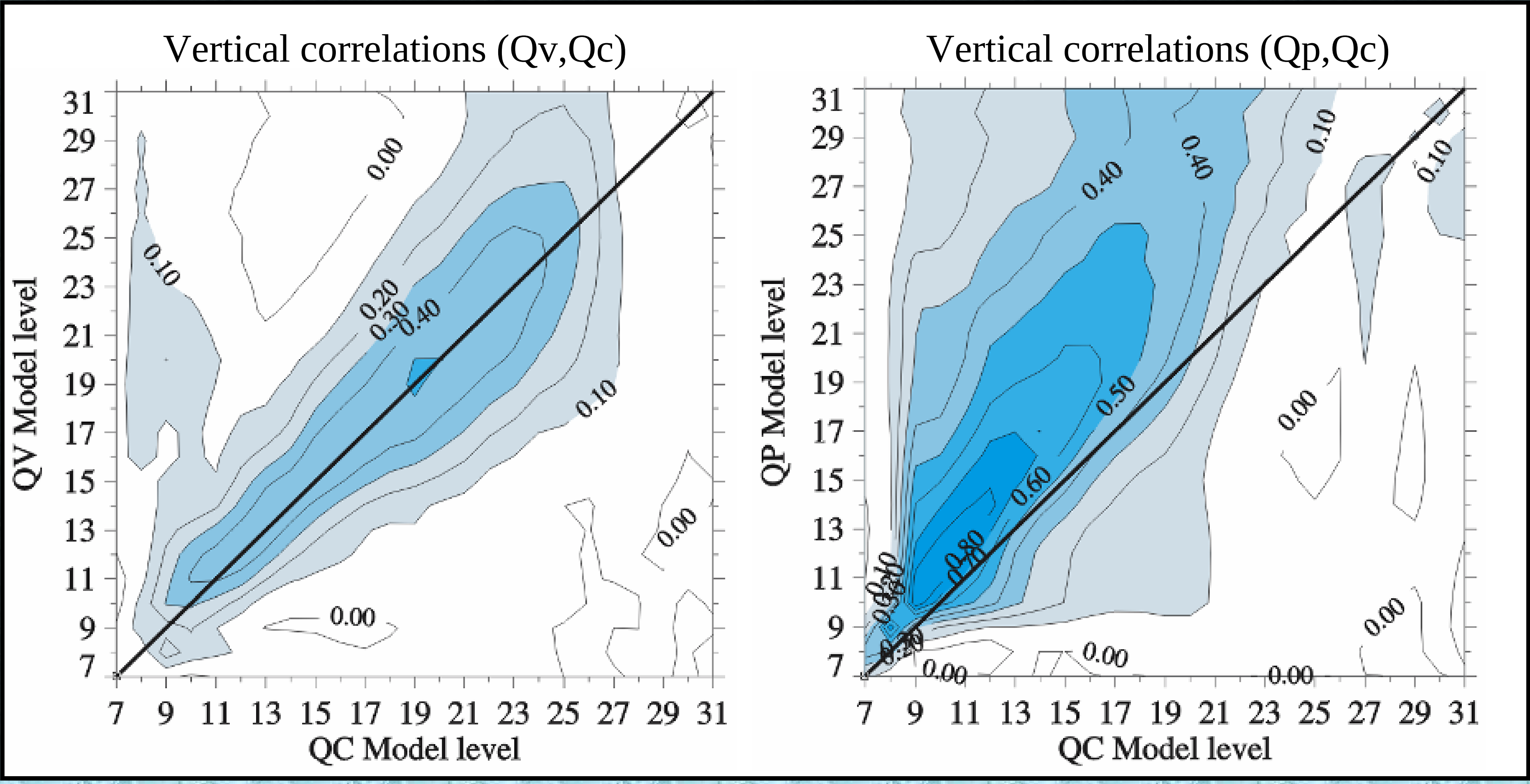
  - distributions not Gaussian (sometimes multi-modal), unless some change of variable is applied (e.g. Errico *et al.* 2000).

  - flow-dependent error statistics (esp. correlations in space)?

Hydrometeors as control variables in data assimilation?

Including precipitation in the assimilation control vector requires the definition of corresponding model error statistics.

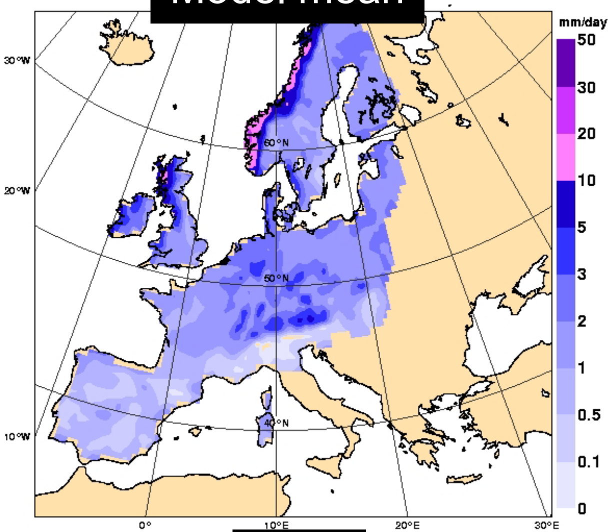
Results from NMC-type calculations with Météo-France's ARPEGE model (T213 L31) using a large-scale condensation parameterization with prognostic variables for cloud (Qc) and precipitation (Qp) amounts.



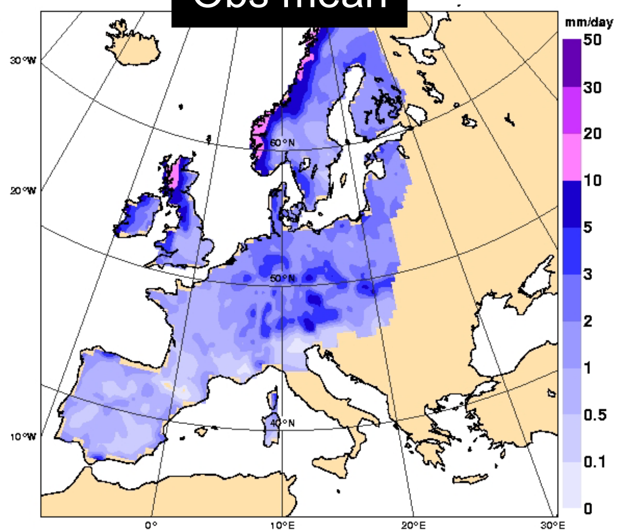
How can we assess model error for data assimilation (R matrix)?

Comparison of +6→+30h simulated precipitation with ELDAS gridded rain-gauge observations (T511 L60 ECMWF model, January 2000).

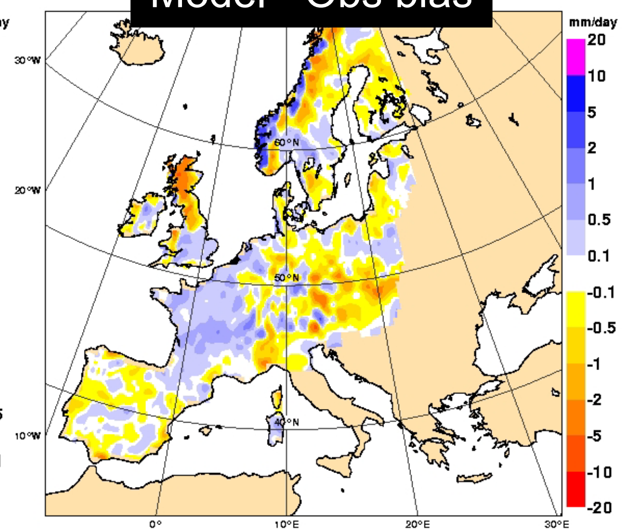
Model mean



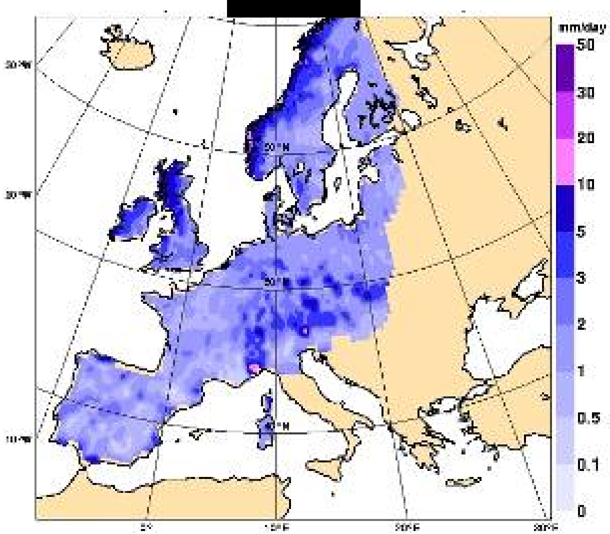
Obs mean



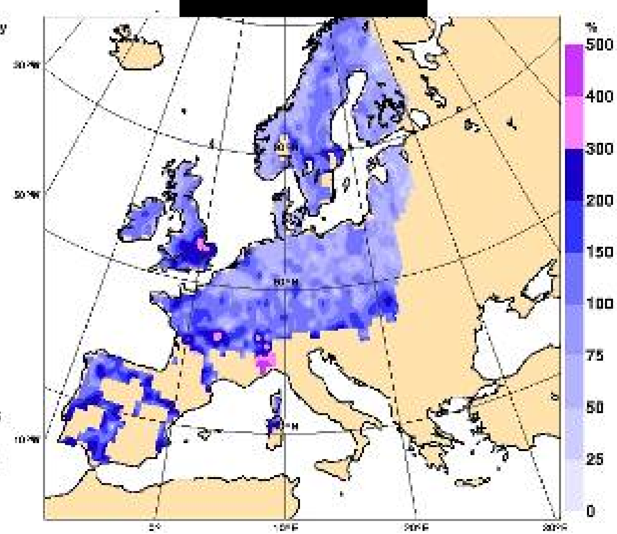
Model - Obs bias



RMS



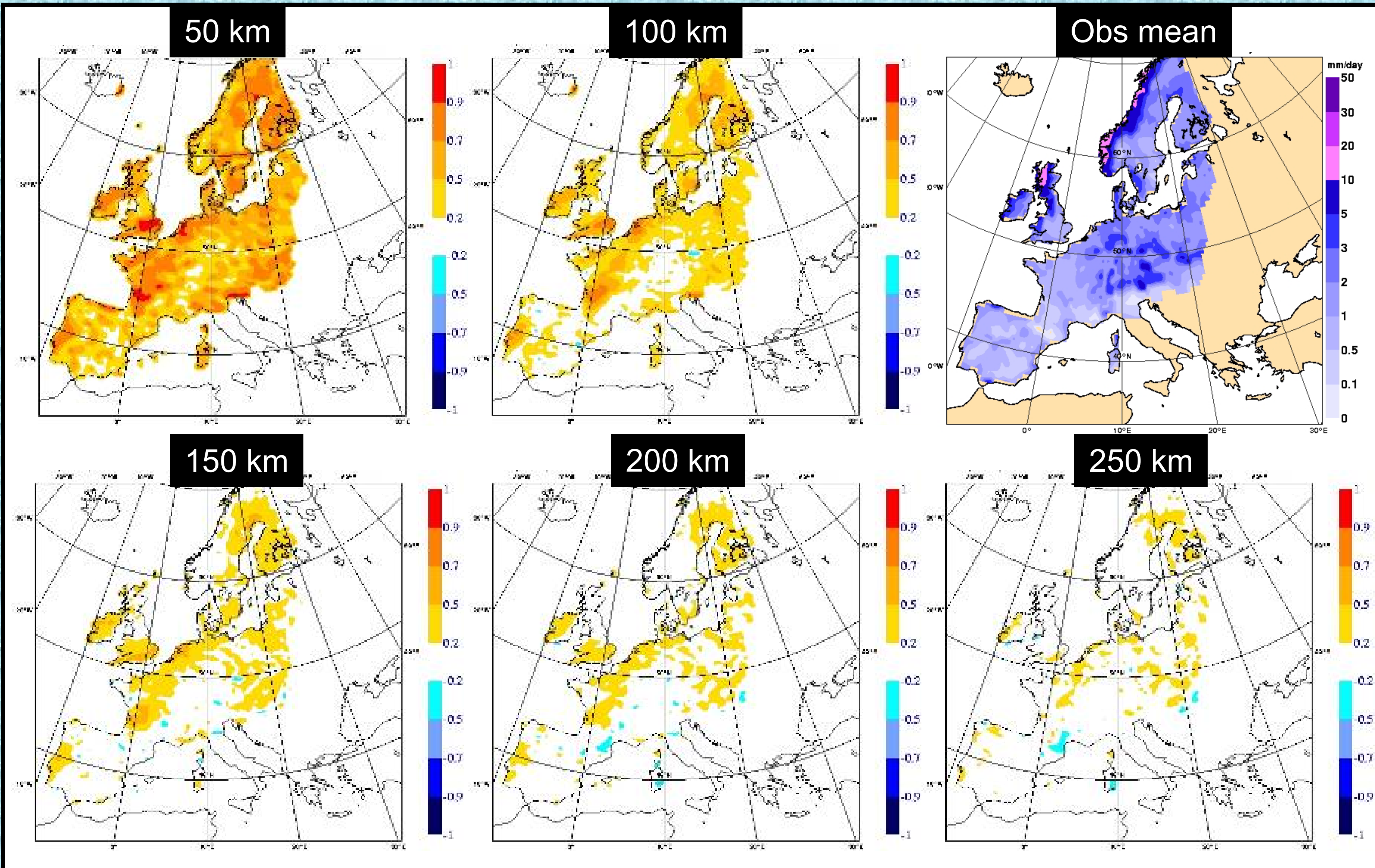
RMS / Obs



- Difficult to find good predictors: orography, CAPE, flow,…?
- Relative error or not?
- Not obvious to isolate modeling error from background and observation errors.

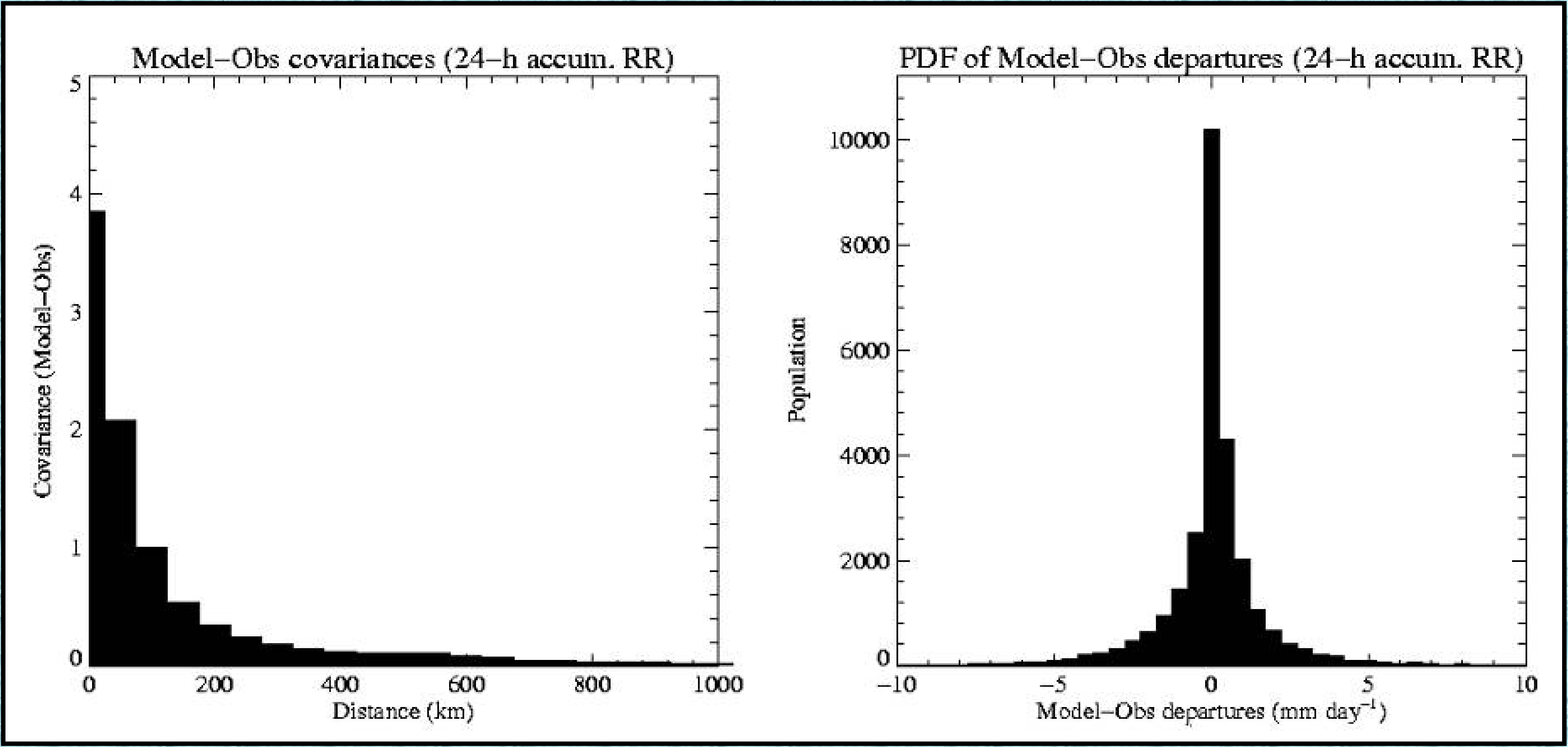
Model-obs precipitation error correlations for various distances

Comparison of +6→+30h simulated precipitation with ELDAS rain-gauge data over Europe (T511 L60 ECMWF model, January 2000).



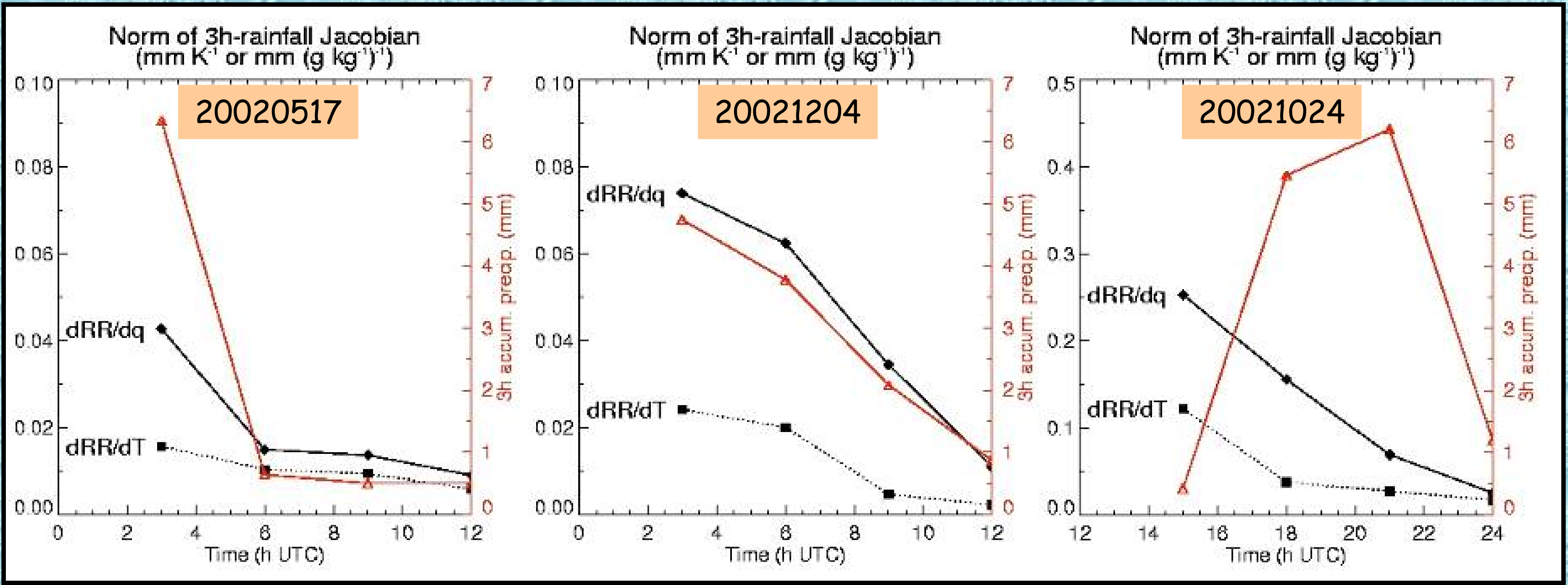
Tentative estimation of Model-Obs precipitation error statistics

Comparison of +6→+30h simulated precipitation with ELDAS rain-gauge data over Europe (T511 L60 ECMWF model, January 2000).



Time evolution of precipitation Jacobians (2D-Var)

Maximum sensitivity of simulated 3-hour accum. precipitation to initial T and q over 2D-Var 12-hour assimilation window (from rain-gauge assimilation exp.)

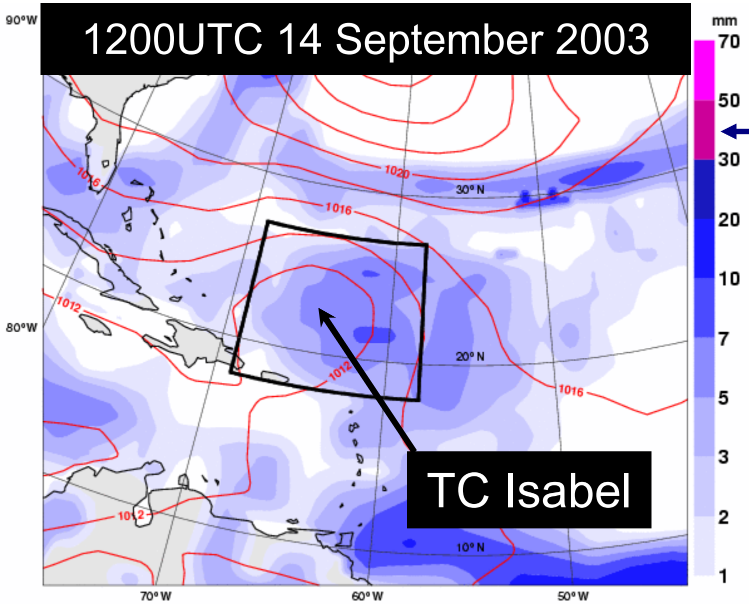


In 2D-Var, the sensitivity of the simulated precipitation to initial T and q decreases in time and does not necessarily depend on the amount of rainfall in the model.

→ The weight given to rain-gauge observations during the 2D-Var minimization decreases in time through the assimilation window.

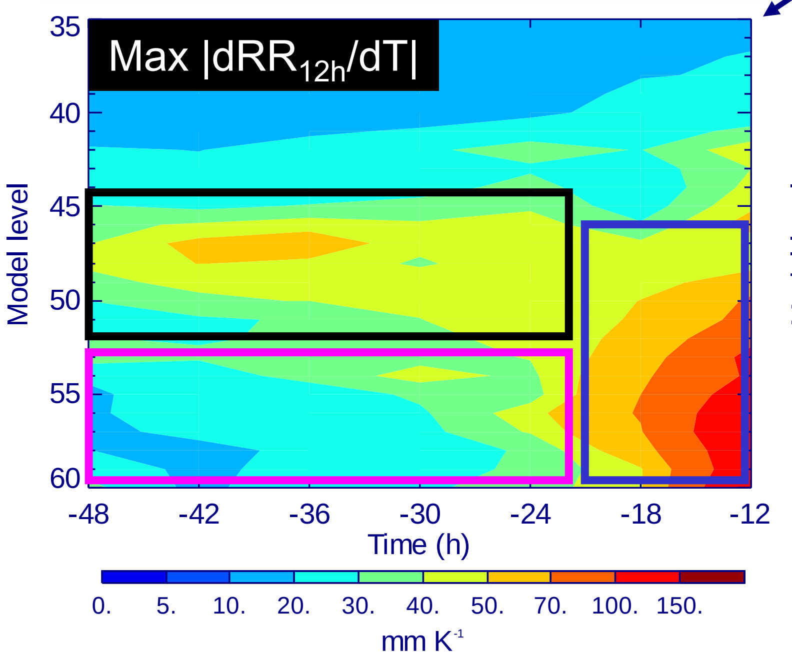
Would this also be true in 4D-Var?

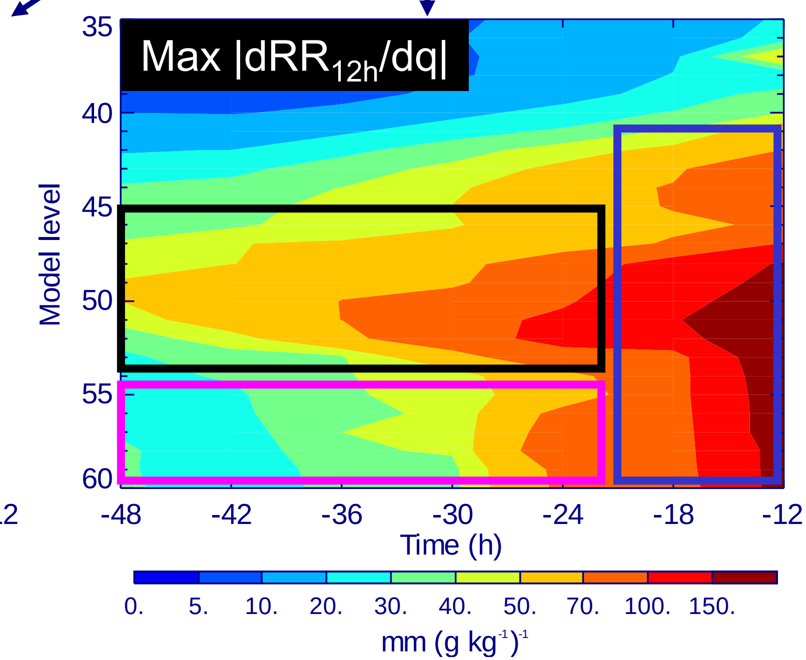
Time evolution of precipitation Jacobians from 3D AD integration



12-hour surface rainfall (RR_{12h}) and MSLP
48-hour T95L60 forecast started at 1200UTC 12 September 2003.

Time evolution of the maximum 3D adjoint sensitivities of RR_{12h} to T (left) and q (right) for lead times of up to 36h prior to precipitation accumulation.





Time evolution of precipitation sensitivities from 3D AD integration

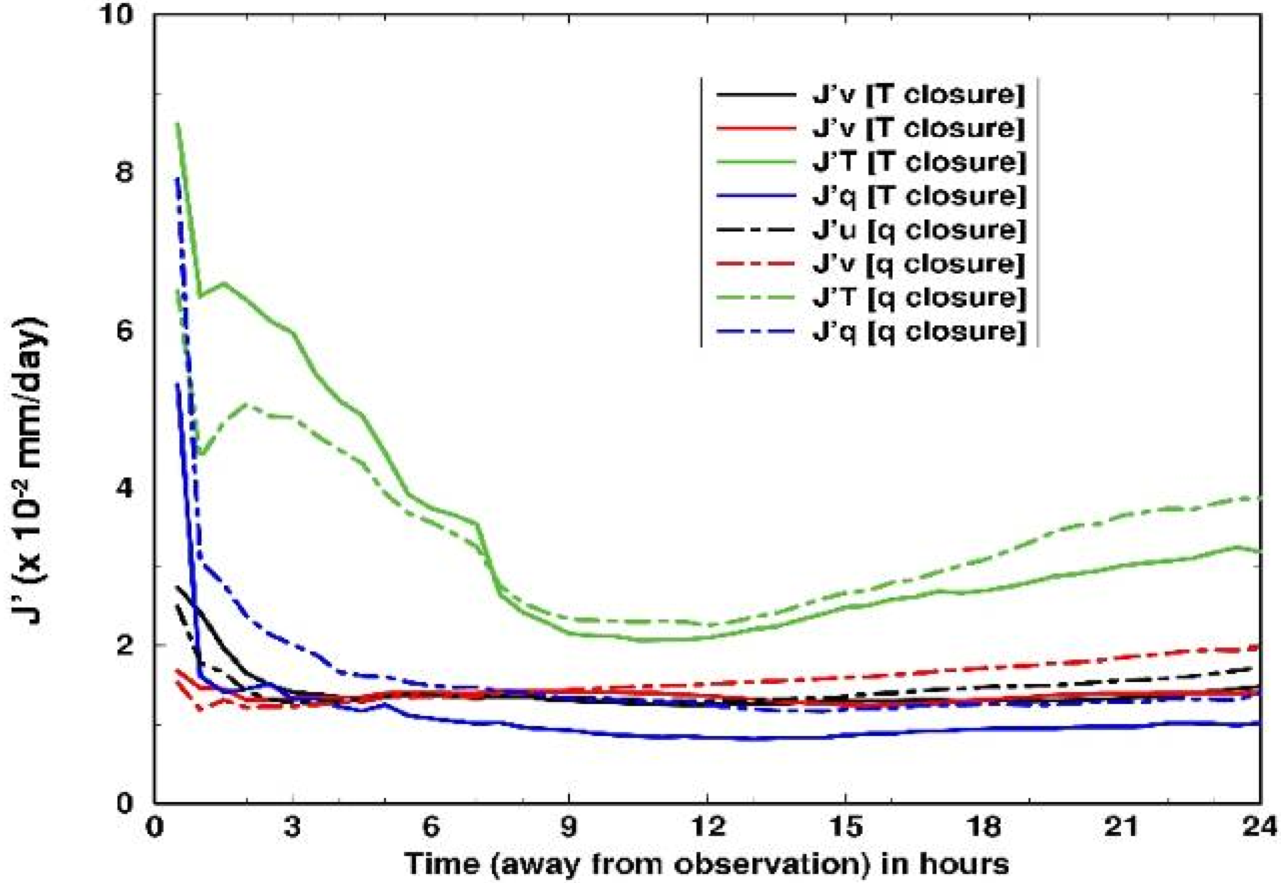
Results from Mahfouf and Bilodeau (2005):

Time evolution of the changes of

J = [24-hour forecasted precipitation averaged over a North Atlantic frontal system]

due to optimal perturbations of T, q, u and v for lead times of up to 24h.

(~150 km / L28, Kuo-symmetric with T- or q-closure, LS: Haltiner and Williams 1980)



Summary and questions (1)

- Recent developments in parameterizations of precipitation and in radiative transfer modeling used in FC and DA have opened the door to the assimilation of observations affected by precipitation (and clouds).

  - more prognostic variables included,
  - more moist physical processes described,
  - simulation of microwave TBs or reflectivities (P. Bauer's talk).

Questions:

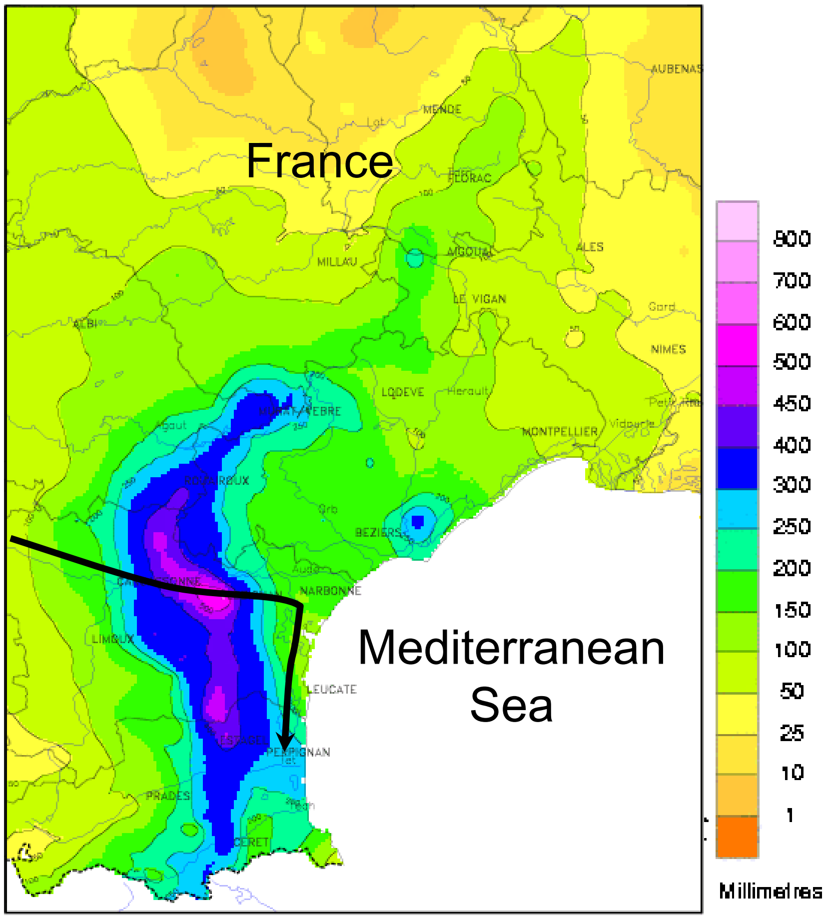
- Are current parameterizations accurate enough?
- What are the current systematic biases and random errors of the available model output parameters (cloud fraction, cloud condensate amounts, precipitation, TB, reflectivity,…)?
- How can we assess model precipitation error statistics for DA (**R** and possibly **B**)?
- How can we improve the validation of model cloud and precipitation: rain-gauges or indirect observations from radars, microwave radiometers, lidars? Other sources?
- What are the relevant control variables for forecasting / assimilating precipitation?

Summary and questions (2)

- Should we include some information about subgrid-scale variability (PDF) to obtain a smoother assimilation?
- How do we deal with the activation of convection / large-scale condensation in DA?
- How can we cope with the reduced predictability of precipitation at higher resolutions (more statistical approach)? What is the smallest predictable scale?
- Are switches really unavoidable in convective parameterizations?
- Is there a limit to the complexity and validity of the linearized physics used in TL and AD, especially at the mesoscale?
  Do we have to keep on "running after" the nonlinear parameterizations indefinitely?
- Do we need observations of more detailed cloud and precipitation characteristics (e.g. particle size distributions)? How could we use them?

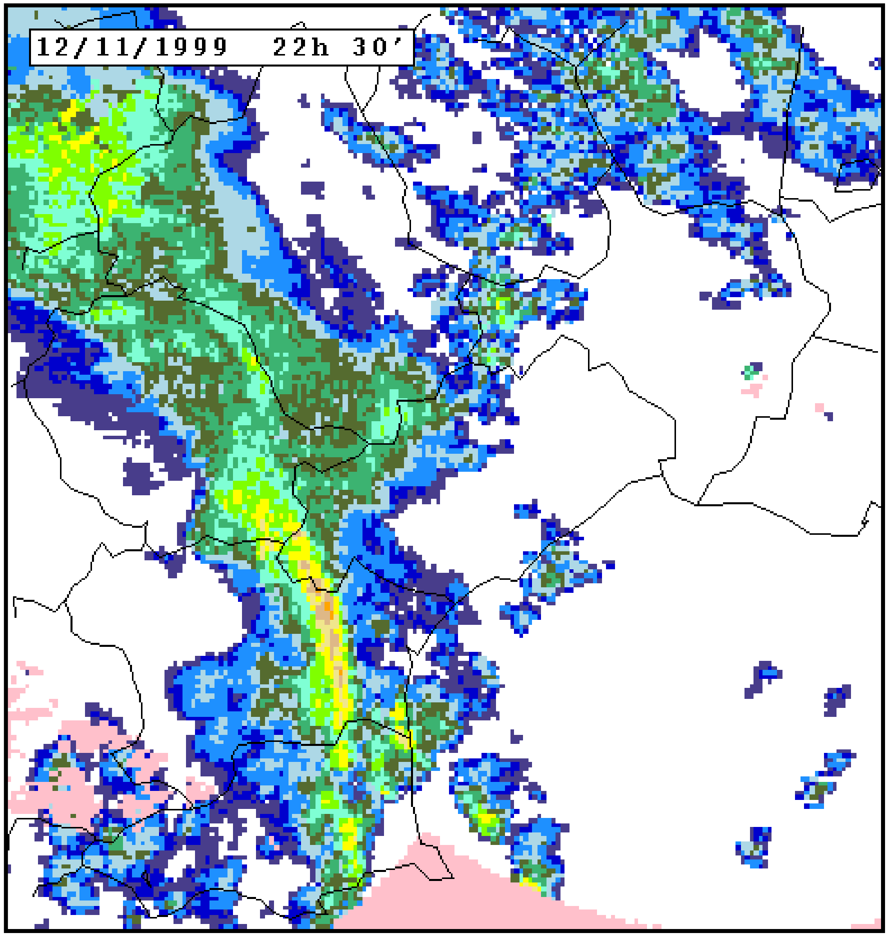
And what matters in the end…

Total precipitation 12-13 Nov 1999



METEO FRANCE

Radar composite



… is that people get the proper warnings on time.