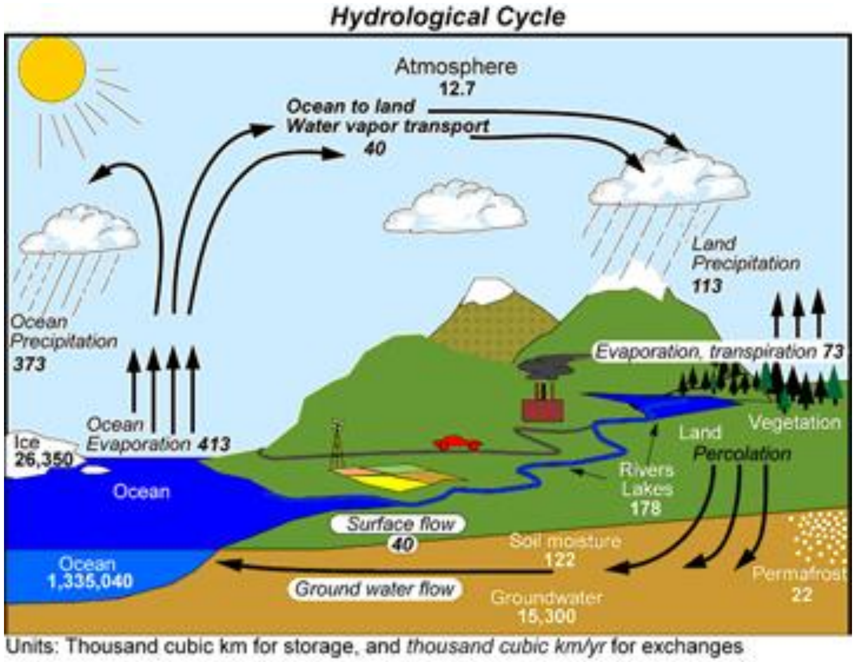
Data assimilation of the hydrological cycle

Jean-François Mahfouf*

Météo-France / CNRM

*** With material from Météo-France (N. Fourrié, E. Gérard, F. Karbou, E. Wattrelot, X. Yan) and ECMWF (P. Bauer, D. Dee, A. Geer, P. Lopez)**

The hydrological cycle


Hydrological Cycle

Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

Trenberth et al. (2007)

- What are we talking about ?
  - – The atmospheric water vapour reservoir
  - – The atmospheric condensed water: ice and water clouds, snowfall and rainfall
- Remaining components presented in other talks

Outline

- Introduction
- Assimilation of observations sensitive to water vapour
- Assimilation of observations sensitive to precipitation
- Conclusions and remaining challenges

The atmospheric water reservoir

- Water vapor and clouds strongly modulate the energy balance of the Earth’s system
- Surface precipitation and cloudiness are among the most important weather parameters to forecast (deterministic and probabilistic, including extreme events)
- Analysis of observed components of the water cycle can provide a consistent picture of « unobserved » ones : *precipitation*, evaporation and runoff

Surface precipitation in ECMWF reanalyses

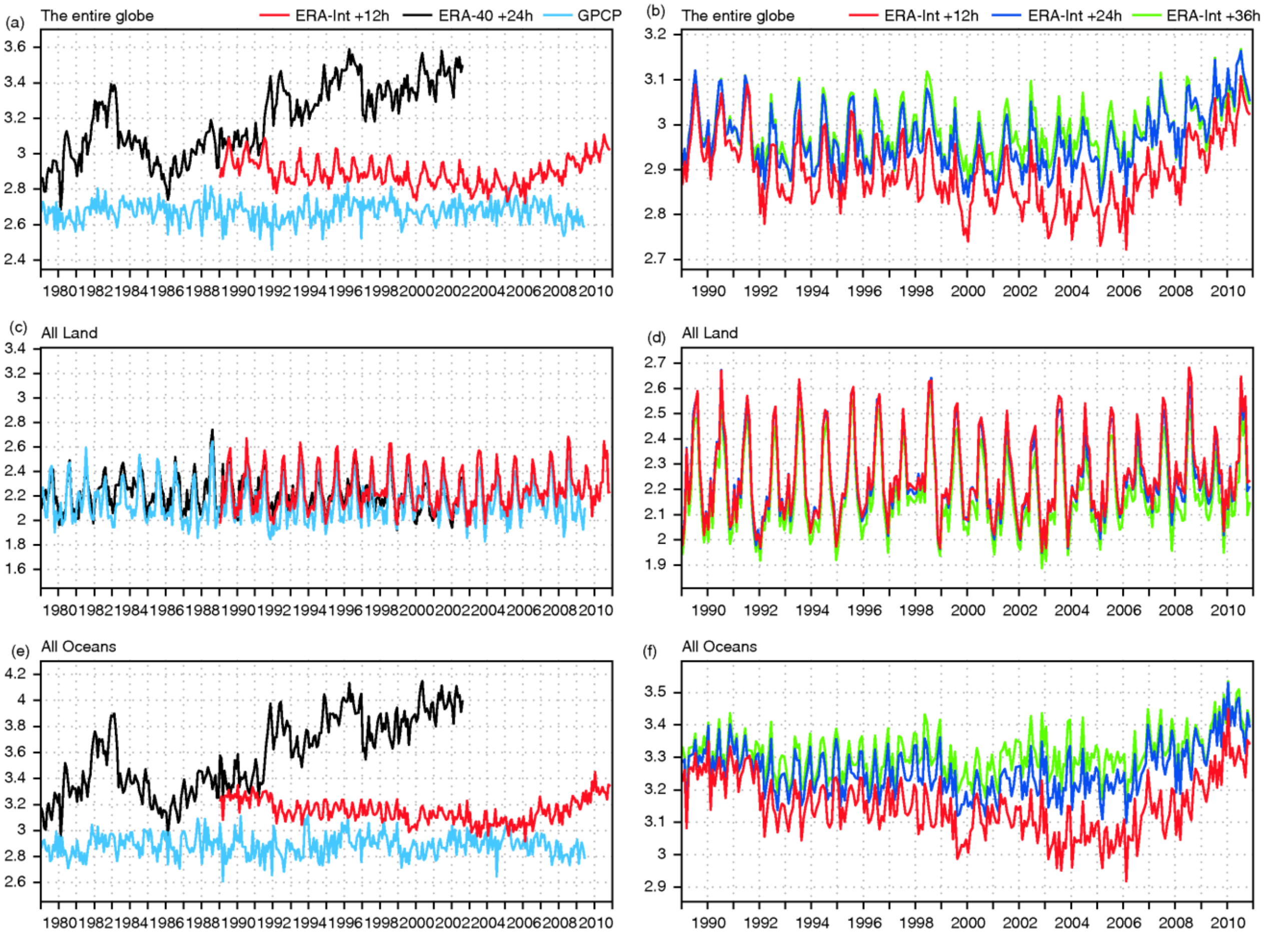
ERA-40+24h

ERA Int +12h

GPCP

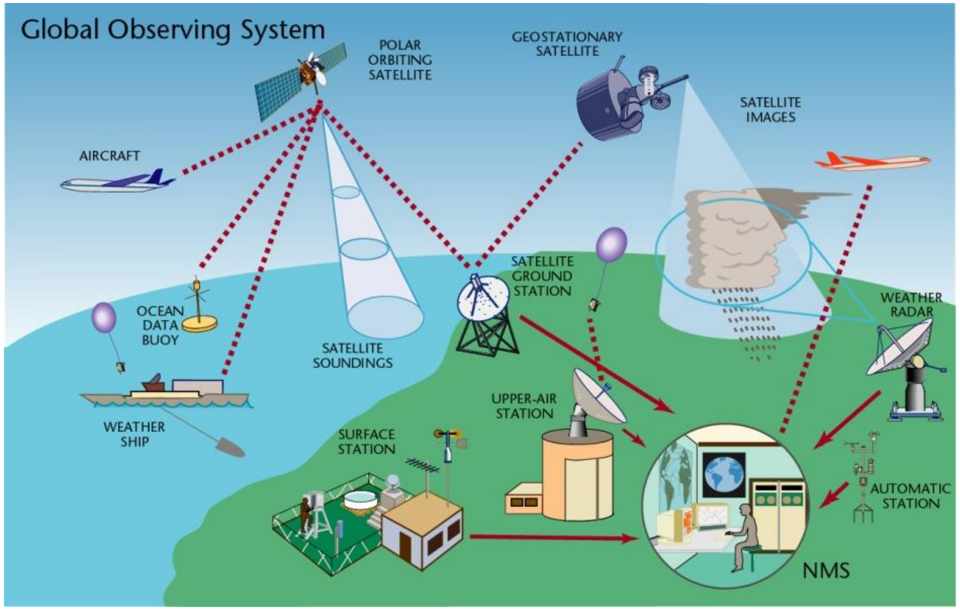
ERA Int + 24h

ERA Int + 36h



Dee et al. (2011)

The current observing system



Where are « moist » observations ?

Data of interest on water

- *Conventional data* : surface and upper-air sondes (relative humidity)
- *Ground based remote sensing* : GPS receivers (total precipitable water) – meteorological radars (precipitating hydrometeors)
- *Satellite instruments* : infra-red and micro-wave radiances (water vapour, condensed water)

Specificities (1)

- Moisture fields have high spatial and temporal variabilities :
  - representativity of local measurements
  - denser networks and more frequent observations
  - background error statistics (case dependent)
- Moisture fields have lower predictability than other fields (U, V, T, Ps)
- Bounded variables with several orders of magnitude (latitude and altitude)

Specificities (2)

- Non trivial choice of variable for atmospheric moisture analysis : q, log(q), RH, $\widetilde{RH}$
- Non-linearities {e_{sat}(T,p)} and thresholds => issues with data assimilation hypotheses
- Observations are often biased : reference measurements of « moist » variables are difficult (or very expensive)

Building blocks of data assimilation

Control vector : $\boldsymbol{x}$	• Principally specific humidity • Few words about cloud and precipitating water contents
Observations : $\boldsymbol{y}$	• Illustrations at global scale and at mesoscale (cf. presentation of Sue Ballard) for a variety of data sensitive to atmospheric water
Observation operator : H ($\mathbf{H}$ and $\mathbf{H}^T$)	• Fast radiative transfer models (RTTOV) to simulate IR and MW radiances in clear-sky and cloudy conditions (+ moist physics) – Radar reflectivity simulators
Background errors: $\mathbf{B}$	• Not much in this presentation. Importance for the extension of the control vector and for sampling cloudy and rainy regions
Other important aspects	• Observation errors, data selection, bias corrections, quality controls

ASSIMILATION OF OBSERVATIONS SENSITIVE TO WATER VAPOUR

Water vapour from satellites

- *Infra-red sounders*: between 6.2 and 7.3 μm
  - (A)TOVS/HIRS
  - AQUA/AIRS, MetOp/IASI
  - GOES, Meteosat, MTSAT
- *Micro-wave imagers and sounders:*
  - 22 GHz : SSMI/S, TMI, AMSR-E
  - 183 GHz : ATOVS/AMSU-B and MHS

IASI water vapour channels

σo=0.5 to 1 K

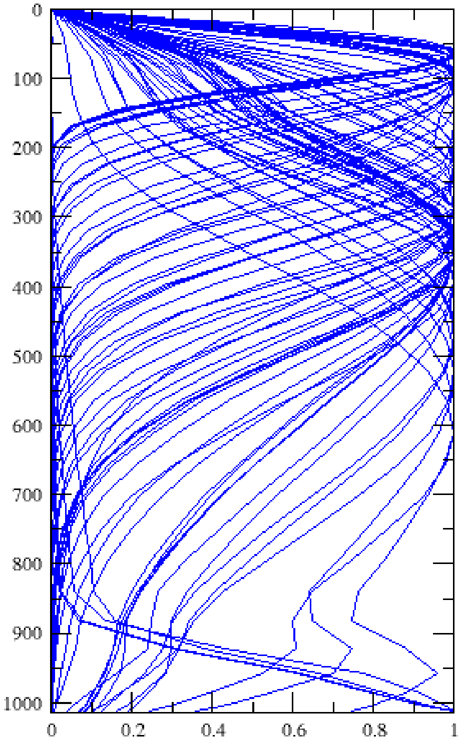
LW - T

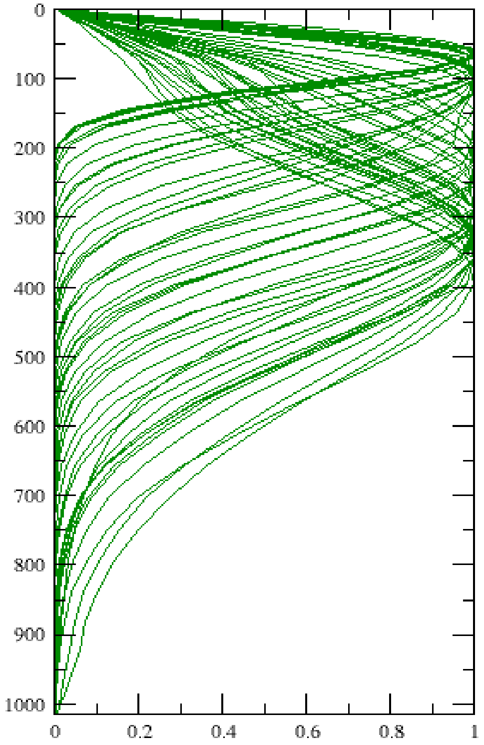
68 over sea

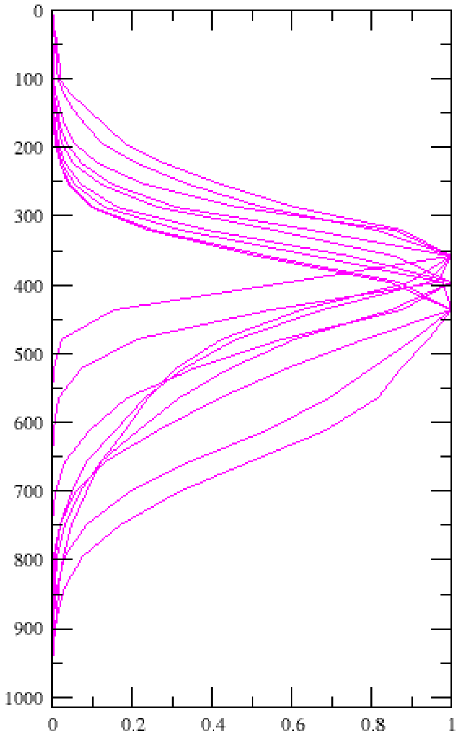
50 over land

σo=4 K

9 WV





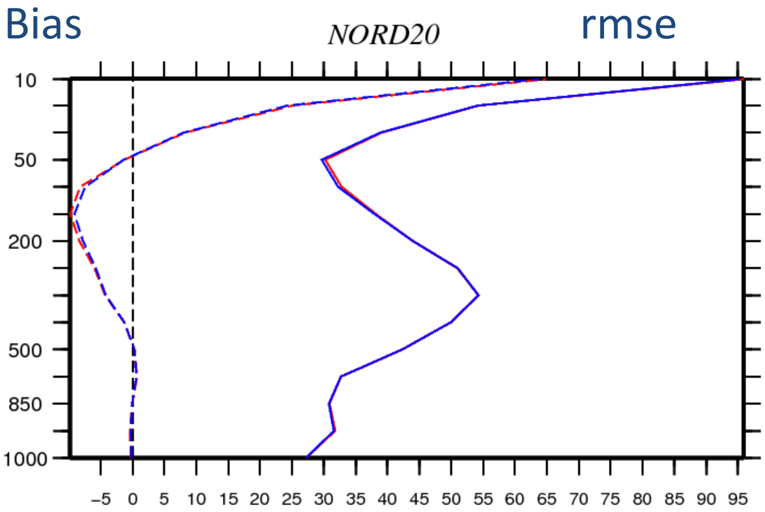


Current usage at Météo-France – over 8461 channels

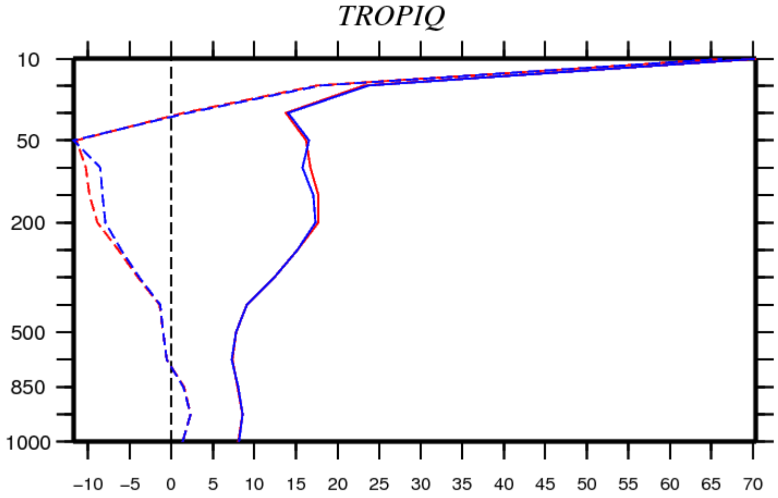
4D-Var assimilation in ARPEGE

- Météo-France global model ARPEGE
- 4D-Var assimilation with 6-h window
- Period : February 2009
- Thinning of satellite data : 250 km
- REF : reference experiment
- IASIWV : REF + assimilation of 9 WV IASI channels

Impact on forecast scores



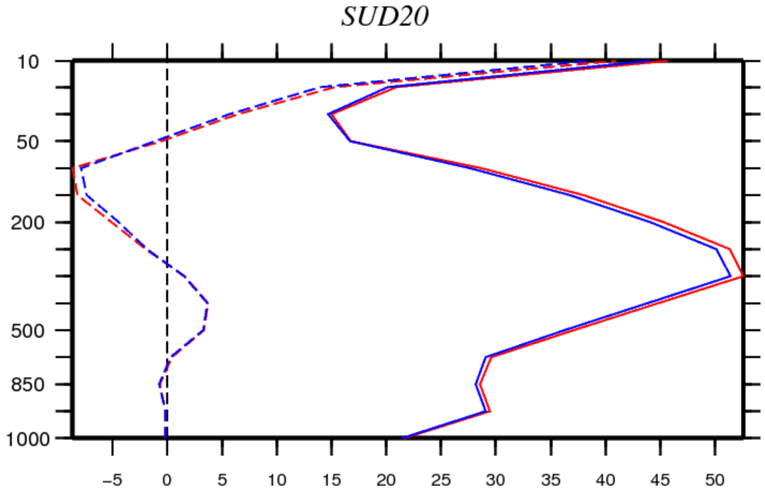
- Slight improvement of innovations (obs- first guess) against other satellite humidity observations (MHS, HIRS 11 & 12)
- Positive impact on forecast scores w.r.t. ECMWF analysis over large domains
- Statistically significant for geopotential in the upper-troposphere for 72-96 h over NH



REF

IASIWV

Geopotential at 96h forecast range



Fourrié (2009)

SSM/I and SSMI/S instruments

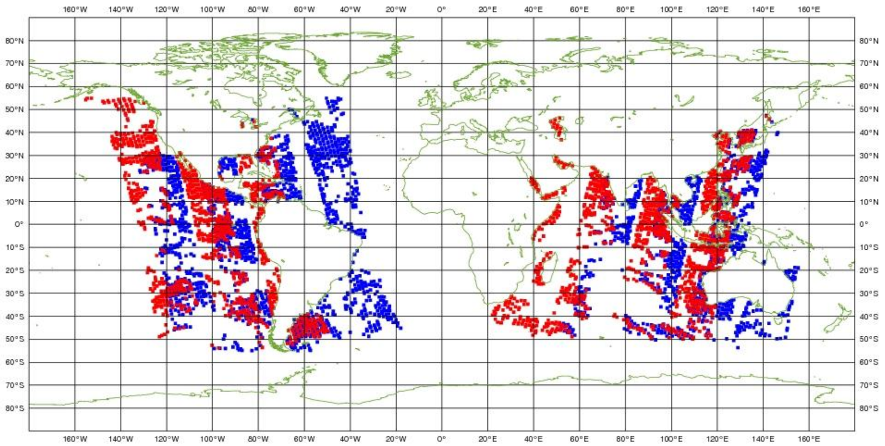
- Passive microwave radiometer with conical scanning
- US DMSP : availability of SSM/I since 1987 followed by SSMI/S since 2005 (additional sounding capabilities)
- Assimilation of TCWV derived from statistical regressions
- Assimilation of 1D-Var retrievals (TCWV + sea surface wind)
- Assimilation of clear-sky radiances over oceans
- Recent progress : Assimilation of clear-sky radiances over land (Gérard et al., 2011) and all sky radiances (Geer et al., 2010)

Frequency (GHz)	Polarisation	Resolution
19.35	H,V	45x74
22.2235	V	45x74
37	H,V	28x45
91.665	H,V	13x16

Assimilation of SSMI/S imager in ARPEGE 4D-Var

- One month assimilation (22 Feb – 22 March 2010) in the Météo-France global model ARPEGE (6-h 4D-Var system)
- EXP : with SSMI/S
- CONT : without SSMI/S
- Thinning of satellite data : 125 km
- Recent experimentation but conclusions very similar to older ones (e.g. Gérard and Saunders, 1999)

Data availability at 00 UTC February 2010

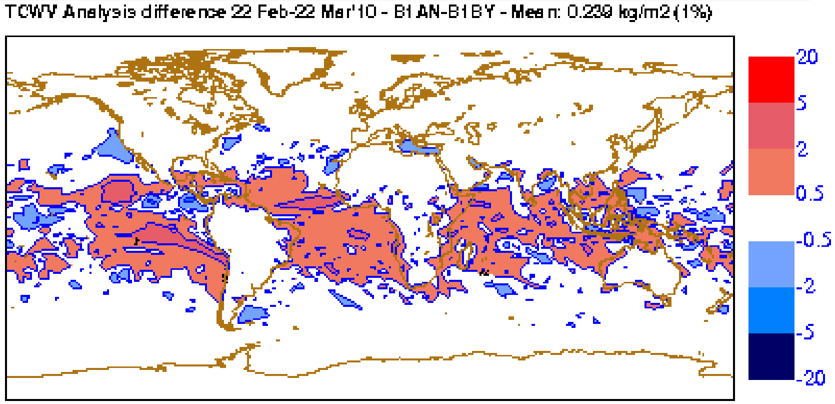


F16 : (171.570 -> 16.699)
F17 : (171.150 -> 14.287)

Gérard (2010)

Impact on global humidity analysis

Exp-Ctr TCWV analysis differences Mean = 0.239 kg.m^{-2} (+1%)



TCWV Analysis difference 22 Feb-22 Mar'10 - B1AN-B1BY - Mean: 0.239 kg/m2 (1%)

Exp: with SSMI/S imager

Ctr: without SSMI/S

Moistening of the model
(first guess & analysis)

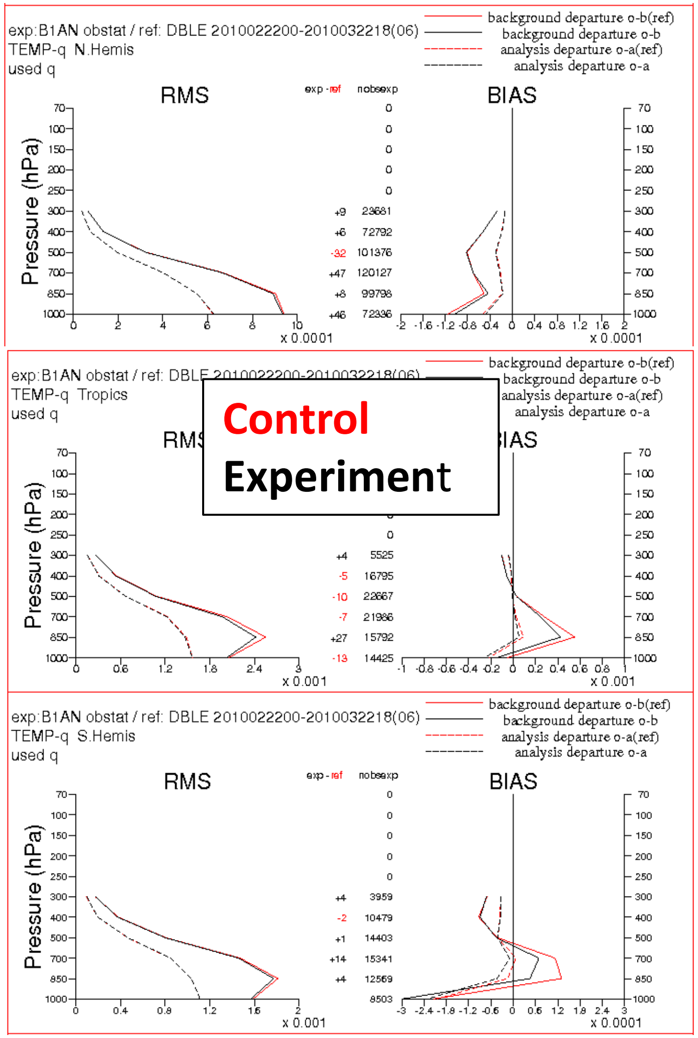
Δ(TCWV) (Exp-Ctr)/Ctr	All points	Land	Sea
Globe	+1.0%	+0.8%	+1.1%
North Hem.	-0.3%	+0.3%	-0.5%
Tropics	+1.6%	+1.0%	+1.8%
South Hem.	+0.5%	+0.8%	+0.5%

Gérard (2010)

First-guess fit to observations

TEMP q

RMS reduction



Control Experiment

NH

-1.3% @850hPa

Tr

-5.3% @850hPa

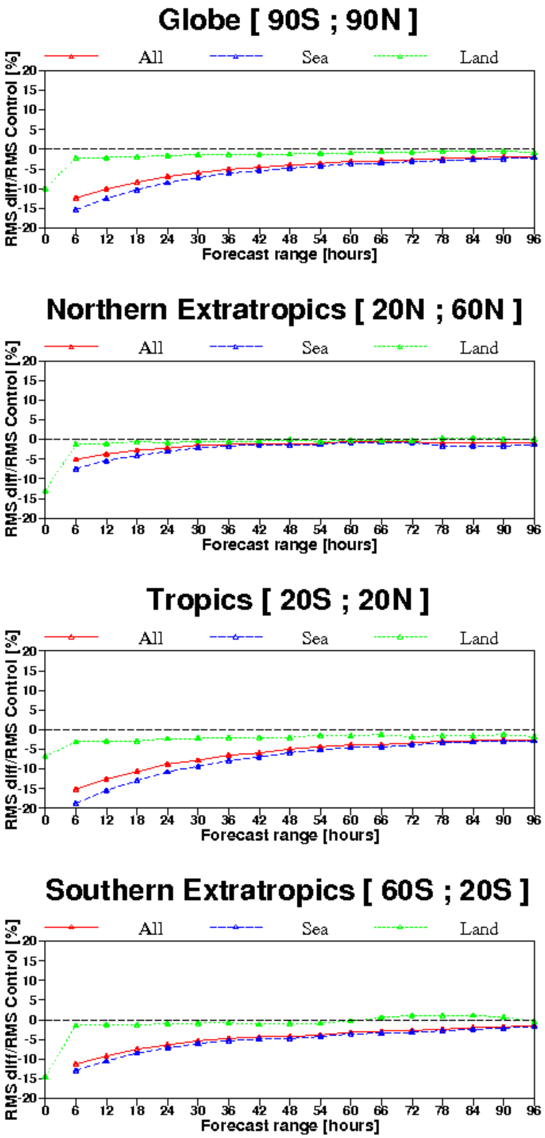
SH

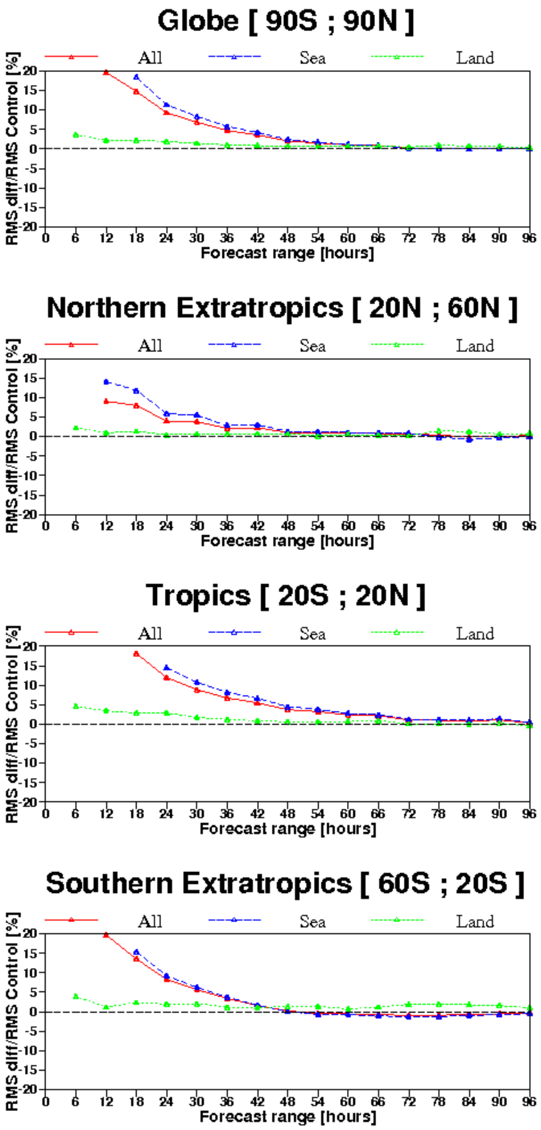
-2.1% @850hPa

Gérard (2010)

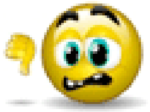
Normalized RMSE of TCWV forecasts

Vs. ECMWF analysis





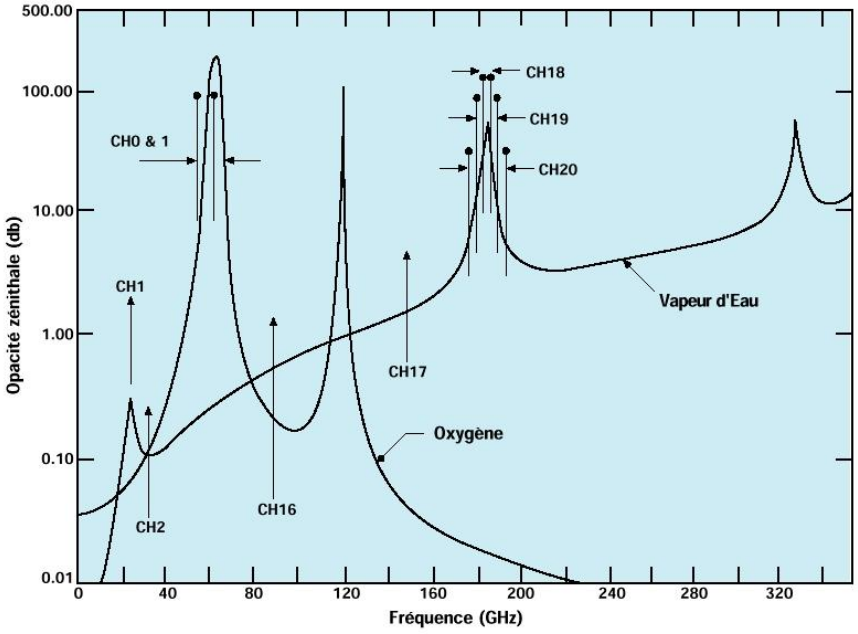
Vs. own analysis



Gérard (2010)

MHS/AMSU-B radiances

- Since 1998, sounding instruments AMSU-B and MHS have been a very valuable source of humidity information (mid-troposphere) from satellites for data assimilation (reduced cloud contamination)
- Recent efforts have enabled an increased usage over land and sea-ice thanks to a better specification of surface emissivity (methodology developed by Fatima Karbou, Météo-France)



Assimilation of AMSU-B over land

Top of the atmosphere radiance

$$T(\theta,\nu) = \varepsilon(\theta,\nu)T_s\tau + [1-\varepsilon(\theta,\nu)]\tau T\downarrow(\theta,\nu) + T\uparrow(\theta,\nu)$$

Surface emissivity deduced from 89 GHz window channel

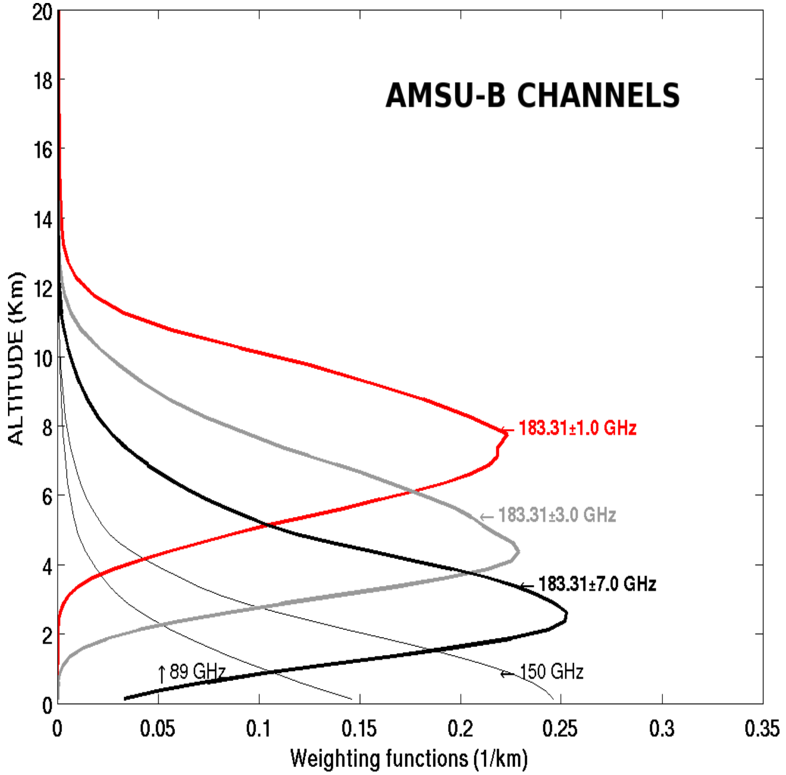
$$\varepsilon(\theta,\nu) = \frac{T(\theta,\nu) - T\uparrow(\theta,\nu) - T\downarrow(\theta,\nu)\tau}{\tau[T_s - T\downarrow(\theta,\nu)]}$$

Emissivity is assigned to sounding channels (no frequency dependency)

From Karbou et al. (2006)

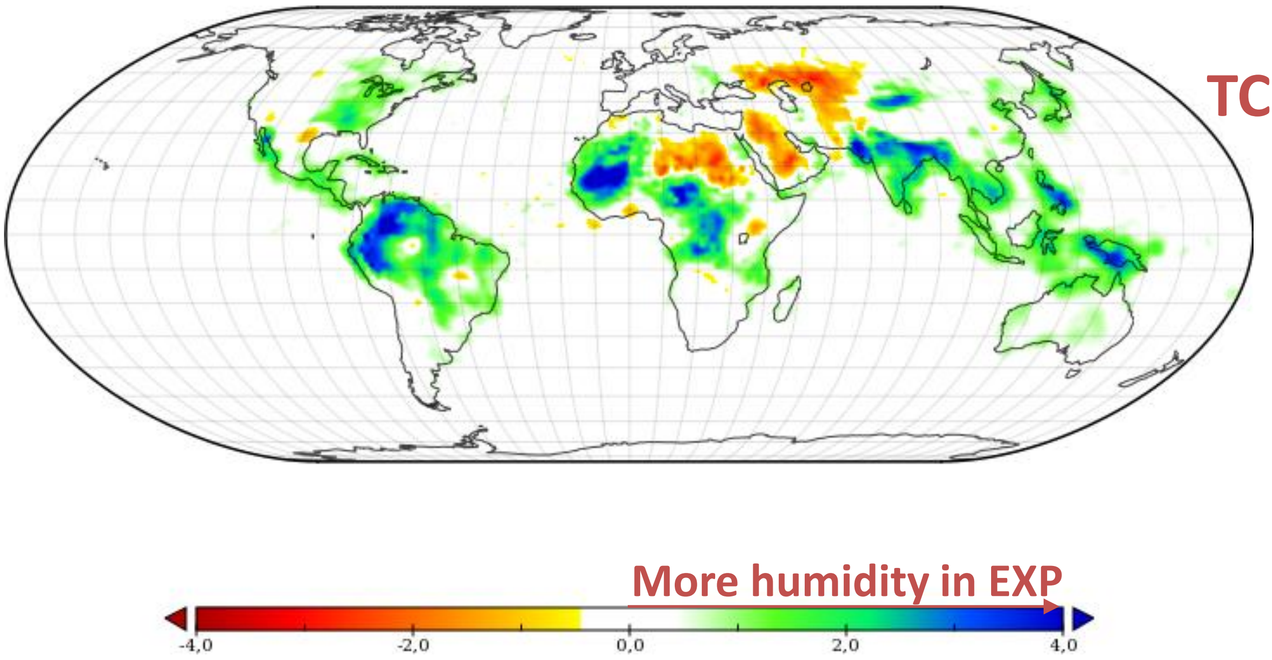
Assimilation of AMSU-B over land

- 4D-Var assimilation with ARPEGE
- 45 day (1 Aug-14 Sep 2006) during AMMA field campaign
- **CTL** = AMSU-B channels **3** and **4**
- **EXP** = CTL + AMSU-B channels 2 (150 GHz) and **5** over land



Karbou et al. (2010)

Impact on total column water vapour

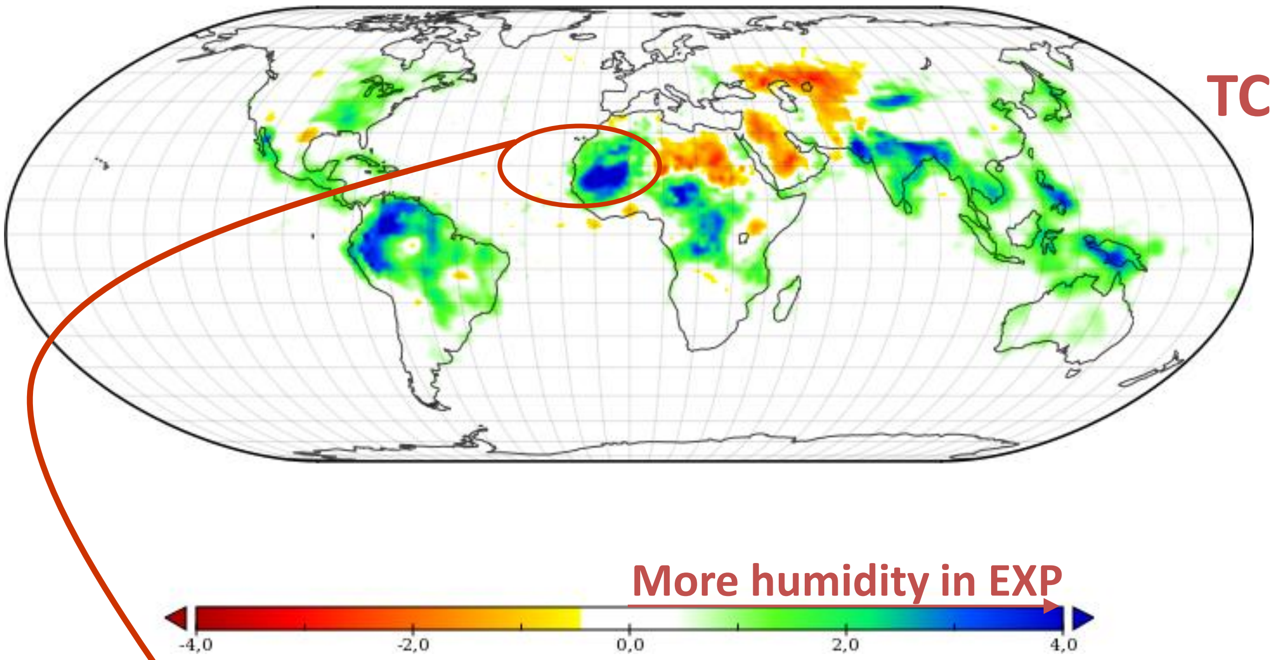


TCWV (EXP-CTL)

More humidity in EXP

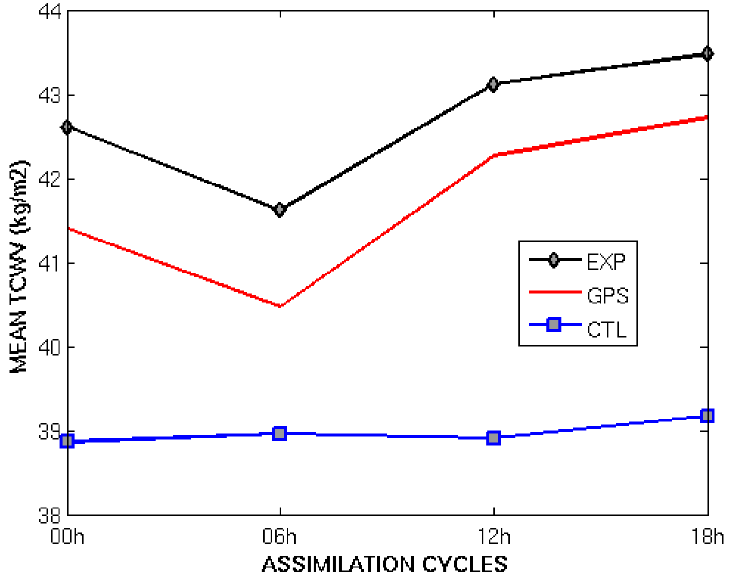
Karbou et al. (2010)

Impact on total column water vapour



TCWV (EXP-CTL)

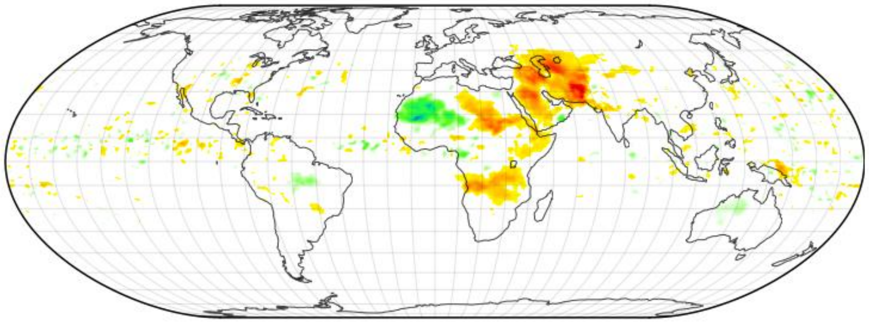
More humidity in EXP



TCWV diurnal cycle, Timbuktu (MALI)

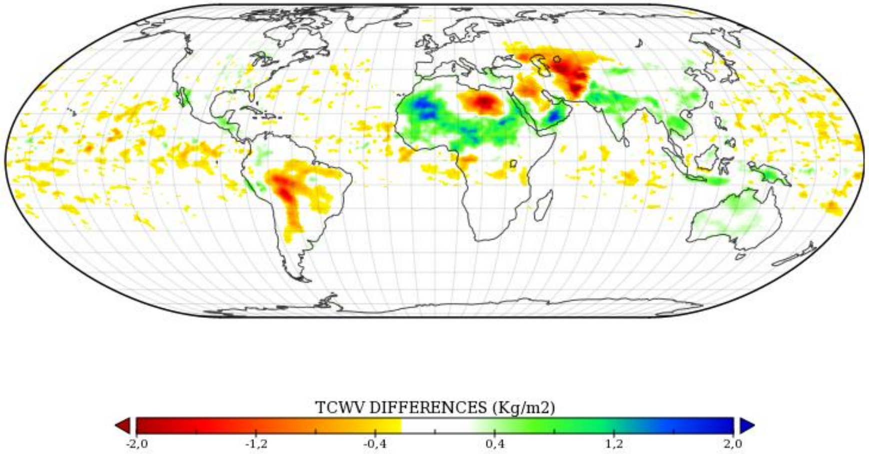
Karbou et al. (2010)

Observation System Experiment (OSE) MERIS (TCWV) versus AMSU-B



TCWV (MERIS-REF) assim at ECMWF

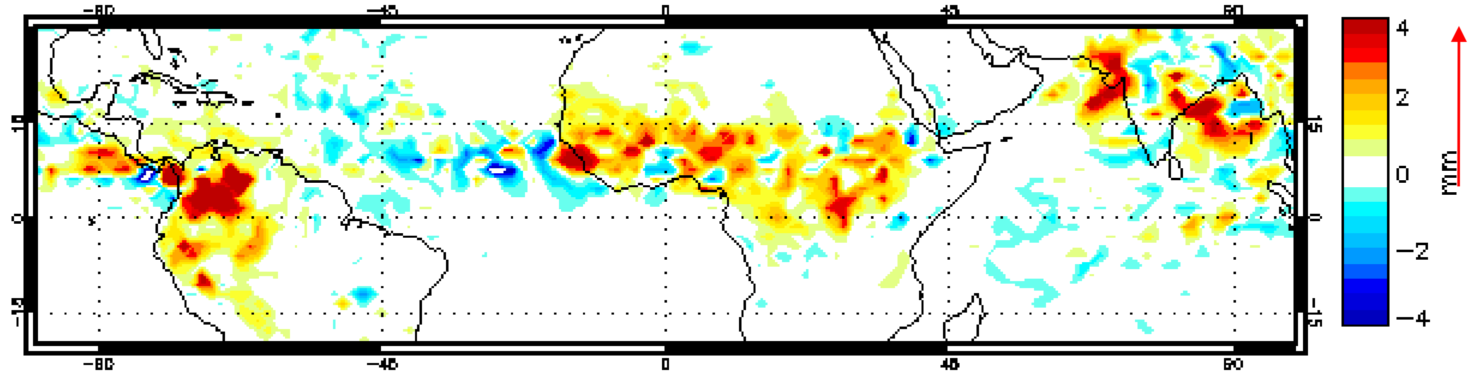
Bauer (2009)



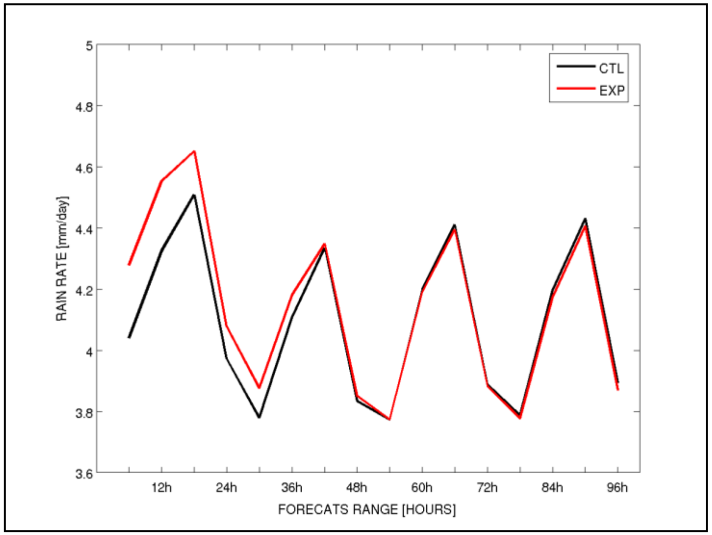
TCWV (AMSUB-REF) assim at ECMWF

Impact on rainfall rates

24-h Rainfall rate accumulation (EXP-CTL)



More rain in EXP



Better comparison with GPCP data but increased spin-down

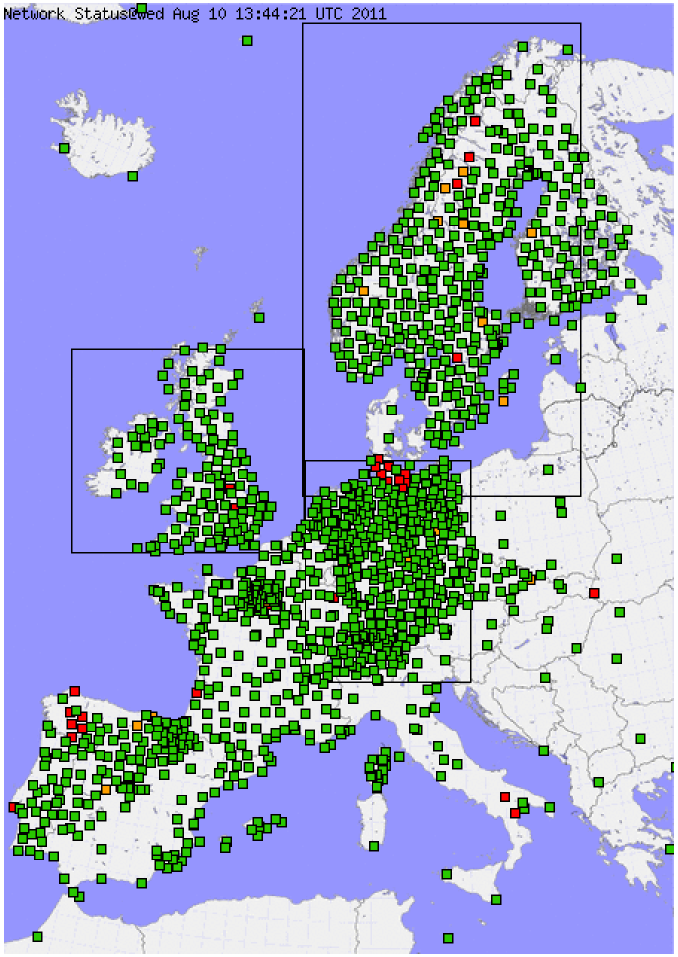
Karbou et al. (2010)

Assimilation of GPS observations

Information on **Total Precipitable Water** from the delay induced in the troposphere between a GPS transmitter and GPS stations.

Available in all conditions (L-band) at high temporal frequency

Zenith Total Delay (ZTD) observation operator coded in variational assimilation systems



European network – E-GVAP

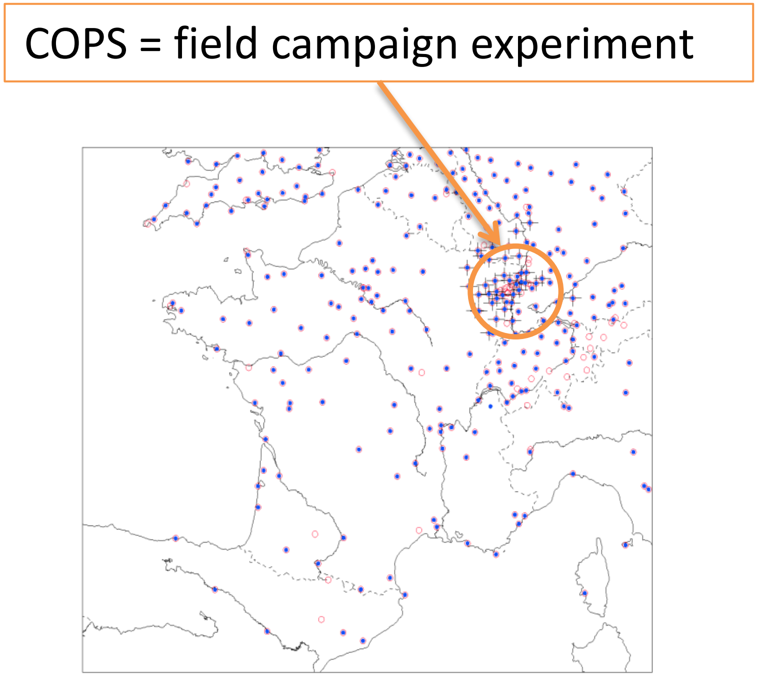
Assimilation of GPS observations

- Currently more interest for data assimilation in regional models than in global models :
  - Lack of global data exchange from regional networks
  - Temporal frequency compatible with « Rapid Update Cycle » data assimilation systems
  - Total column water vapour => information on low tropospheric humidity [highly relevant for the initiation of deep moist convection at mesoscale : Ducrocq et al. (2000)]

Assimilation of GPS data in AROME

- AROME : Météo-France NH model (2.5 km) with explicit deep convection with 3D-Var (3-hour cycling)
- Pre-processing : data selection according to GPS station and processing centre – spatial thinning – error assignment – bias correction

- ***REF*** *: reference*
- ***COP*** *: REF + GPS E-GVAP and COPS*
- ***OPR*** *: REF + GPS E-GVAP*



COPS = field campaign experiment

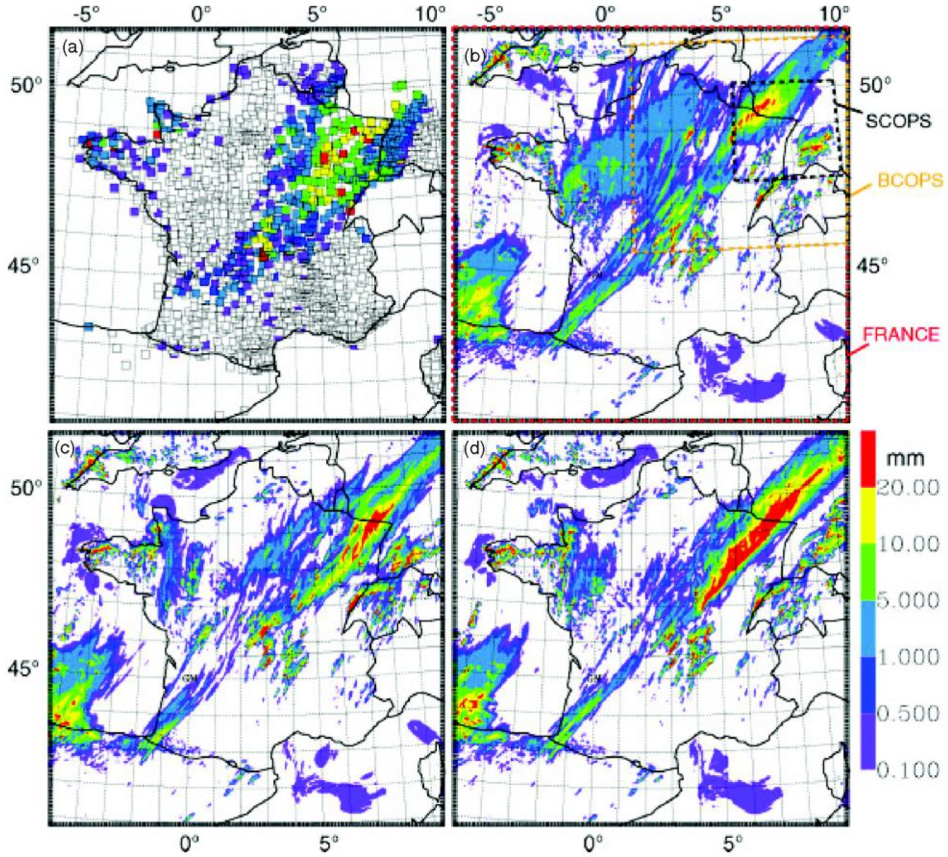
Experimental domain with 316 GPS stations (E-GVAP + COPS)

Yan et al. (2009)

Impact on precipitation forecasts

Raingauges

REF AROME



COP AROME

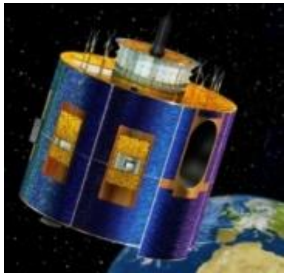
OPR AROME

12 accumulated precipitation from 03 to 15 UTC on 19 July 2007

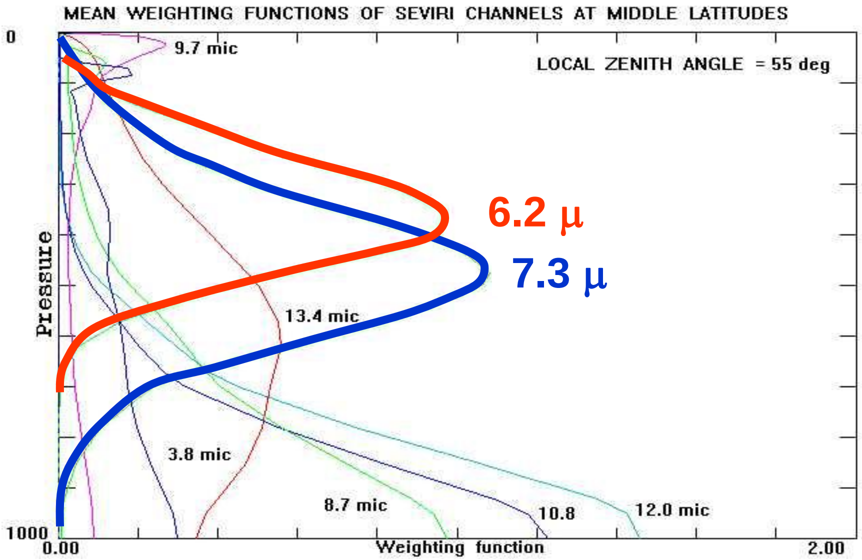
Yan et al. (2009)

Mesoscale assimilation of MSG/SEVIRI radiances

- Importance of satellite geostationnary infra-red radiances for mesoscale data assimilation (temporal frequency)
- Assimilation in Météo-France mesoscale models (ALADIN and AROME) over sea and land (also above low level clouds)
- Ongoing efforts to assimilate more channels over land (significant fraction of LAM domains)



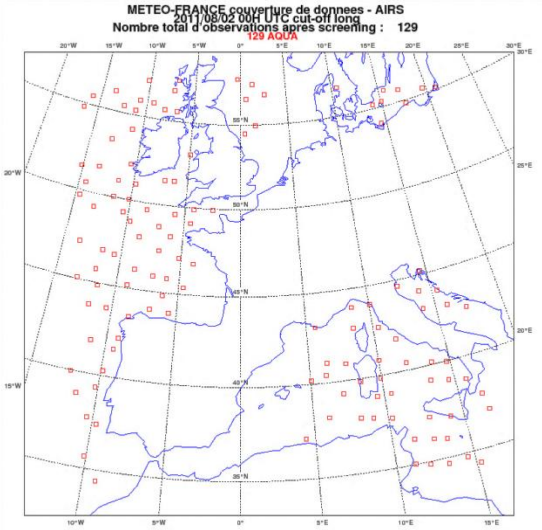
MSG/SEVIRI
water vapour
sounding
channels

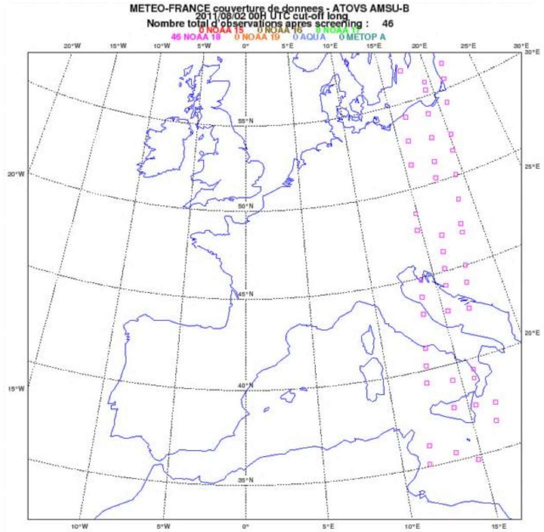


Montmerle et al. (2007)

Satellite data over ALADIN France

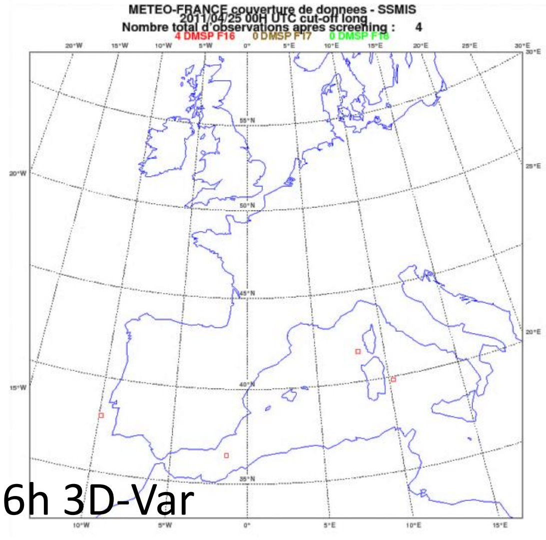
AIRS
(129)

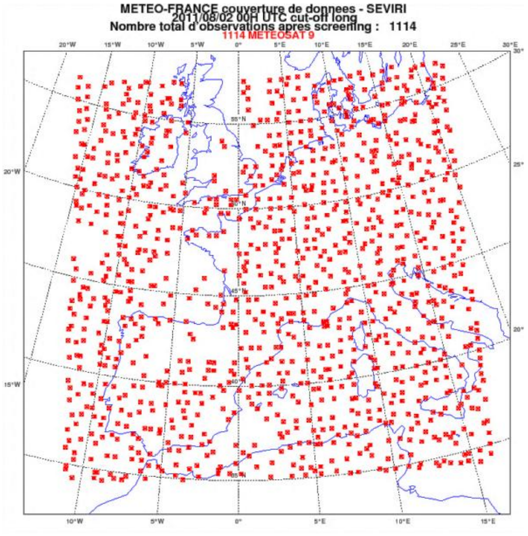




MHS
(46)

SSM/IS
(4)





SEVIRI
(1114)

Assimilated in a 6h 3D-Var

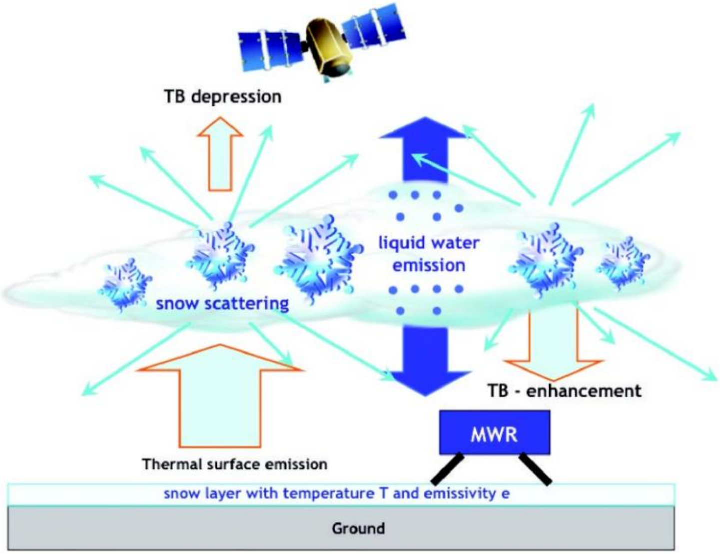
ASSIMILATION OF OBSERVATIONS SENSITIVE TO PRECIPITATION

A short history

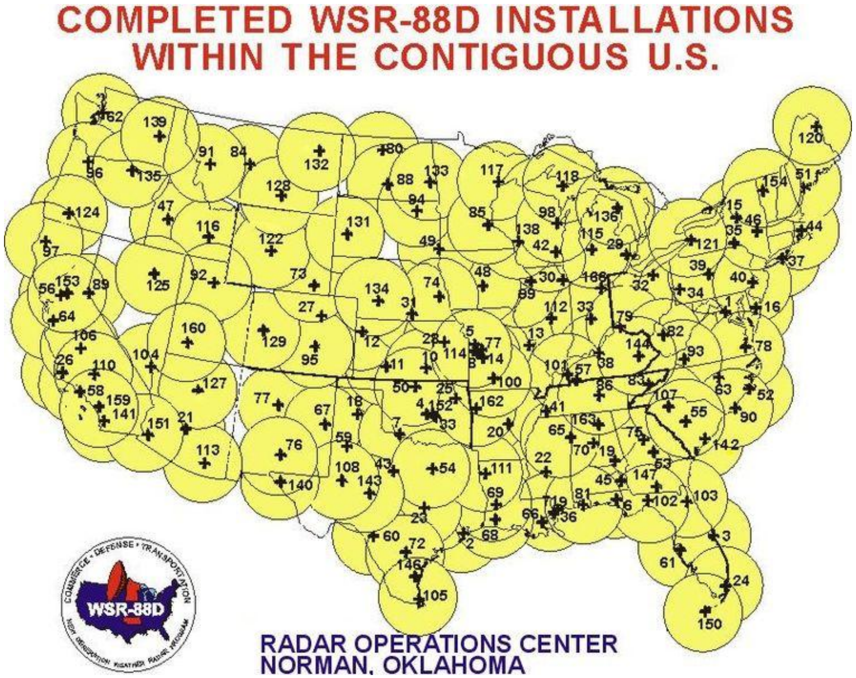
- Use of diabatic heating rates derived from observed precipitation (physical initialization at global scale, nudging schemes at mesoscale)
- Development of linearized physics in Var schemes : assimilation of surface precipitation and of rainy microwave satellite radiances
- Assimilation of radar reflectivities in limited area models
- *Assimilation of infra-red satellite radiances affected by clouds*

Precipitation from remote sensing

Radar reflectivities



Micro-wave radiances



NEXRAD

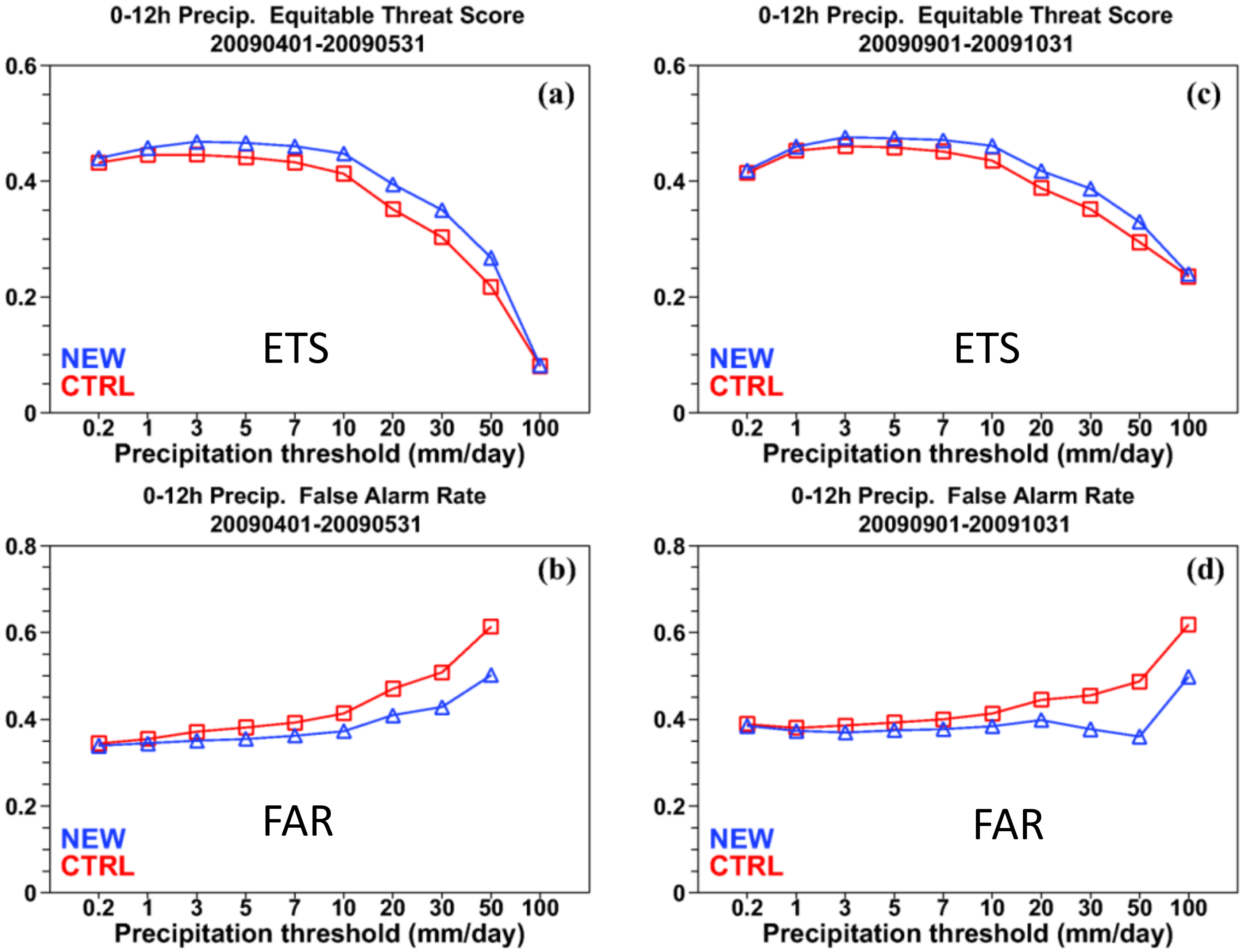
Variational assimilation of precipitation information

- Feasibility studies in « simplified » 4D-Var systems (Zupanski and Mesinger, 1995; Zou and Kuo, 1996; Tsuyuki, 1996)
- Feasibility studies in the ECMWF 4D-Var system using a two step approach : assimilation of 1D-Var retrievals of TCWV using TRMM rainfall rates (Marécal and Mahfouf, 2002)
- Operational assimilation at JMA in a 4D-Var LAM (Tsuyuki et al., 2002)
- Operational assimilation at ECMWF of rainy MW radiances with 1D+4D-Var approach (Bauer et al., 2006) and with direct 4D-Var (Geer and Bauer, 2009)
- Recent experimentation with US radar derived precipitation direct assimilation in the ECMWF 4D-Var (Lopez, 2011)

Lopez (2011) experimental design

- Change of variable : $\ln(RR6h+1)$
- Screening of observations : selection of « non zero » precipitation observations where model precipitation is also « non zero »
- Observation error : $\sigma_0 = 0.18$
- Bias correction scheme : $BC = \sum_{i=0}^{2} \alpha_i \, \overline{\ln(RR6h+1)}^{i}$
- Evaluation periods : April-May 2009 and September-October 2009
- ECWMF 12-h 4D-Var system : T511L90 - one experiment with NEXRAD (**NEW**) and one without NEXRAD (**CTRL**)

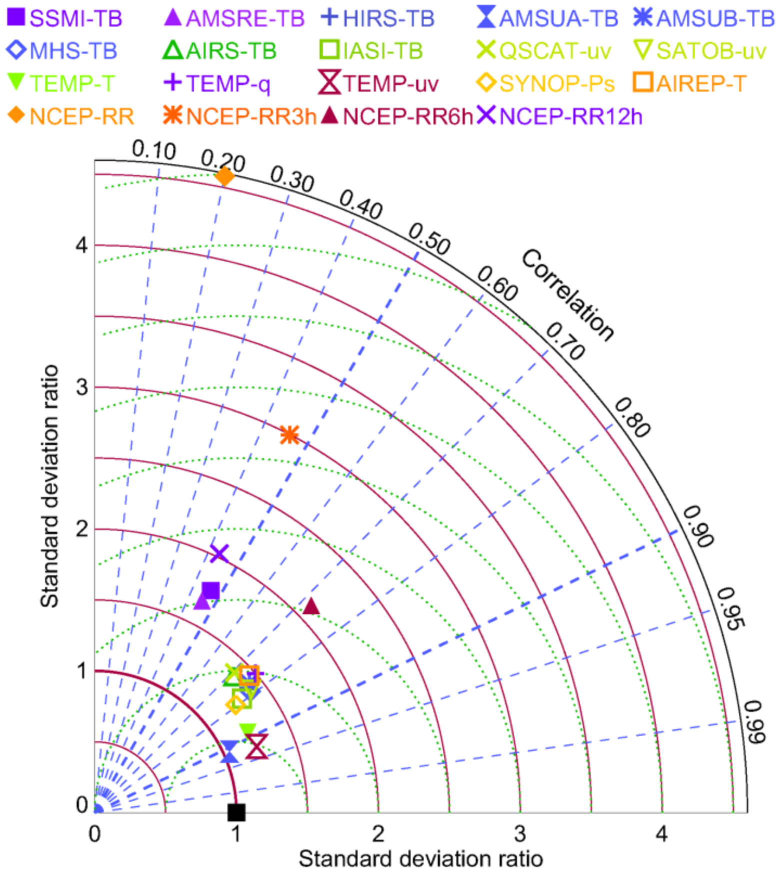
12h precipitation forecast scores



against NEXRAD observations

Lopez (2011)

Behaviour of the minimization



Taylor diagram

Model – observation :

-> $D_{minim} = H(x_b)+\mathbf{H}\delta x - y$

-> $D_{traj} = H(x_b+\delta x) - y$

Trajectory : T799 (~25 km)

First minimization : T95 (~200 km)

One single 12h 4D-Var cycle

(01 April 2009 at 00 UTC)

Lopez (2011)

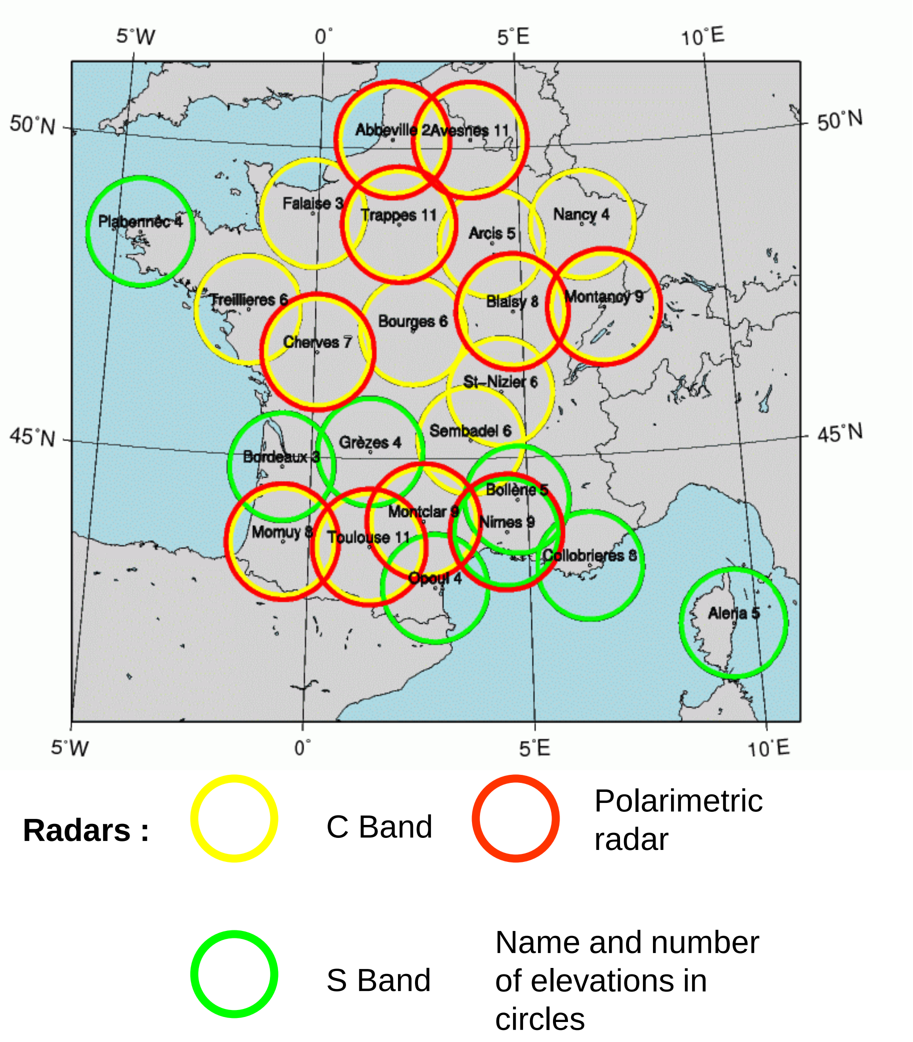
Assimilation of radar reflectivities : Météo-France example

French ARAMIS network :

- 24 Doppler radars, 10 Polarimetric, between 3 and 11 PPIs in 15’

Within 3D-Var AROME (NH LAM 2.5 km) :

- Radial wind from 15 radars since December 2008; from 22 radars since 24 November 2010 (Grèzes and Plabennec missing)
- Reflectivity from 24 radars since 6 April 2010



1D+3D-Var method (1)

- Choice of retrieving humidity information (RH)
- 1D Bayesian inversion
- Use of background information in the neighbourhood of an observation to create a database of profiles
- Need for radar reflectivity observation operator (but no TL/AD)
- Importance of QC (a-priori and a-posteriori)

$$\mathrm{E}(RH) = \sum_i RH_i \frac{exp\left[-\frac{1}{2}\|Z_o - Z_s(RH_i)\|^2\right]}{\sum_j exp\left[-\frac{1}{2}\left\|Z_o - Z_s(RH_j)\right\|^2\right]}$$

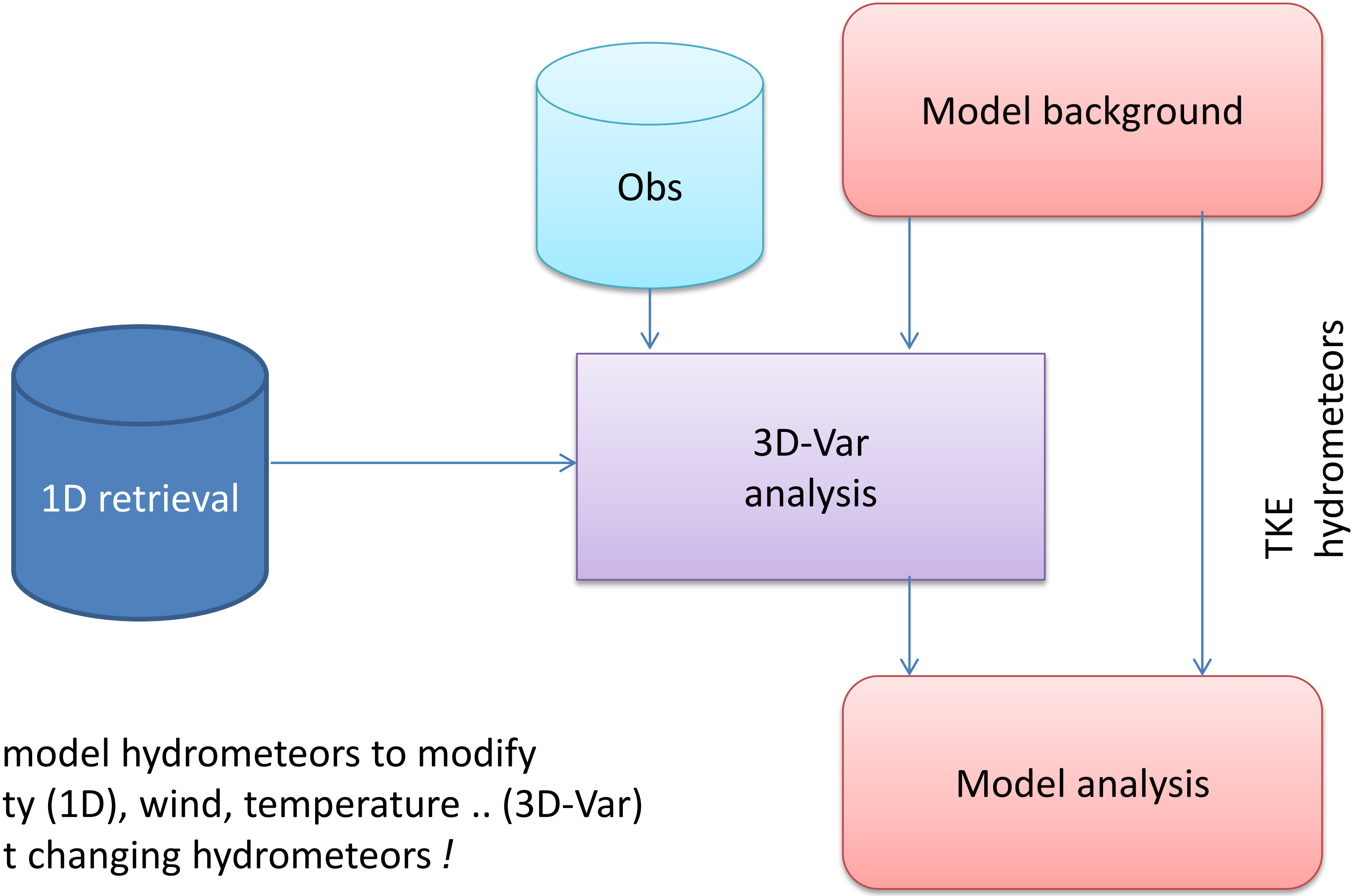
RH = relative humidity

Zo= observed reflectivity

Zs = simulated reflectivity

Caumont et al. (2009)

1D+3D-Var Method (2)



Obs

Model background

1D retrieval

3D-Var analysis

TKE
hydrometeors

Model analysis

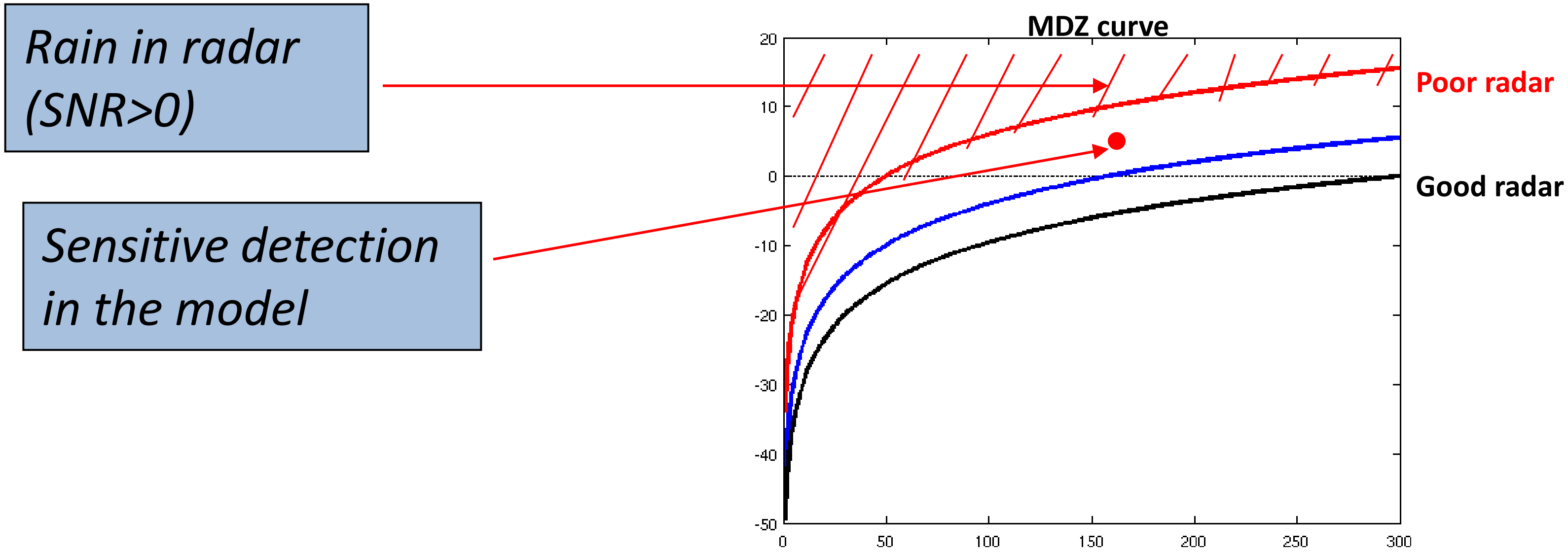
Use of model hydrometeors to modify humidity (1D), wind, temperature .. (3D-Var) without changing hydrometeors *!*

« No rain » information (1)

Importance of accounting for the « no-rain » information in the assimilation : better balance between creation and destruction of rainy areas in the model, reduced variance of analysis increments, reduced model humidity bias.

What is a precipitating signal ?

- RADAR: rain when measured reflectivity is above a threshold : the minimum detectable reflectivity (**MDZ**) prescribed for each pixel
- AROME: as soon as precipitating hydrometeors are produced in the model



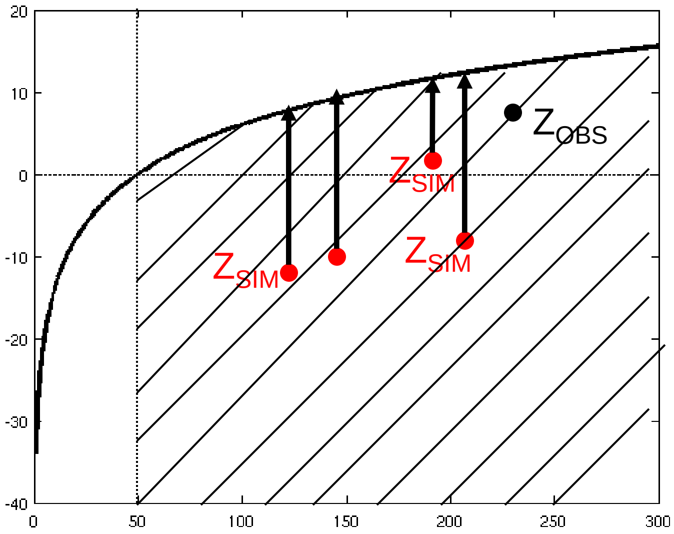
Rain in radar (SNR>0)

Sensitive detection in the model

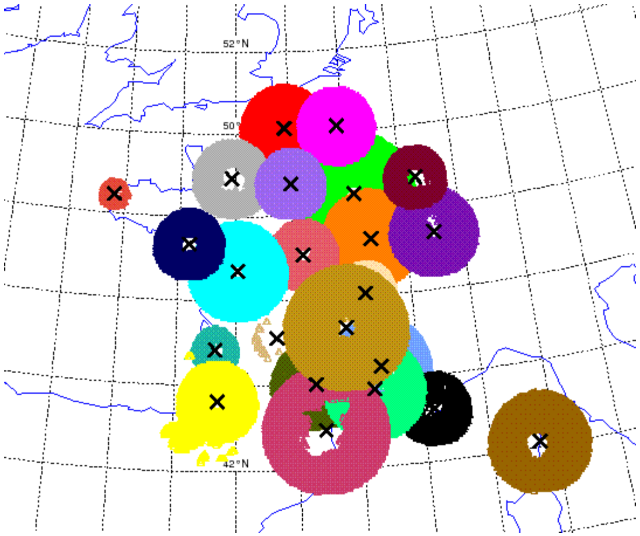
Wattrelot et al. (2011)

« No-rain » information (2)

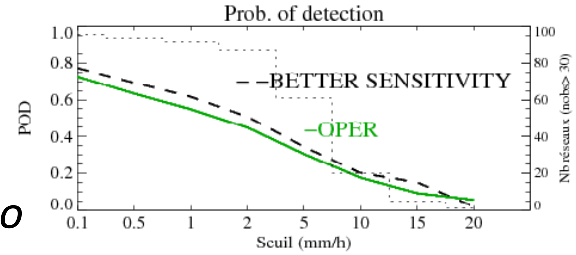
When Z_{SIM} < MDZ the model value is set to the radar one (Z_{SIM} = MDZ). This prevents from wrongly removing undetected weak rainfall events

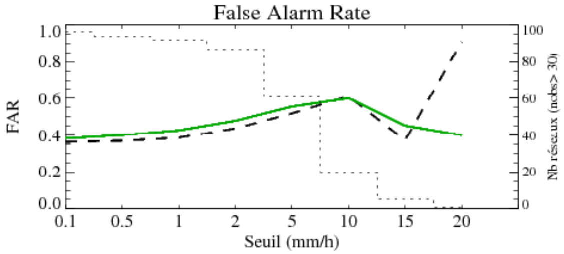


Example of areas of possible model « drying » from the ARAMIS network



Large impact on precipitation scores – 29 April to 12 May 2010



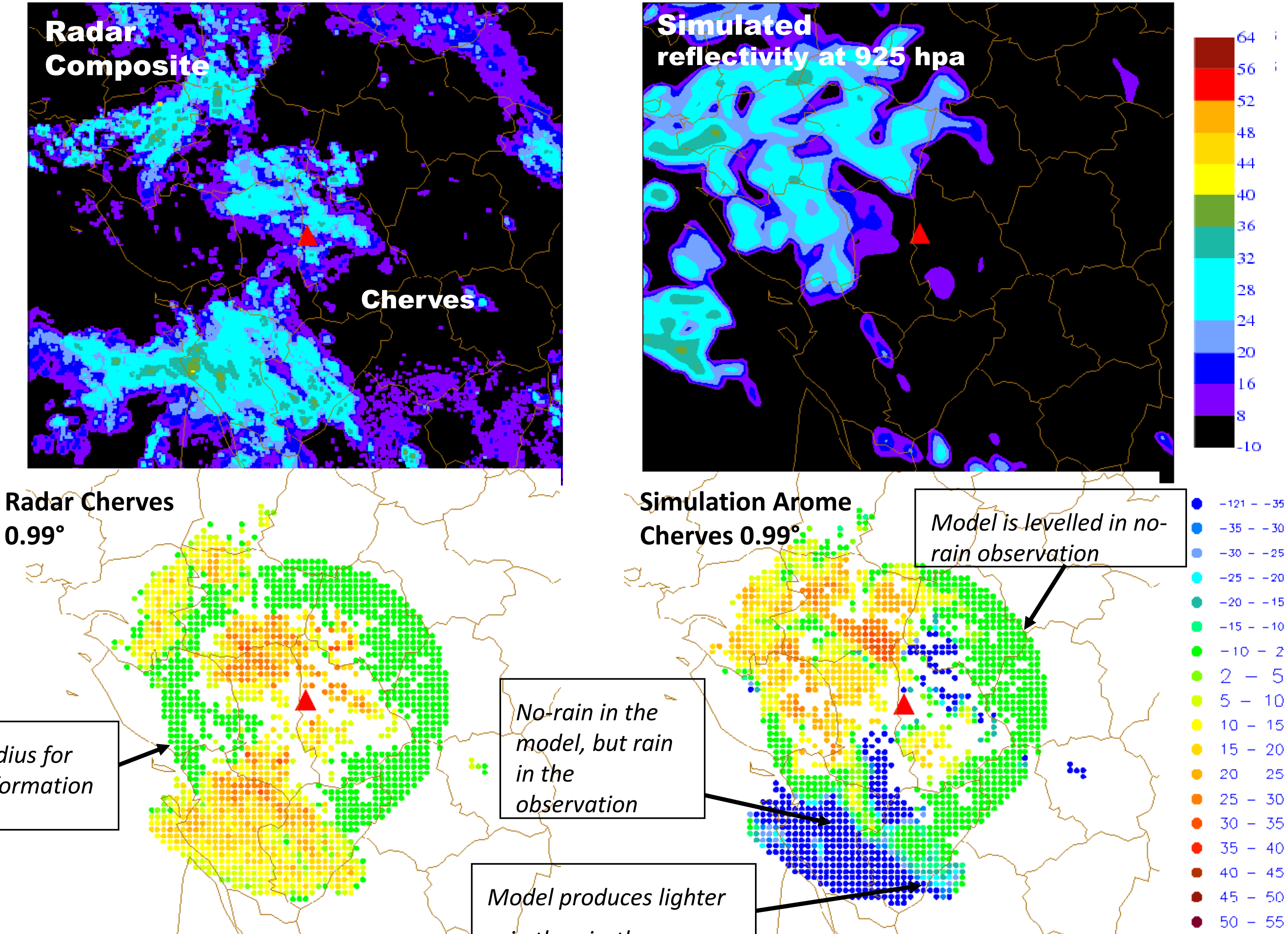


Wattrelot et al. (2011)

Illustration – reflectivity field – radar and model

CAPPI

PPI



Limited radius for no-rain information collection

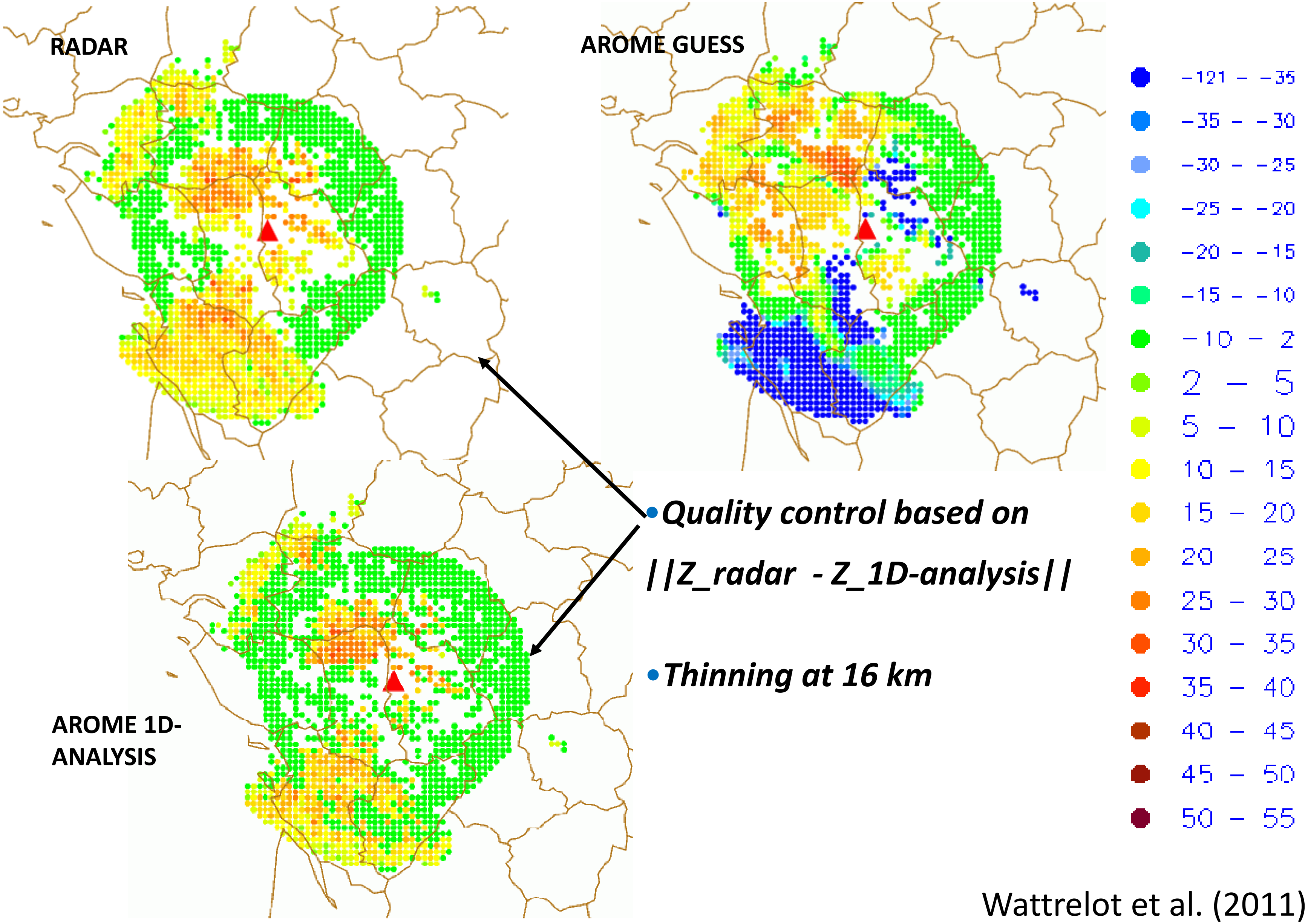
No-rain in the model, but rain in the observation

Model is levelled in no-rain observation

Model produces lighter rain than in the observation

Wattrelot et al. (2011)

Illustration – comparison between radar reflectivity and reflectivity 1D analysis : 1D convergence and quality control



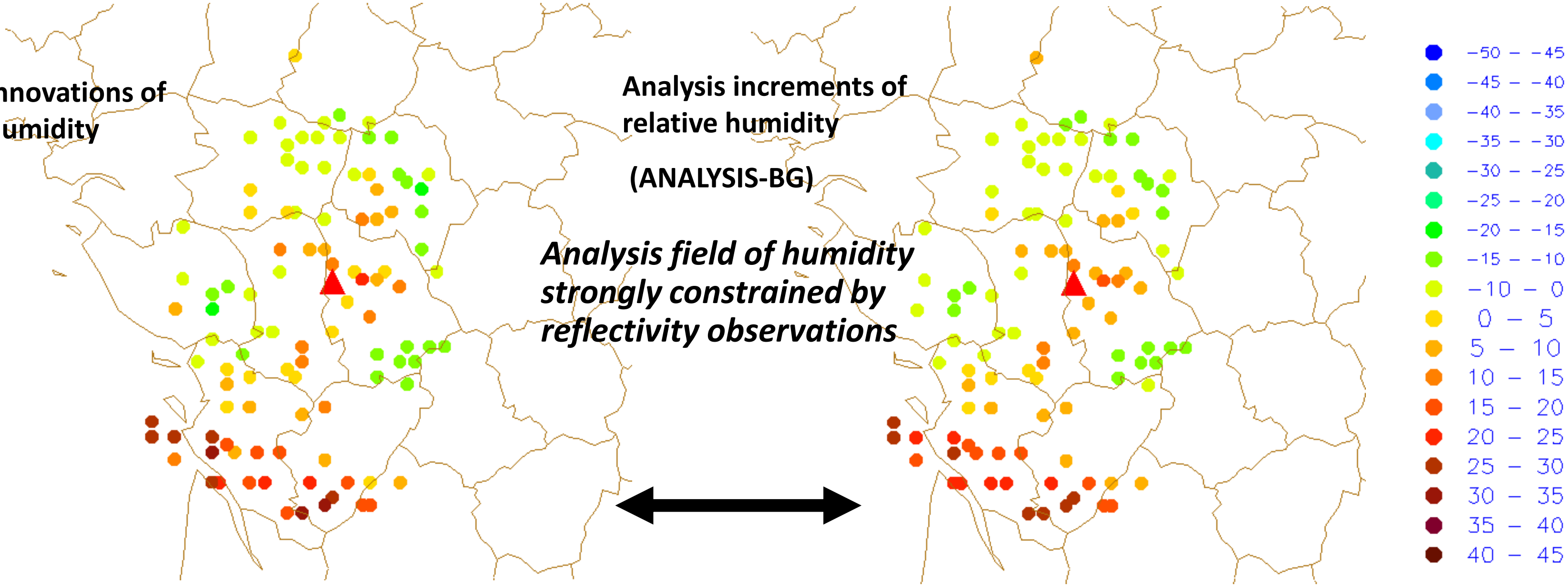
- ***Quality control based on***

  ||Z_radar - Z_1D-analysis||

- ***Thinning at 16 km***

Wattrelot et al. (2011)

Illustration – Active data of humidity retrievals and 3D-Var analysis increments



Pseudo-innovations of relative humidity

(OBS-BG)

Analysis increments of relative humidity

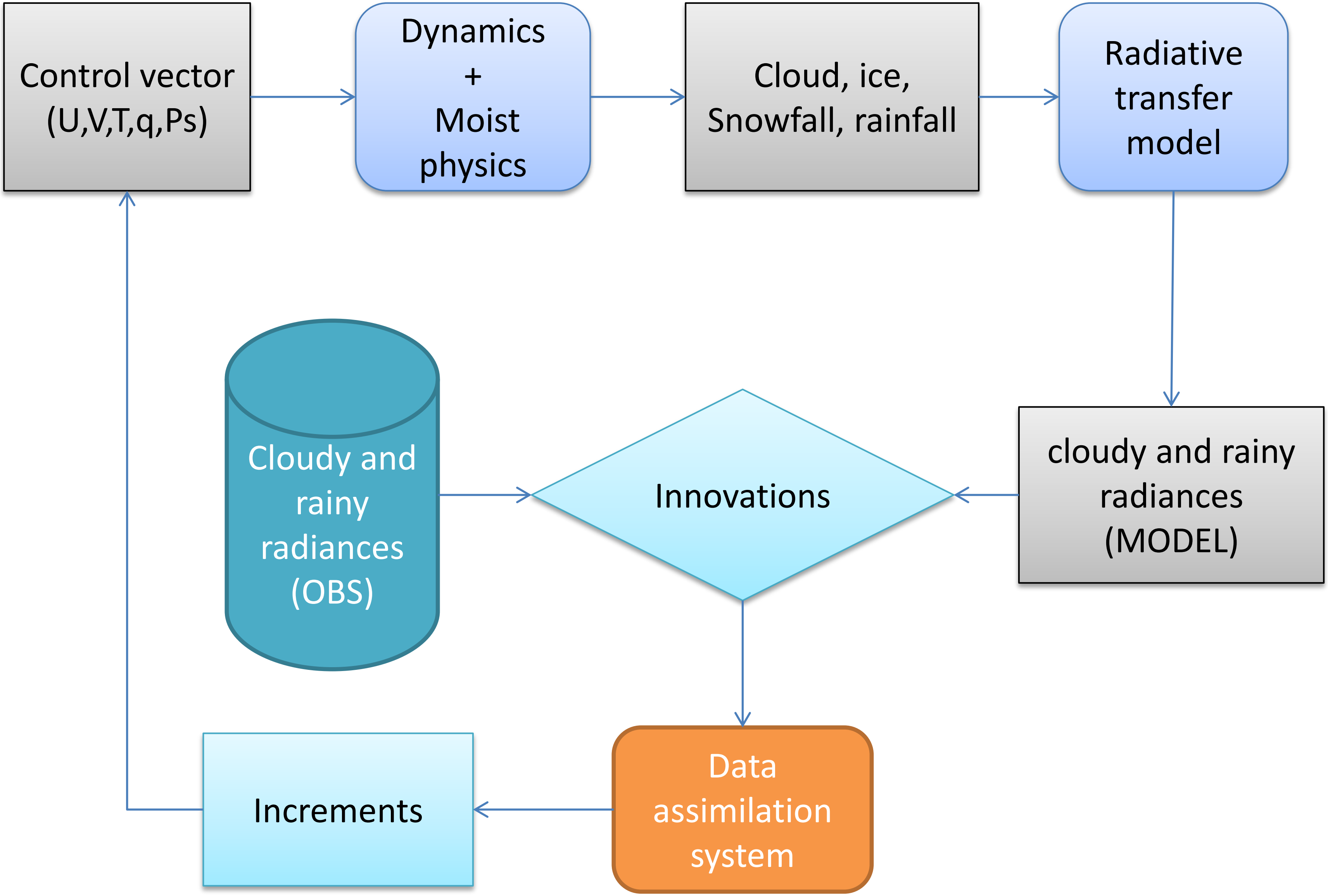
(ANALYSIS-BG)

Analysis field of humidity strongly constrained by reflectivity observations

Wattrelot et al. (2011)

Towards the assimilation of cloudy/rainy radiances

- Direct simulation of cloudy radiances possible with radiative transfer models (single cloud layer, multi-layer clouds with absorption and scattering processes)
- *IR region* : importance of cloud geometry – most clouds are opaque. Retrieval of single layer cloud properties (P_{top}, $N\varepsilon$) to allow the assimilation of radiances having sensitivity above cloud top.
- *MW region* : clouds are more transparent. Use of hydrometeor profiles from moist physics. Importance of scattering processes at high frequencies.



Control vector (U,V,T,q,Ps)

Dynamics + Moist physics

Cloud, ice, Snowfall, rainfall

Radiative transfer model

cloudy and rainy radiances (MODEL)

Innovations

Cloudy and rainy radiances (OBS)

Data assimilation system

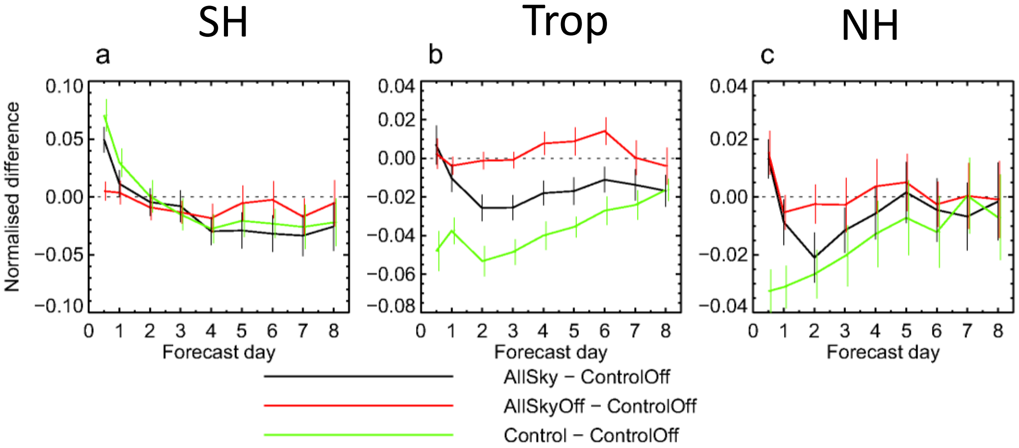
Increments

Assimilation of all-sky microwave radiances at ECMWF

- ECMWF 12h 4D-Var T511L91
- Experiments :
  - ControlOff : No MW radiances (clear sky and cloudy)
  - Control : 4D-Var for clear sky MW radiances and (1D+4D-Var) for cloudy radiances
  - Allsky : 4D-Var for clear sky and cloudy radiances
  - Allskyoff : No MW radiances but physics in 1st minimisation
- More recent design : « symmetric » cloud concept for observation errors and background check (normalized departures)

Normalized forecast scores

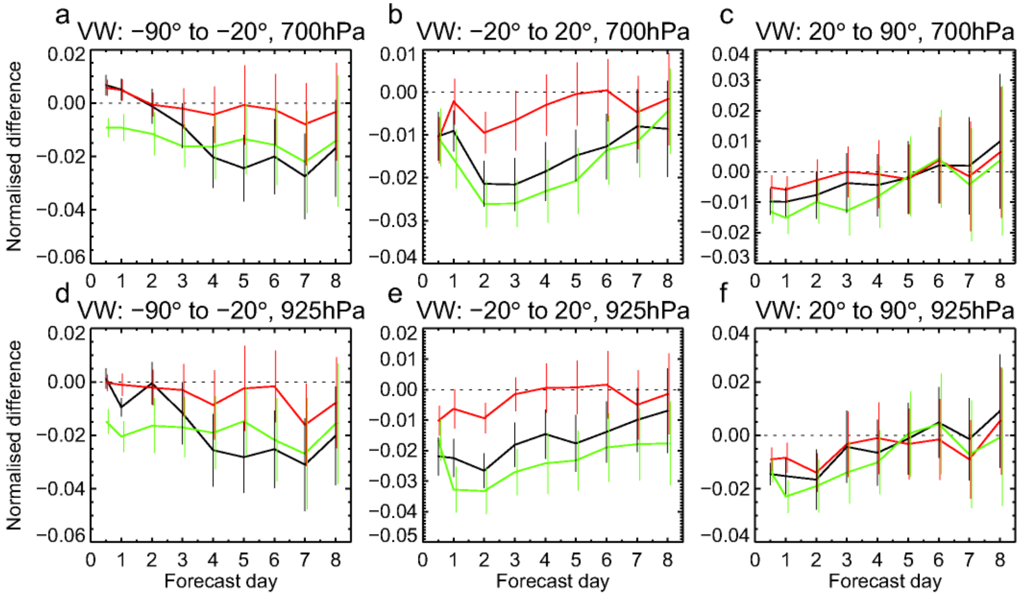
TCWV



Impact of 4D-Var all sky
Impact of 1D+4D Var
Impact of physics in 4D-Var

VW at 700 hPa

VW at 925 hPa



CONCLUSIONS AND REMAINING CHALLENGES

Conclusions

- Assimilation of the atmospheric water cycle has significantly progressed during the last 20 years due to :
  - Data assimilation systems allowing complex operators between observations and control variables
  - New observing systems (remote sensing principally) and better usage of existing ones
  - Improved description of physical parametrization schemes (cloud microphysics) – realistic simulation of radiances and reflectivities – (model evaluations in observation space)
- Sensitivity studies have shown positive impacts in terms of forecast skill scores on humidity, precipitation, winds, and temperature – Improved reanalyses of humidity

Remaining challenges (1)

- Extension of the control vector to hydrometeors
- Background error statistics (new + revised)
- High temporal availability of observations for mesoscale data assimilation (which method ?)
- High spatial resolution of observations (error correlations) and mesoscale models (scale issues)
- Mislocation of cloudy and rainy structures
- Combined assimilation with other components (e.g. atmospheric moisture + soil moisture)
- Importance of new (revised) diagnostic tools => impact of « moist » observations in NWP systems
- Importance of field campaign experiments : HYMEX (water cycle over the Mediterranean basin) – autumn 2012

Remaining challenges (2)

- Improved usage of existing satellite instruments (+radars) and preparation of new ones (NPP, Mégha-tropiques, GPM, EarthCARE)
- Revised description of microphysical processes (dual-polarization radars, high frequencies from MW radiometers)
- Ground based networks :
  - Global data availability is needed : GPS and radar (remain only available at national or continental levels – EUMETNET OPERA initiative)
  - New surface networks : vertically pointing cloud radars, lidars and radiometers

Thank you for your attention !