Cloud assimilation from satellites in NWP models:

Current status and prospects

Jean-François Mahfouf

Meteorological Service of Canada

MRB/RPN

Dorval (Canada)

Thanks to F. Chevallier, P. Lopez, P. Bauer, G. Deblonde, C. Burlaud

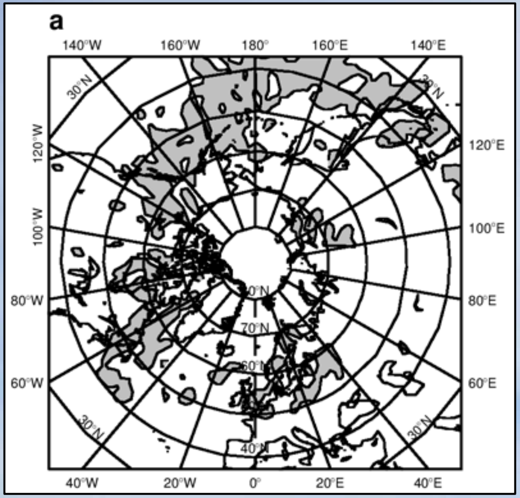
Goal of my presentation

- **Initiate discussions for the working groups**
- Define the interest for cloud assimilation (and how to remain optimistic and pragmatic)
- Review what has been done so far (with few examples)
- Describe specific problems on cloud data assimilation (including precipitating clouds)
- Propose areas to explore and issues to address in the near future

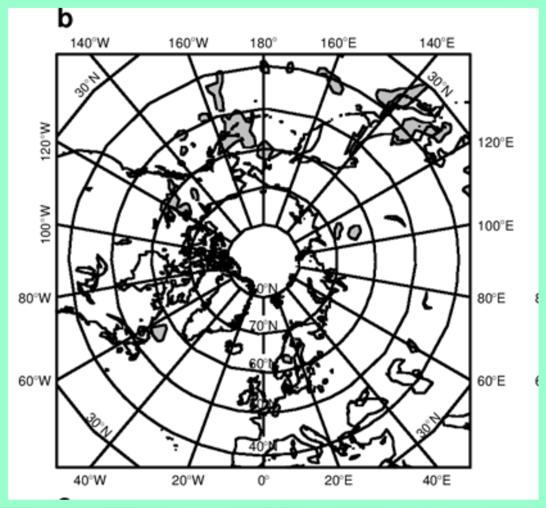
Context

- “Cloud assimilation” not “cloud analysis” => *improving* the initial conditions of NWP models
- No interest in clouds per-se but on model variables for which the initialization will affect the resulting forecasts => sampling sensitive areas of the atmosphere located in cloudy regions

Adjoint sensitivity temperature perturbations near 600 hPa (S) [mean absolute value Dec. 1999]

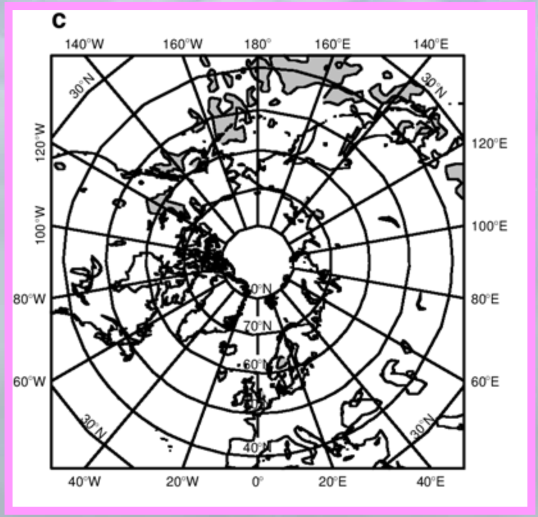


Perturbations modified by high cloud cover



S*=S.F(cc,h)

Perturbations modified by low cloud cover



McNally (2002)

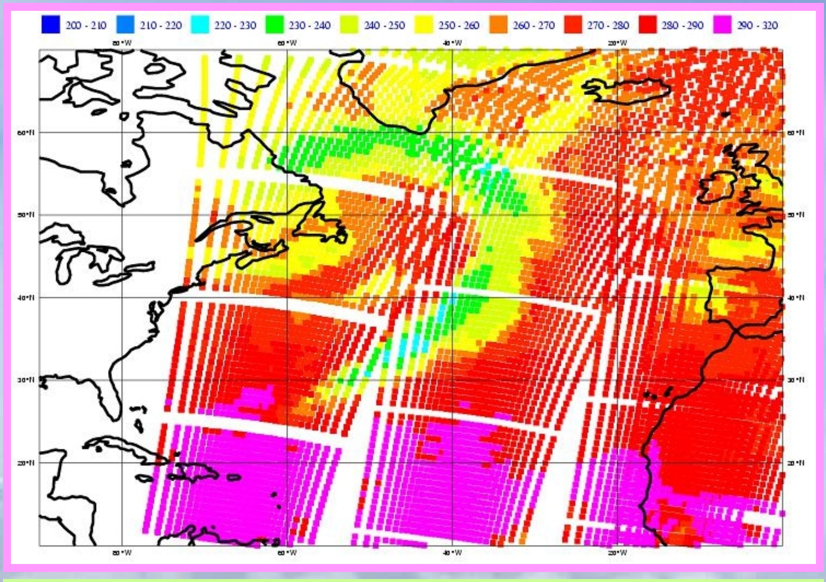
Why assimilate clouds from satellites ?

- The atmosphere is full of clouds
- Data are there in NWP centers – and new ones are coming (A-Train, EarthCARE, NPOESS)
- Clouds contain extremely valuable information on the atmosphere (T, q, ω, q_c, q_i)
- QPF need improvements : little hope in predicting accurate precipitation with “wrong” clouds
- NWP models have some skill in forecasting clouds
- Data assimilation problem : **how to extract such information ?**

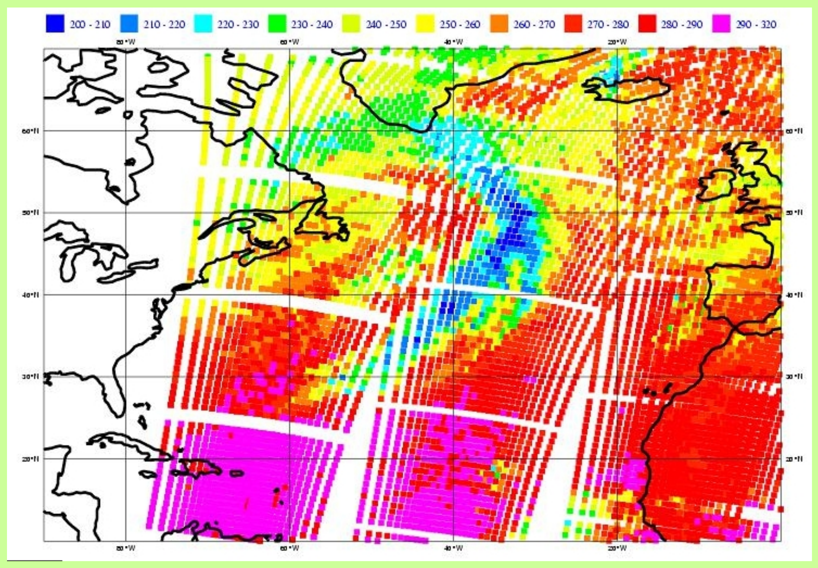
Mid-latitude cyclones as seen from HIRS-8

ECMWF ERA-40, 13/01/1987
06 UTC

Model



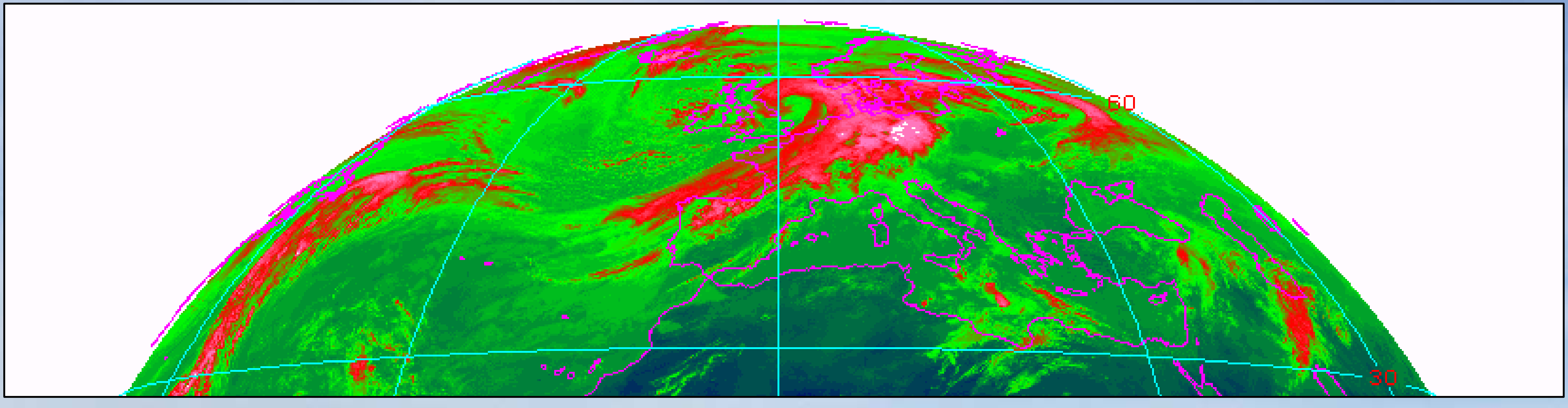
Observations



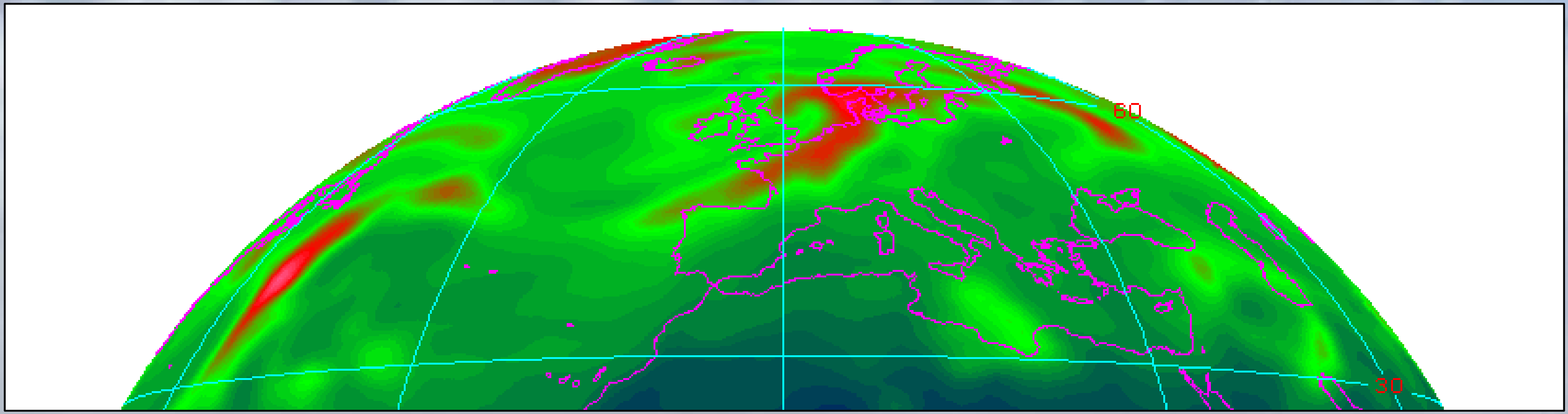
Chevallier et al. (2001)

Meteosat-7 11µm image

30/10/2000 12UTC



Meteosat-7 11µm image simulated with operational ECMWF 12H FC



Chevallier and Kelly (2002)

“Useful” clouds

- “Visible” signature of moist regions of the atmosphere
- Passive clouds (tracers) : signature of horizontal advection (link with rotational wind)
- Active clouds : signature of strong vertical motion (link with divergent wind and atmospheric stability)
- Need to be embedded in a resolved dynamical environment

How to assimilate cloud observations ?

- General data assimilation problem solved using the optimal estimation theory
- Provides an optimal atmospheric state x_a from observations y_o (with associated errors **R**) and an a-priori information x_b (with an associated errors **B**):

$$\boxed{x_a = x_b + HB^T (HBH^T + R)^{-1} [y_o - \mathit{H}(x_b)]}$$

where *H* is an observation operator and **H** and $\mathbf{H}^{\mathbf{T}}$ its linearized versions

General framework

- Techniques : 4D-Var and EnKF
  - Merits : flexibility to include any type of observation [asynoptic data (MATS) / complex observation operators H / coherence with other observations] and the right questions need to be addressed
  - Drawbacks : some of the underlying assumptions of optimal estimation theory may not be valid for cloud observations (e.g. weak non-linearity of the observation operator) – strong constraint on model capability to generate realistic cloud properties (MATS) - computational cost

Current status

- Current operational methodologies
  - Mesoscale models : empirical techniques relating cloud top pressure and cloud optical depth (from geostationary satellites) into humidity or condensed water profiles (ex: RUC, MOPS)
  - Global models : 1D+4D-Var assimilation of SSM/I radiances (precipitating clouds)
- Feasibility studies
  - 1D-Var : Chevallier – Benedetti - Janiskova (no link with dynamics)
  - 2D-Var : Lopez et al. (no link with dynamics but temporal consistency of T and q profiles required – synergy of observations)
  - 4D-Var : Vukicevic et al. (warm clouds in 25 km mesoscale model – 3h window – GOES radiances – unable to create clouds)

Specific issues

- Wide range of spatial/temporal scales
  - Data filtering (or selection) at model scale
  - Unpredictability of small scales (no need to initialize)
- Complex observation operators (cloudy radiances or cloud retrievals) –need to specify associated errors
- Incremental 4D-Var assimilation (global systems) :
  - Analysis of large-scale increments – pb of scale dependency of physical parameterization schemes
  - Perfect model assumption : extend the control variable for model errors (initial value problem ?)
  - Background error statistics (a-priori info): no distinction between cloudy and clear-sky regions (mean values)
  - Gaussian statistics (two moments)

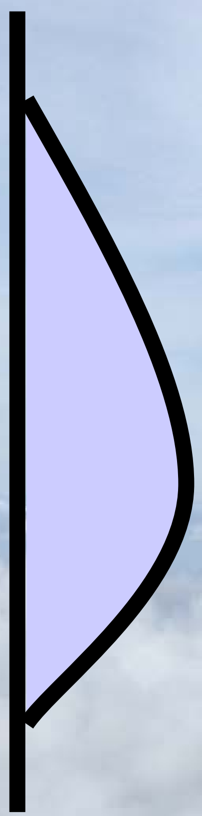
Required cloud properties for NWP and H

- Water budget
  - Macro-scale : fractional coverage (horizontal – vertical) –overlap assumption – cloud/ice water contents
- Observable moments of PSD
- Energy budget (radiation)
  - Optical properties : optical depth, effective radius, single scattering albedo, asymmetry factor, extinction coefficient

Satellite data available

- Passive sensors : radiances in VIS/IR/MW – polar orbiting and geostationary satellites – sounding and window channels
  - Passive VIS/IR : cloud top pressure, cloud amount, optical depth, ice top concentration
  - Passive MW : ice/water contents (integral)
- Active sensors : radar reflectivity – lidar backscatter (A-Train)
  - Vertical profile, cloud ice/water, particle size
- Complementary information => importance of synergy

Actual profile



Model profile

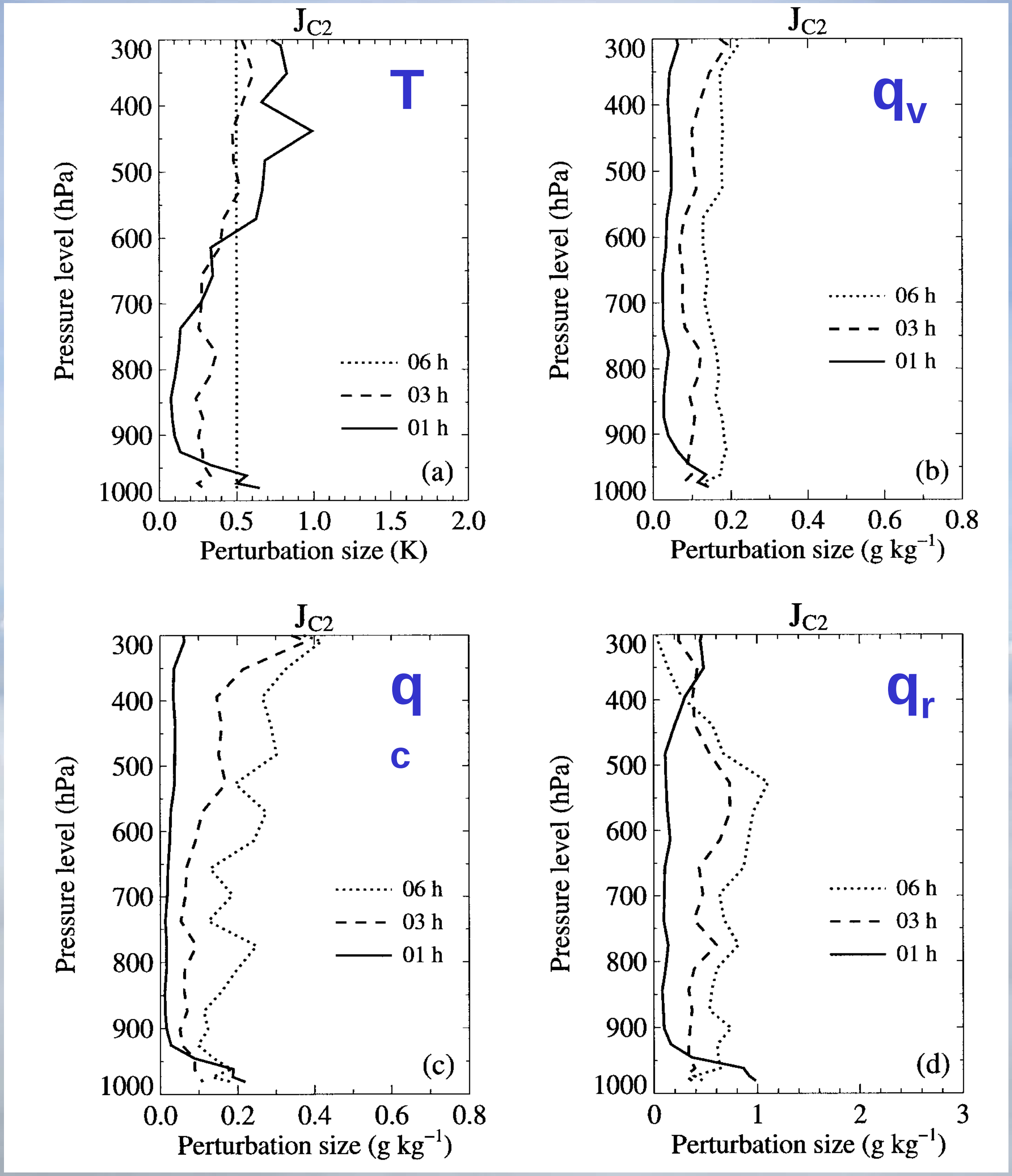
MW info $$\boxed{\int q_l^{o} dp = \int q_l^{fg} dp}$$

IR info $$\boxed{p^{o}_{top} \neq p^{fg}_{top}}$$

Variables to initialize

- Can we simply initialize the thermodynamics (T,q_v) and let the condensed variables (q_c) adjust (definition of control variable) ?
- Possible for large-scale models :
  - assimilation window > cloud time scale (but not for CRMs)
- Sensitivity to initial cloud and rain contents (Lopez, 2003)
- Less critical problem in 4D-Var : with a 12-h window the model is constraining the cloud variables through other variables that are modified by assimilated observations.
- Grid-scale clouds : importance of T since $q=q_s(T)$
- Balance constraint to provide consistent dynamics :

$$\boxed{\delta\omega = F(\delta T, \delta q)}$$



$$J_{c2} = \sum q_c^{\ 2}$$

How to modify the initial conditions (T, q_v, q_c, q_r) to impact the forecast of J_{c2} ?

$$\delta T = 0.5K \Rightarrow \delta J_{c2}$$

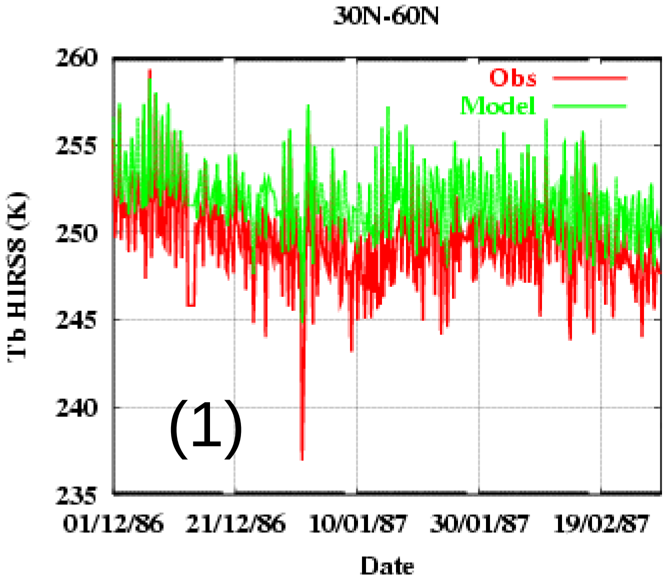
$$\delta q = ? \Rightarrow \delta J_{c2}$$

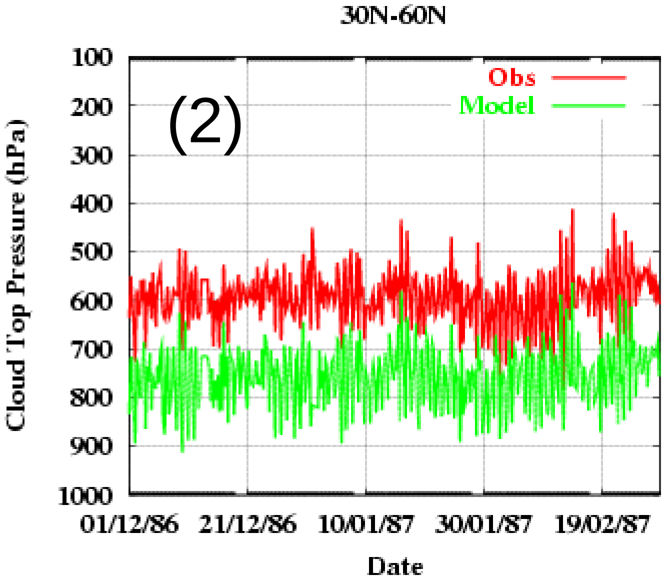
Lopez (2003)

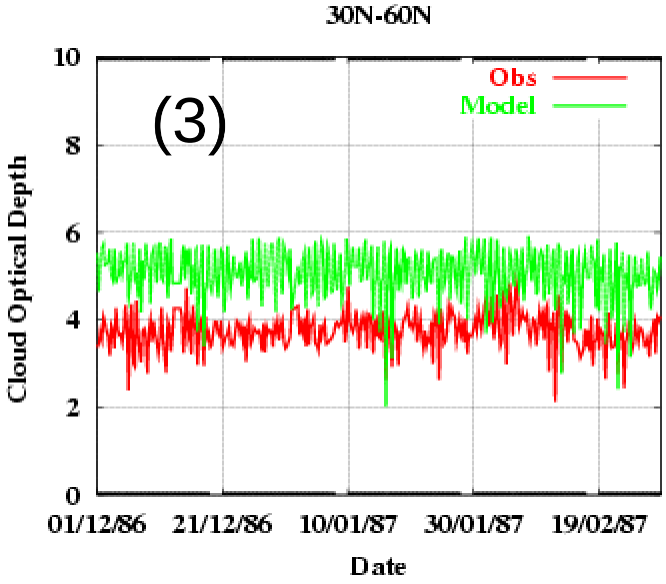
Towards the assimilation of cloudy radiances

- Step 1: develop an observation operator (moist physics + RT model)
- Step 2: compare model and obs in radiance space – evaluate physics (identification of biases – model errors) – spatial and temporal consistency between model and observations.
- Step 3 : Sensitivity study (Jacobians) of observation operator – evaluation of the TL approximation (for variational assimilation)
- Step 4 : 1-D assimilation
- Step 5 : 4-D assimilation (coupling with dynamics -> how much from B, how much from M ?)

- ERA-40 time series of latitude band mean over oceans
  1. HIRS-8 (11 µm) radiance
  2. Cloud-top pressure
  3. Cloud optical depth





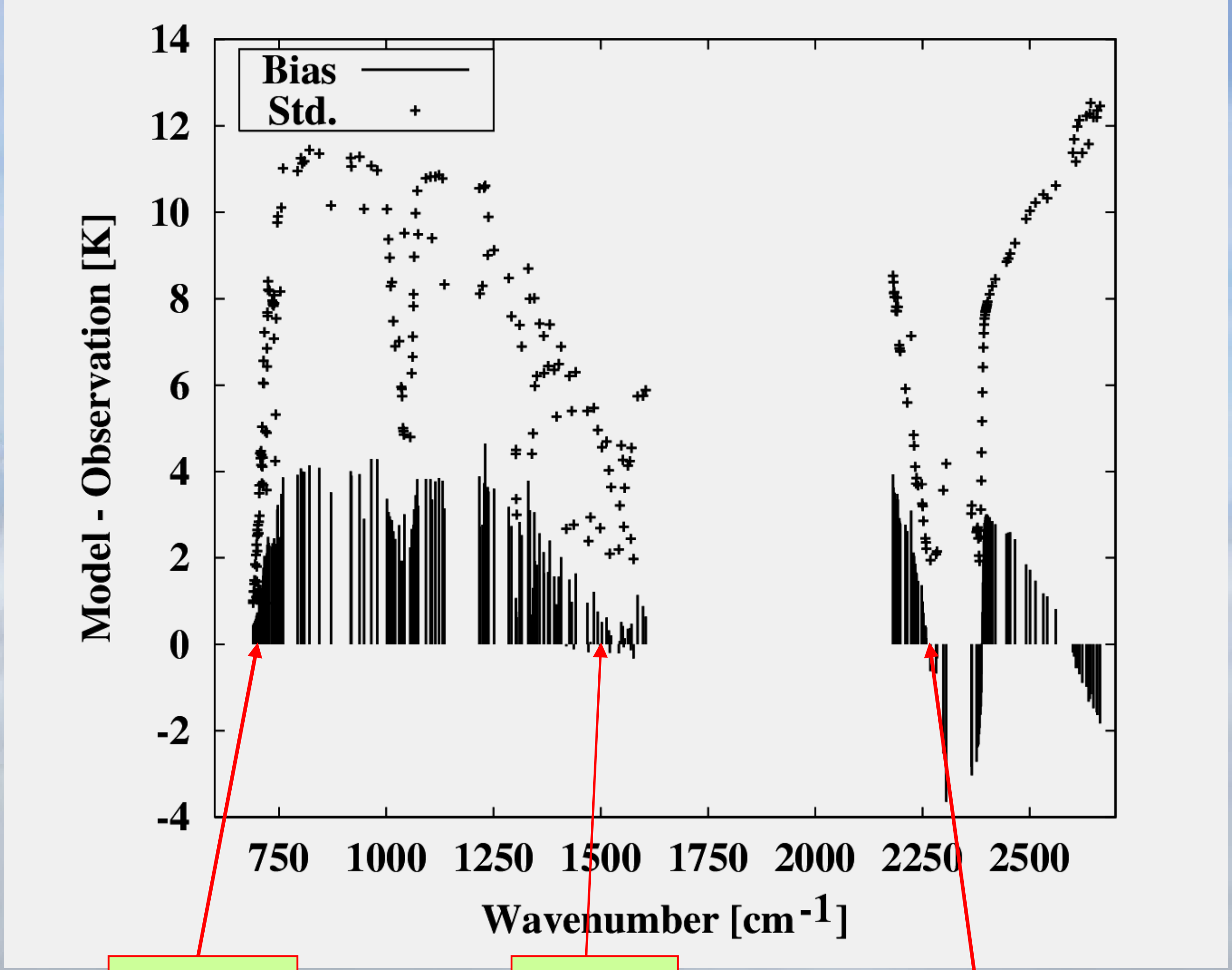


Chevallier et al. (2001)

Cloudy radiance observation operator

- Convection : probably hopeless for clouds if implicit (too crude description of microphysics) - closure problem : link between cloud fluxes and resolved variables
- Stratiform : smooth transition for cloud creation and rain formation (reduced thresholds – statistical approaches : e.g. Tompkins and Janiskova, 2004)
- Difficulties : ice (type, shape, density) + subgrid-scale description (empirical PDF)

Cloud affected AIRS brightness temperatures (O-P) differences – 30/11/2002 –ECMWF physics



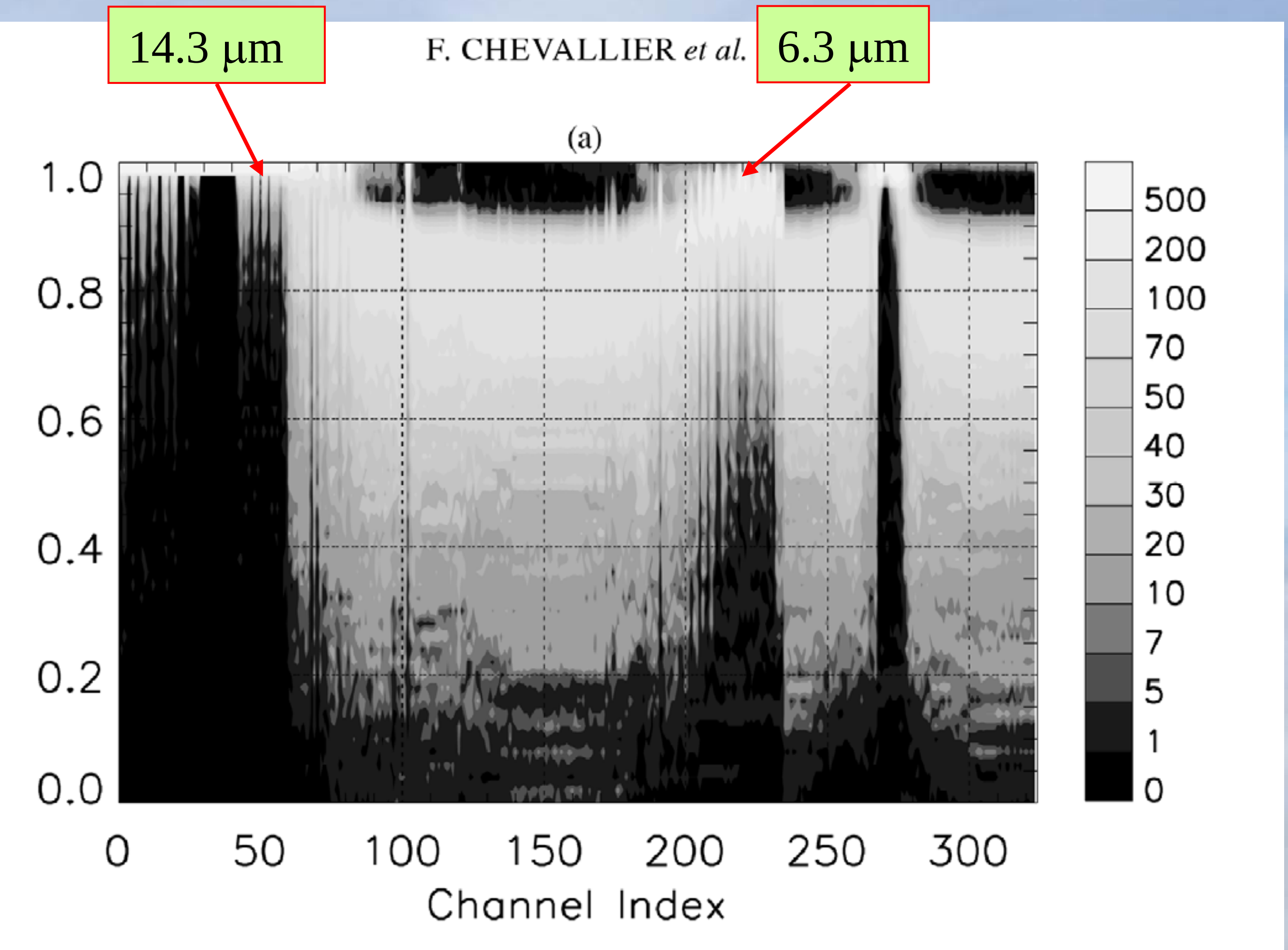
14.3 µm

6.3 µm

4.5 µm

Chevallier et al. (2004)

Non-linearities in radiance space

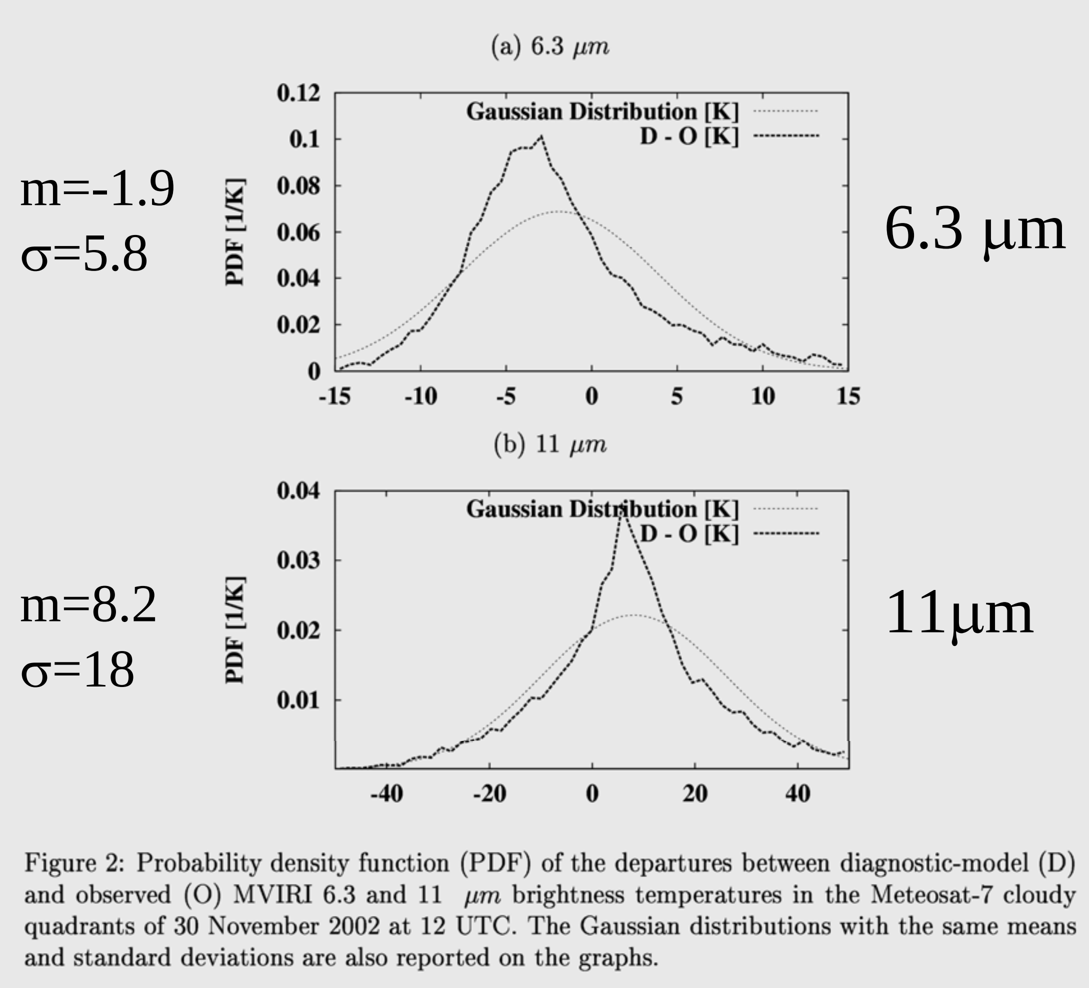


35 channels
out of 324 :
- clouds
- corr > 0.85
- (O-P)< 6K

DF of correlations between $H(x+\delta x)-H(x)$ and $\mathbf{H}(\delta x)$ for AIRS channels

Error PDF in radiance space

Meteosat
Cloudy radiances
(P-O) distribution
ECMWF physics



m=-1.9
σ=5.8

6.3 μm

m=8.2
σ=18

11μm

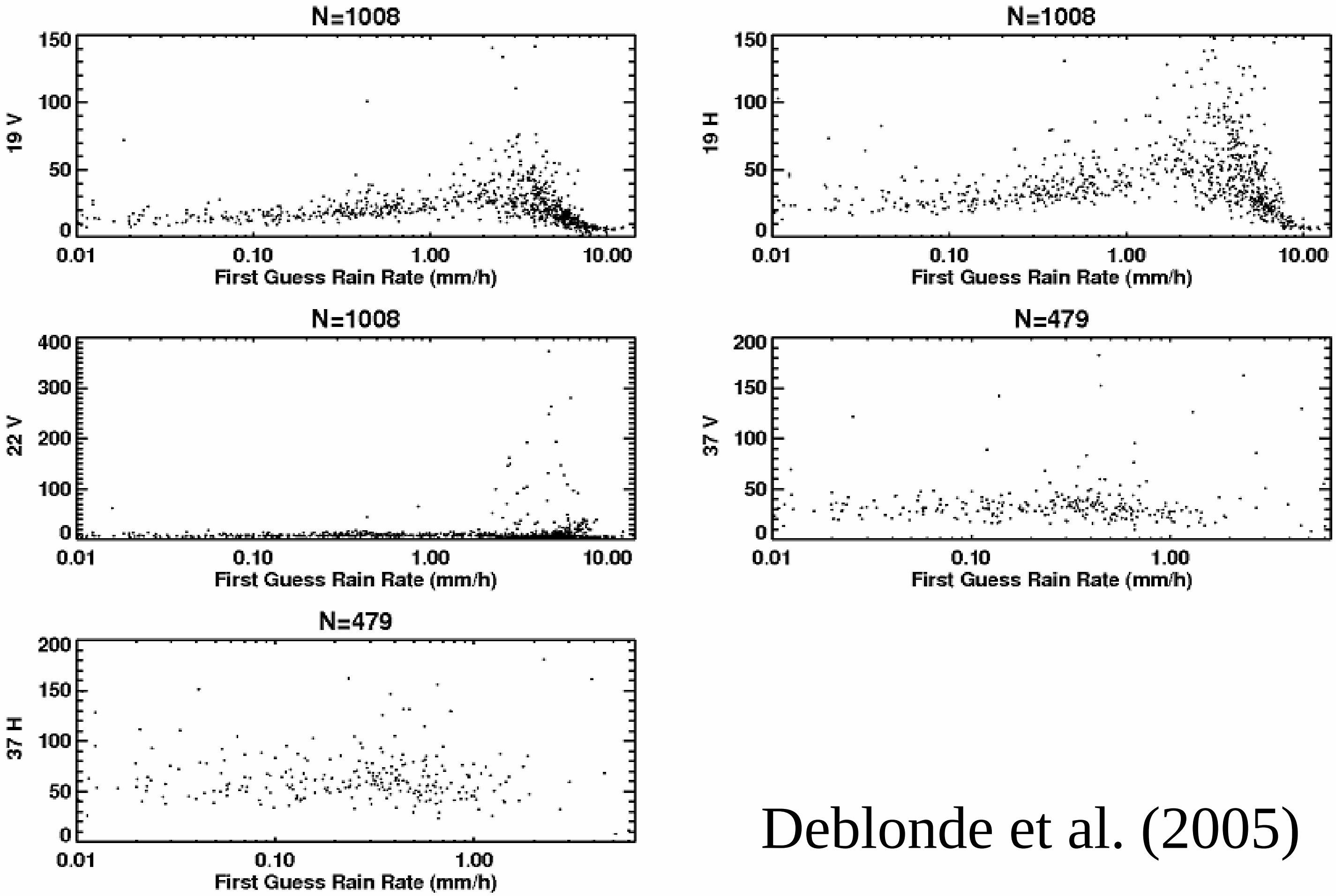
Figure 2: Probability density function (PDF) of the departures between diagnostic-model (D) and observed (O) MVIRI 6.3 and 11 μm brightness temperatures in the Meteosat-7 cloudy quadrants of 30 November 2002 at 12 UTC. The Gaussian distributions with the same means and standard deviations are also reported on the graphs.

Chevallier et al. (2004)

Errors of forward operator (moist physics + RT)

$$\boxed{\sigma_o = \sqrt{HBH^T}}$$

Errors of simulated SSM/I Tbs

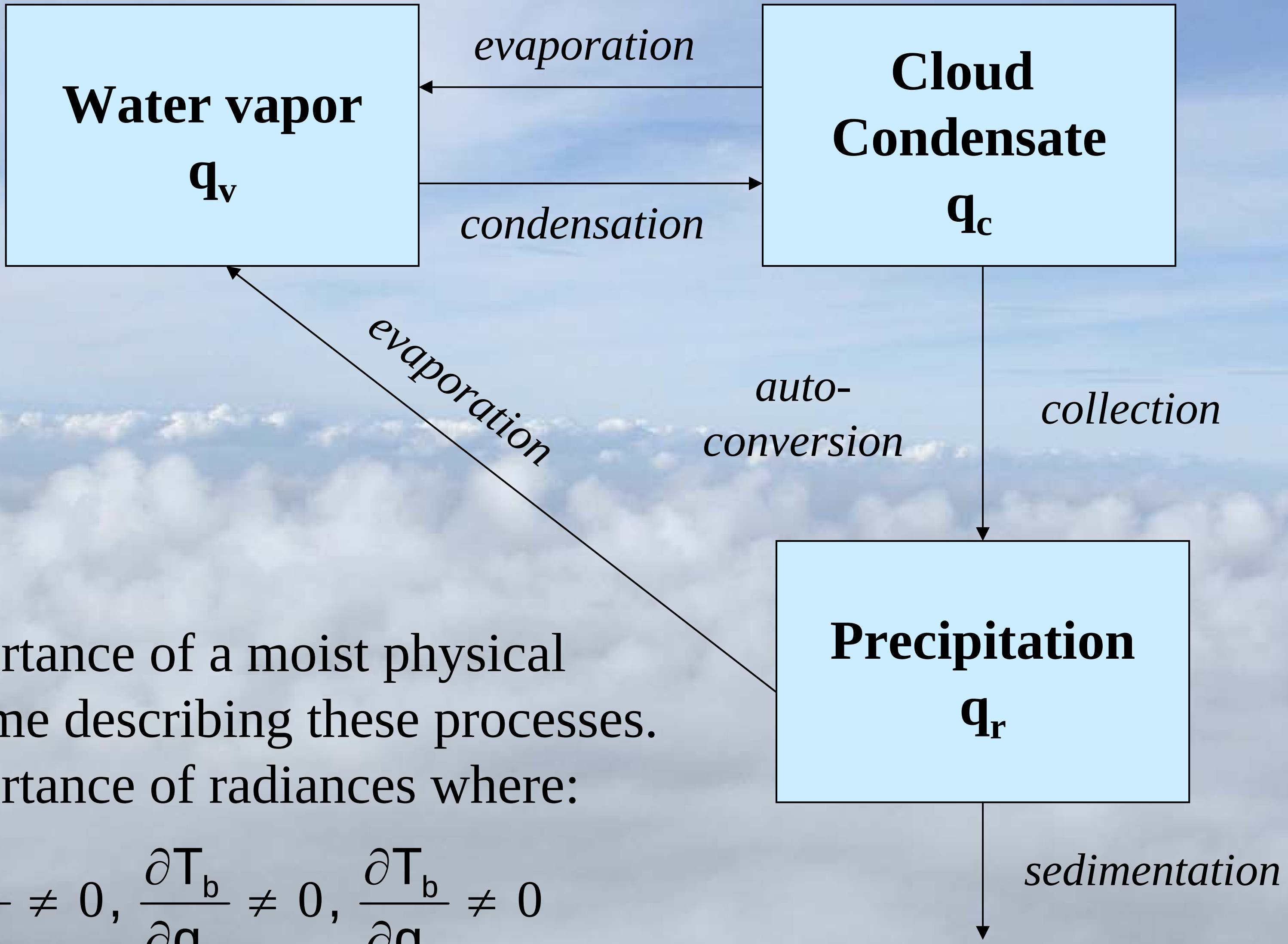


Deblonde et al. (2005)

Thresholds in radiance space

- SSM/I brightness temperatures are sensitive to integrated q_v, q_c and q_r
- Interest in using sounding channels that are sensitive to clear-sky and cloudy situations (e.g. AMSU, SSMIS, CMIS)
- If an observation operator can describe these transitions => possibility to trigger clouds and to constrain T/q profiles when removing model clouds.

Requirements for the observation operator



Water vapor
q_v

evaporation

condensation

Cloud Condensate
q_c

evaporation

auto-conversion

collection

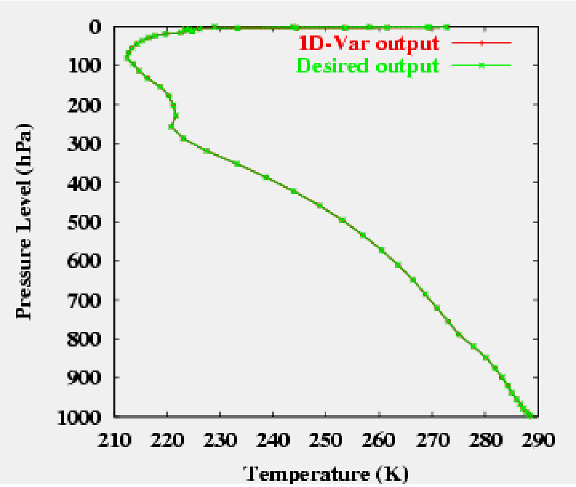
Precipitation
q_r

sedimentation

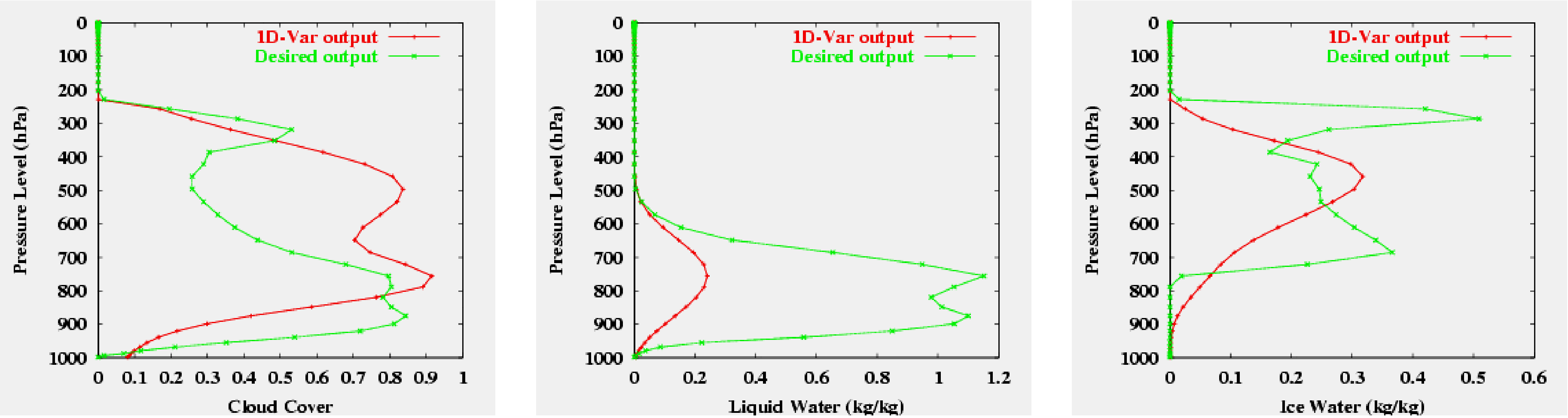
Importance of a moist physical scheme describing these processes.
Importance of radiances where:

$$\frac{\partial T_b}{\partial q_v} \neq 0, \frac{\partial T_b}{\partial q_c} \neq 0, \frac{\partial T_b}{\partial q_r} \neq 0$$

Creation of clouds using 1D-Var



- $T(p)$, $q_v(p)$, $cc(p)$, $q_c(p)$, $q_i(p)$
- First guess = no cloud
- Simulated observations = RTTOV (cloud)
  - HIRS (5 channels), AMSU-A (6 channels)



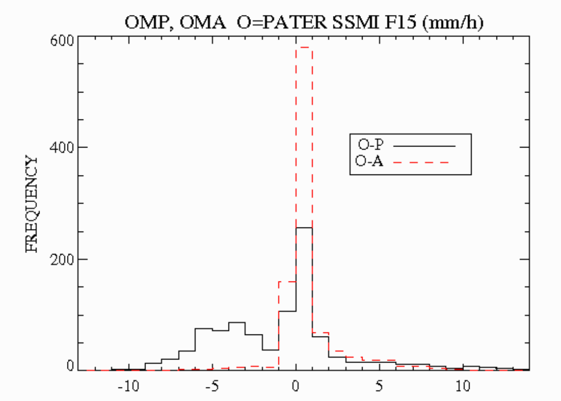
North Atlantic front

Scale factor 10000 on liquid and ice water

Chevallier at al. (2002)

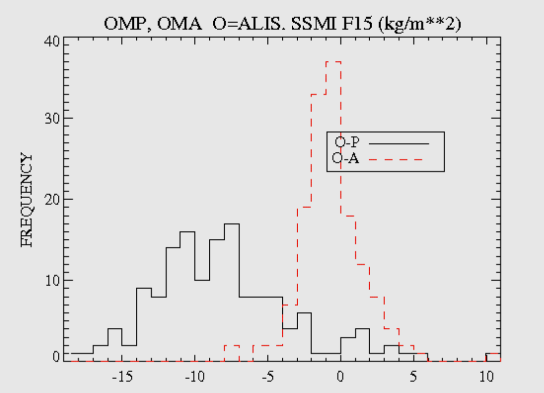
1D-Var assimilation of SSM/I radiances
Consistency of various "moist" retrievals

Surface Rain Rate



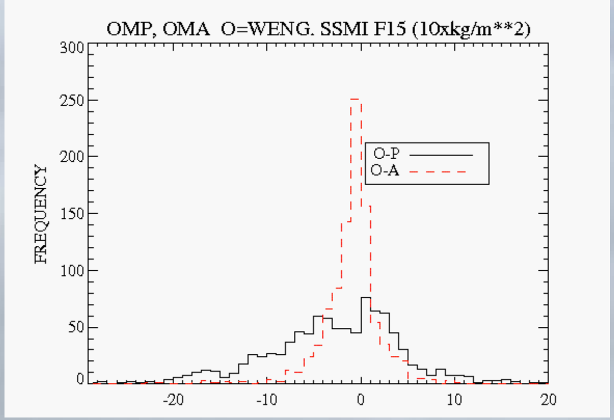
N=959 -0.98 3.94 / 0.66 1.85 (mm/h)

Integrated Water Vapor



N=148 -8.02 4.86 / -0.62 2.25 (kgm^{-2})

Cloud Liquid Water Path



N=951 -0.285 0.71 / -0.096 0.31 (kgm^{-2})

Tropical Cyclone Zoe 2002
12 27 000 UTC SSM/I F15
(O-P) and (O-A)

Deblonde et al. (2005)

Preliminary conclusions (1)

- The amount of satellite observations on **water vapor** is steadily increasing in operational data assimilation systems
- The assimilation of **precipitation** and **rainy radiances** has also been studied for many years (e.g. pre-operational at ECMWF)
- Consistency between those two is required and is provided by **clouds**
- Assimilation of cloudy radiances is becoming feasible :
  - Improved physical parameterization schemes for moist physics
  - New flexible data assimilation systems (4D-Var and EnKF)
  - New satellite data (active sensors, high resolution passive sounders)
  - Important similarities between cloudy and rainy radiances

Preliminary conclusions (2)

- Thresholds : less a problem in radiance space for channels sensitive to water vapor and condensed water
- Non-linearities : possibility to choose not too non-linear channels (high resolution sounders)
- Non-gaussian statistics : less a problem in radiance space
- Advices (t.b.d.):
  - Assimilate radiances (that are reasonably well modelled) instead of satellite derived products
  - Assimilate only clouds that are explicitly resolved by the NWP model (=> “useful” observations depend upon model resolution)
  - Assimilate “averaged” quantities ($<T_b>$,$T_b=T_b$(LWP)) – MW less sensitive to vertical distribution (pb of model vertical discretization)

Areas to explore [1]
(to be discussed in WG)

- Improvements in cloud physics
    - Validation in terms of satellite radiances/reflectivities (quantification of model errors and biases)
    - Adaptation to data assimilation requirements (e.g. linearity, smoothness, closer link with observables, consistency with RT microphysics)
- Follow (or contribute to the) improvements of DA systems:
    - Inclusion of model errors and bias correction schemes
    - Balance constraints in B matrix
    - New control variables and associated B (e.g. q_{tot})
    - Non-incremental 4D-Var formulations – realistic EnKF
- These aspects should help to make the assimilation of cloud observations more effective
- Adaptation of usual smoothing and filtering treatments for cloud observations (predictability of small scales, temporal accumulations)

Areas to explore [2]
(to be discussed in WG)

- **Diagnostic and sensitivity studies**
- Moist studies in a variational context (similar to what has been done for q_v and q_r but for q_c) :
  - Sensitivity studies to q_c (LWP)
  - Singular vector computations using q_c in the control variable or in the final norm
- Specification of background errors in cloudy regions (e.g. statistics using radiosondes, GPS, NMC method, EnKF, or Ensemble analyses)
- How to validate data assimilation systems using cloud observations ?