Advances in model physics and their relevance to satellite data assimilation

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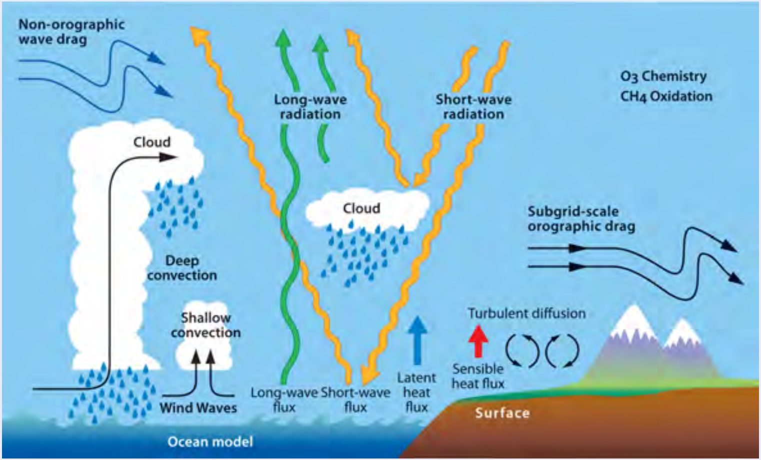
A number of questions

- Where does model physics take place in data assimilation ?
- Is it useful to care about model physics for satellite data assimilation ?
- If yes, what are the most important physical processes to consider ?
- Is there an interest for a better synergy ?
- What are the challenges to come with new satellite data and new assimilation systems ?

Atmospheric model physics

The most important diabatic processes

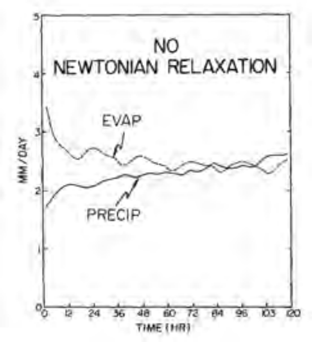


Outline

- First attempts in the 80's towards the use of physics with satellite data
- Ongoing activities on the assimilation of satellite radiances in clouds
- Towards the assimilation of satellite radiances within land surface models
- Interest in evaluating model physics using the data assimilation framework
- Summary of future challenges

Physical initialization

The spin-up problem

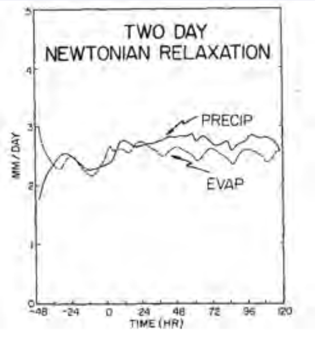


Krishnamurti et al. (1988)

- Water cycle imbalances in tropical regions
- Less observations and less geostrophy
- Use of satellite data to constraint model diabatic heating rates with consistent dynamics

Physical initialization

The spin-up problem



Krishnamurti et al. (1988)

- Use of IR satellite temperatures (cold clouds) as rainfall rate proxy (RR)
- Inversion of a simple convection scheme (Kuo type) : $\Delta q = K^{-1}(\Delta RR)$
- Newtonian relaxation to induce consistent changes to the wind divergent from humidity corrections
- Reduced model spin-up and improved short-range tropical forecasts

The 4D-Var assimilation

A better framework to address the physical initialisation problem ?

The cost function

$$J(\mathbf{x}_0) = \frac{1}{2}(\mathbf{x}_0 - \mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}_0 - \mathbf{x}_b) + \frac{1}{2}(H(\mathbf{x}_t) - \mathbf{y}_o)^T \mathbf{R}^{-1}(H(\mathbf{x}_t) - \mathbf{y}_o)$$

Where is the model physics ?

- In the J_o term to compute $\mathbf{x}_t = M(\mathbf{x}_0)$,
- In the $\mathbf{B}$ matrix (ensemble of forecasts with M)
- In the observation operator H (e.g. surface boundary layer scheme for T_{2m} or V_{10m})

The gradient of the cost function

$$\nabla J(\mathbf{x}_0) = \mathbf{B}^{-1}(\mathbf{x}_0 - \mathbf{x}_b) + \mathbf{M}^T \mathbf{H}^T \mathbf{R}^{-1}(H(\mathbf{x}_t) - \mathbf{y}_o)$$

What are the requirements for linearized model physics ?

- Incremental 4D-Var : can survive in the low resolution inner loops with only surface friction
- Important in adjoint sensitivity studies (e.g. reduction of forecast errors from observations sensitive to humidity)
- Essential for the assimilation of observation sensitive to condensed water : rainfall, cloudy satellite radiances, radar reflectivities, lidar backscatter
- Issues with thresholds and non linearities : need of simplifications and regularizations for improving the validity of the tangent-linear approximation
- ECMWF comprehensive package of linearized physics (Janisková and Lopez, 2012)

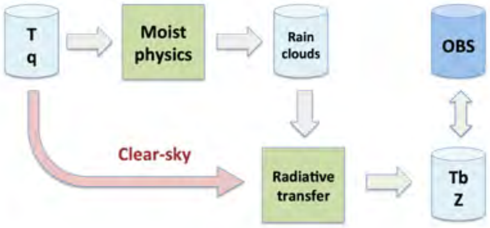
Assimilation from a satellite perspective

- What we are good at :
  - Clear sky radiances over oceans
- What we are improving on :
  - Clear sky radiances over land and sea-ice
  - Infra-red radiances above cloud top
  - Cloudy microwave radiances at low frequencies (below 50 GHz)
- What remains a challenge (and where the physics could help) :
  - Cloudy satellite radiances (high frequency microwave and infra-red)
  - Coupled assimilations with surfaces
  - Satellite radiances in extreme atmospheric conditions (snow, cold surfaces)
  - Measurements from active sensors

Assimilation of remote sensing observations in clouds

Diagnostic moist physics

- Assimilation framework unchanged : moist physics = additional observation operator
- Need of linearized versions in variational assimilation



Use of diagnostic moist physics at ECMWF

Linearized moist physics in 4D-Var

- Moist convection scheme based on a mass-flux approach (Lopez and Moreau, 2005) and stratiform precipitation and cloud scheme based on a statistical approach (Tompkins and Janisková, 2004)
- Trade-off : Non-linear behaviour close to the operational physical schemes (with simplifications) but with improved validity of the tangent-linear approximation (thanks to regularizations)
- Operational assimilation of rainy radiances in the microwave since 2006 (Alan Geer's presentation)
- Preparatory studies towards the assimilation of cloud radar and lidar data (Marta Janisková's presentation)

Assimilation of remote sensing observations in clouds

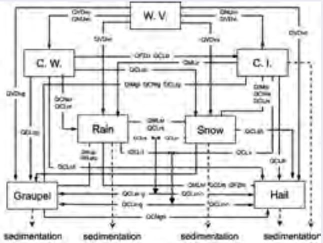
Advanced moist physics: prognostic schemes

- Is it a blessing or a curse ?
- NWP models with higher horizontal resolution : more explicit description of clouds
- More realistic information available to simulate cloudy radiances or radar reflectivities (reduced biases ?)
- Possible inconsistencies of microphysical assumptions with the ones in the observation operator
- Level of complexity of microphysical schemes may depend upon the measurements to be assimilated

Issues with improved physics

- Improved description of physical processes implies generally more complexity :
  - more non-linearities
  - more thresholds (not necessarily)
  - more prognostic variables : inclusion in control vector requires a dedicated **B** matrix
  - more tunable parameters

Ice cloud microphysical scheme



Towards the assimilation of cloudy IASI radiances

A courageous path : AROME simulations with RTTOVCLD

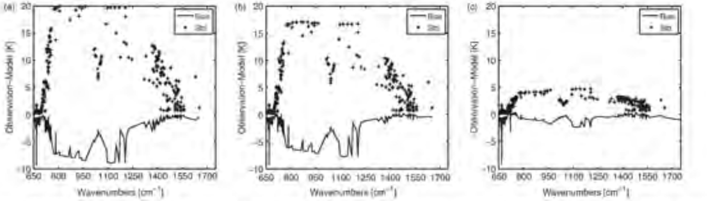
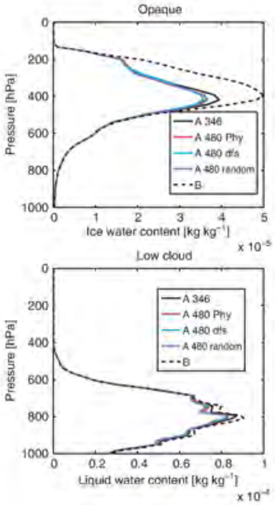


Figure 5. Bias and standard deviation (Std) of the differences between the model and the cloud-affected observed IASI brightness temperatures over a 30 day period from 7 October 2010–7 November 2010 on the Mediterranean Sea. Left panel: considering all overcast observations; middle panel: all homogeneous overcast scenes; right panel: only homogeneous overcast scenes with a constraint on the AVHRR brightness temperature difference.

(Martinet et al., 2013)

(a): all overcast obs, (b): all homogeneous overcast obs, (c): as (b) with mean AVHRR $|T_{b\ obs} - T_{b\ mod}| < 7$ K

Towards the assimilation of cloudy IASI radiances



1D-Var assimilation of cloud water contents

- Specification of a multivariate **B** matrix with hydrometeors
- Choice a-priori of cloud optical properties
- Need for a specific channel selection
- Assumption of constant cloud fraction (overcast scenes)

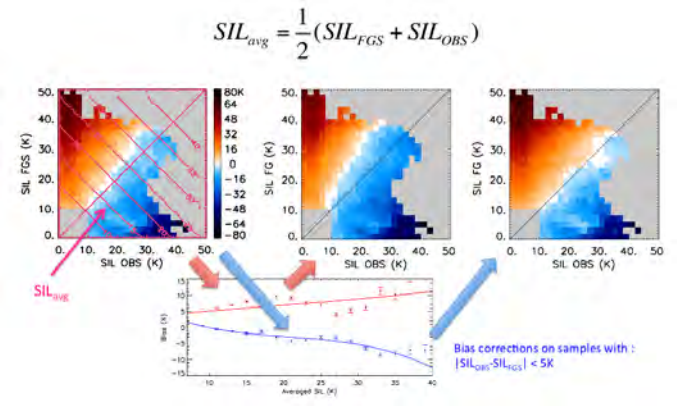
Could it be simpler with an ensemble assimilation ?

Experiments with WRF using an ensemble variational assimilation system [MLEF from M. Zupanski] (Chambon et al., 2014)

- Satellite microwave radiances over land (SSMI/S, AMSR-E, MHS) to initialize hydrometeors
- Need to define a specific bias correction scheme for observations (errors in cloud location and in radiative transfer model)
- Flow dependent background errors cannot elleviate completely issues associated with discontinuities in cloud physics

Bias correction on rain affected radiances

SIL = Scattering Index over Land (Grody, 1991)
Innovations (OBS-FGS) for SSMI/S at 150 GHz



$$SIL_{avg} = \frac{1}{2}(SIL_{FGS} + SIL_{OBS})$$

Bias corrections on samples with :
$|SIL_{OBS}-SIL_{FGS}| < 5K$

Experimental design

Single observation experiments

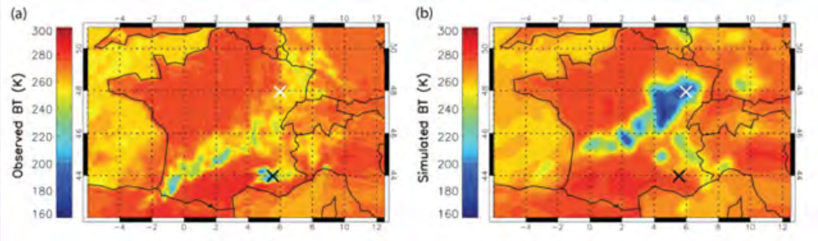
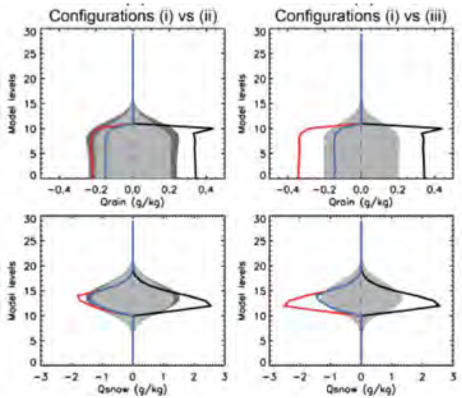


Figure : (a) SSMI/S T_b at 91 GHz V and (b) WRF forecast at 06:00 UTC 2010-09-07

- Configuration (i) : SSMI/S 91V with $\sigma_o = 25$ K - 32 members
- Configuration (ii) : Id. as (i) with 64 members
- Configuration (iii) : Id. as (i) with $\sigma_o = 5$ K

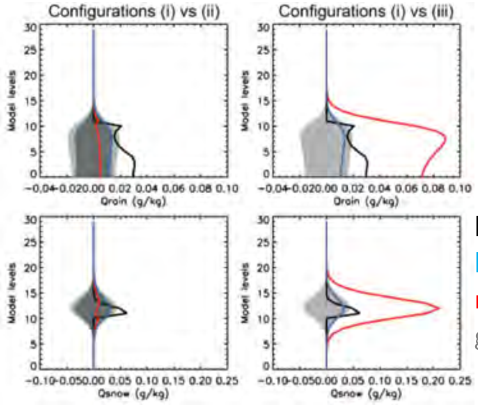
Reduce model precipitation



Config	(OBS- FG)	(AN-FG)
(i)	64.6	30.3
(ii)	64.6	35.5
(iii)	64.6	**57.3**

black = background profile
blue = analysis increments from (ii)
red = analysis increments from (iii)
grey = background errors

Increase model precipitation



Config	(OBS- FG)	(AN-FG)
(i)	- 53.2	-8.9
(ii)	-53.2	-3.7
(ii)	-53.2	**-27.7**

black = background profile

blue = analysis increments from (ii)

red = analysis increments from (iii)

grey = background errors

Errors in radiative transfer modelling

- High microwave frequencies (> 50 GHz) : importance of scattering by solid particules (snow, ice, graupels, hail)
- Scattering dependent upon particle shape, density and size distribution
- Common assumptions : shape=spheres; snow=ice+air; Mie theory + Marshall-Palmer PSD
- Recent progresses : Use of DDA method with data bases for various shapes and densities, revised PSD (normalized distributions), random orientation (Geer and Boardo, 2014)
- Optimisation through systematic model comparison in T_b space

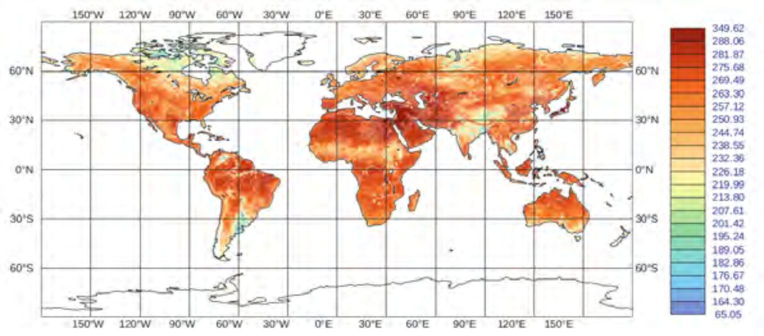
Soil moisture from space

SMOS : ESA mission launched in 2009

- First official dedicated mission on soil moisture (and ocean salinity)
- L-band (1.4 GHz) radiometer sensitive to surface microwave emission (about 5 cm)
- Allows to probe the superficial soil moisture (is it really interesting ?)
- Measurements also influenced by water elsewhere : vegetation, lakes, snow, oceans

Relevant model physics : surface heterogeneities and vertical soil discretization

SMOS brightness temperature

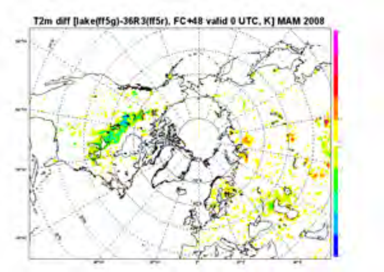


Importance of inland open water

- Lake fraction (need to improve existing databases)
- Lake temperature (specified or modelled)

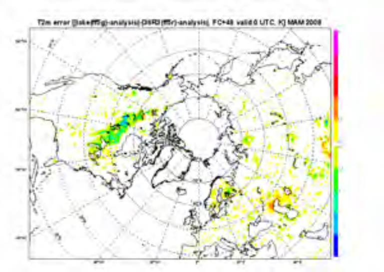
A lake model in the ECMWF IFS

Forecast sensitivity on T_{2m}



Cooling - **Warming**

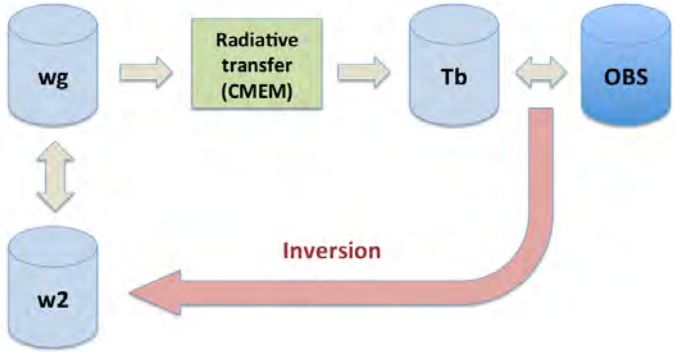
Forecast impact on T_{2m}



Improvement - **Degradation**

Balsamo et al. (2012)

Land Data Assimilation System



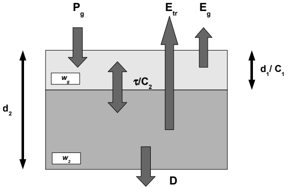
- EKF : ECMWF, Météo-France, MetOffice
- EnKF : CMC, NASA, USDA

Link between superficial and deep soil moisture

ISBA 2L scheme (Noilhan and Mahfouf, 1996)

$$\frac{\partial w_g}{\partial t} = \frac{C_1}{\rho_w d_1}\left[P_g - E_g(T_s)\right] - \frac{C_2}{\tau}(w_g - w_2) \qquad d_1 = 1\ cm$$

$$\frac{\partial w_2}{\partial t} = \frac{1}{\rho_w d_2}\left[P_g - E_g - E_{tr}(T_s)\right] - D \qquad d_2 \simeq 2\ m$$

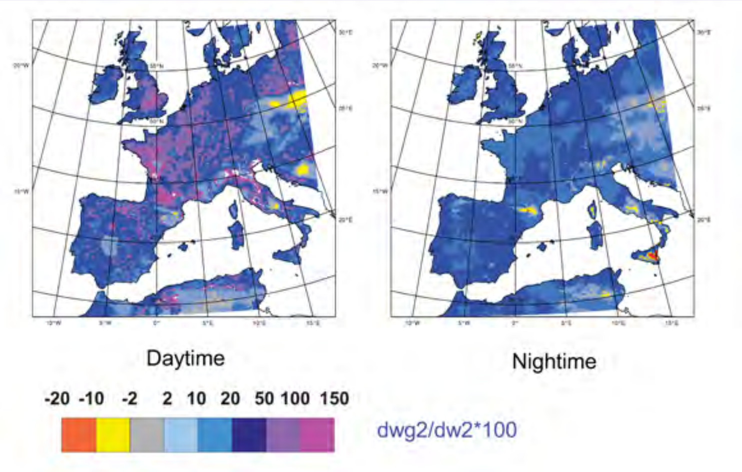


Analytical Jacobians

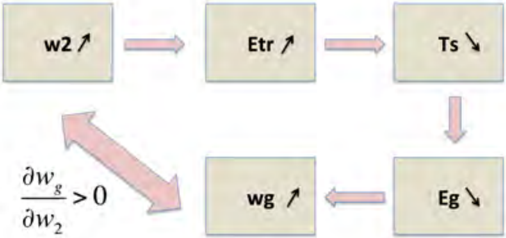
$$\frac{\partial w_g^t}{\partial w_2^0} = 1 - \exp\left(-\frac{C_2 t}{\tau}\right) < 1$$

Model physics from a Jacobian perspective

Jacobians of the ISBA-2L scheme



ISBA-2L : spurious Jacobians



w2 ↗

Etr ↗

Ts ↘

Eg ↘

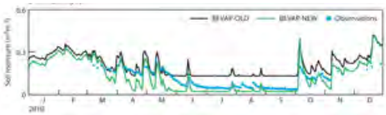
wg ↗

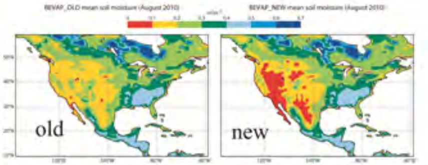
$$\frac{\partial w_g}{\partial w_2} > 0$$

- Surface energy balance : one single T_s for bare soil and vegetation layer + strong non linear behaviour of transpiration near the wilting point
- Undesirable effect : significant changes in w_2 from w_g observations. *Satellite observations appear more informative than they actually are* (enhanced with a two-layer scheme)

Bare soil evaporation

- Importance of an accurate simulation of the superficial soil moisture : observation operator $T_b = T_b(w_g)$
- Improved description of bare soil evaporation in HTESSEL at ECMWF : $E(w_g = 0) = 0$ instead of $E(w_g = w_{wilt})$=0





Albergel et al., 2012

Bare soil evaporation

Impact on simulated SMOS brightness temperatures

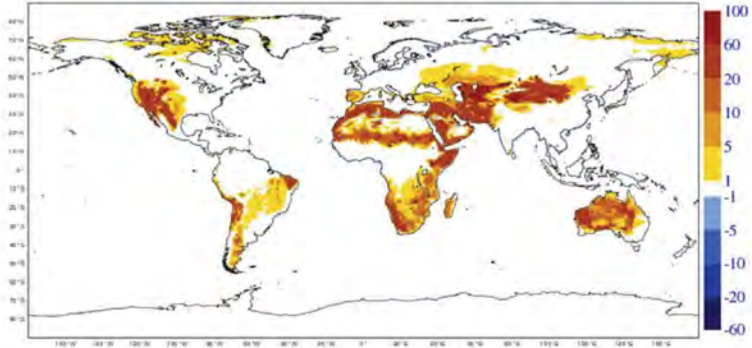


Fig. 5. Map of differences between TB (in K) simulated using model fields from BEVAP_NEW and BEVAP_OLD for August 2010 (06:00 UTC).

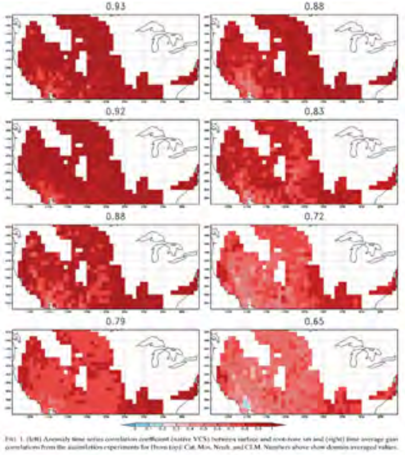
Soil vertical discretization

Year	Levels (ATMOS)	Levels (SOIL)
1996	31	4
1999	50	4
1999	60	4
2006	91	4
2013	137	4

Table : Evolution of the number of vertical levels in the atmosphere (ATMOS) and in the soil (SOIL) at ECMWF over the last 18 years

Is there an interest from a data assimilation perspective to increase the number of soil layers ?

Impact of soil layers on assimilation



Correlation (wg,w2) Mean Kalman gain

Kumar et al. (2009)

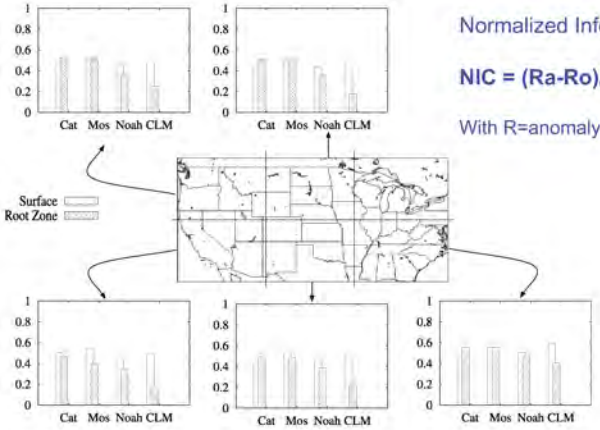
Catchment (2 layers)

Mosaic (3 layers)

Noah (4 layers)

CLM (10 layers)

Impact of soil layers on assimilation



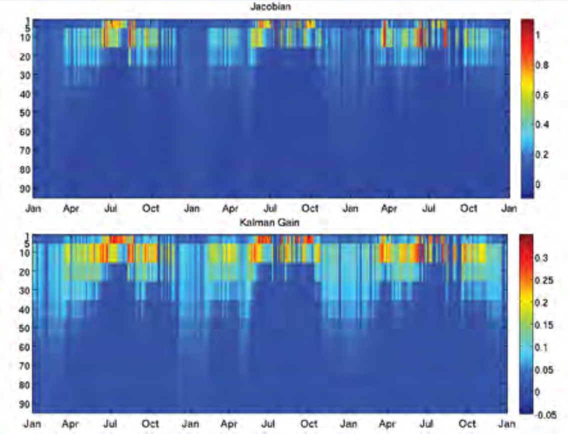
Normalized Information Content

NIC = (Ra-Ro)/(1-Ro)

With R=anomaly time series correlations

Jacobians with a multi-layer scheme

3-year time series at local scale of $\mathbf{H} = \partial w_{g1}/\partial w_{2i}$ and $\mathbf{K}$



Parrens et al. (2014)

Conclusions (1)

- During the last 10 years there has been significant progress in the assimilation of satellite data thanks to an increased usage of model physics :
  - More (explicit) microphysics in cloud and precipitation processes : assimilation of cloudy and rainy radiances (and reflectivities) instead of surface precipitation
  - Improved surface modelling is paving the way towards the assimilation of satellite data from dedicated missions (SMOS, SMAP) : lake modelling, multi-layer soil schemes, improved description of land evaporation, multiple energy balance (mosaic approach)
- A useful example at ECMWF :
  - Level of complexity in the description of the surface physics consistent with observations to be assimilated
  - Comparisons of model outputs in observation space : diagnosis of systematic errors and then improved physics (observation operator)

Conclusions (2)

- Interest in prognostic microphysical schemes : improved coupling with observation operators (T_b and Z), two-moment schemes with explicit condensation from aerosol nuclei (coupling with aerosols), three-moment schemes for radar reflectivity assimilation ?
- Ensemble assimilation techniques offer a natural extension of the control vector to hydrometeors with associated **B** matrix : non-linearities and thresholds present in the model physics will remain (more difficult to identify and cure)
- Interest in evaluating model physics (as part of the observation operator) in terms of Jacobians : spurious behaviours
- Increased usage of satellite radiances over land, but surface retrievals remain "sink variables"

A sample of possible evolutions

- Towards coupled land and atmosphere data assimilations (ensemble systems). Could also be true for other surfaces
- Towards dynamical vegetation with improved radiative transfer in the canopy for the assimilation of FaPAR, LAI, and BRDF
- Challenges with new satellite missions or instruments : 3MI on EPS-SG (solar spectrum, polarized radiation), ICI on EPS-SG (cloud ice), SWOT (hydrology)
- High resolution models : detailed surface physiography (PROBA-V, Sentinel programme), inclusion of 3D effects (clouds), upscaling issues to satellite footprint

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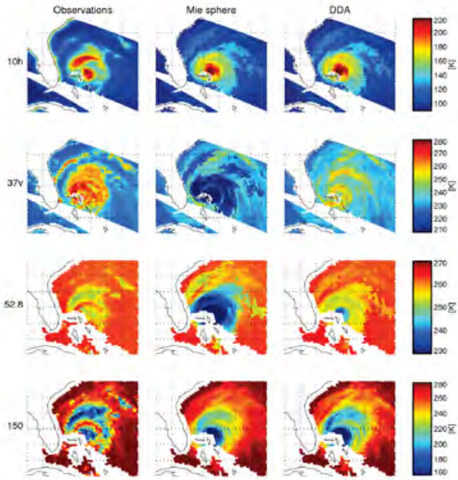
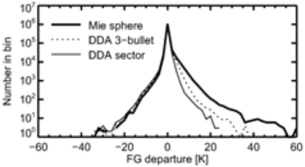
Thank for your attention !

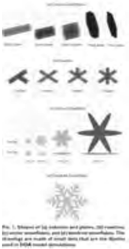
Errors in radiative transfer modelling

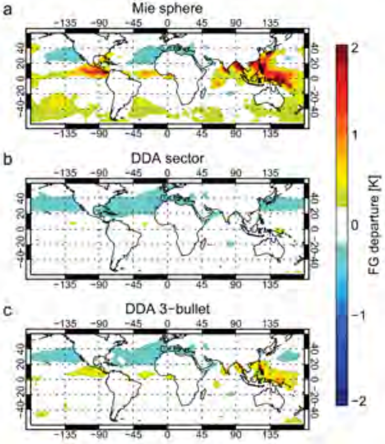


(Geer and Boardo, 2014)

Errors in radiative transfer modelling







Microphysics and data assimilation

Various observables depending upon PSD

$$Z \propto \int N(D) D^6 dD \qquad LWC \propto \int N(D) D^3 dD \qquad N \propto \int N(D) dD$$

- What is the level of complexity required in terms of cloud microphysics ?
- Twin experiments in a 1D-Var context proposed by Laroche et al. (2005) : rain sedimentation and evaporation below cloud base (2km)

Microphysics and data assimilation

Microphysical scheme evolving in time the moments M_m of the PSD :

$$\frac{dM_m}{dt} = \left(\frac{dM_m}{dt}\right)_{dyn} + \sum_n f_{PRC(n)}(M_m, M_p)$$

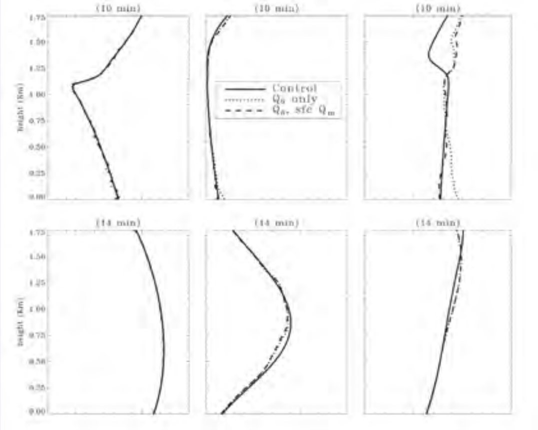
Minimisation of a cost-function : $J(\mathbf{x}) = [F(\mathbf{x}) - \mathbf{y}]\mathbf{W}_y^{-1}[F(\mathbf{x}) - \mathbf{y}]$ where $\mathbf{x}$ are the initial and upper conditions of the predictive moments M_m (in log-space).

Experimental set-up

- At model lid the PSD is specified with a M.-P. distribution ($N_0 \exp(-\lambda D)$) with Z varying in time.
- First guess estimated from a M.-P. distribution with N_0 halfed with respect to the reference run

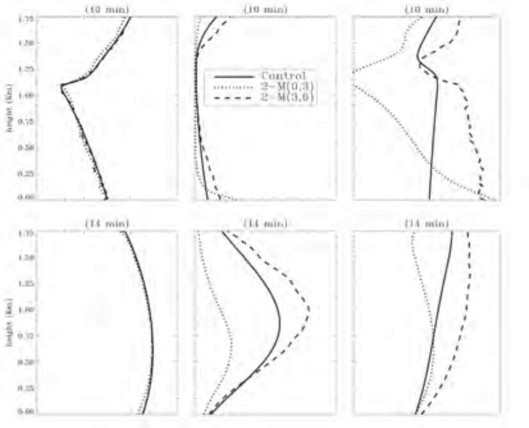
Microphysics and data assimilation

Three-moment scheme : (M_0, M_3, M_6)



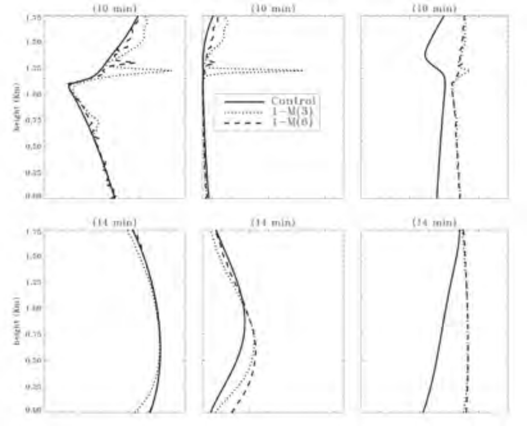
Microphysics and data assimilation

Two-moment scheme : $(M_0,\ M_3)$ or (M_3, M_6)



Microphysics and data assimilation

One-moment scheme : (M_3) or (M_6)



Towards coupled assimilations

T_s retrieved from SEVIRI 10.8 μm vs. T_s predicted by ALADIN

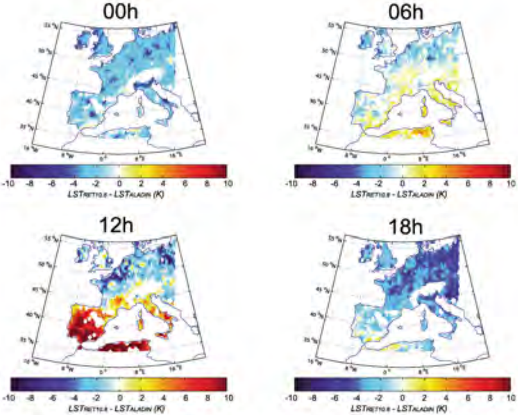


Figure 4. Mean maps of $LST_{RET10.8}$ minus LST_{ALADIN} over the ALADIN/France domain at 0, 6, 12, and 18 h. Results are for the period 15 July to 15 August 2009. Blue (red) indicates that $LST_{RET10.8}$ is colder (warmer) than LST_{ALADIN}.

Guedj et al. (2011)