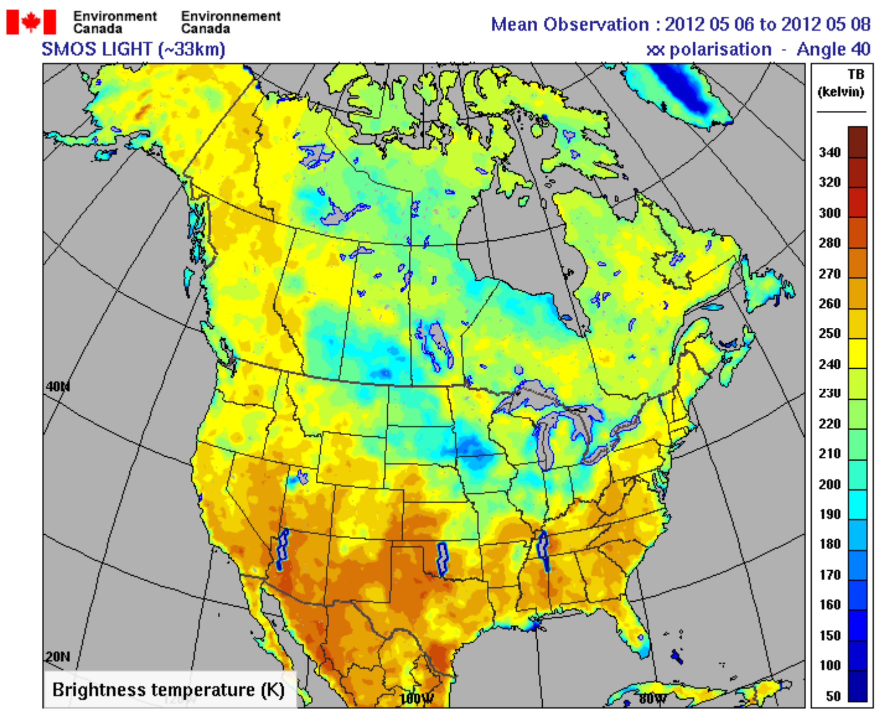
The Inclusion of L-band Soil Moisture Brightness Temperatures within CaLDAS
Description and Preliminary Evaluation



Marco L. Carrera, Stéphane Bélair, Bernard Bilodeau, Sarah Dyck, Vincent Fortin, Nathalie Gauthier, Evangelia Ioannidou, and Sheena Solomon

RPN Seminar – Dorval

18 May 2012

Environment Canada Environnement Canada

Canada

OUTLINE OF TALK

1. Update : CaLDAS-SCREEN

2. Generation of ensemble of precipitation forcing using the Canadian Precipitation Analysis (CaPA).

3. Research and Development themes.

    (i) Synthetic Experiments
    (ii) Real Data Case : CanEX-SM10

4. Proposed operational implementation outlook.

Current Projects

- CaLDAS Screen : Land-surface analysis for the GDPS.
- CaLDAS SMOS/SMAP : Provide updated soil moisture conditions for the planned National LAM at 2.5 km.
- CaLDAS Snow : Provide updated snow conditons for the planned National LAM at 2.5 km. (Solomon et al. 2012)

The CANADIAN LAND DATA ASSIMILATION SYSTEM (CaLDAS)

IN

Ancillary land surface data

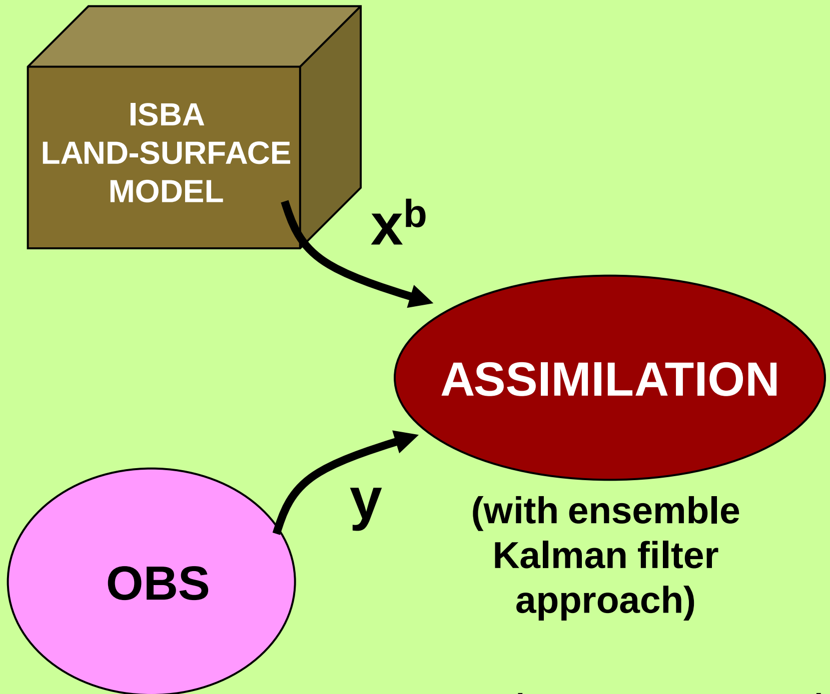
Orography, vegetation, soils, water fraction, ...

Atmospheric forcing

T, q, U, V, Pr, SW, LW

Observations

Screen-level (T, Td)
Surface stations snow depth
L-band passive (SMOS,SMAP)
MW passive (AMSR-E)
Multispectral (MODIS)
Combined products (GlobSnow)



$$x^a = x^b + K \{ y - H(x^b) \}$$

with

$$K = BH^T (HBH^T + R)^{-1}$$

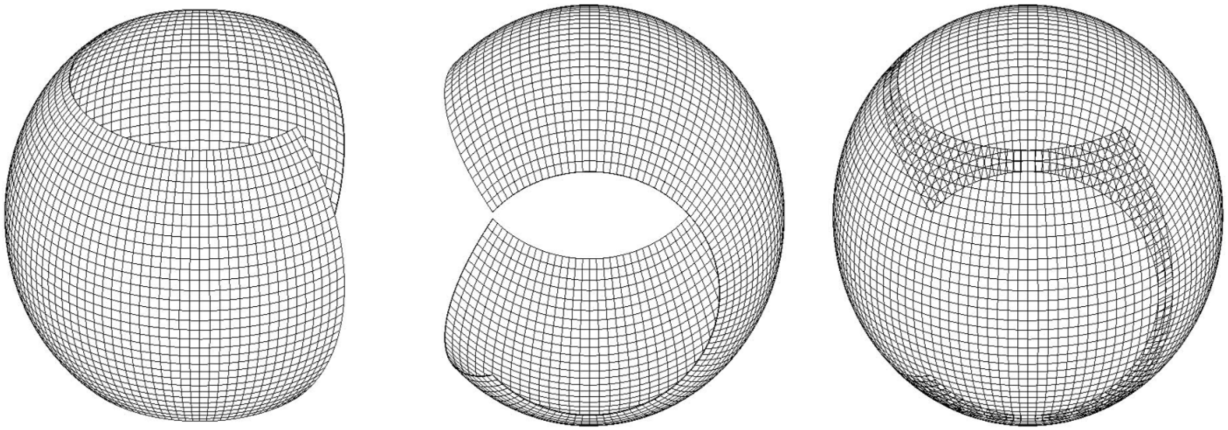
OUT

Land surface initial conditions for NWP and hydro systems

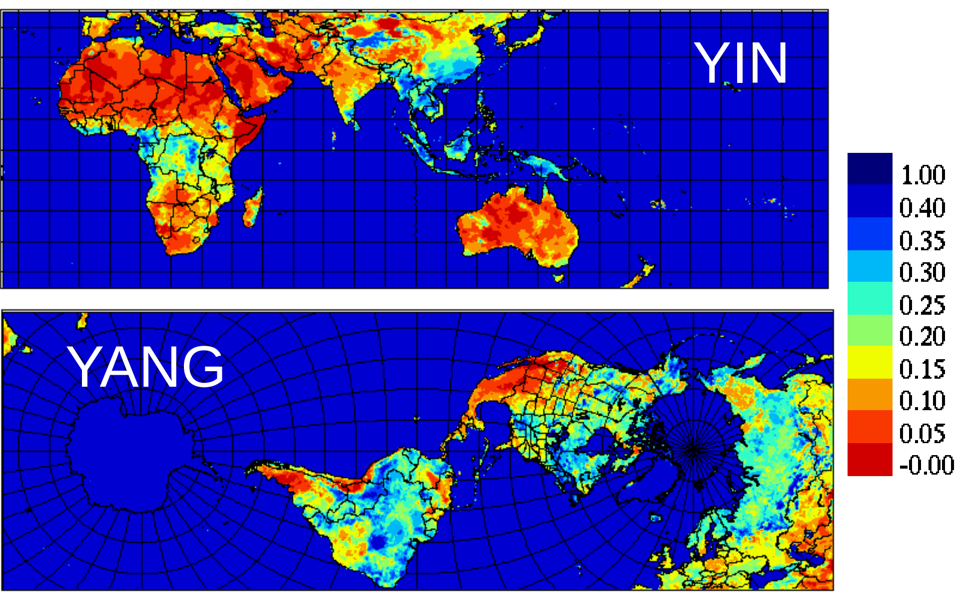
Land surface conditions for atmospheric assimilation systems

Current state of land surface conditions for other applications (agriculture, drought, ...

LAND SURFACE ANALYSES for the GLOBAL DETERMINISTIC PREDICTION SYSTEM (GDPS)



YIN-YANG



Global, 15km (for GDPS)

Obs: T_2m, Td_2m, SD

Ctrl variables: w2, T2, SWE

24 or 48 members

Assimilation step: 3h or 6h

First cycle from April 2008 to March 2009 ongoing

Impact on GDPS being evaluated

Verification Scores : CaLDAS Screen

- Assimilation of screen-level temperature and dew-point temperature. Use forecast errors in these parameters to correct the root zone soil layer.

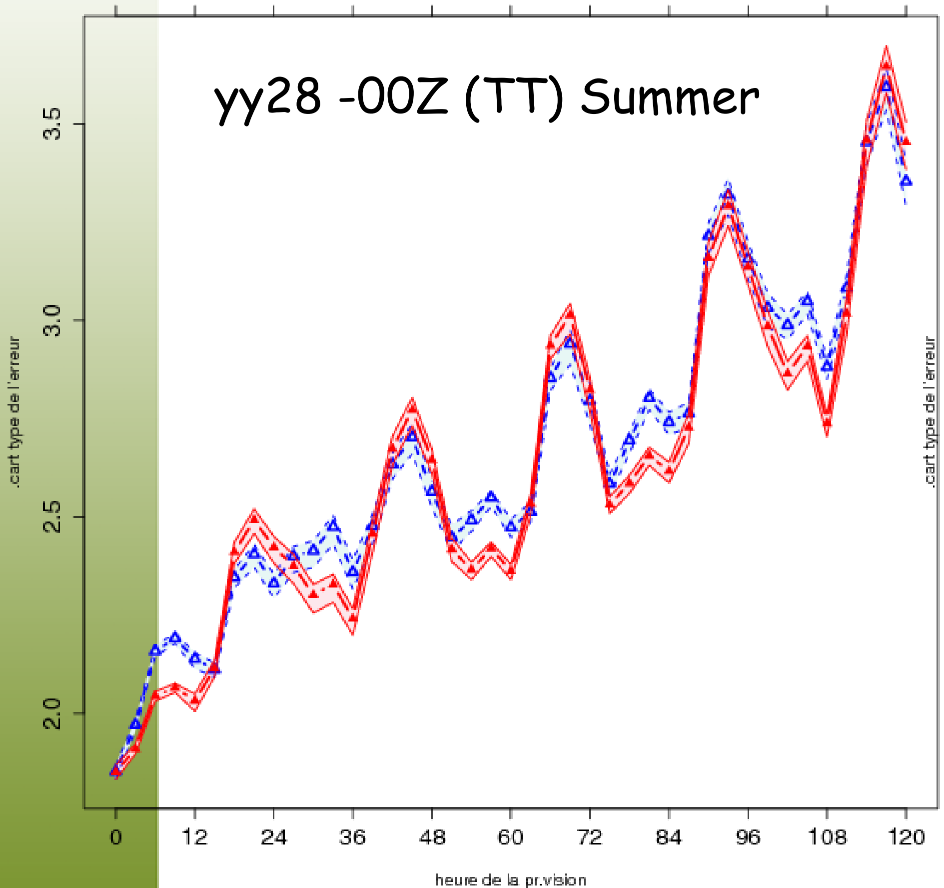
- The new "analyses" of soil moisture produced by CaLDAS are then inserted as initial conditions for the GDPS and the model is integrated out to 6 days.

- These runs are compared with the operational model which uses the current OI based surface assimilation.

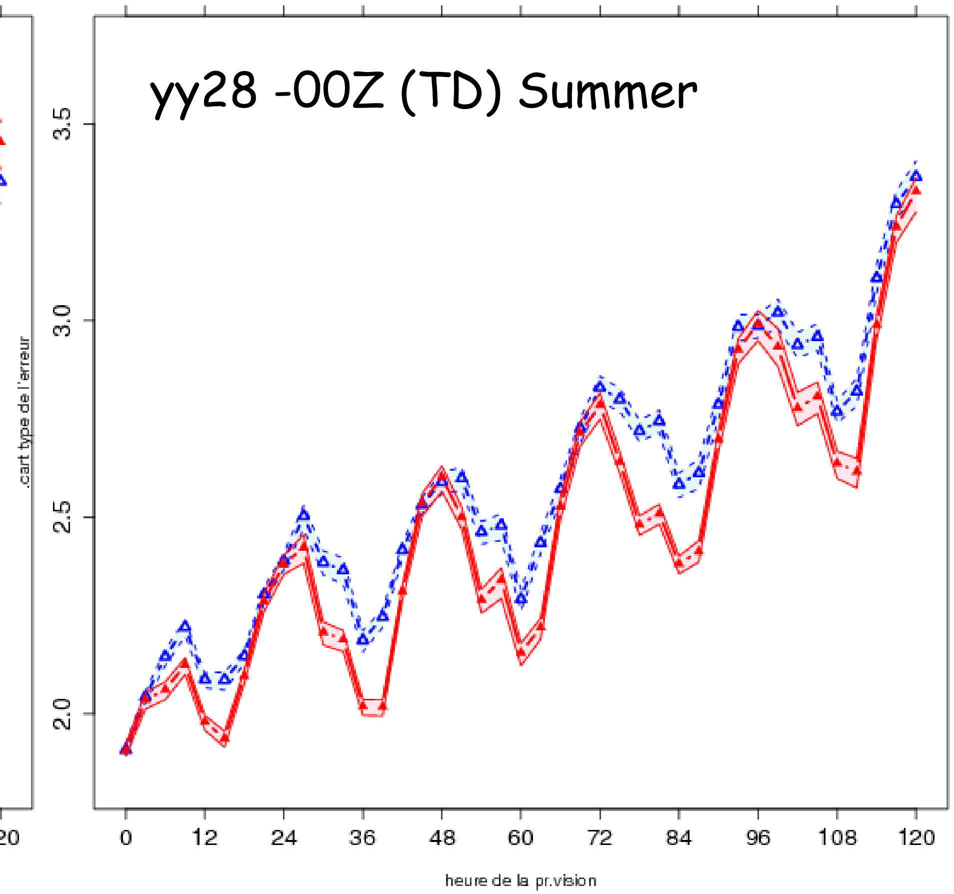
- Not currently coupled with the upper-air data assimilation system yet.

Standard Deviation of Forecast Errors
Summer 2008

Temperature



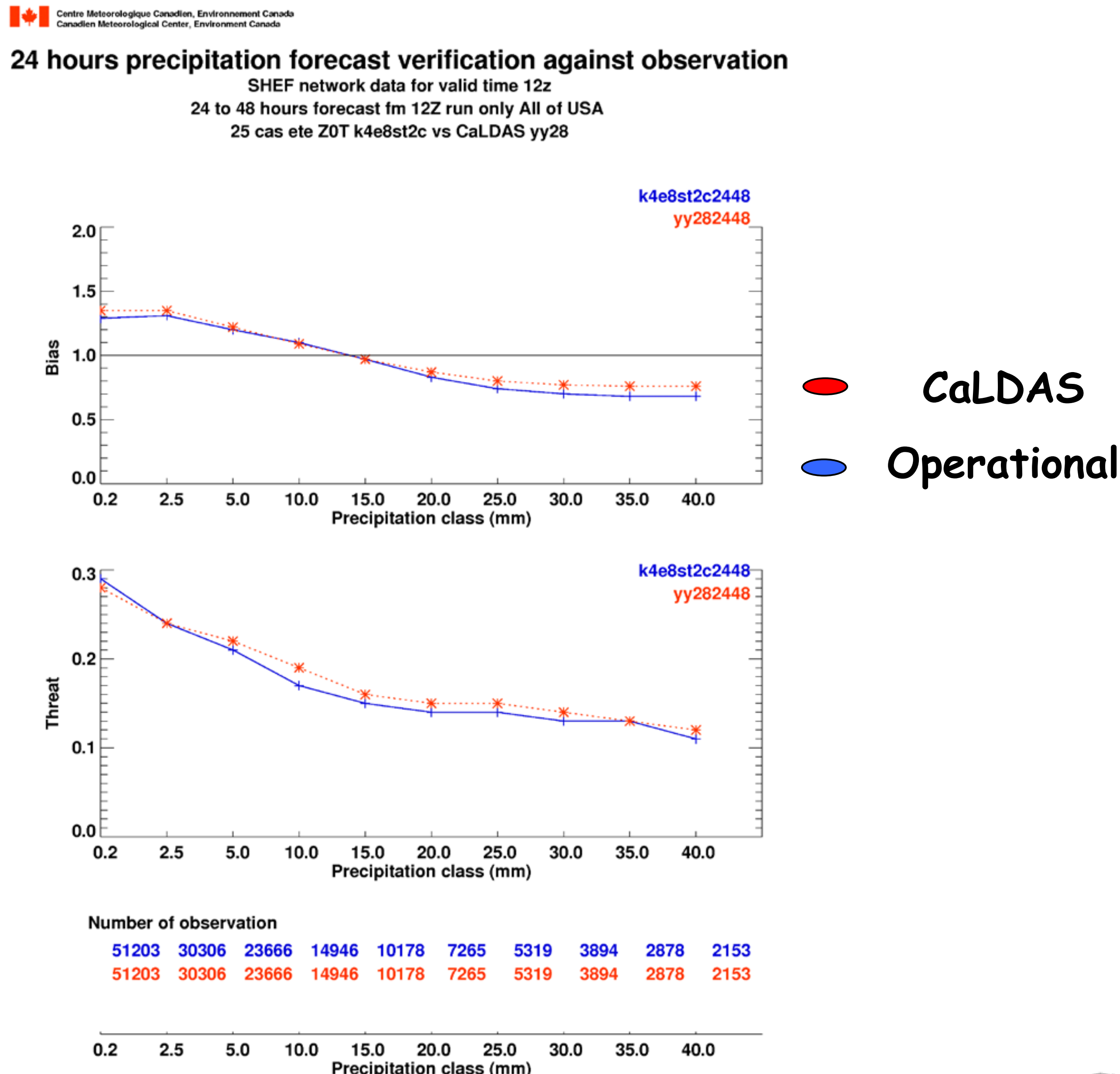
Dew-Point Temperature



CaLDAS

Operational

Precipitation Verification 24-48 hrs : SHEF network



CaLDAS SCREEN

- Improvements in TT are modest, with a gain in the standard error during the nighttime.
- Larger improvements in TD while upper-air scores are mostly neutral (as expected).
- Precipitation threat and bias scores are improved for day 2, while day 1 scores are mostly neutral.
- Winter scores so far are mostly neutral.
- Finishing final configuration tests and will soon transition to the new 15-km Yin-Yang grids and the new verification period 2011-2012.
- Coupling with the EnVar and the upper-air data assimilation system is anticipated this summer.

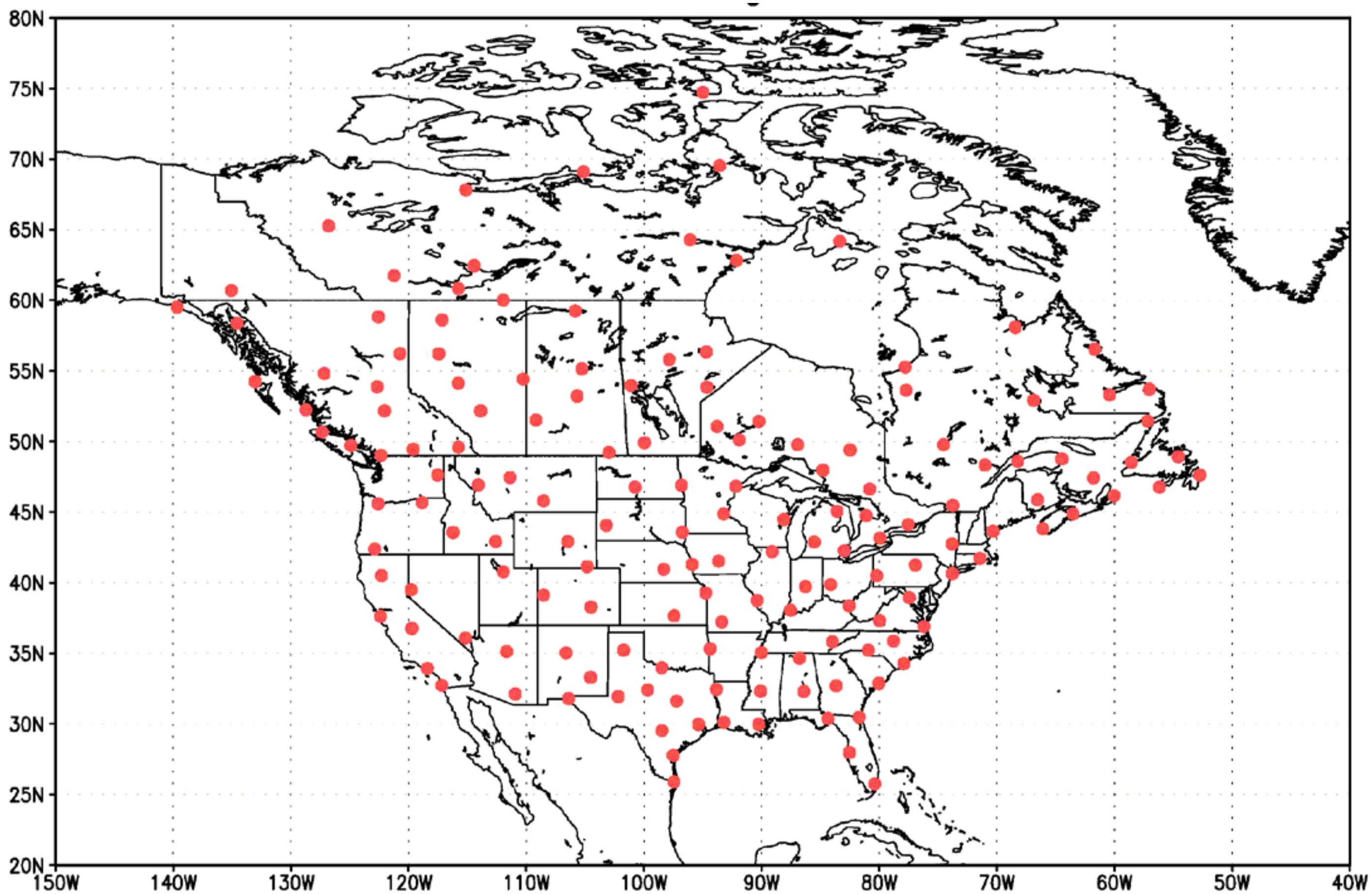
Generation of Precipitation Ensembles

- CaPA is used within CaLDAS to generate an ensemble of precipitation analyses.

- At each analysis time the observation error (σ_o), background error (σ_b) and correlation length scale (L) are estimated by means of a fit to the experimental semivariogram.

  – RDPS first-guess precipitation fields are spatially perturbed to account for horizontal displacement errors ;
  – Gaussian noise with mean 0 and variance (σ^2_o) is added to the precipitation gauge observations in cube root transformed space. <u>Observations of zero precipitation are not perturbed</u>.

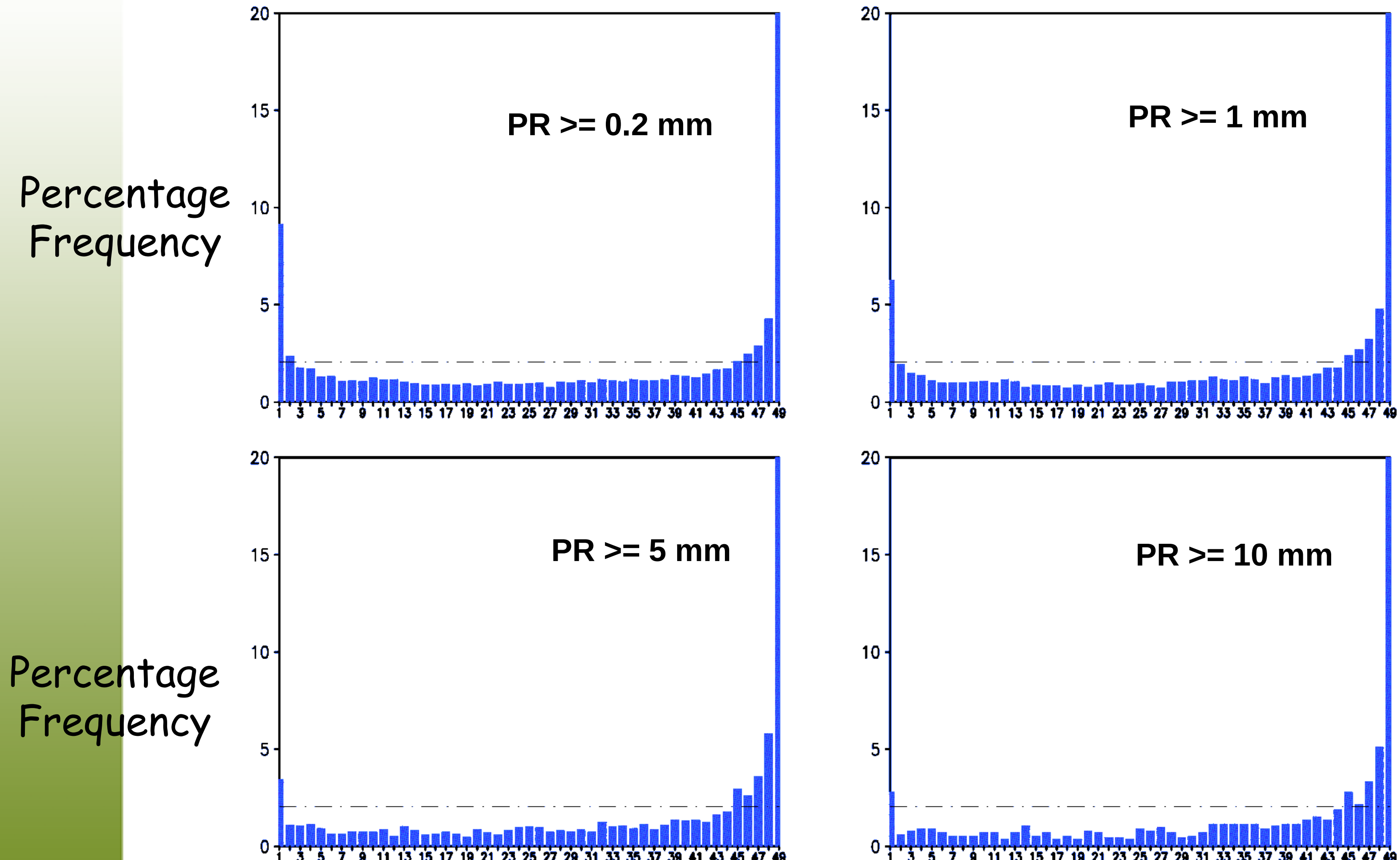
Stations Used For Rank Histogram Calculations
14 April 2009 – 30 August 2009



158 Stations

Acknowledgements : Dr. Lavaysse

Rank of Observed 6-hr Precipitation among 48 Ensemble Members



Under dispersive : Too many cases where observations are greater or less than all members

Inclusion of Soil Moisture Brightness Temperatures within CaLDAS

Passive Remote Sensing of Soil Moisture

- Passive remote sensing of soil moisture is based upon the large contrasts in the dielectric constant between water (~80) and dry soils (~ 3-4).

- At L-band the electromagnetic signal is sensitive to moisture in a thin surface layer (2-10 cm). At L-band emissivity for wet soils is on the order of 0.6 compared to values near 0.9 for dry soils which leads to a dynamical range of ~ 100 K for measured brightness temperatures.

Remote-Sensing Missions

• The Soil Moisture Ocean Salinity (SMOS) mission was launched by the European Space Agency in November 2009. A passive radiometer measures radiation naturally emitted from the earth's surface between 1.4 and 1.427 GHz. Spatial resolution is roughly 40 km.

• The Soil Moisture Active Passive (SMAP) mission is in the development phases at NASA with an expected launch date in late 2014. In addition to a passive radiometer, the SMAP payload will include an active L-band radar which will measure surface backscatter at 1.26 GHz.

• Both SMOS and SMAP are polar-orbiting satellites with a revisit time of 3 days (at the equator) and 1.5 days in mid-latitudes.

Synthetic Experiments : Assimilation of L-band Brightness Temperatures

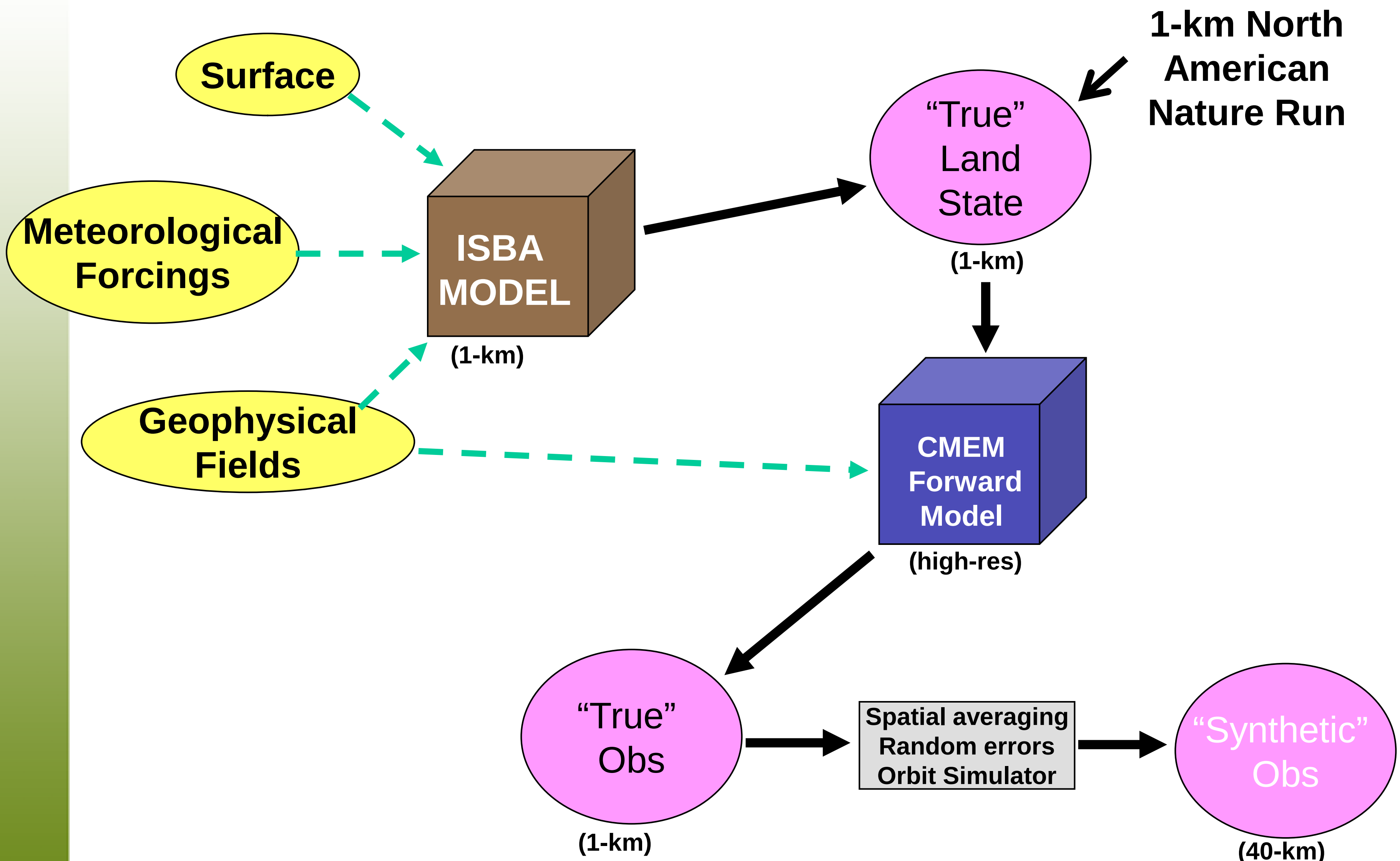
(Carrera et al.)

Synthetic experiments are purely numerical experiments

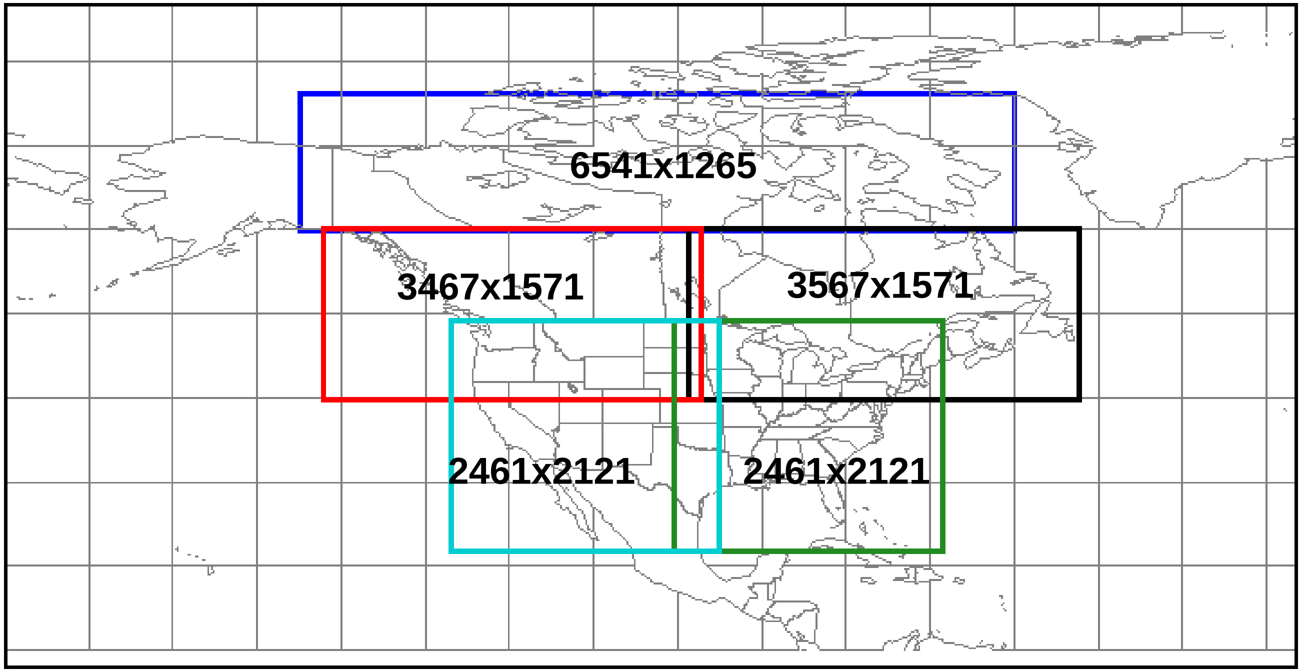
i) the "mechanics" of the EnKF filter ;

ii) assess the ability to analyze the root-zone soil moisture from indirect observations of the surface soil moisture state.

Synthetic Experiment : Generation of Synthetic Observations



High-Resolution : Nature Runs "Truth Runs"



• 1-km resolution integrations of the ISBA land-surface model;

• Atmospheric forcing provided by short-range forecasts from the Regional GEM model;

• Geophysical fields generated from high-resolution land-surface databases;

•Time period : 30 March 2009 – 31 March 2010.

• North America : 5 separate integration grids

Community Microwave Emission Modelling (CMEM) Platform

• Developed at ECMWF and calculates a brightness temperature at the top of the atmosphere (T_{Bp}) from the given predicted land-surface state.

• CMEM is based upon the tau-omega model and is modular in nature. Four separate modules are used to calculate the contribution of T_{Bp} from the soil, vegetation, snow and the atmosphere.

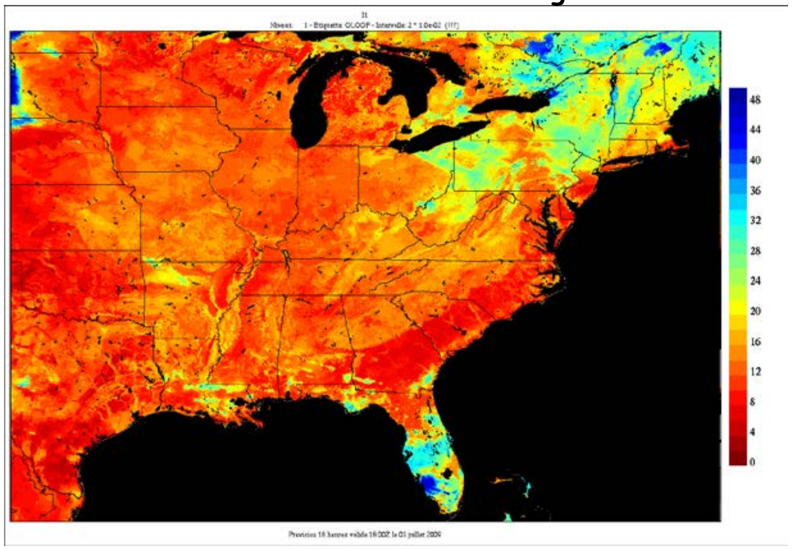
$$T_{Bp} = T_s e_p e^{-\tau_p} + \underbrace{T_c (1-\omega)(1-e^{-\tau_p})}_{vegetation \quad layer}(1 + r_p e^{-\tau_p})$$

• The vegetation optical depth (τ_p) is expressed as a function of the vegetation water content (VWC). Typically the VWC is calculated based upon the LAI (leaf-area index).

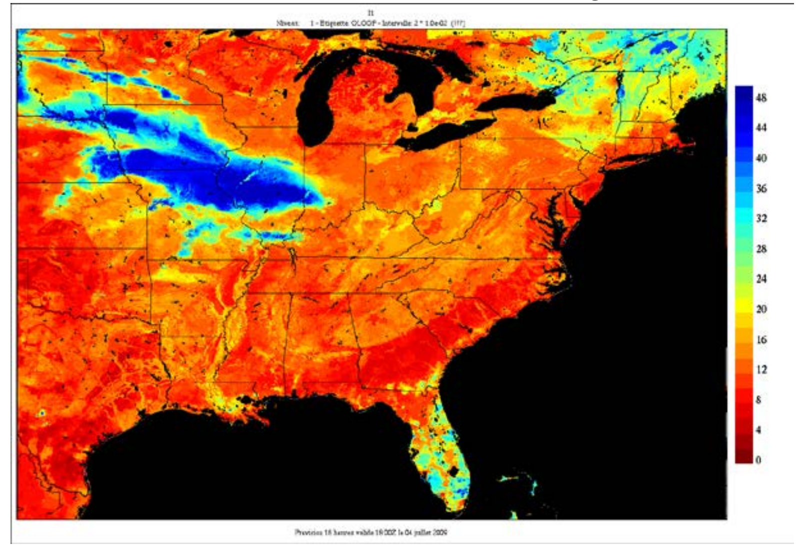
SOIL MOISTURE from the NATURE RUN

Forward Model

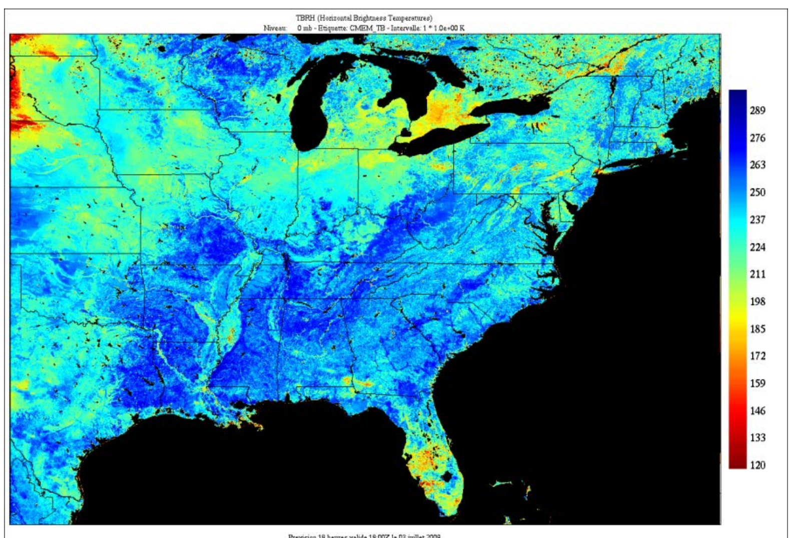
18Z 3 July 2009 : (w_g)



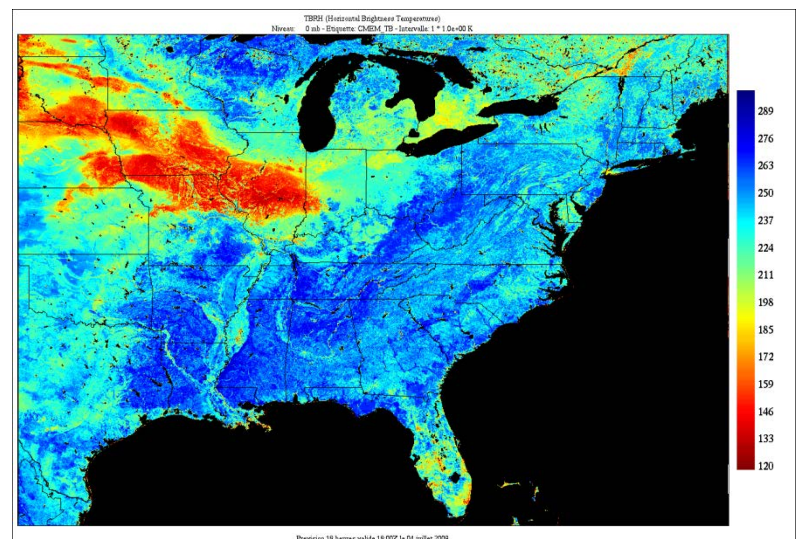
18Z 4 July 2009 : (w_g)



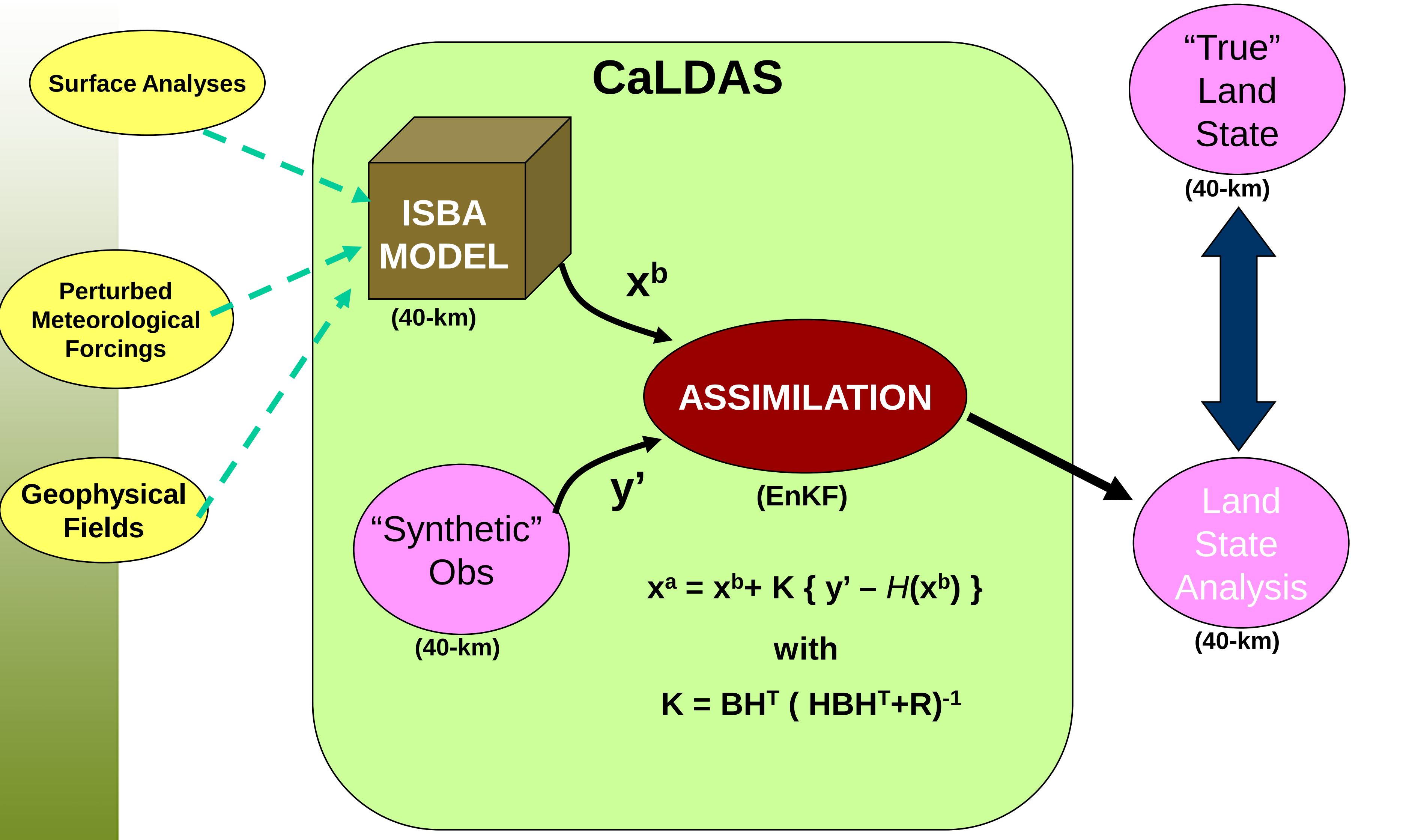
18Z 3 July 2009 : L-band TbH



18Z 4 July 2009 : L-band TbH



Synthetic Experiment : EnKF Assimilation Run



Configuration of EnKF Synthetic Experiment

- 48 members with an assimilation window of 6 hours;
- Domain : North America at a resolution of 40 km.
- Time period : 15 April 2009 – 30 August 2009.
- Control variables are superficial and root zone soil moisture.
- Brightness temperature observation error is constant at 4 K.
- Forward model is the CMEM radiative transfer model developed at ECMWF;
- Initial conditions : 240-hr forecast from GDPS.
- Atmospheric forcings : 30-42 hr forecasts from RDPS.
- An open-loop (**OL**) simulation is also performed for the same time period where no synthetic brightness temperature information is assimilated.

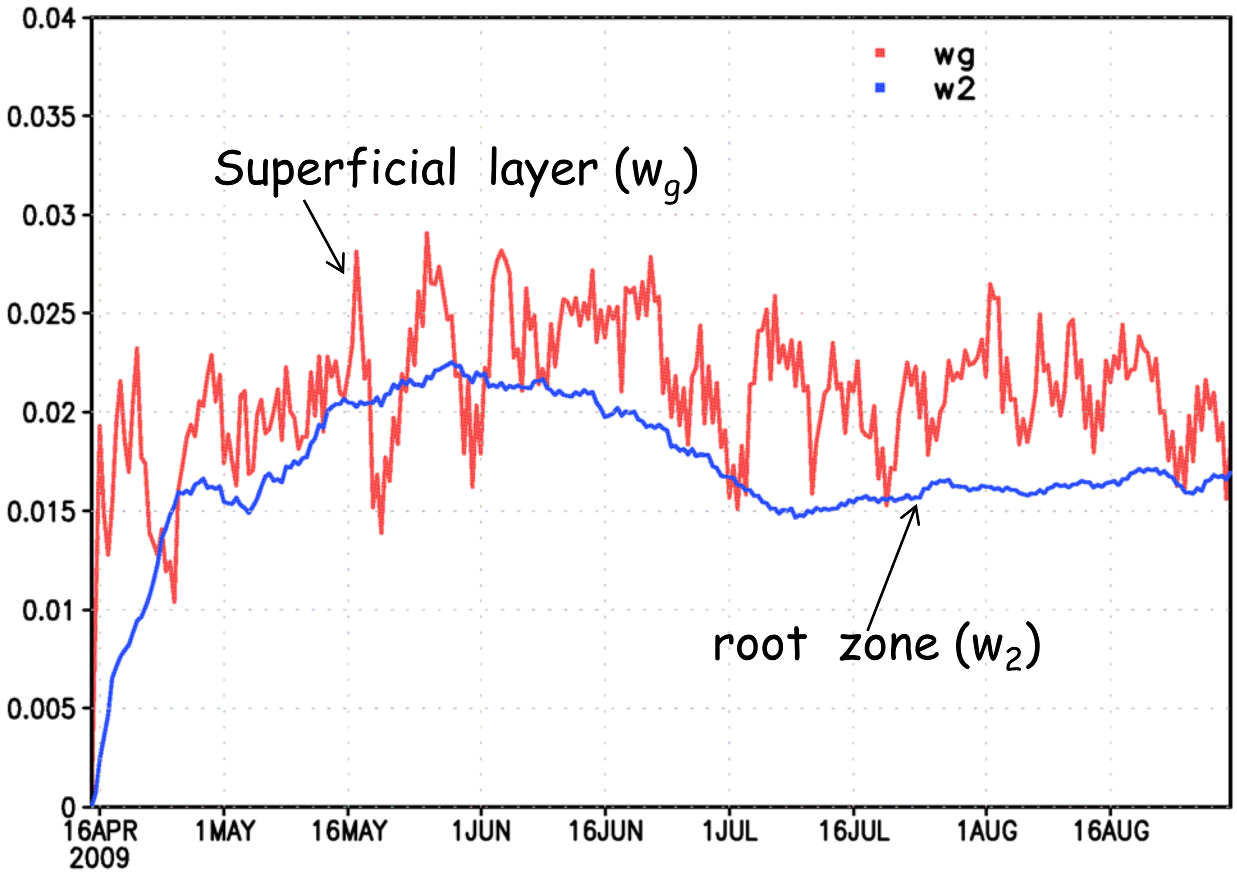
RMSD

Root Mean Squared Difference

(Open Loop : EnKF)

Volumetric Soil Moisture

$m^3\ m^{-3}$



Time

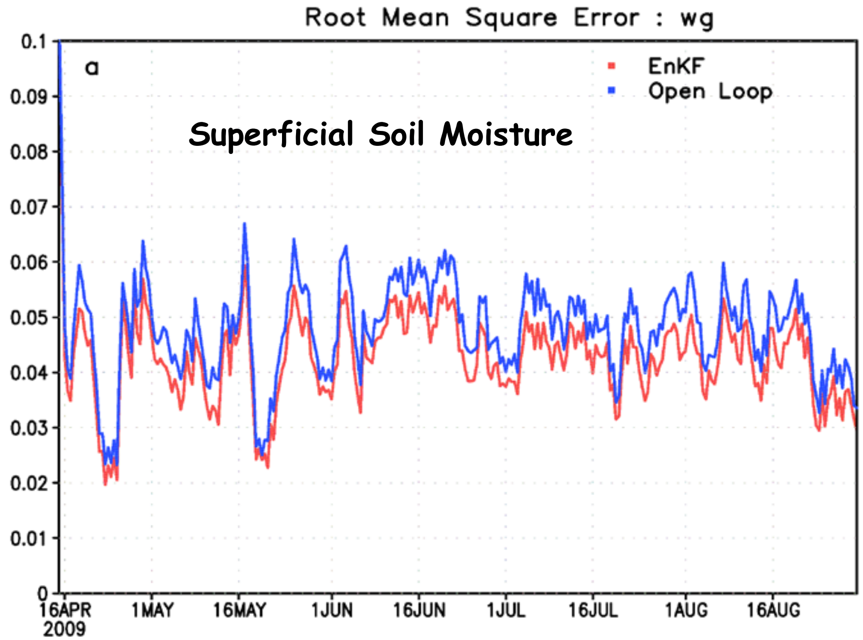
Environment Canada Environnement Canada

Canada

RMSE

Volumetric Soil Moisture

$m^3\ m^{-3}$

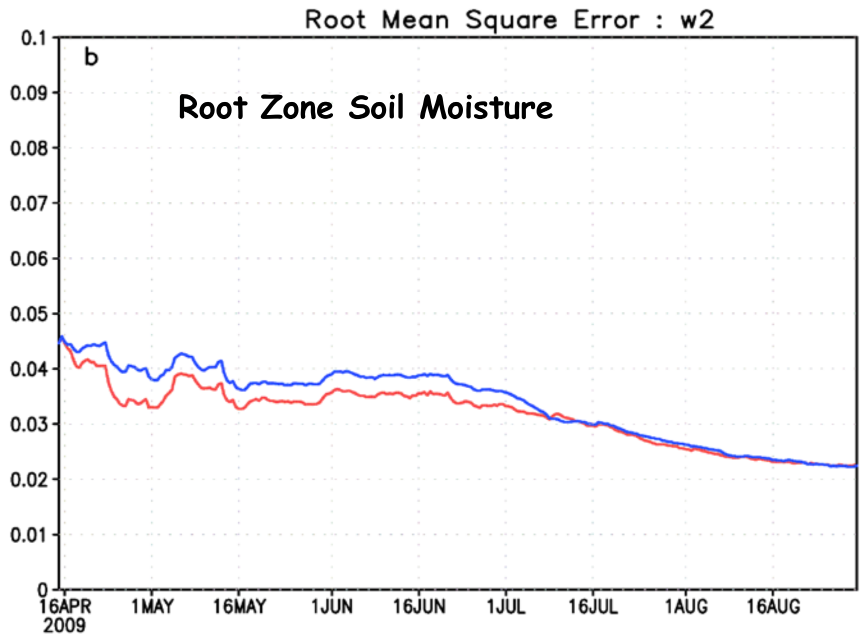


EnKF : 0.043 $m^3\ m^{-3}$

Open Loop : 0.048 $m^3\ m^{-3}$

Volumetric Soil Moisture

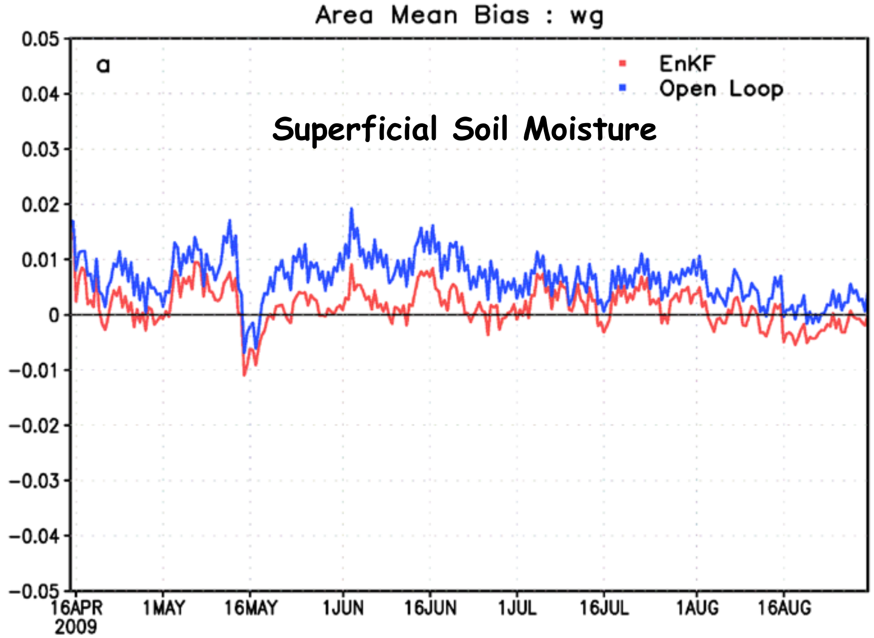
$m^3\ m^{-3}$



EnKF : 0.031 $m^3\ m^{-3}$

Open Loop : 0.033 $m^3\ m^{-3}$

BIAS

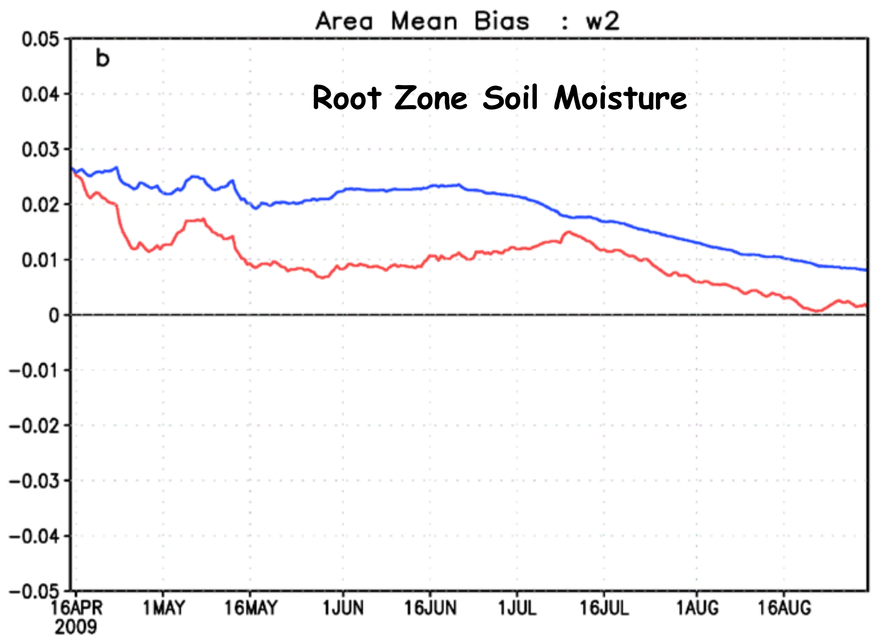


Volumetric Soil Moisture

$m^3\ m^{-3}$

EnKF : 0.001 $m^3\ m^{-3}$

Open Loop : 0.006 $m^3\ m^{-3}$



Volumetric Soil Moisture

$m^3\ m^{-3}$

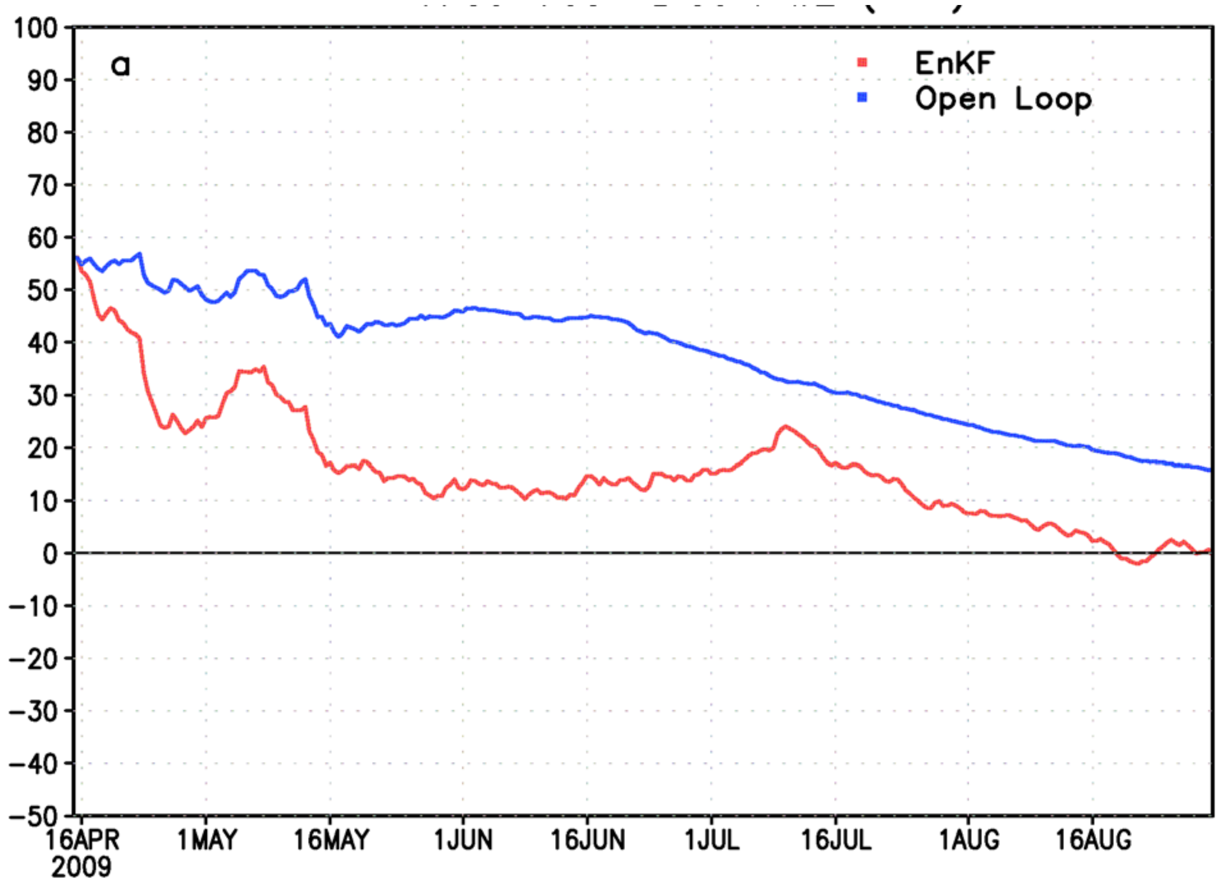
EnKF : 0.009 $m^3\ m^{-3}$

Open Loop : 0.019 $m^3\ m^{-3}$

Bias Expressed in Soil Water

Soil Water Content

mm



soil water = $w_2 \times d2$

d2 = depth of root zone

Real-Data Case
Canadian Experiment for Soil Moisture
(CanEX-SM10)

(Carrera et al.)

Canadian Experiment for Soil Moisture in 2010 (CanEX-SM10)

- Originated as an experiment for Canadian researchers to support SMOS Cal/Val activities over land and to develop soil moisture retrieval algorithms.
- Experiment was expanded to include pre-launch validation and algorithm development for SMAP through a collaboration with US scientists.
- **Period** : 31 May – 17 June 2010
- **Study Sites** :
- (i) Kenaston agricultural site (~ 80 km south of Saskatoon) (33 km x 71 km).
- (ii) BERMS (Boreal Ecosystem and Research and Monitoring Sites) in northern Saskatchewan (33 km x 71 km).

CanEX-SM10

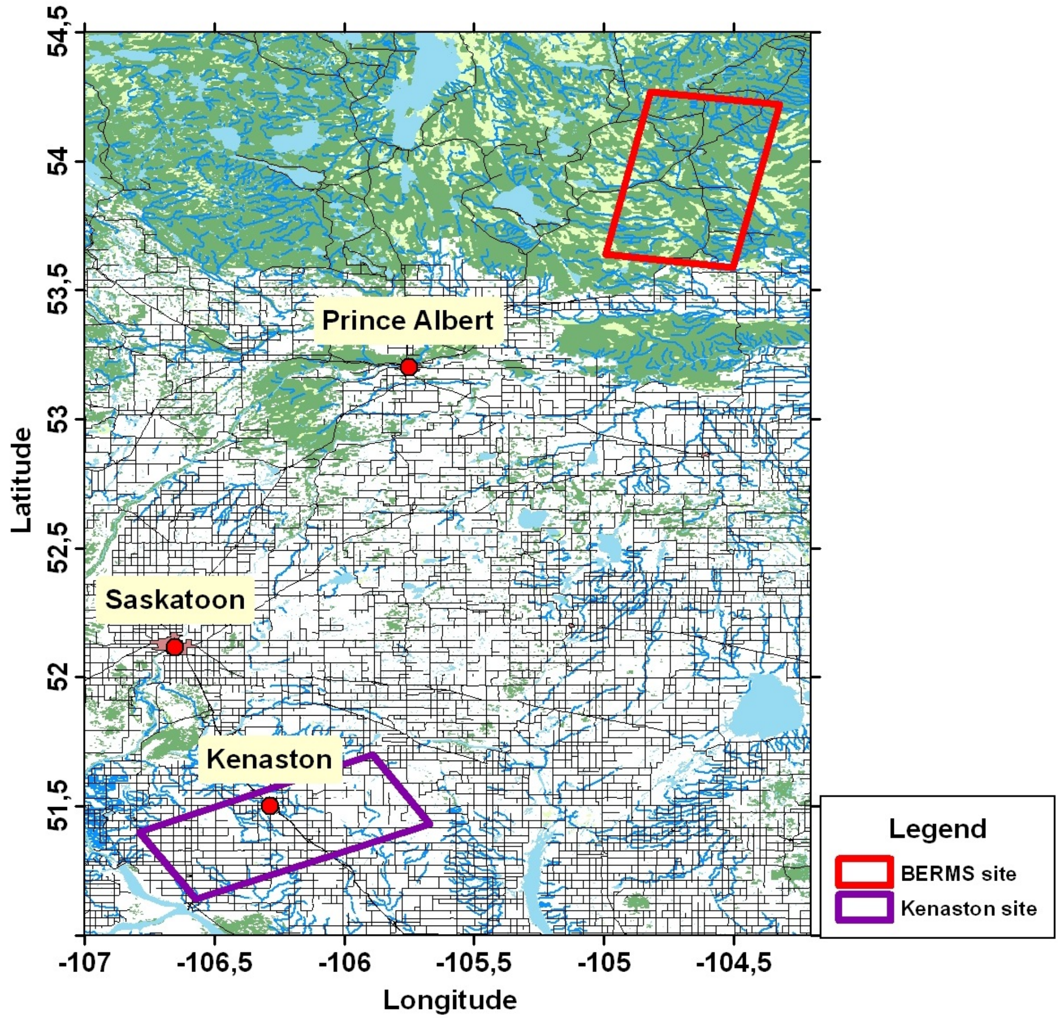
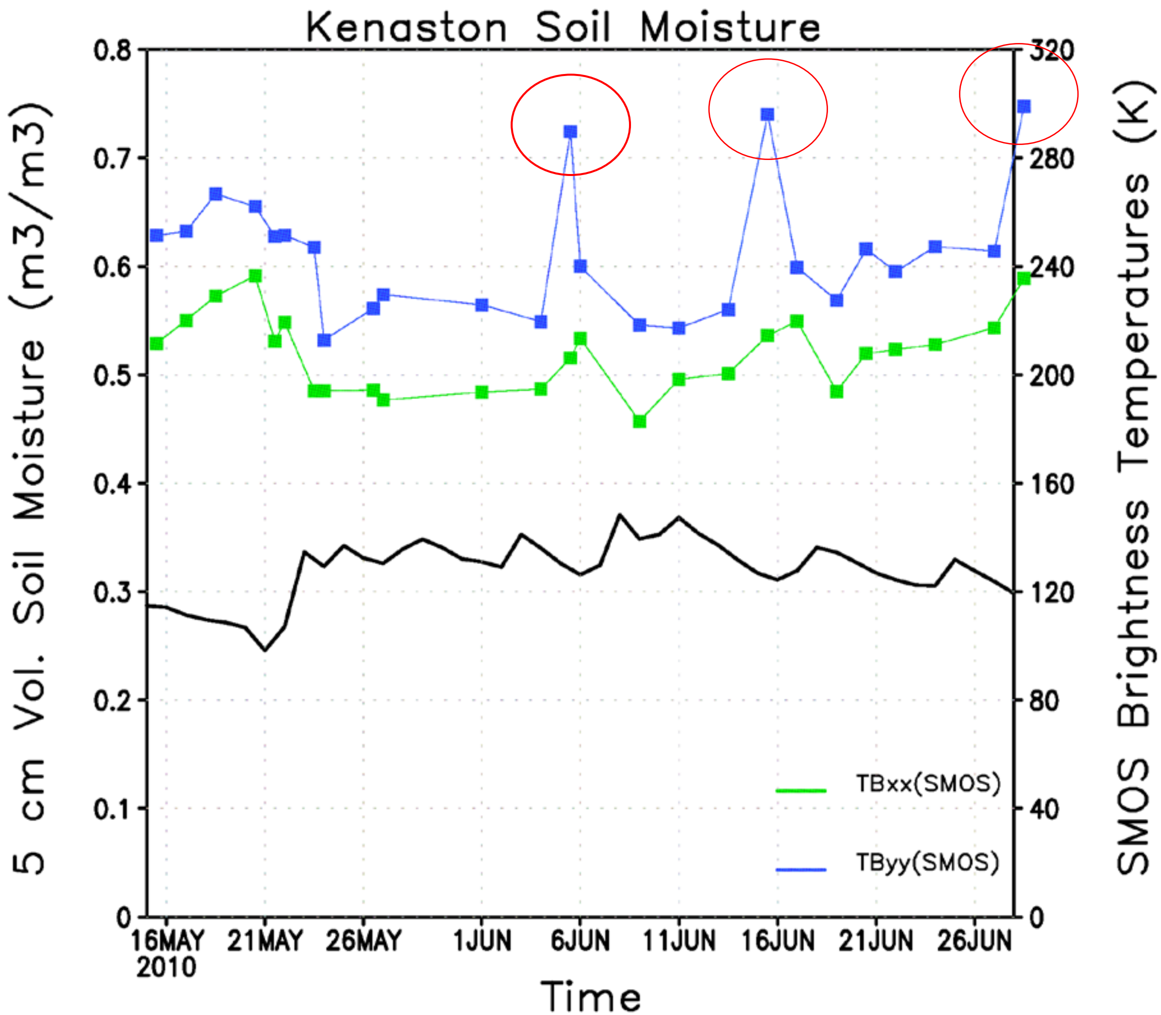


Image courtesy R. Magagi

Kenaston Site :

- High-density network : 24 permanent Environment Canada monitoring sites with measurements of soil moisture at depths of 5, 20 and 50 cm.
- Low-density network : 16 sites operated by the University of Guelph recording soil moisture at depths of 5, 20 and 50 cm.
- Additional 20 manual survey sites were added for CanEX-SM10 which record soil moisture at a depth of 6 cm.
- National Research Council Twin Otter aircraft equipped with a passive microwave radiometer measuring emission in L-band at 40° incidence angle. NASA UAVSAR fully polarimetric L-band radar.

SMOS Level 1C Brightness Temperatures (40º Incidence Angle)



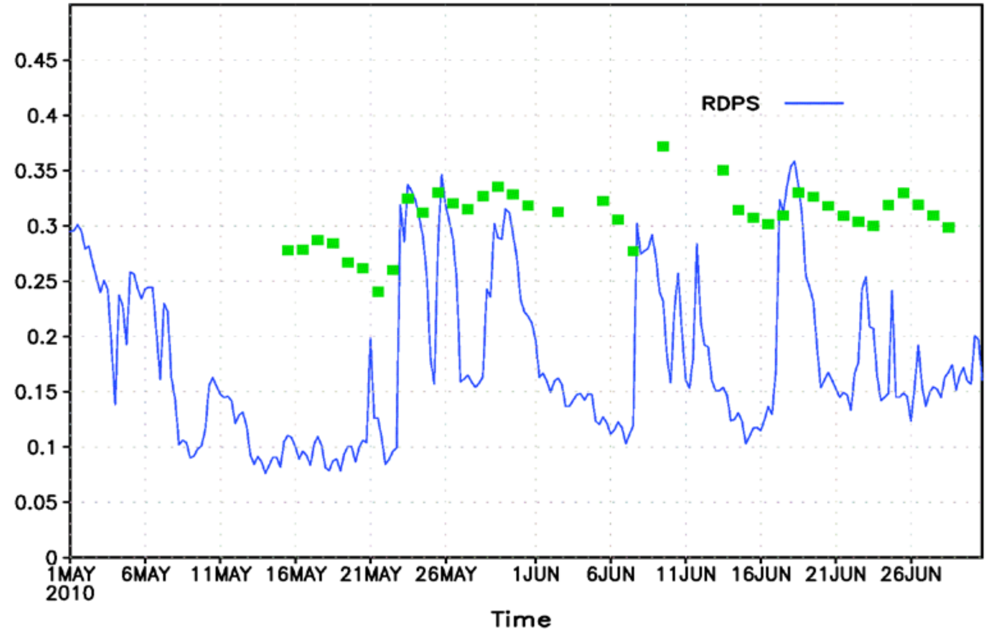
Very wet conditions on the ground.

Temporal trends in soil moisture captured well by SMOS.

Considerable inter-field variability in superficial soil moisture values.

How well did the Operational RDPS perform ?

Superficial Soil Moisture ($m^3\ m^{-3}$)

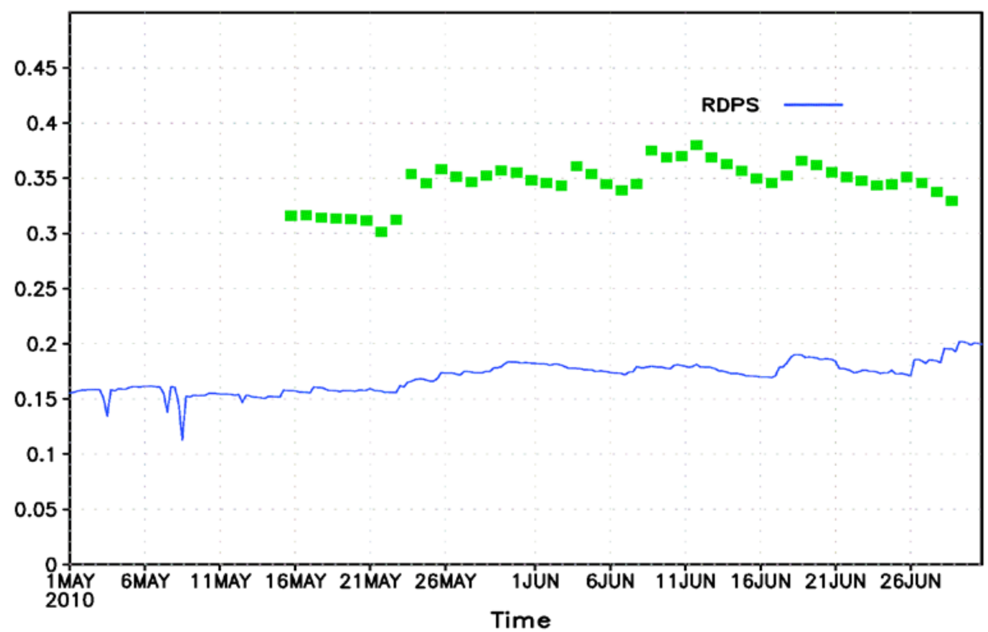


5-cm soil moisture

w_{fc} not correctly specified.

Dry-downs are too fast.

Root Zone Soil Moisture ($m^3\ m^{-3}$)



Mean soil moisture sfc-50 cm

EnKF Assimilation Experiment Set-up

- Ensemble Kalman Filter (EnKF) with 48 members.
- Domain : Canadian Prairies region, 15-km resolution.
- SMOS TBs for the period 12 May 2010 to 30 June 2010. Consider both ascending and descending paths and assimilate data every 6 hours where available.
- SMOS TB observation error of 4 K which is homogeneous in space.
- Forward operator is the CMEM (Community Microwave Emission Model) model combined with a rotation of the first-guess TBs from the earth frame to the SMOS antenna frame.
- Control variables are superficial soil moisture (top 10 cm) and root zone soil moisture.
- An open-loop (OL) simulation is also performed for the same time period where no SMOS brightness temperature information is assimilated.

Bias Correction SMOS Brightness Temperatures

- Linear CDF (Cumulative Distribution Function) matching to re-scale the SMOS observations to match the first-guess brightness temperatures (Reichle and Koster 2005).

$$TB^{C}_{SMOS} = \overline{TB_{OL}} + B \bullet (TB_{SMOS} - \overline{TB_{SMOS}})$$

$$B = \sqrt{\frac{VAR(TB_{OL})}{VAR(TB_{SMOS})}}$$

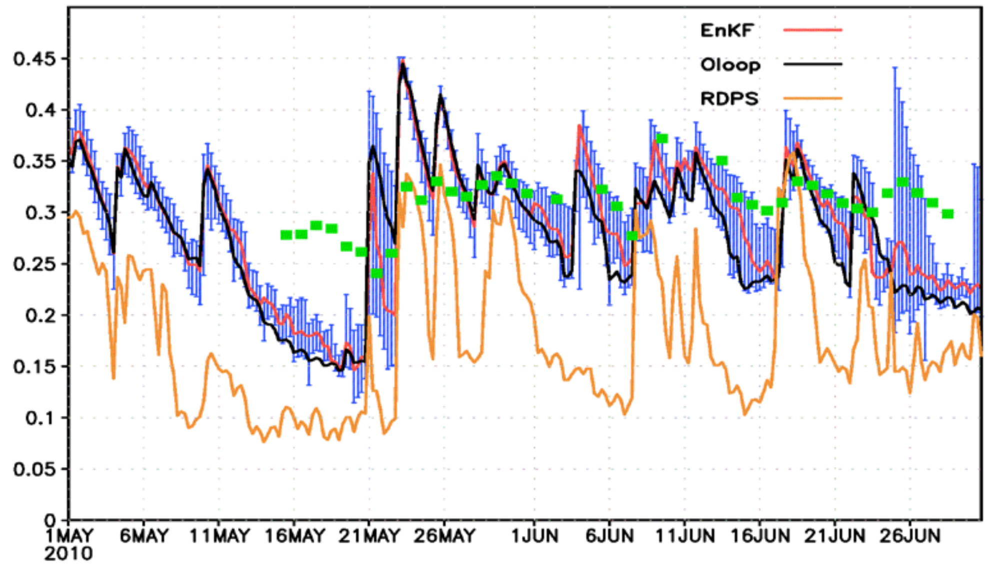
$$TB_{OL} = \text{Brightness Temperatures Open} - \text{loop}$$

$$TB^{C}_{SMOS} = \text{Corrected SMOS Brightness Temperatures}$$

- Choose sub-areas (~5° x 5°) to perform the CDF matching. In this way we exchange space for time and enhance the number of data points entering the CDF calculations.

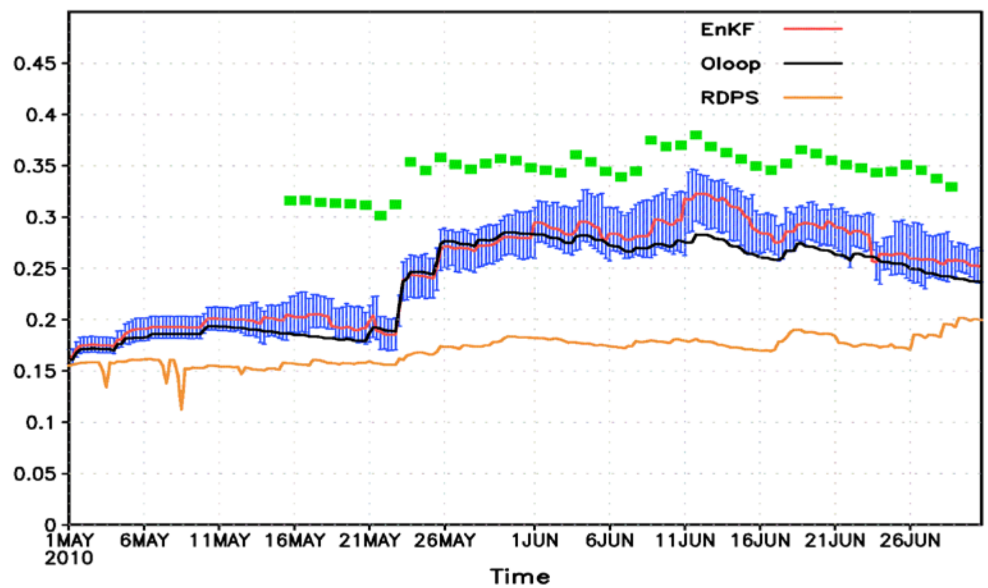
Soil Moisture Simulations : CanEX-SM10 : Kenaston

Superficial Soil Moisture ($m^3\ m^{-3}$)



5-cm soil moisture

Root Zone Soil Moisture ($m^3\ m^{-3}$)



Mean soil moisture sfc-50 cm

Summary

- Assimilation experiments were successful in improving (modestly) the analysis of the root zone soil moisture through assimilation of indirect observations of the surface layer soil moisture.

- In the two-layer version of ISBA the physical link between w_g and w_2 is through transpiration. Thus the analysis of w_2 from w_g observations relies on the sensitivity of w_g to changes in w_2 which varies depending upon meteorological and vegetation conditions.

- In general the root-zone soil moisture is well simulated by ISBA provided that the atmospheric forcing is of good quality.

- In assimilation mode, where no direct or indirect observations of w2, the w2 analysis is strongly related to the skill in simulating wg (i.e., wg innovations).

Proposed Implementation Timelines

Early 2013	CaLDAS-EnKF for screen-level data for the Global Deterministic Prediction System (GDPS) – together with Yin-Yang and with EnVar (other systems could follow: REPS, GEPS, monthly, seasonal)
2013	GEM-Surf 200m over Canada, including all cities.
2013-2014	CaLDAS-EnKF with space-based remote sensing data (SMOS for soil moisture; GlobSnow and MODIS / VIIRS for snow) in the National LAM-2.5km (and potentially other systems)
2015-2016	CaLDAS-EnKF with SMAP data for soil moisture, and other improvements (e.g., higher horizontal resolution)

Merci De Votre Attention

SMAP-Canada Website

Current analyses of surface temperature, soil moisture and snow.

Near Real Time Monitoring of the SMOS Brightness Temperature Data

http://collaboration.cmc.ec.gc.ca/science/rpn/SMAP/SMAP.html

Username : smap
Password : smap

PROPOSED APPROACHES for CaLDAS

Currently operational: *assimilation of screen-level data to analyze surface temperatures and soil moisture*

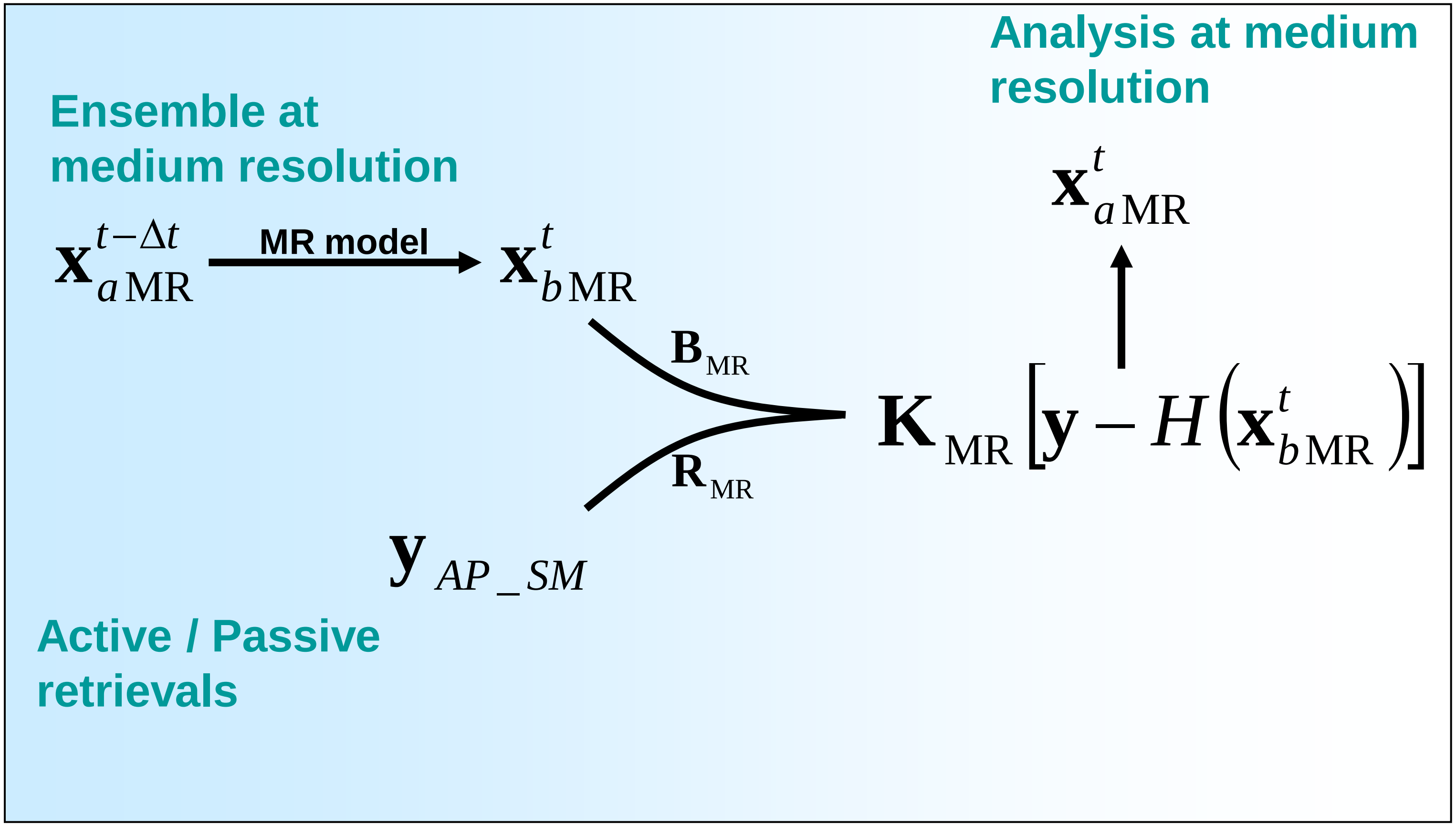
Proposed-1: *joint assimilation of screen-level, brightness temperatures, and backscatters for surface temperatures and soil moisture*

Proposed-2: *sequential assimilation... screen-level data for surface temperatures and SMAP data for soil moisture*

Proposed-3: *hybrid approach... screen-level data used as forcing (stronger constraint on first guesses) and SMAP data assimilated for soil moisture*

ASSIMILATION of PASSIVE / ACTIVE SMAP OBSERVATIONS
OPTION: MEDIUM-RES ASSIMILATION (GLOBAL)

MEDIUM-RESOLUTION (10 km)



PREVIOUS ANALYSIS

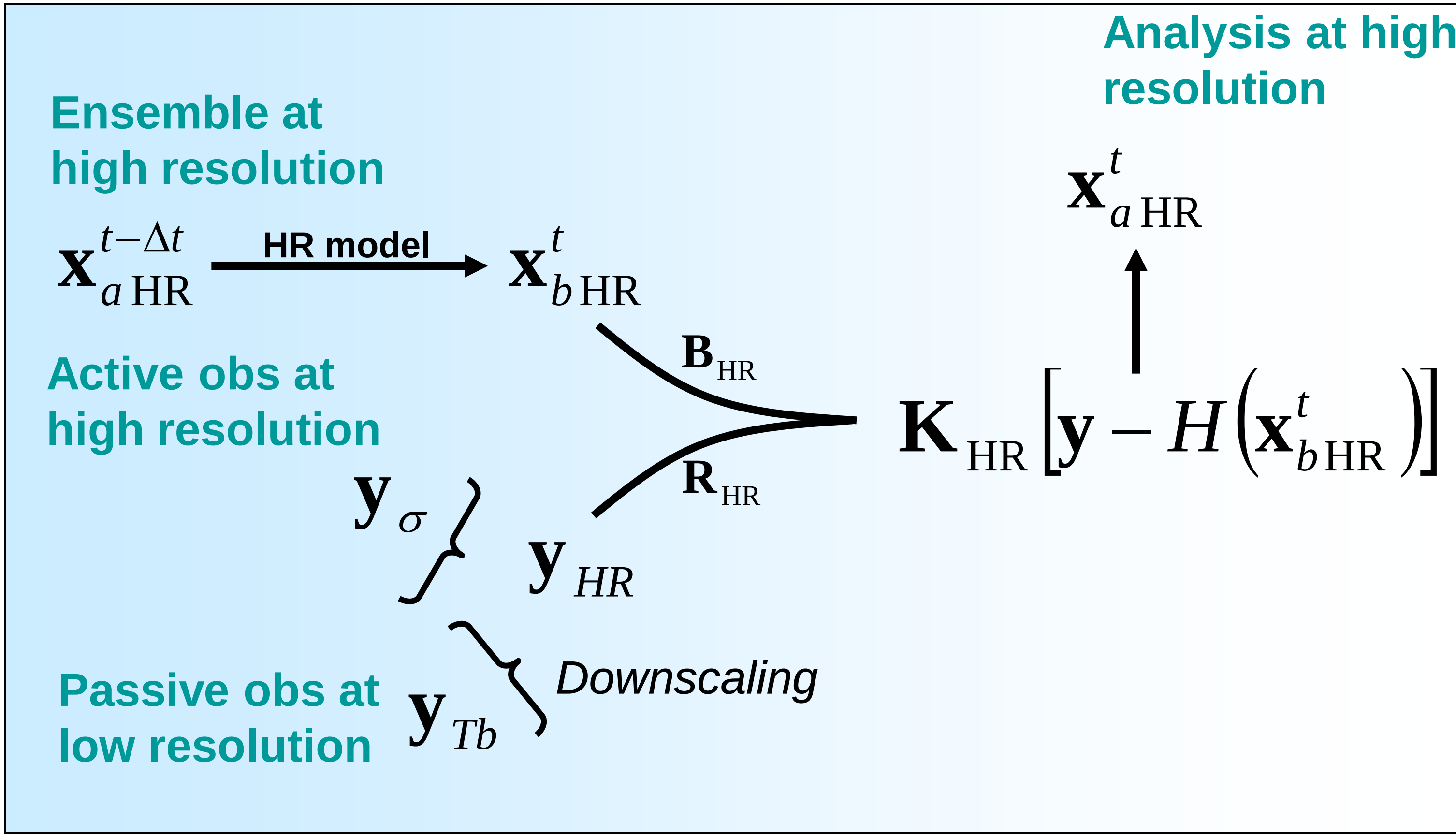
BACKGROUND and OBSERVATIONS

NEW ANALYSIS

ASSIMILATION of PASSIVE / ACTIVE SMAP OBSERVATIONS
OPTION: HIGH-RESOLUTION ASSIMILATION (LOCAL/REGIONAL)

HIGH-RESOLUTION (1-3 km)

LOW-RESOLUTION (10km-40km)

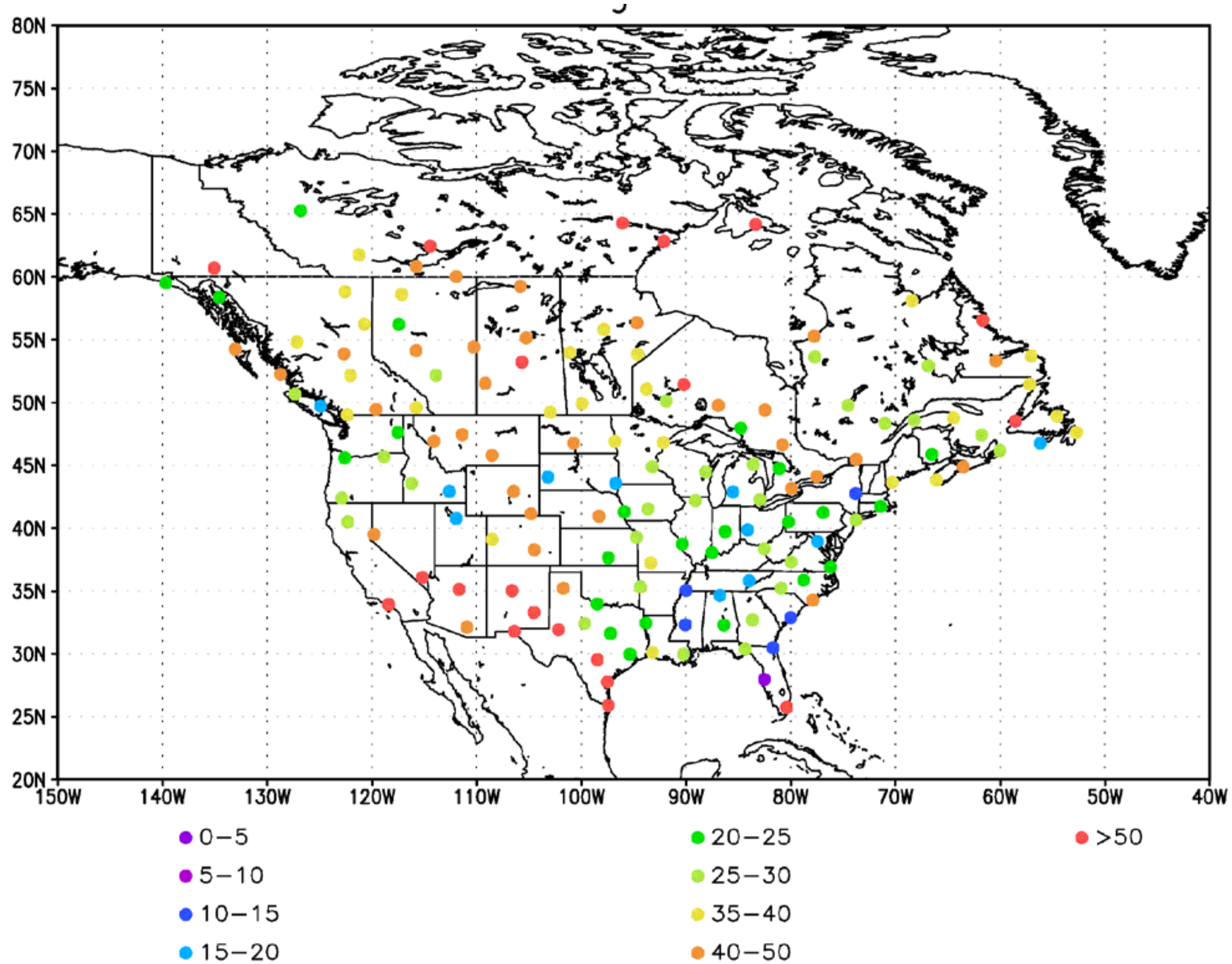


PREVIOUS ANALYSIS

BACKGROUND and OBSERVATIONS

NEW ANALYSIS

Spatial Distribution of the 49th Rank

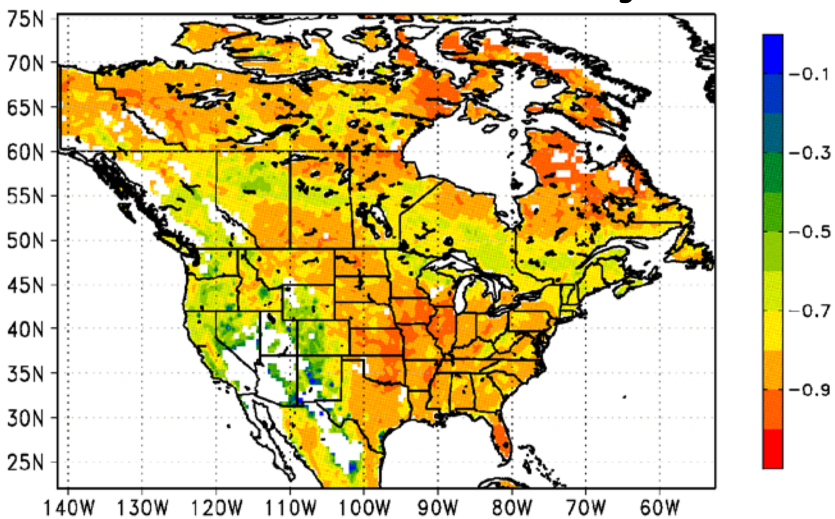


Environment Canada Environnement Canada

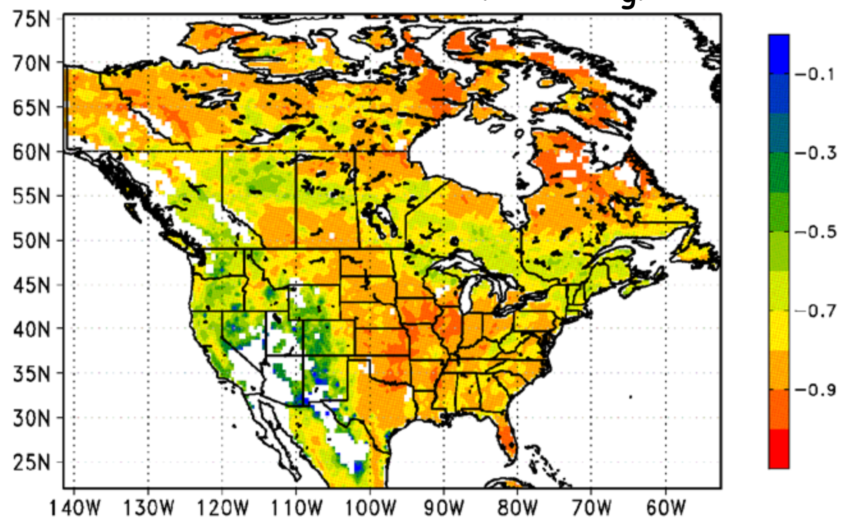
Canada

Information Content : Synthetic Observations

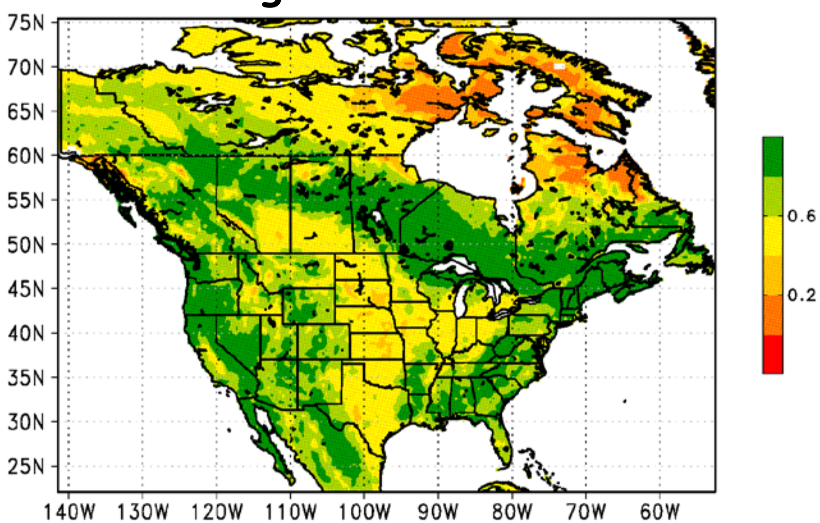
Correlation : R (TBH,w_g)



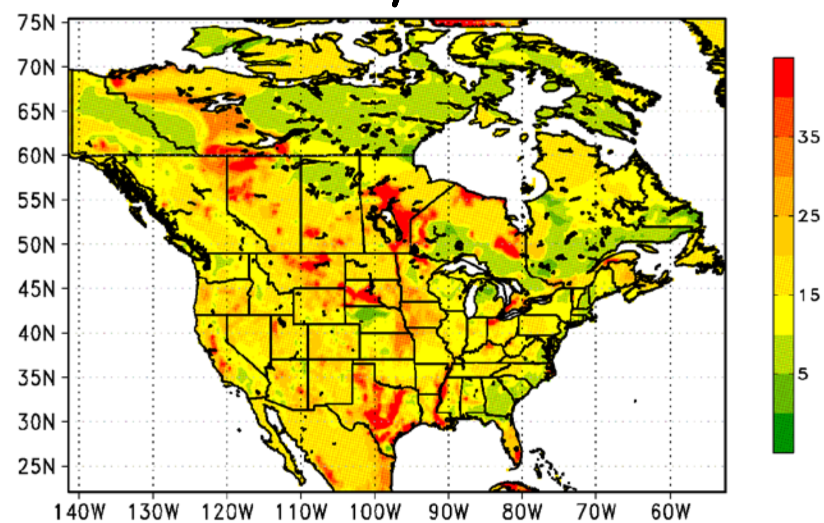
Correlation : R (TBV,w_g)



Vegetation Fraction

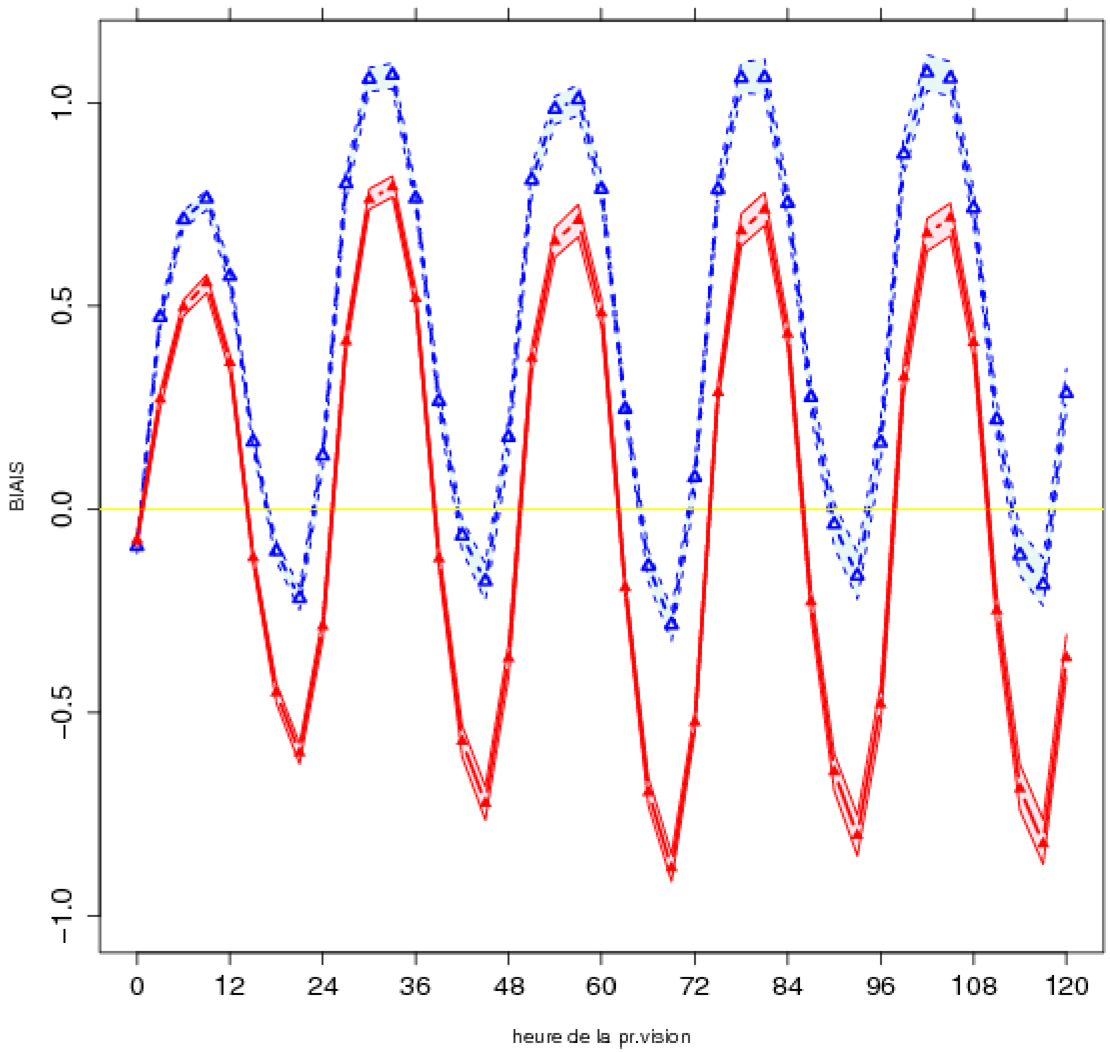


Soil Clay Fraction

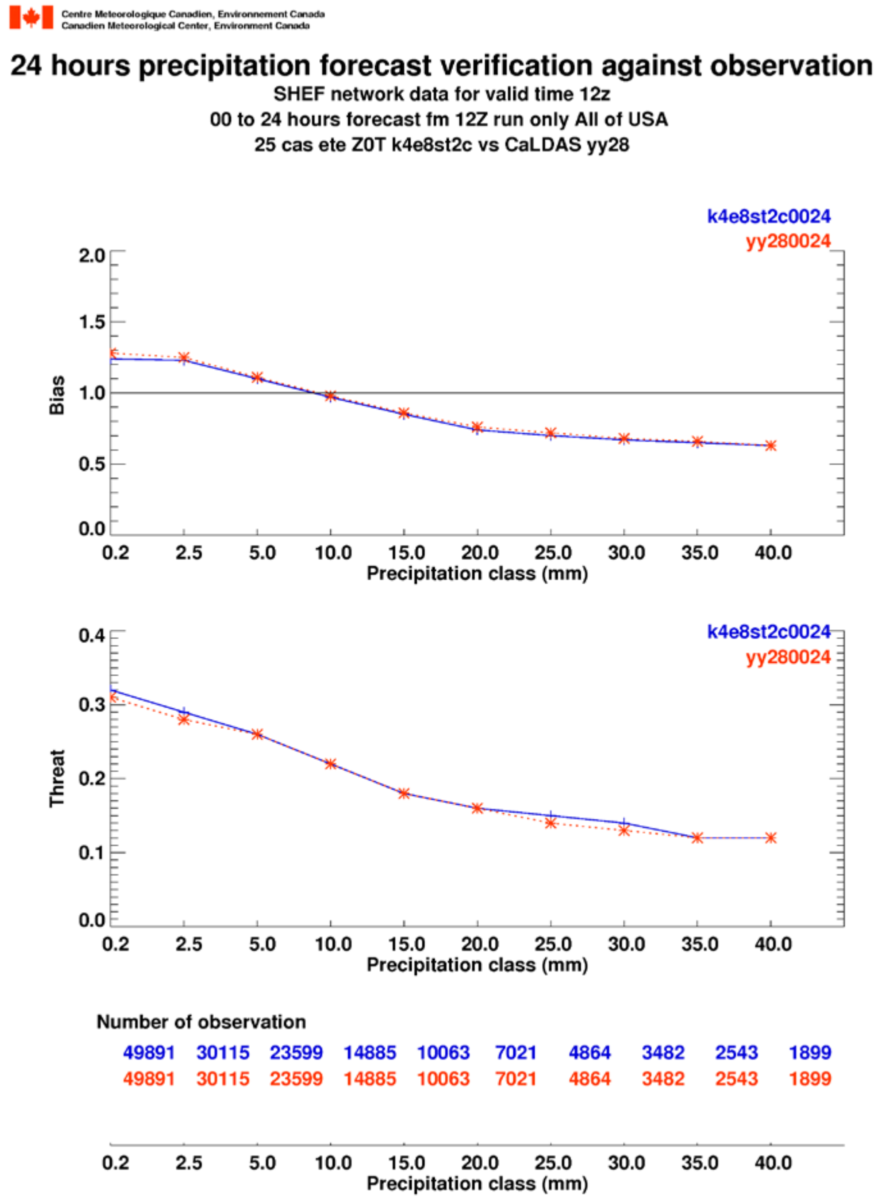


Vegetation Structure to Correlation

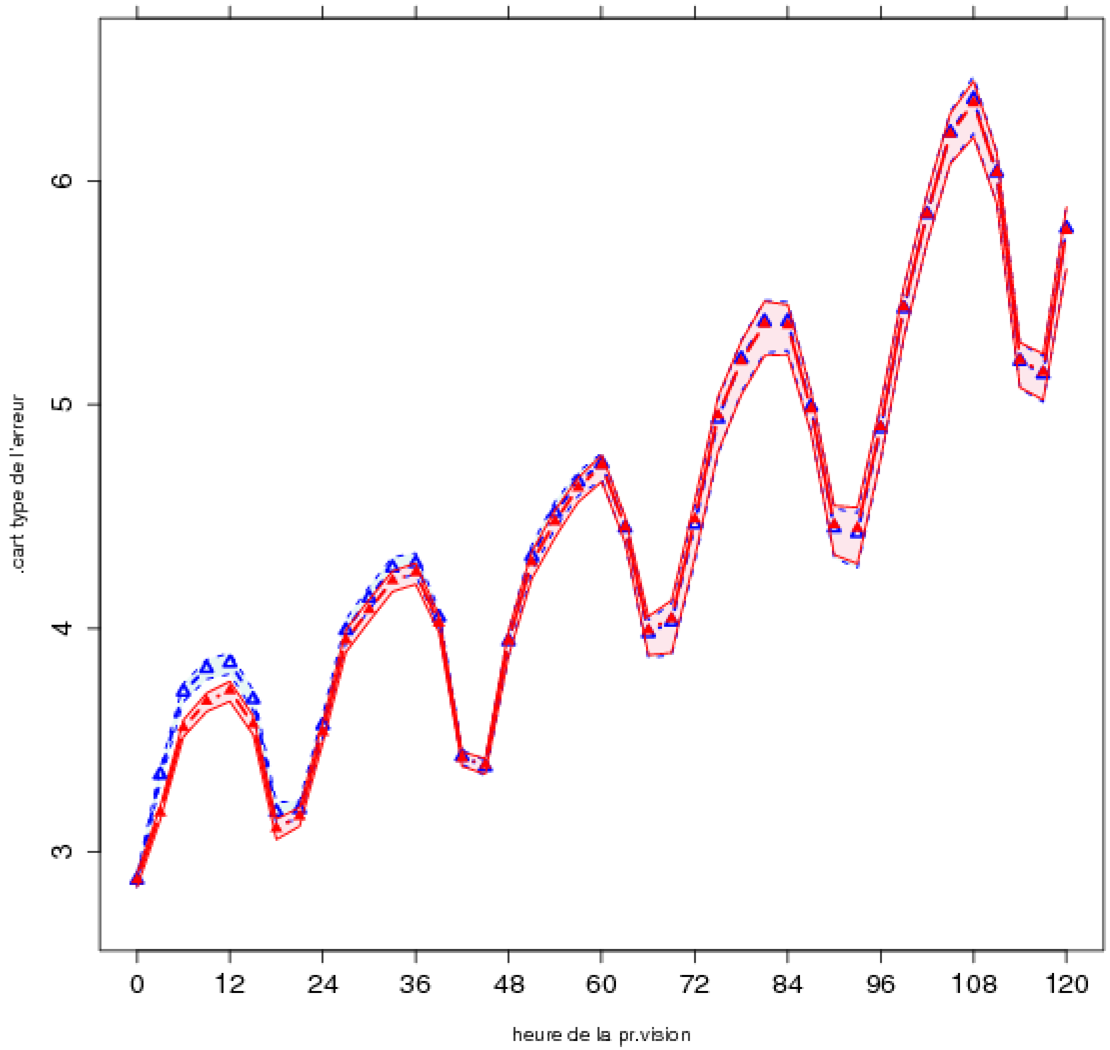
yy28 : TT Bias (00z) : Summer 2008



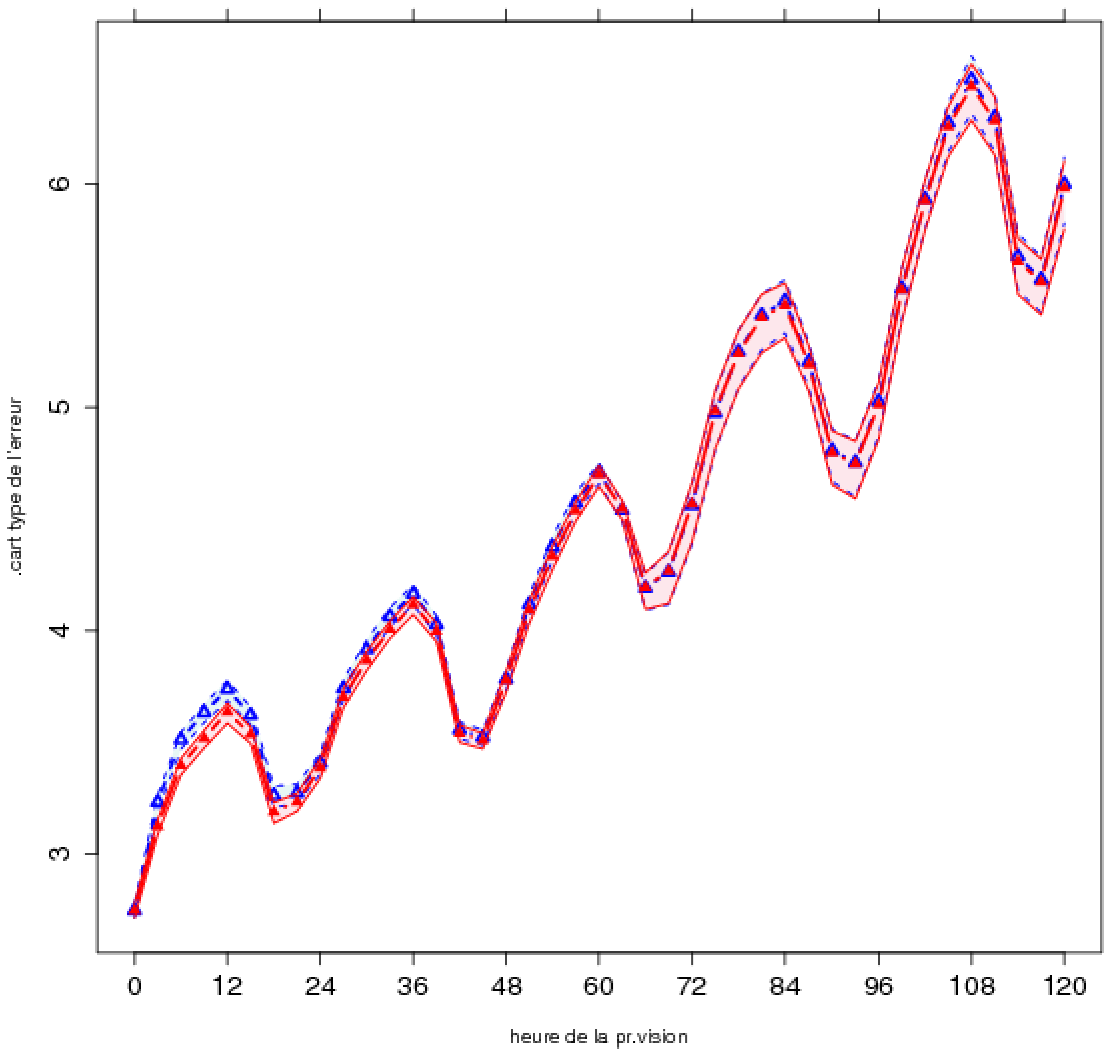
Precipitation Verification 00-24 hrs : SHEF network



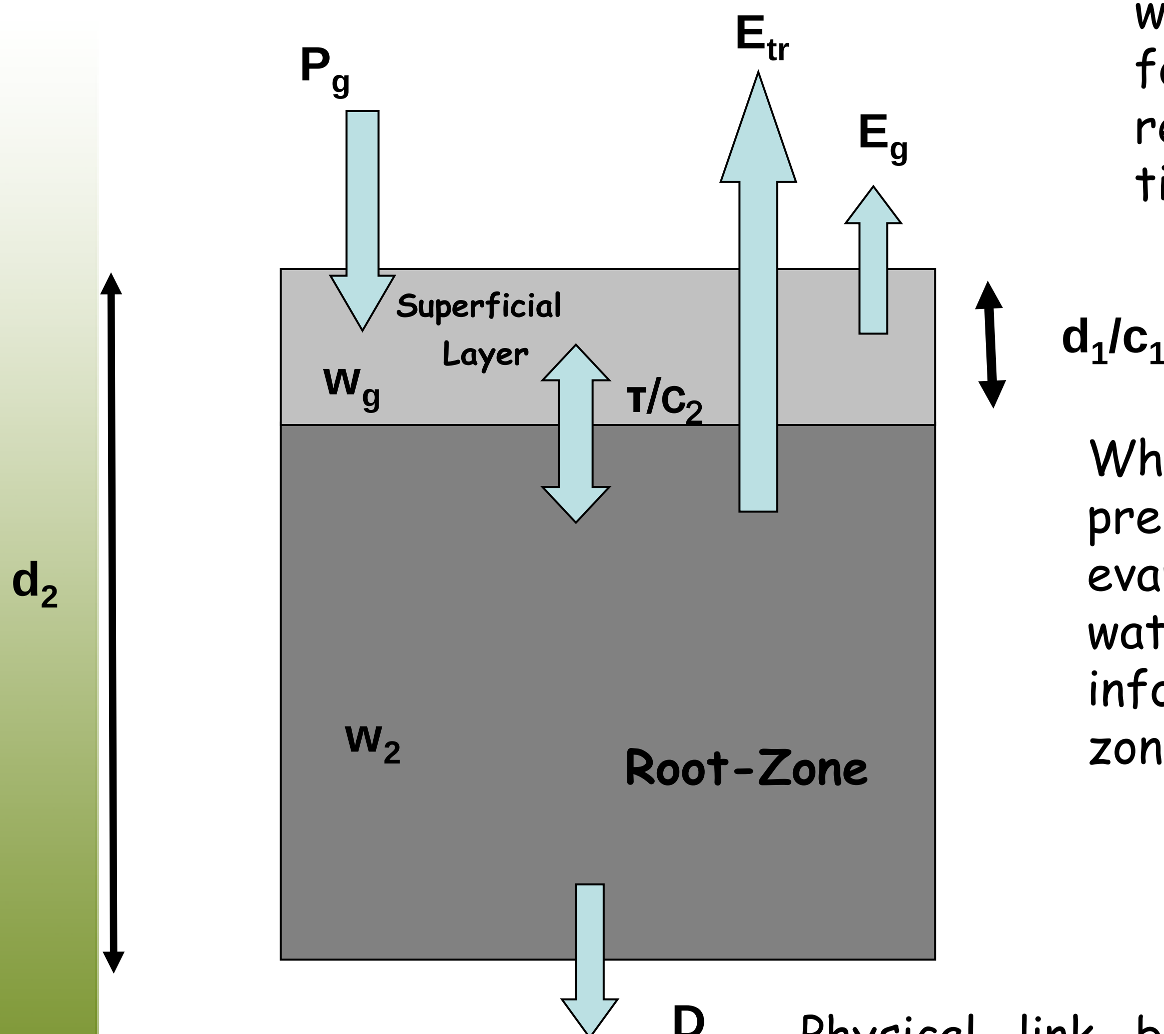
Standard Error of Forecasts yy28 – hiver TT



Standard Error of Forecasts yy28 – hiver TD



2-layer ISBA



w_g evolves according to a forcing term (P_g-E_g) and is relaxed toward w_{geq} with a time constant of τ/c_2.

When the forcing is strong (i.e, precipitating event or strong evaporation), the surface water content (w_g) is not informative about the root zone w_2.

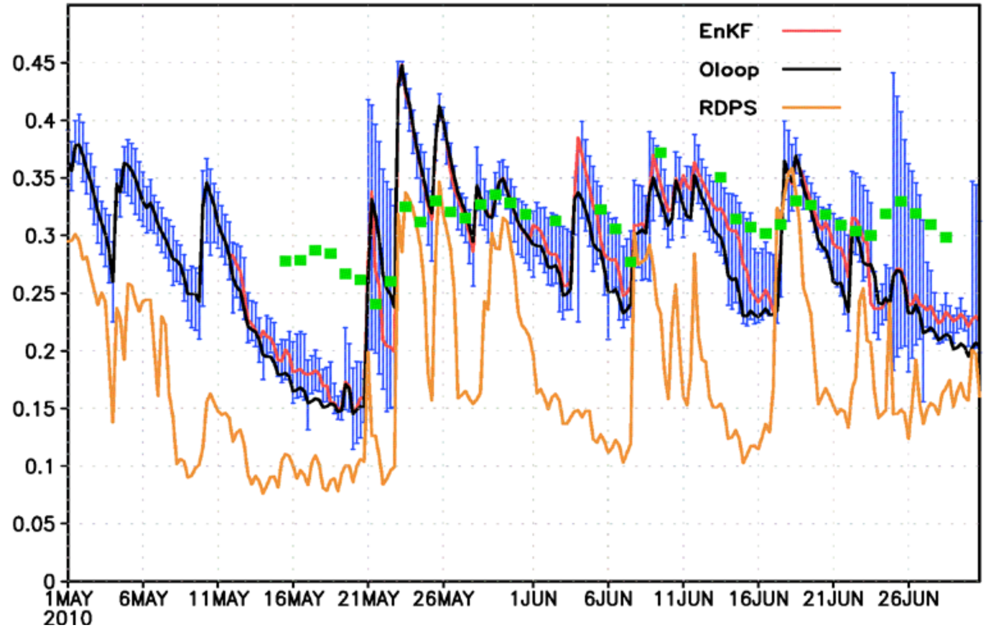
Physical link between w_g and w_2 is through transpiration (E_{tr}). Analysis of w_2 from w_g observations must rely on the sensitivity of wg to changes in w_2.

Soil Moisture Simulations : CanEX-SM10 : Kenaston

Superficial

Soil Moisture

($m^3\ m^{-3}$)

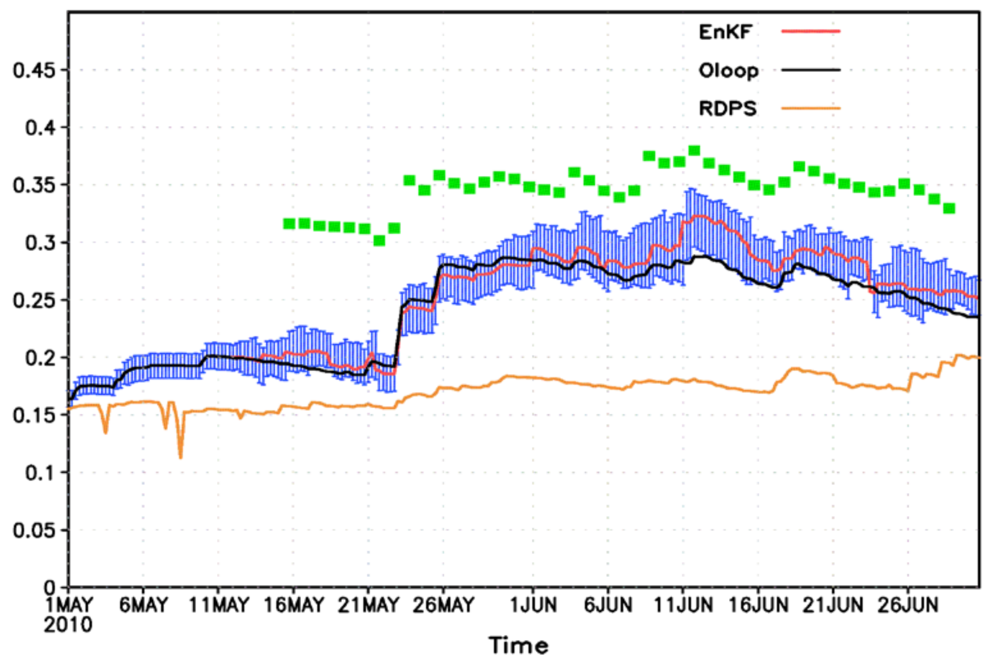


5-cm soil moisture

Root Zone

Soil Moisture

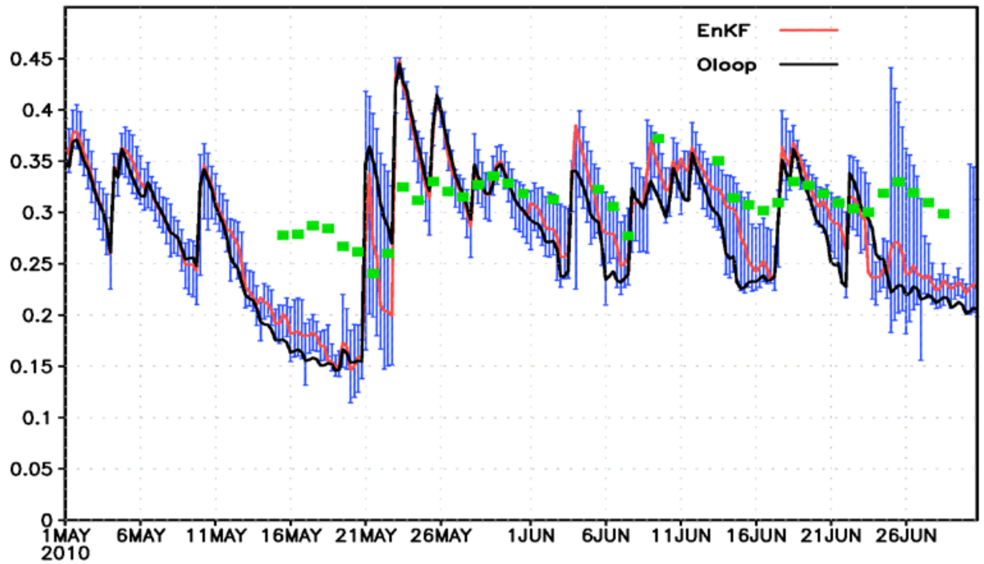
($m^3\ m^{-3}$)



Mean soil moisture sfc-50 cm

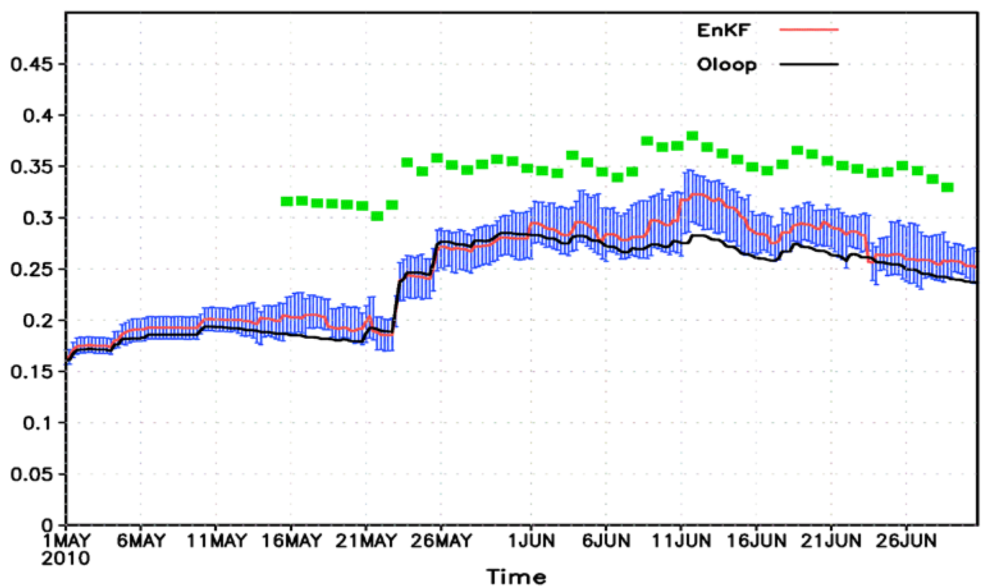
Soil Moisture Simulations : CanEX-SM10 : Kenaston

Superficial Soil Moisture ($m^3\ m^{-3}$)



5-cm soil moisture

Root Zone Soil Moisture ($m^3\ m^{-3}$)



Mean soil moisture sfc-50 cm