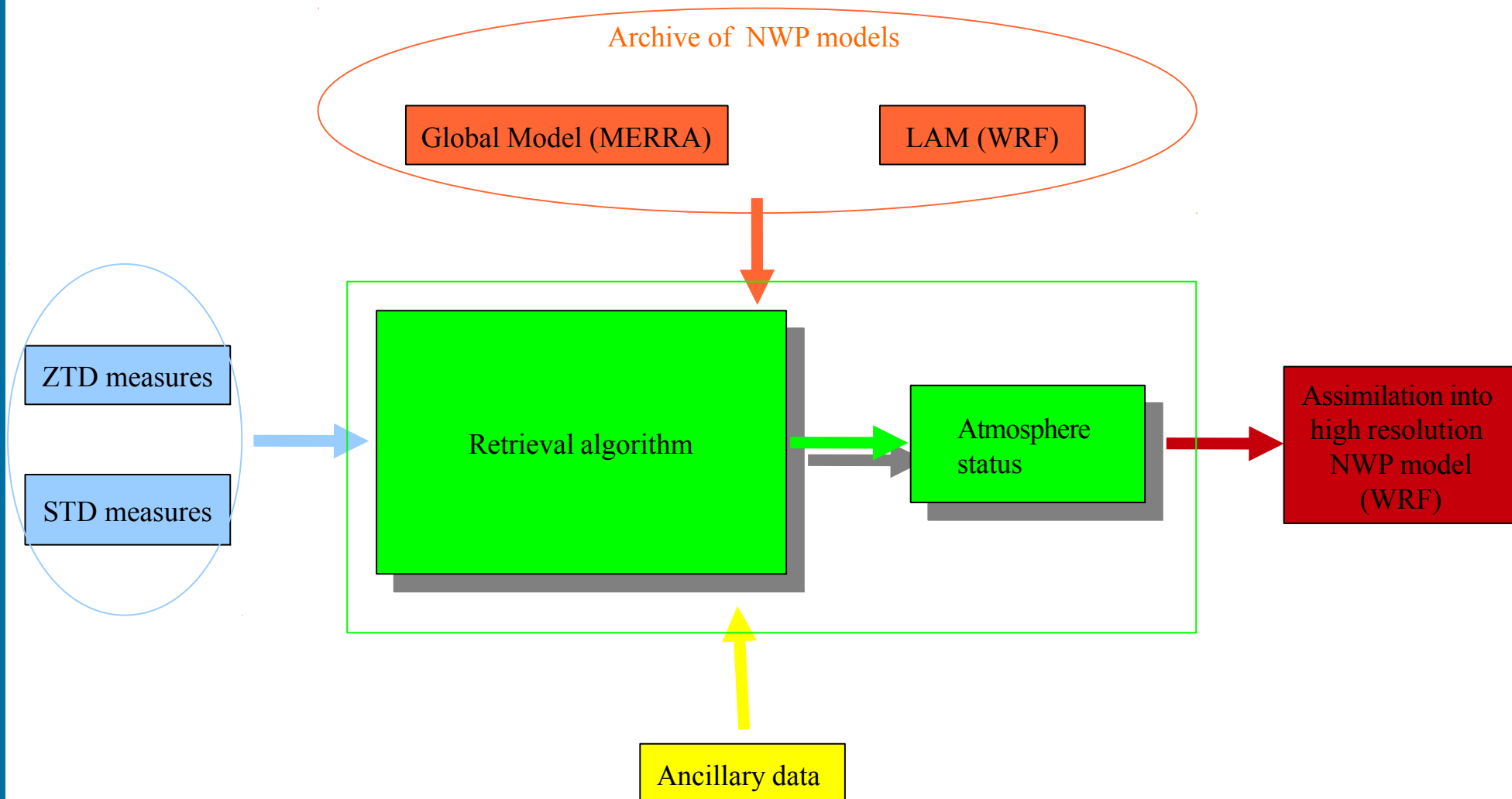




A Bayesian approach for atmospheric sounding from GNSS signals.

- Introduction
- GNSS Meteorology: classical approach
- Description of the adopted method and of its implementation
- Results of the method and validation with ancillary data
- Simulation of the COSMEMOS observational scenario
- Future developments

Development of atmosphere status retrieval algorithm



GNSS-based ZPD (Zenith Path Delay) (IGS)

<ftp://cddis.gsfc.nasa.gov/pub/gps/products/troposphere/zpd/>

Index of <ftp://cddis.gsfc.nasa.gov/pub/gps/products/troposphere/zpd/2011/>

Up to higher level directory

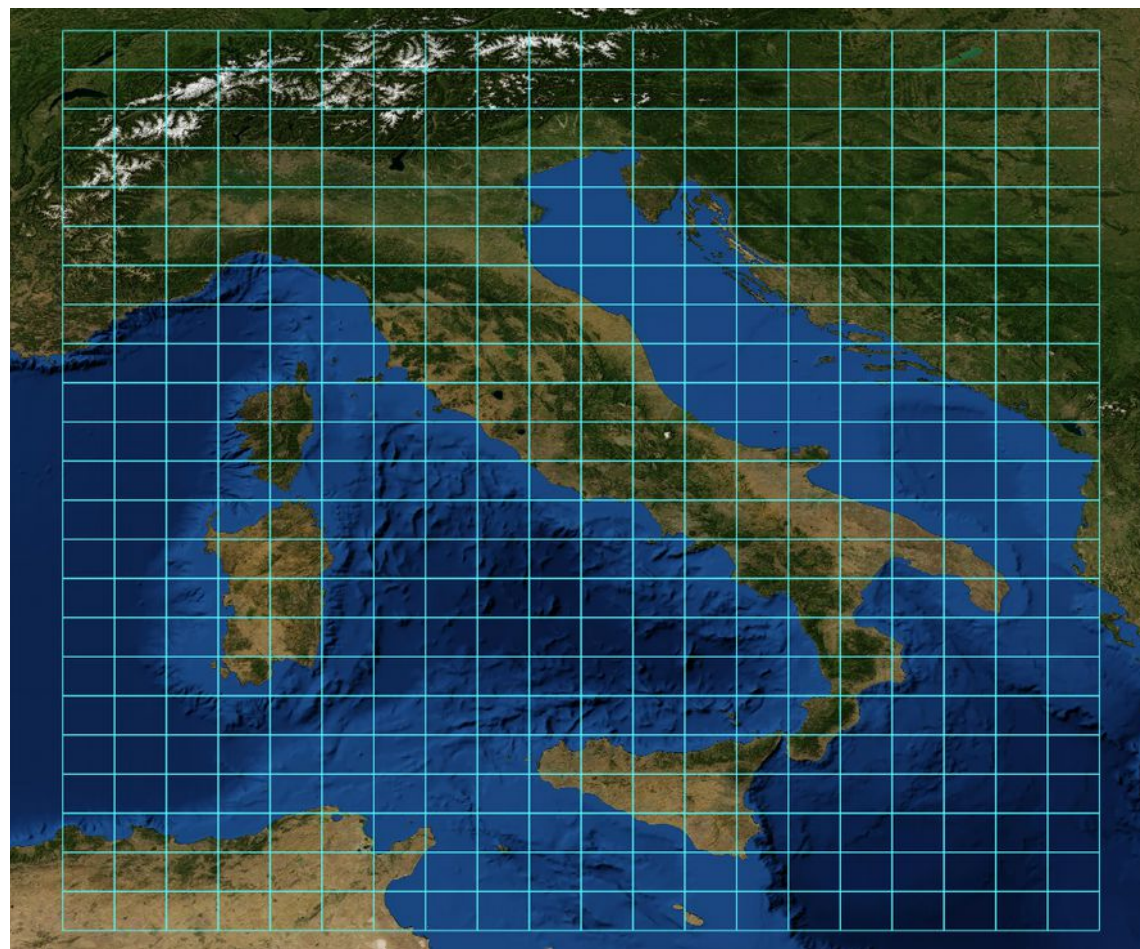
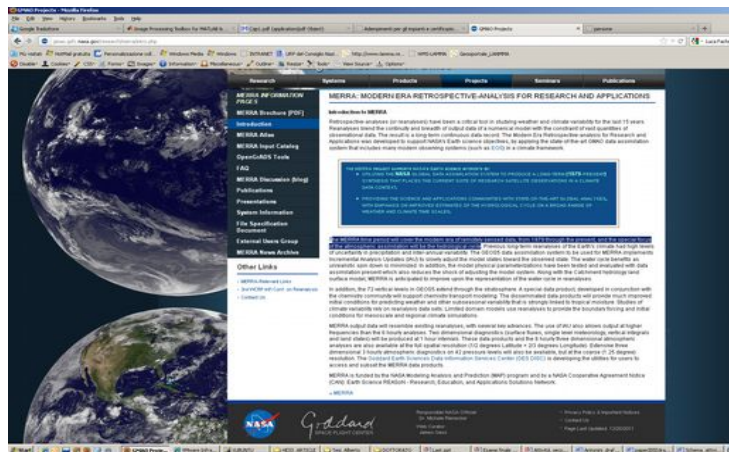
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| 003 | | 17/02/2011 0:00:00 |
| 004 | | 17/02/2011 0:00:00 |
| 005 | | 17/02/2011 0:00:00 |
| 006 | | 17/02/2011 0:00:00 |
| 007 | | 17/02/2011 0:00:00 |
| 008 | | 17/02/2011 0:00:00 |
| 009 | | 17/02/2011 0:00:00 |
| 010 | | 17/02/2011 0:00:00 |
| 011 | | 17/02/2011 0:00:00 |
| 012 | | 17/02/2011 0:00:00 |
| 013 | | 17/02/2011 0:00:00 |
| 014 | | 17/02/2011 0:00:00 |
| 015 | | 17/02/2011 0:00:00 |
| 016 | | 24/02/2011 0:00:00 |
| 017 | | 24/02/2011 0:00:00 |
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| 020 | | 24/02/2011 0:00:00 |
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| 028 | | 24/02/2011 0:00:00 |
| 029 | | 24/02/2011 0:00:00 |
| 030 | | 18/03/2011 0:00:00 |
| 031 | | 19/03/2011 0:00:00 |
| 032 | | 19/03/2011 0:00:00 |
| 033 | | 19/03/2011 0:00:00 |



NWP model MERRA reanalysis

| Variable | Dimensions | Description | Units |
|---------------|---------------|-------------------------------------|-------------------------------|
| SLP | 2D | Sea Level Pressure | Pa |
| PS | 2D | Surface Pressure | Pa |
| h | 3D | Geopotential Height | m |
| T | 3D | Air Temperature | K |
| u | 3D | Eastward wind component | m s⁻¹ |
| v | 3D | Northward wind component | m s⁻¹ |
| q | 3D | Specific humidity | Kg Kg ⁻¹ |
| o3 | 3D | Ozone mixing ratio | kg kg⁻¹ |

<http://gmao.gsfc.nasa.gov/research/merra/intro.php>

The screenshot shows the 'Introduction' page for MERRA (Modern Era Retrospective-Analysis for Research and Applications). The page title is 'MERRA: MODERN ERA RETROSPECTIVE-ANALYSIS FOR RESEARCH AND APPLICATIONS'. It includes a 'Introduction' section, a 'MERRA Reanalysis (POT)' section, and a 'MERRA Reanalysis (POT)' section. The page also features a sidebar with navigation links and a footer with NASA and Goddard Space Flight Center logos.

Weather Balloon Sounding

<http://weather.uwyo.edu/upperair/sounding.html>



| Region | Type of plot | Year | Month | From | To | Station Number |
|--------|--------------|------|-------|--------|--------|----------------|
| Europe | Text List | 2012 | Jan | 26/00Z | 26/00Z | 26038 |

Click on the image to request a sounding at that location or enter the station number above.



Recalculate Data

Interested in studying meteorology? Check out our [graduate program](#) or undergraduate degree in [Earth System Science](#).

Questions about the weather data provided by this site can be addressed to Larry.Colman@uwoolnar@uwyo.edu

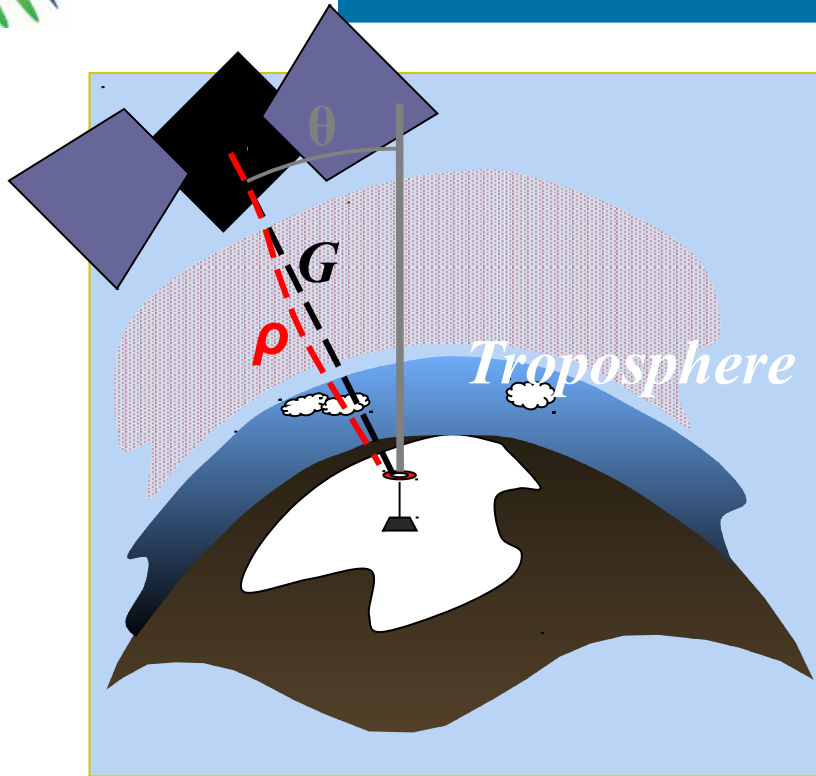


Weather stations data network



High resolution LAM [WRF 1km]





Tropospheric delay

$$\Delta L = \rho - G = \int_L n(s) ds - G$$

Refractivity in troposphere

$$N = (n - 1) 10^6$$

$$N = k_1 \left(\frac{P_d}{T} \right) Z_d^{-1} + k_2 \left(\frac{e_w}{T} \right) Z_w^{-1} + k_3 \left(\frac{e_w}{T^2} \right) Z_w^{-1}$$

Zenith Tropospheric Delay

$$ZTD = \Delta LM(\theta)$$

Hydrostatic and wet components

$$ZTD = ZHD + ZWD$$

$$ZHD = (2.2779 \pm 0.0024) \frac{P_s}{f(\lambda, H)}$$

$$ZWD = 10^{-6} \left[k'_2 \int \frac{e_w}{T} dz + k_3 \int \frac{e_w}{T^2} dz \right]$$

IWV and PW estimation:

$$T_m = \frac{\int \frac{P_v}{T} dz}{\int \frac{P_v}{T^2} dz}$$

weighted "mean temperature" of
the atmosphere

IWV: the mass of vapour per unit of area

$$IWV = \int \rho_v dz \approx ZWD \quad \frac{1}{k} = 10^{-6} \left(\frac{k_3}{T_m} + k'_2 \right) R_v$$

PW: the height of an equivalent unit vertical column of liquid water

$$IWV = \rho PW \quad \Rightarrow \quad \frac{PW}{ZWD} = \frac{k}{\rho}$$

The value of k must be estimated using a value of T_m tuned to the specific area and season

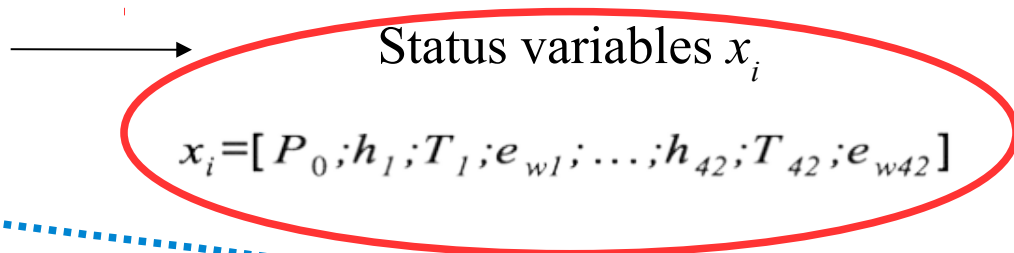
Following Basili et al. 2002

$$T_m = m T_s + c \text{ [K]} \quad m = 0.7162 \quad c = 71.7054$$

T_s is the surface temperature

A dataset of more than 10 years of data coming from a global NWPM able to represent the actual atmosphere status

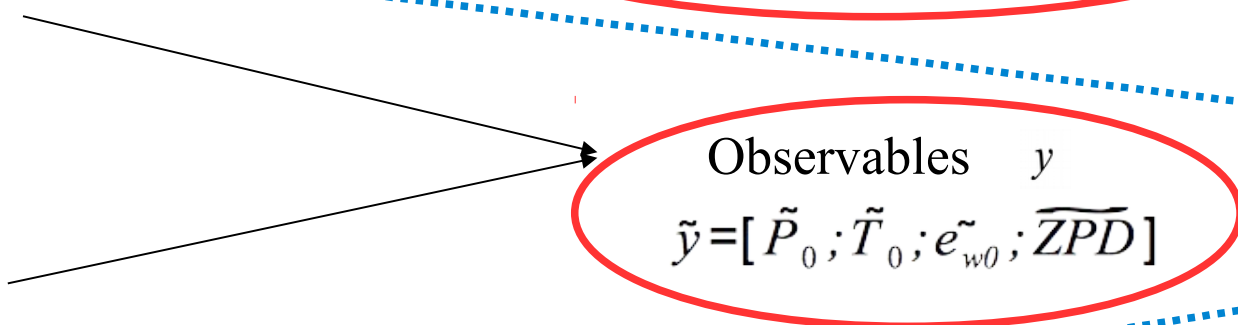
MERRA global model dataset



A dataset of ZPD values

ZPD IGS network

A dataset of P, T, e_w values



Weather station network

Bayes Theorem

$$p(x_i | \tilde{y} I) = \frac{p(x_i | I) p(\tilde{y} | x_i I)}{p(\tilde{y} | I)}$$

GNSS-based atmospheric sensor: theoretical background

Equiprobability of model state variables

To be defined

Prior distribution

Likelihood probability

$$p(x_i | \tilde{y} I) = \frac{p(x_i | I) p(\tilde{y} | x_i I)}{p(\tilde{y} | I)}$$

Posterior probability

Prior distribution of the observables

Desired quantity

Normalisation factor

$$p(x_i | \tilde{y} I) = \frac{p(\tilde{y} | x_i I)}{[\sum_{i=1}^M p(\tilde{y} | x_i I)]^{-1}}$$

$$p(\tilde{y}|x_i) = p(\tilde{P}_0 \tilde{T}_0 \tilde{e}_{w0} \overline{ZPD} | x_i) = p(\tilde{P}_0 | x_i) p(\tilde{T}_0 | \tilde{P}_0 x_i) p(\tilde{e}_{w0} | \tilde{P}_0 \tilde{T}_0 x_i) p(\overline{ZPD} | \tilde{P}_0 \tilde{T}_0 \tilde{e}_{w0} x_i)$$

$$\tilde{P}_0 = \alpha_P + \beta_P P_0$$

$$\tilde{T}_0 = \alpha_T + \beta_T T_1 + \gamma_T \tilde{P}_0$$

$$\tilde{e}_{w0} = \alpha_e + \beta_e e_{w1} + \gamma_e \tilde{T}_0 + \eta_e \tilde{P}_0$$

$$\overline{ZPD} - c_1 \frac{\tilde{P}_0}{\bar{g}} = \alpha_\delta + \beta_\delta \left[ZPD(x) - c_1 \frac{(P_1 - P_{42})}{\bar{g}} \right] + \gamma_\delta \left(c_2 \left\langle \frac{e_{w01}}{T_{01}} \right\rangle + c_3 \left\langle \frac{e_{w01}}{T_{01}^2} \right\rangle \right) (z_1 - z_0)$$

The coefficients $[\alpha_P, \beta_P, \gamma_P, \alpha_T, \beta_T, \gamma_T, \alpha_e, \beta_e, \gamma_e, \eta_e, \alpha_\delta, \beta_\delta, \gamma_\delta]$ can be computed using an opportune dataset.

When the coefficients have been computed the probability distribution functions can be approximated by a fit over the histograms of residuals.

Test 1. Three test sites with only local data

- IGS GNSS stations
- Balloon data
- MERRA model grid
- Test Sites

Observables \tilde{y}

ZPD from IGS stations
 P_0, T_0, e_{w0} from balloon data

Status variables x_i

Merra model profiles

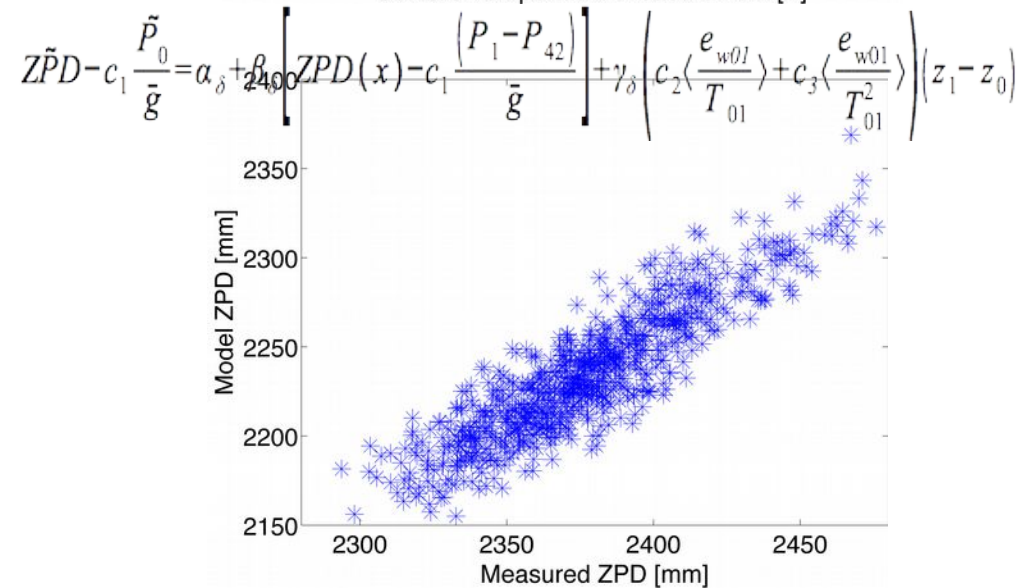
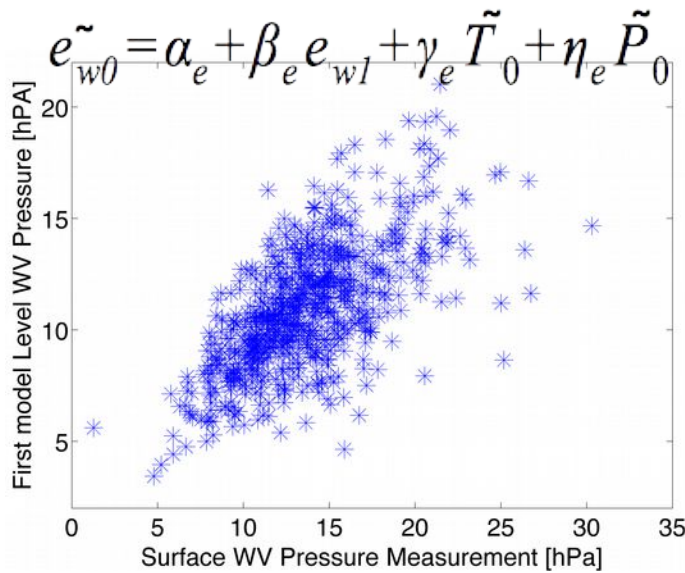
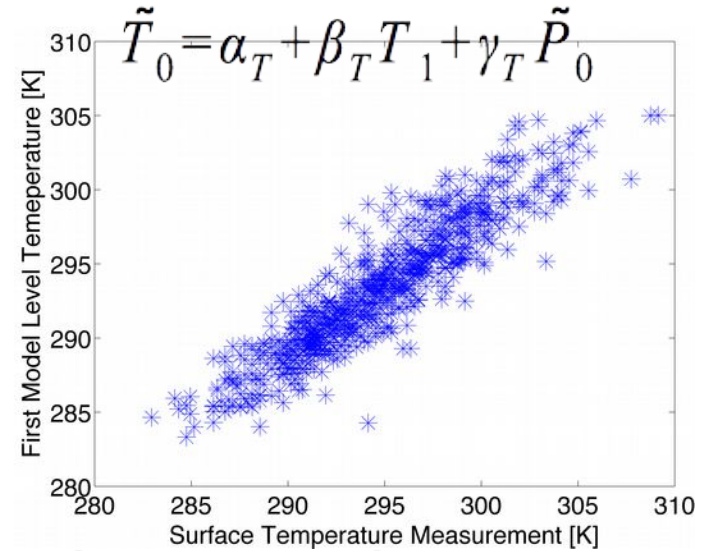
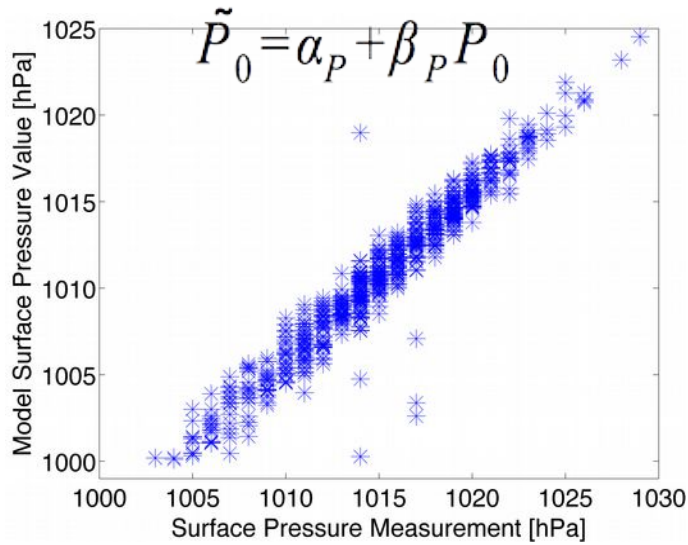


Dataset used for likelihood:
 Observables and MERRA data [2001-2010]

Dataset used for tests: observables 2011

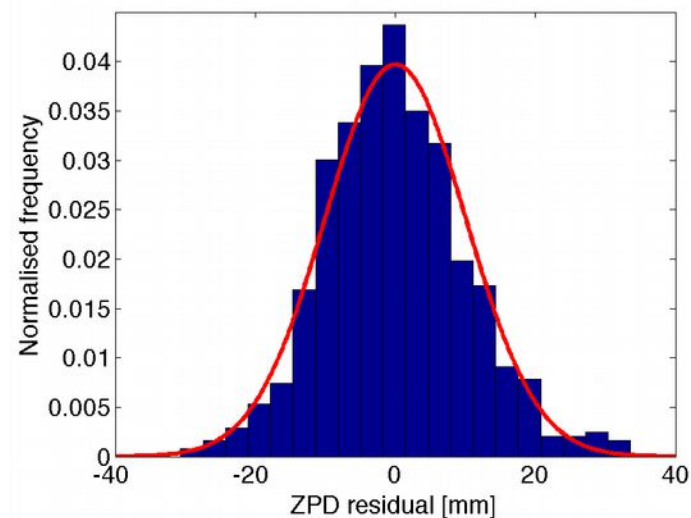
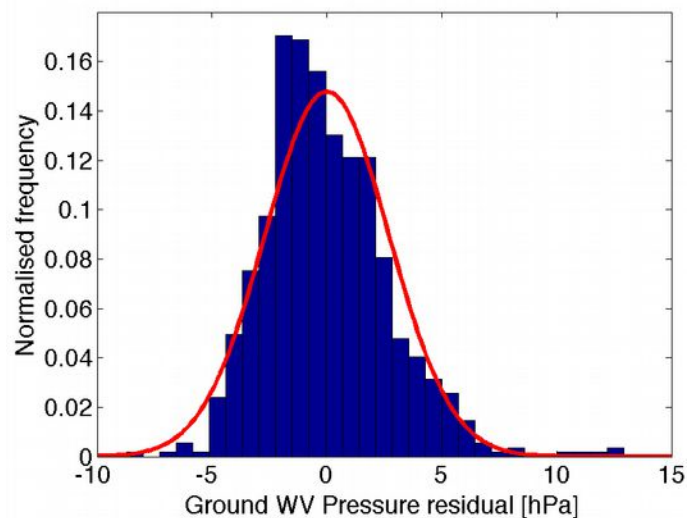
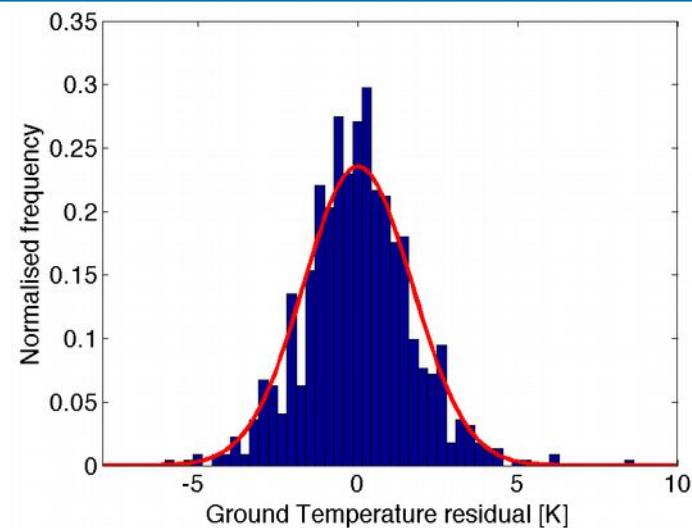
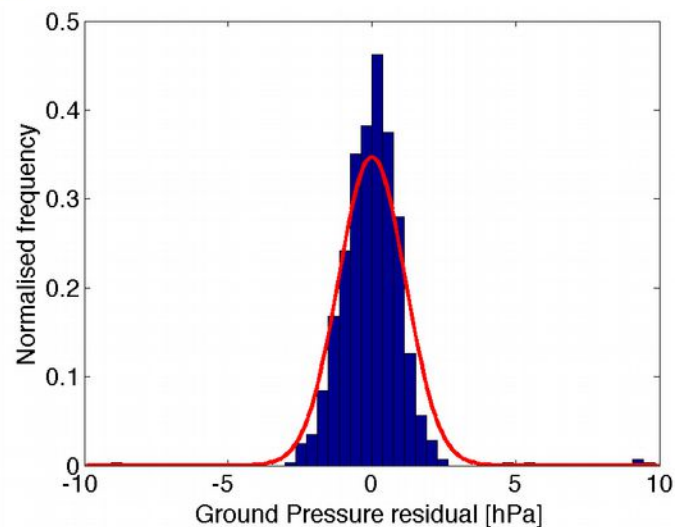
Test 1. Three test sites with only local data

Cagliari station



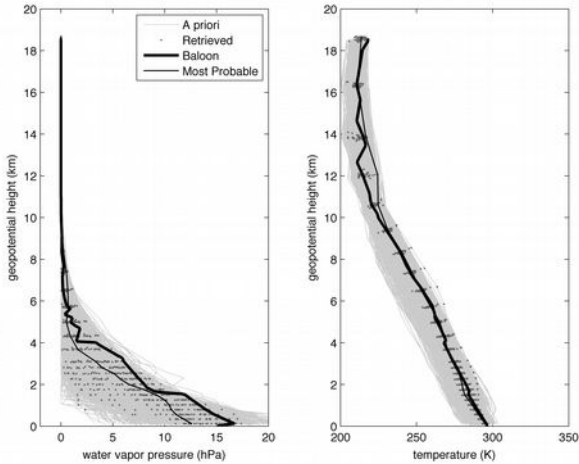
Test 1. Three test sites with only local data

Cagliari
station



Test 1. Three test sites with only local data

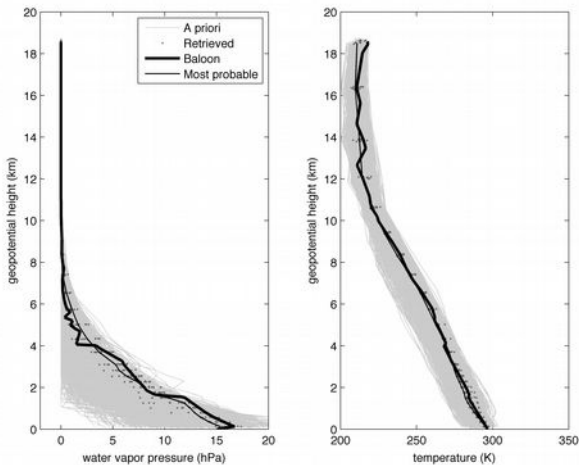
Only surface observables (no GNSS observation)



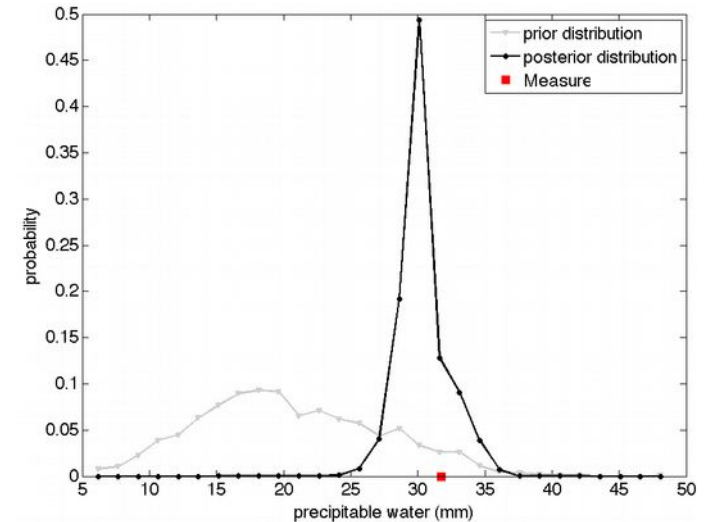
CASE STUDY: 2011/10/07 @ 12 UTC

Station: Cagliari

Complete set of observables (including GNSS observation)

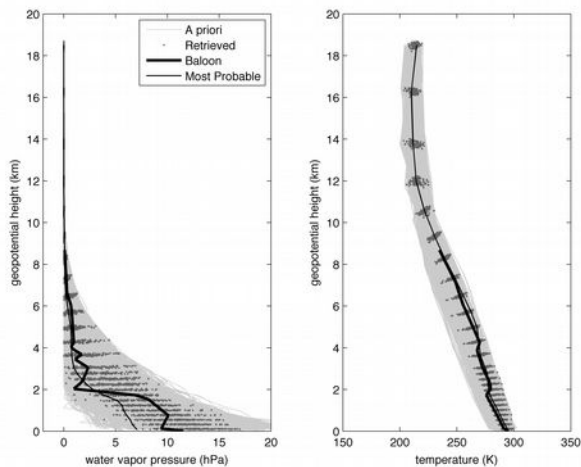


PW



Test 1. Three test sites with only local data

Only surface observables (no GNSS observation)

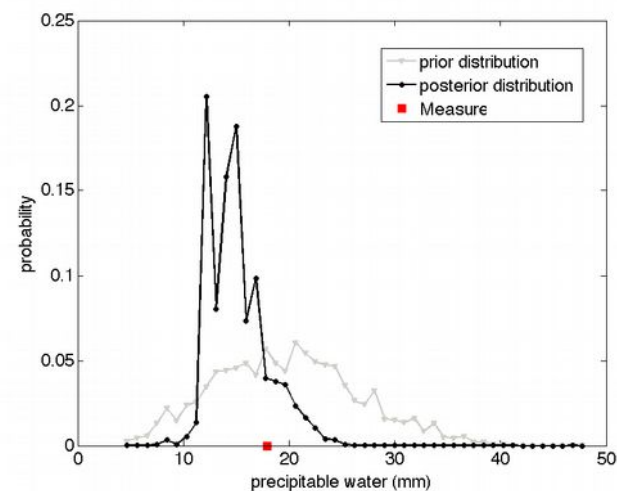
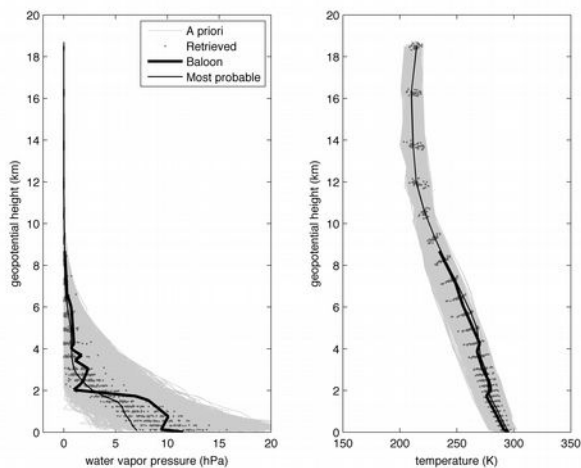


CASE STUDY: 2011/10/07 @ 12 UTC

Station: Ajaccio

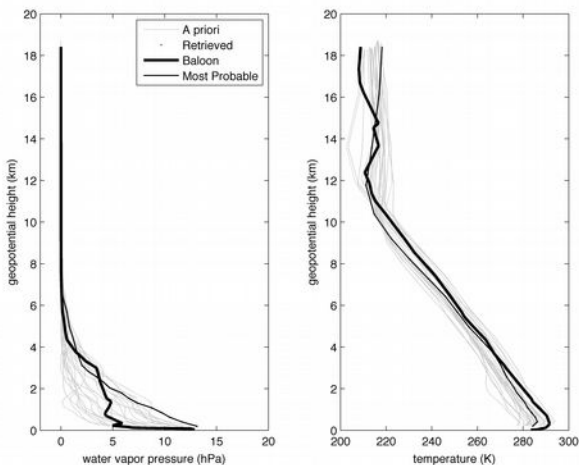
PW

Complete set of observables (including GNSS observation)



Test 1. Three test sites with only local data

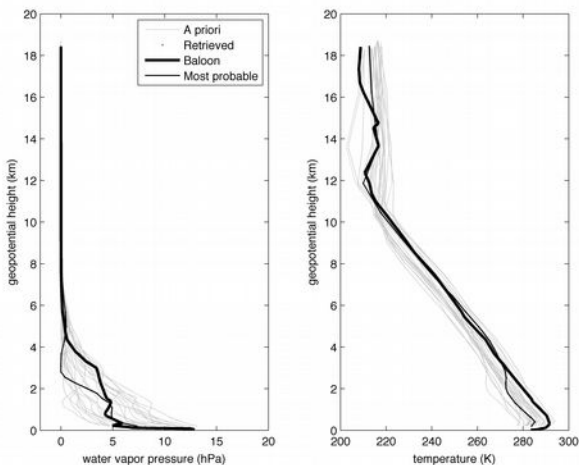
Only surface observables (no GNSS observation)



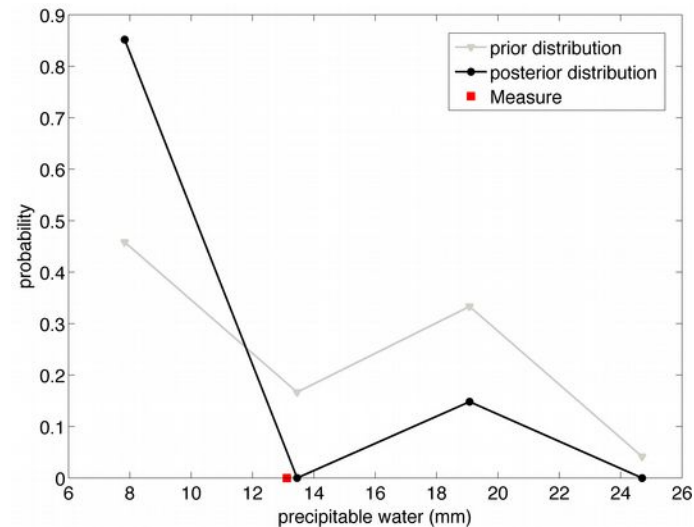
CASE STUDY: 2011/04/11 @ 12 UTC

Station: Medicina

Complete set of observables (including GNSS observation)

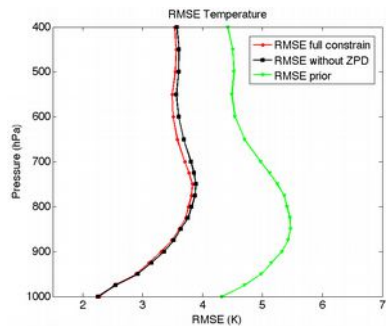
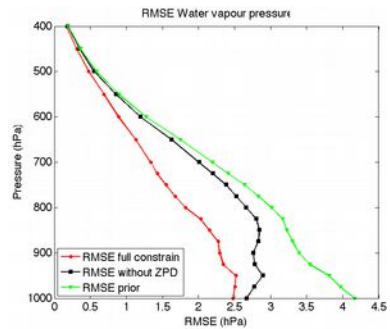
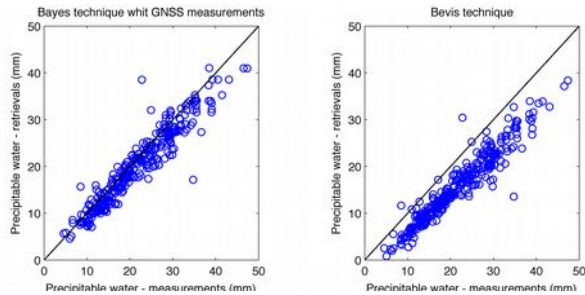


PW

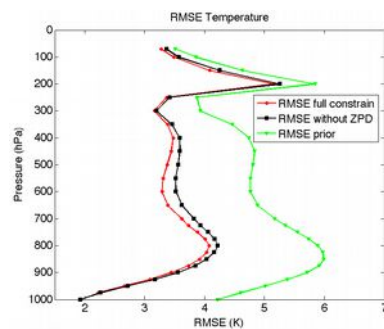
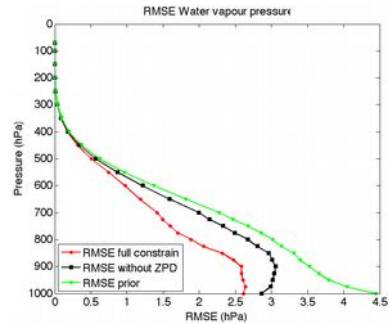
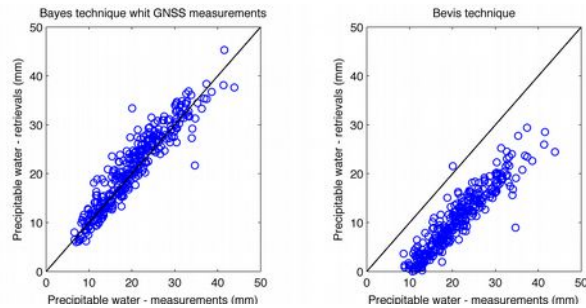


Test 1. Three test sites with only local data

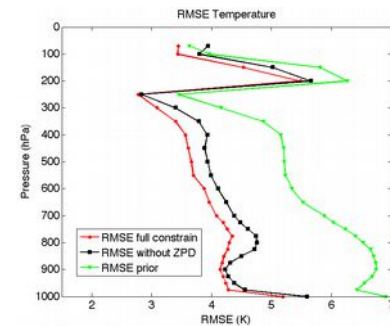
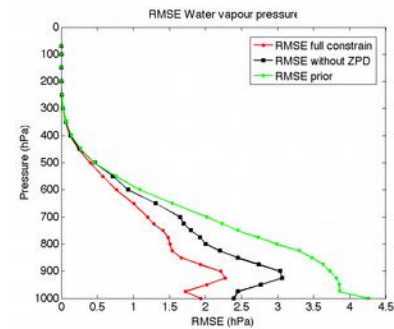
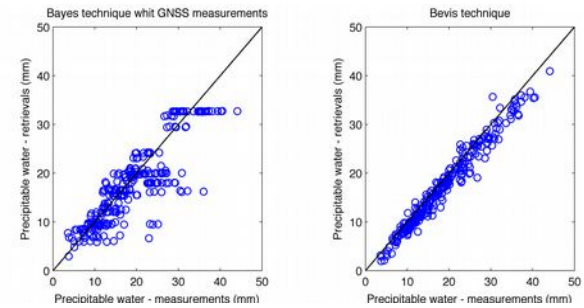
Ajaccio – full year 2011



Cagliari – full year 2011



Medicina – full year 2011



Test 2. Validity for the whole area

- IGS GNSS stations
- Balloon data
- MERRA model grid
- Weather stations
- Areas of coefficient tuning
- Test Sites

Observables \tilde{y}

ZPD from IGS stations

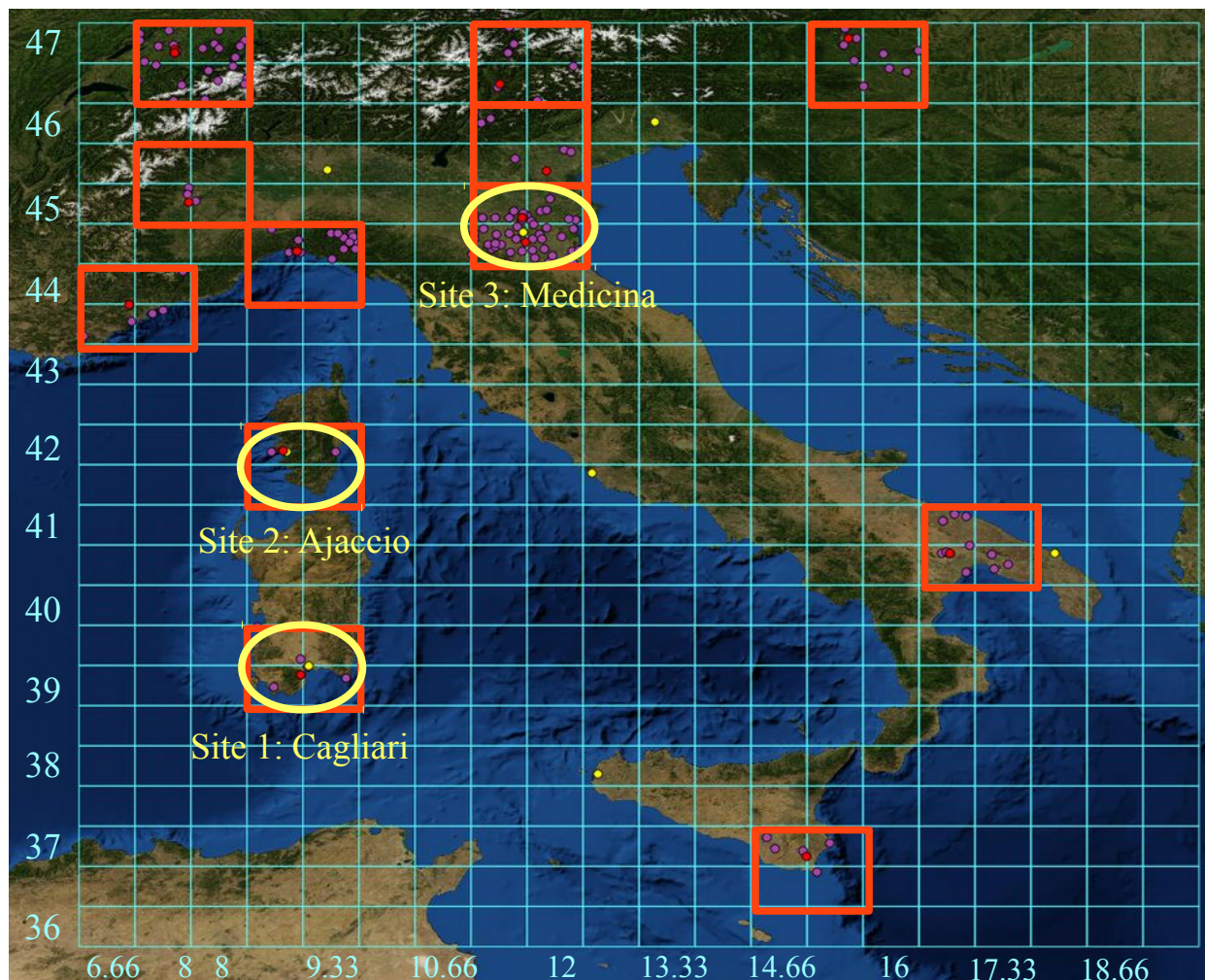
P_0, T_0, e_{w0} from weather stations

Status variables x_i

Merra model profiles

Dataset used for likelihood:
Observables and MERRA data [2001-2010]

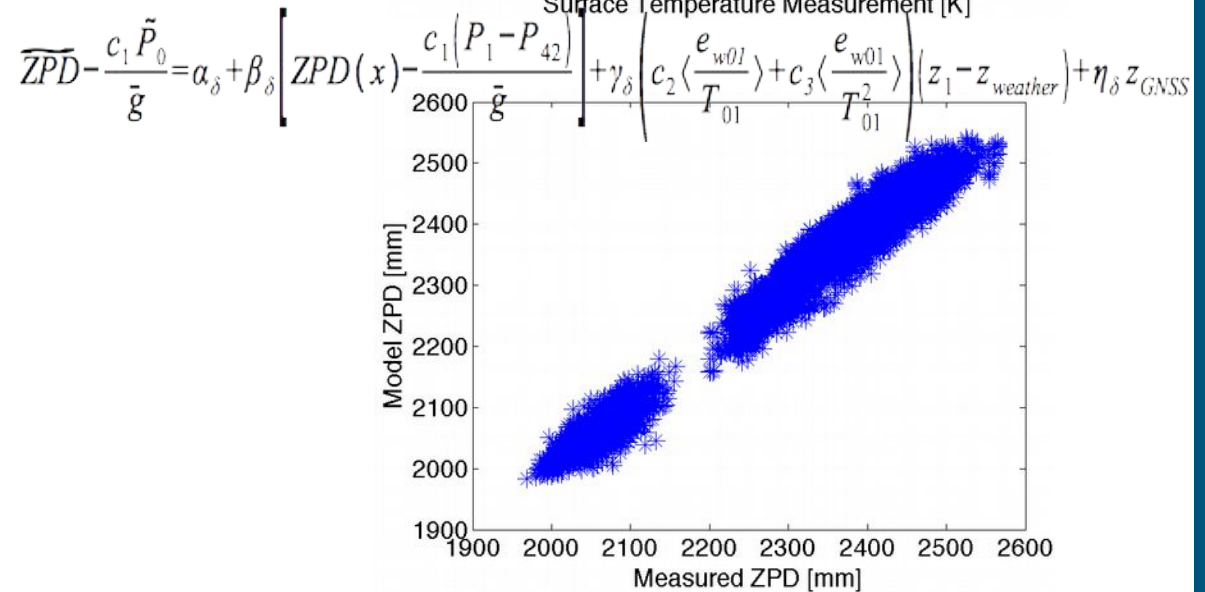
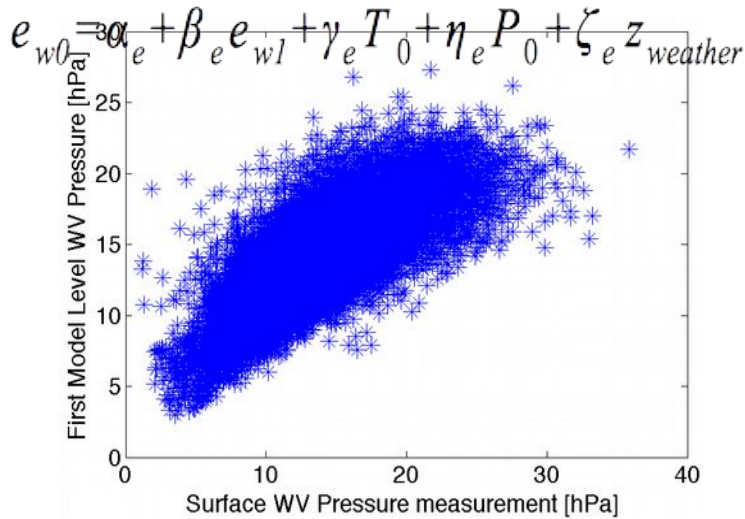
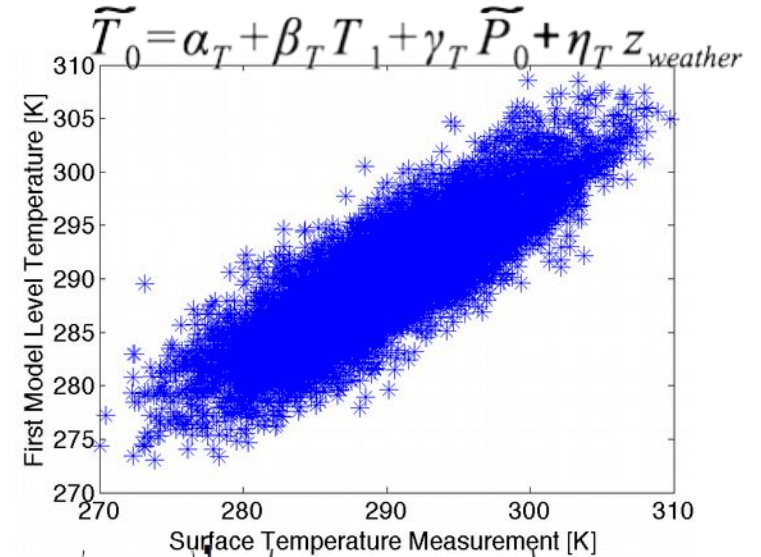
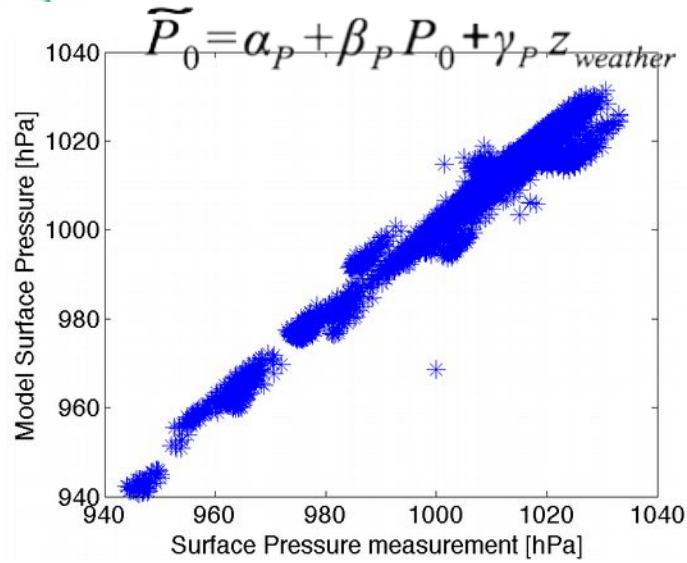
Dataset used for tests: observables 2011



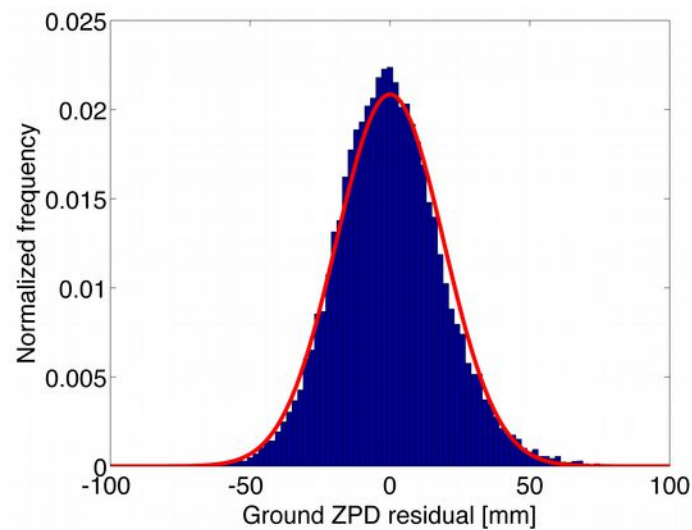
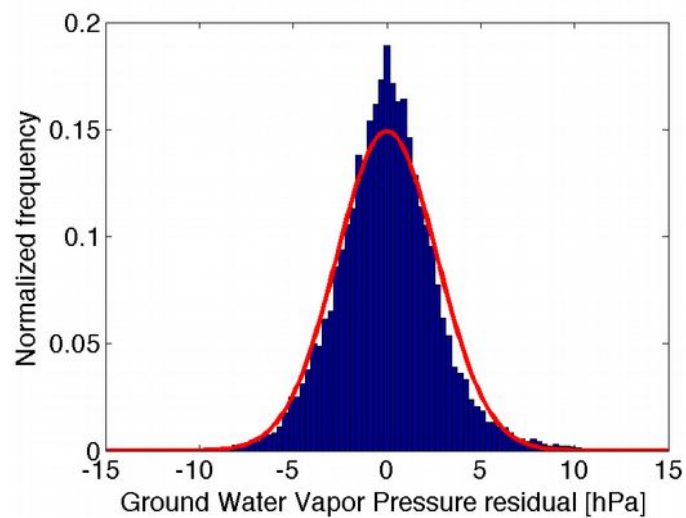
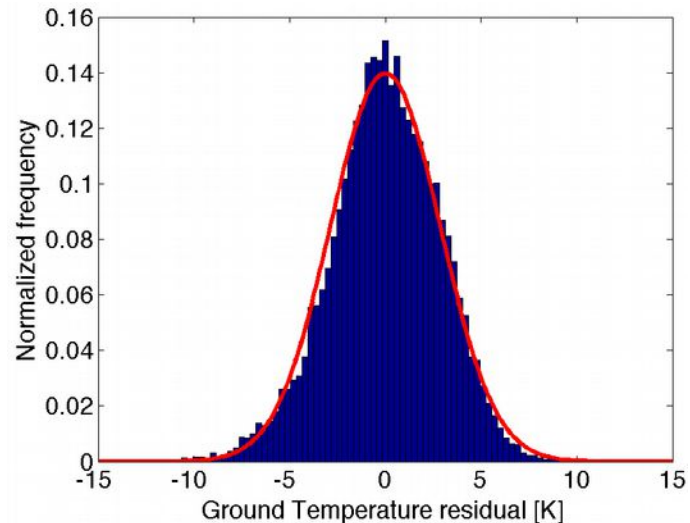
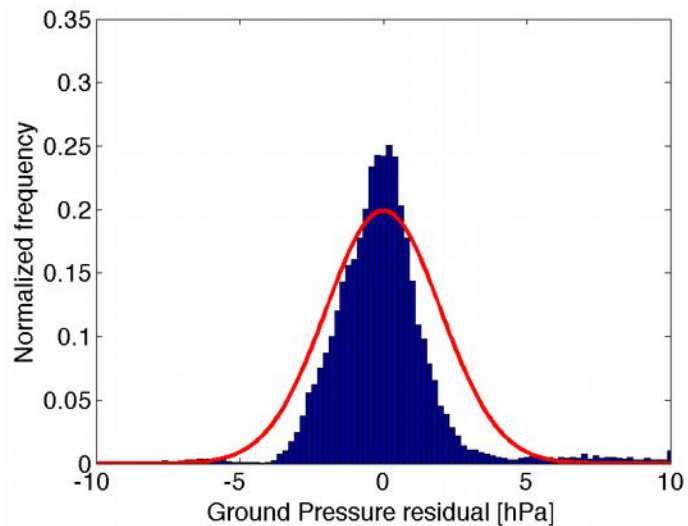
N.B. The test sites are excluded from the dataset used for the likelihood computation.



Test 2. Validity for the whole area

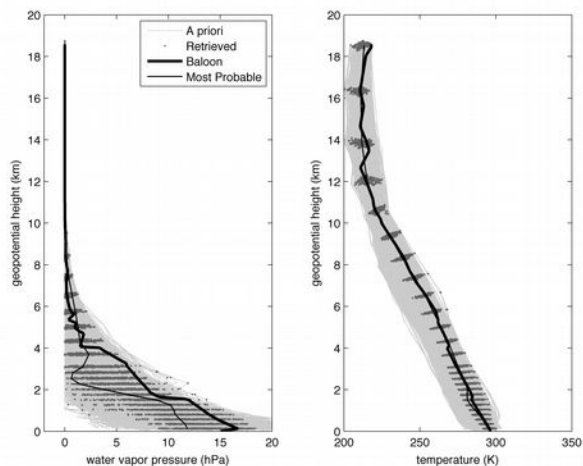


Test 2. Validity for the whole area



Test 2. Validity for the whole area

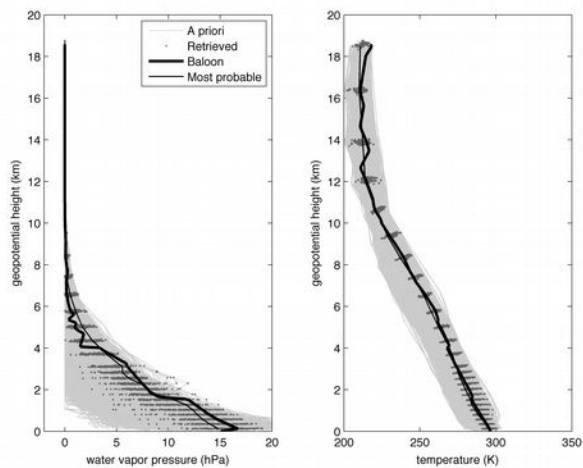
Only surface observables (no GNSS observation)



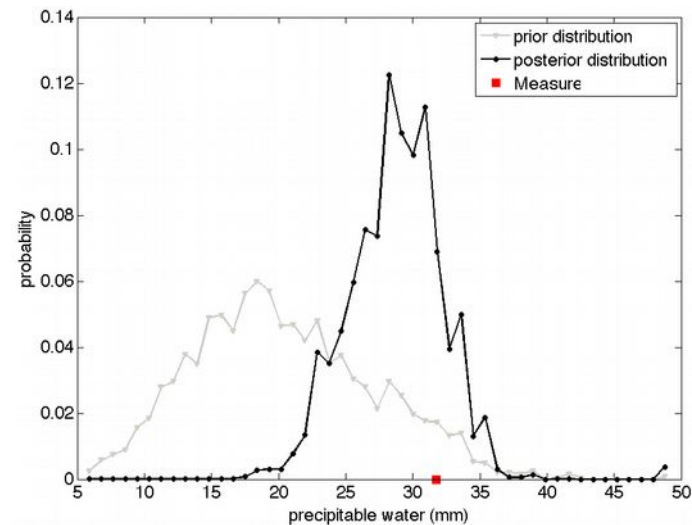
CASE STUDY: 2011/10/07 @ 12 UTC

Station: Cagliari

Complete set of observables (including GNSS observation)

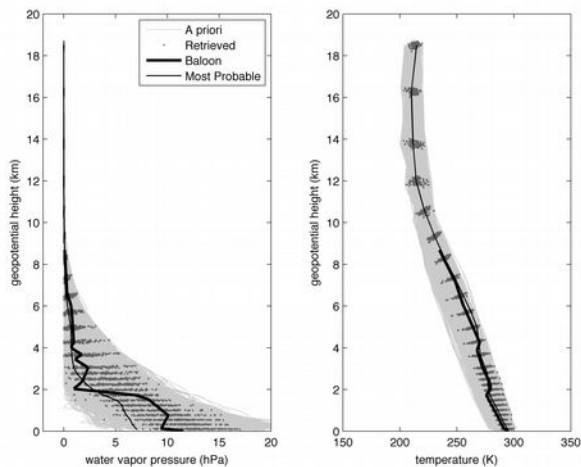


PW



Test 2. Validity for the whole area

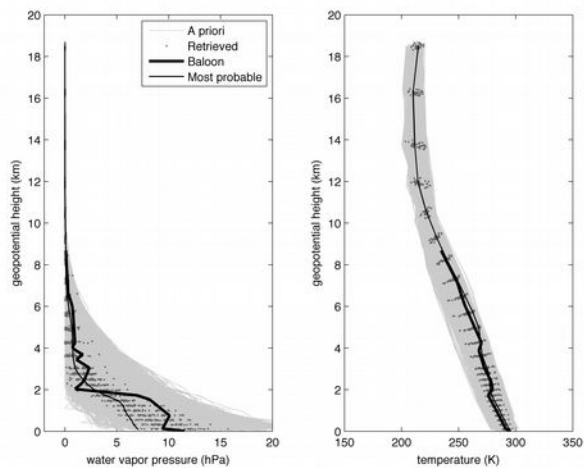
Only surface observables (no GNSS observation)



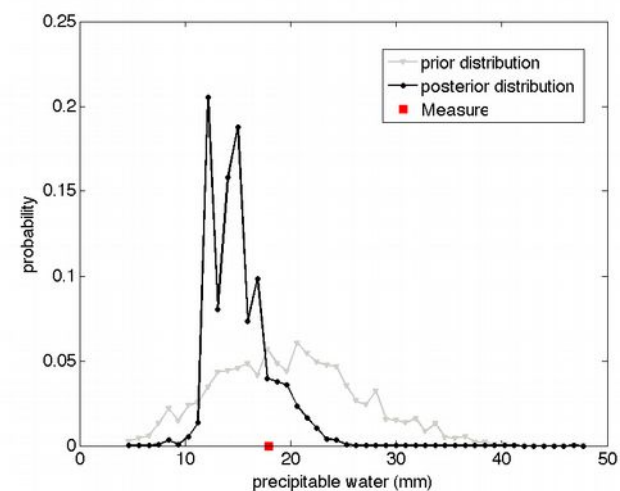
CASE STUDY: 2011/10/07 @ 12 UTC

Station: Ajaccio

Complete set of observables (including GNSS observation)

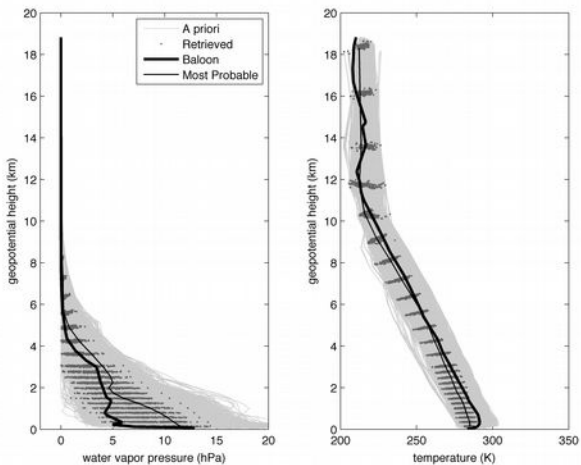


PW



Test 2. Validity for the whole area

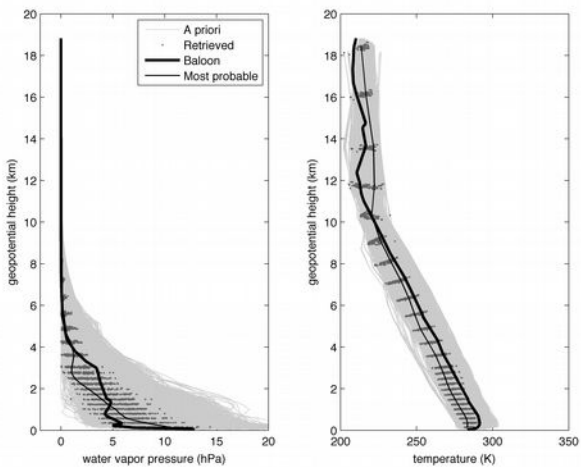
Only surface observables (no GNSS observation)



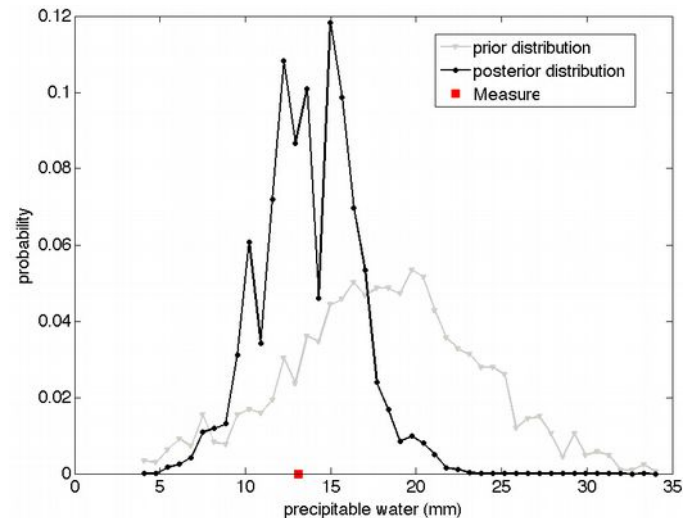
CASE STUDY: 2011/04/11 @ 00 UTC

Station: Medicina

Complete set of observables (including GNSS observation)

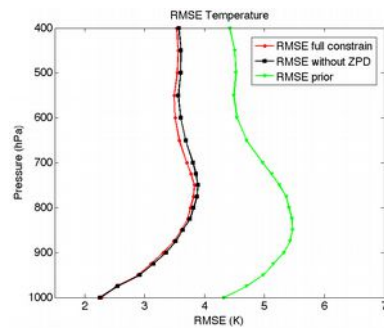
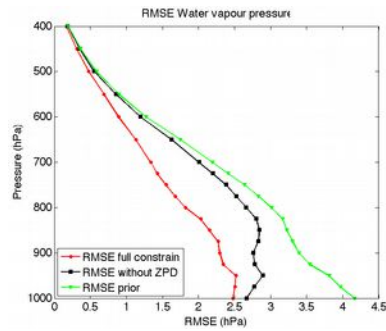
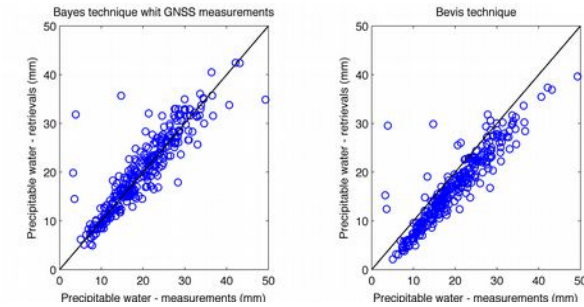


PW

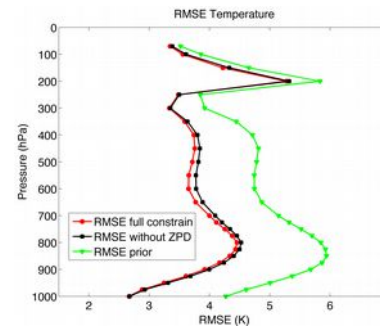
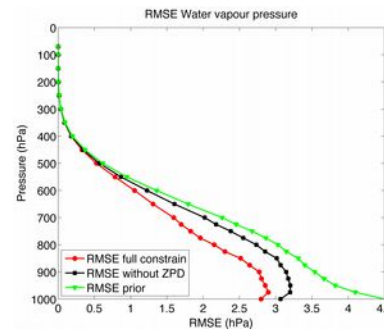
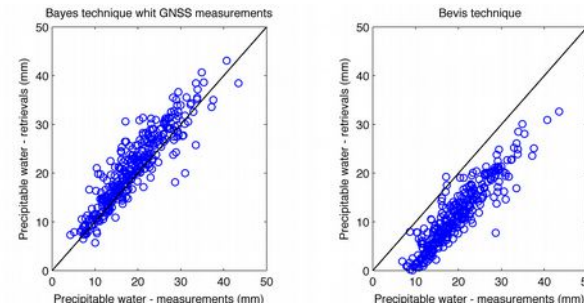


Test 2. Validity for the whole area

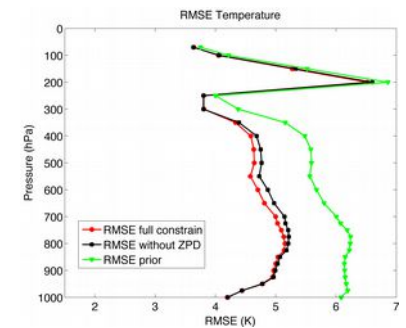
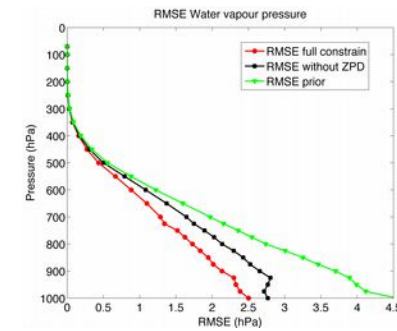
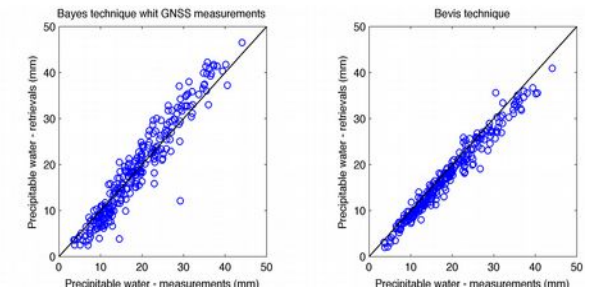
Ajaccio – full year 2011



Cagliari – full year 2011

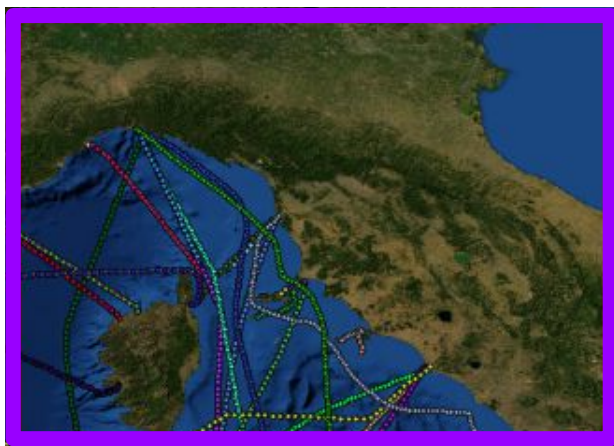


Medicina – full year 2011



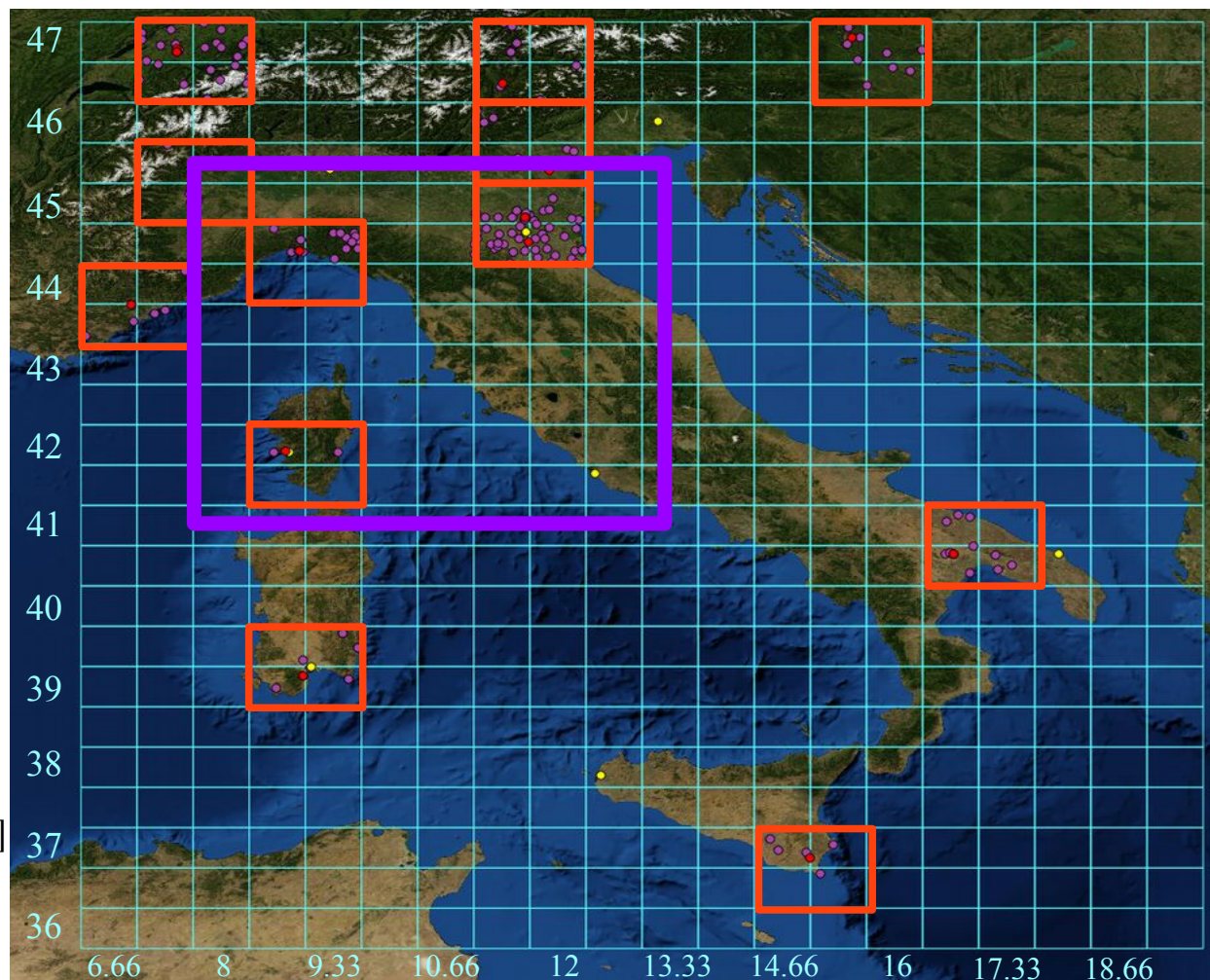
Test 3. Simulation of retrieval from ship

- IGS GNSS stations
- Balloon data
- MERRA model grid
- Areas of coefficient tuning
- Spatial domain of WRF @ 1km

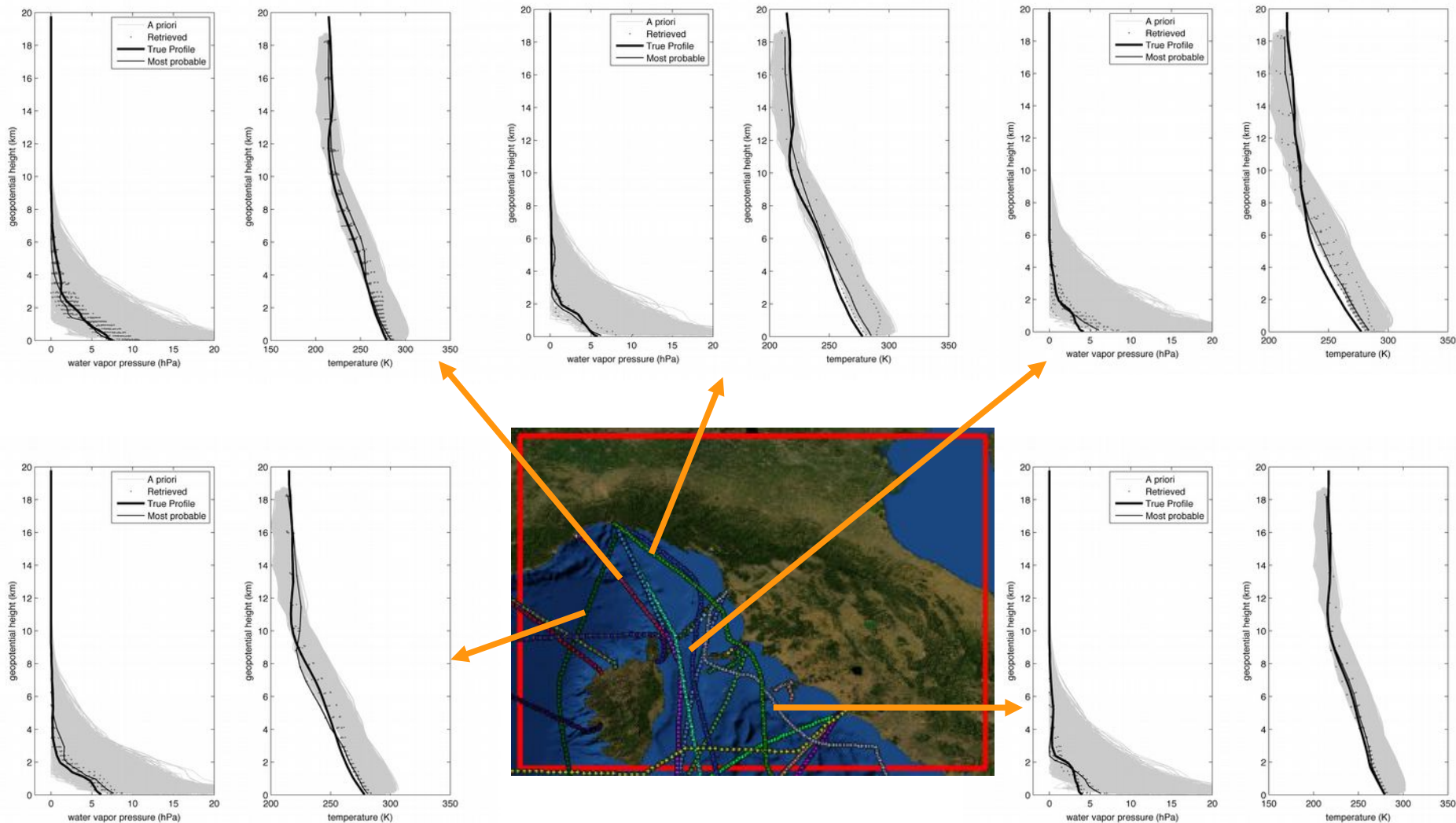


Dataset used for likelihood:
Observables and MERRA data [2001-2010]

Dataset used for tests: simulated
observables for case study:
2010/12/16 from 12:00 to 24:00



Test 3. Simulation of retrieval from ship



- **Profiling:** The possibility to provide not only integrated values but also profiles, with a dense sampling.
- **Related errors:** From the retrieved quantities, as they are provided with an associated probability, it is possible to reconstruct the associated errors.
- **Robustness and flexibility:** The method can work with some data missing, without needs of any additional assumption, but with some accuracy degradation, as a consequence.

...but also some problems!

- The dataset is not enough extended to be able to cover all the cases.
- The MERRA model pixels are $0.5^\circ \times 2/3^\circ$ large, so there are difficulties to refer to point vertical profiles.
- The spatial distribution of the dataset is not homogeneous over the area of study.
- Needs of more ZPD and weather data (for example EUREF network).



Installation of instruments on board of MEII



Weather station

GNSS station



Thank You!