Applied Spectroscopy

Kalman Filter Retrieval of Surface Temperature from SEVIRI: Improved Forward Modeling, Validation and Inter-Comparison Case Studies

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Outline

1. Background
2. Aim and scope
3. Description of the Methodology
   - Physical Retrieval
   - Forward Model
4. Results
   - Surface Temperature (ST) and Emissivity (ε)
   - Comparison
     - With ECMWF analysis
     - With Ground Based Measurements
     - With MODIS Products
5. Conclusions

Why we developed the KF for SEVIRI

- The work originated within EUMETSAT (P. Watts)
  - Objective: To study and formulate a general strategy to apply **spatial and temporal constraints** to the estimation of geophysical **parameters** from radiance measurements made **from geostationary platforms**, to apply the strategy to a particular example problem and to recommend a way forward to more general application to MTG FCI imager and IRS sounder data.
- The study was also motivated by the quest of methodologies capable to perform a **dimensionality reduction of the data space**
  - In NWP the numbers of observations varies considerably, but global models perhaps assimilate of order 10^6 observations per 12 hour window. With SEVIRI the number of observations is of order 10^8 per 15 minutes

Background

- Continuity is felt important in order to dynamically separate emissivity from temperature. In order words, try to exploit the different variability time scale of the two: minutes for temperature, days for emissivity.
- Dimensionality reduction is felt important also in view of MTG: FCI and IRS mission.

Kalman Filter

- KF is an assimilation system (may incorporate the basic physics involved in the problem: radiative transfer and dynamics).
- Acting on the dynamics, we can put appropriate constraint in order to take advantage of the different time scale of emissivity and temperature.
- Exploiting the time sequential architecture of KF, the dimensionality of the data space is kept *scalar* in time, i.e., observations are processed as they come and are not accumulated as it would be in an ordinary static Optimal Estimation method.

KF development for SEVIRI, funding

Since 2011, The analysis has been performed under the projects:

- EUMETSAT
  - EUM/CO/14/4600001329/PDW
  - EUM/CO/11/4600000996/PDW
- CNR/MIUR,
  - RITMARE (CNR/MIUR) Ricerca ITaliana per il MARE
- Regione Basilicata,
  - PO FSE Basilicata 2007-2013
- LSA SAF
  - IPMA, Instituto Portugues do Mar e da Atmosfera LSASAF_VS2016-02

Inverse Model: Kalman filter + persistence

analysis at time t

$$\begin{cases} \mathbf{R_t} = F(\mathbf{v_t}) + \boldsymbol{\varepsilon}_\mathbf{t} \\ \mathbf{v_{t+1}} = \mathbf{H}\mathbf{v_t} + \boldsymbol{\eta}_\mathbf{t} \end{cases}$$

observation equation

state/evolution equation

update or analysis

$$\begin{cases} \hat{\mathbf{v}}_\mathbf{t} = \hat{\mathbf{v}}_\mathbf{a} + \left(\mathbf{K_t^T S_\varepsilon^{-1} K_t} + \mathbf{S_a^{-1}}\right)^{-1} \mathbf{K_t^T S_\varepsilon^{-1}}\left(\mathbf{y_t} - \mathbf{K_t}\left(\hat{\mathbf{v}}_\mathbf{a} - \mathbf{v_o}\right)\right) \\ \mathbf{S_t} = \left(\mathbf{K_t^T S_\varepsilon^{-1} K_t} + \mathbf{S_a^{-1}}\right)^{-1} \end{cases}$$

forecast

forecast at time t

$$\begin{cases} \hat{\mathbf{v}}^\mathbf{f}_\mathbf{t+1} = \mathbf{H}\hat{\mathbf{v}}_\mathbf{t} \\ \hat{\mathbf{S}}^\mathbf{f}_\mathbf{t+1} = \mathbf{H}\hat{\mathbf{S}}_\mathbf{t}\mathbf{H^T} + \mathbf{S}_{\boldsymbol{\eta}} \end{cases}$$

covariance of η_t

$$\begin{cases} \mathbf{v_a} = \hat{\mathbf{v}}^\mathbf{f}_\mathbf{t+1} \\ \mathbf{S_a} = \hat{\mathbf{S}}^\mathbf{f}_\mathbf{t+1} \end{cases}$$

Forward Model: σ-SEVIRI

- σ-IASI (σ-SEVIRI) is a general purpose pseudo-monochromatic radiative transfer model:
  - It computes Spectral High-resolution quantities for RTE

$$R(\theta_r,\varphi_r,\sigma)=\varepsilon(\theta_r,\varphi_r,\sigma)\tau_0(\theta_r,\varphi_r,\sigma)B(T_s)+R_u(\theta_r,\varphi_r,\sigma)+R_r(\theta_r,\varphi_r,\sigma)$$

$$R_u(\theta_r,\varphi_r,\sigma)=\int_0^{+\infty}B(T)\frac{\partial\tau}{\partial h}dh$$

$$R_r(\theta_r,\varphi_r,\sigma)=\tau_0(\theta_r,\varphi_r,\sigma)\int_0^{2\pi}d\varphi_i\int_0^{\frac{\pi}{2}}f(\theta_r,\varphi_r,\theta_i,\varphi_i,\sigma)R_i(\theta_i,\varphi_i,\sigma)\cos\theta_i\sin\theta_i d\theta_i$$

It takes into account both Specular and Lambertian reflection

$$\chi_{i,N,\sigma}=\rho_{i,N}\left(C_{i,N0,\sigma}+C_{i,N1,\sigma}\Delta T_i+C_{i,N2,\sigma}\Delta T_i^2\right)$$

  - It is based on look-up table of optical depth + interpolation procedure
  - Simple dependence of the Optical Depth with respect to the Temperature and the gas concentration

Analytical derivative, Fast and Accurate

Speed up the Forward Model: σ-SEVIRI

- PCA (Principal Component Analysis) based approach to Radiative Transfer Model for SEVIRI

- Spectral High-res quantities are computed for a selected number of predictors (n_p)
- That, with a PCA based approach , are represented with a limited number of Principal Components (n_c)

- It convolves at SEVIRI ISRF with linear regression

- ***Very Fast and Accurate***

$$\mathbf{R}_{\mathbf{high}} = \mathbf{u} \cdot \mathbf{s} \cdot \mathbf{v}^{\mathbf{t}}$$

$$\underset{[n_c \times 1]}{\mathbf{c}} = \underset{[n_p \times n_c]}{\mathbf{u}^{\mathbf{t}}} \cdot \underset{[n_p \times 1]}{\mathbf{R}_{\mathbf{high}}}$$

$$\underset{[n_l \times 1]}{\mathbf{R}_{\mathbf{low}}} = \underset{[n_l \times n_p]}{\mathbf{W}} \cdot \underset{[n_c \times 1]}{\mathbf{c}}$$

References

Atmos. Meas. Tech., 6, 3613–3634, 2013
www.atmos-meas-tech.net/6/3613/2013/
doi:10.5194/amt-6-3613-2013

Atmospheric Measurement Techniques

Kalman filter physical retrieval of surface emissivity and temperature from geostationary infrared radiances

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Atmos. Meas. Tech., 8, 2981–2997, 2015
www.atmos-meas-tech.net/8/2981/2015/
doi:10.5194/amt-8-2981-2015

Atmospheric Measurement Techniques

Kalman filter physical retrieval of surface emissivity and temperature from SEVIRI infrared channels: a validation and intercomparison study

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Surface parameters from SEVIRI observations through a Kalman filter approach: application and evaluation of the scheme in Southern Italy

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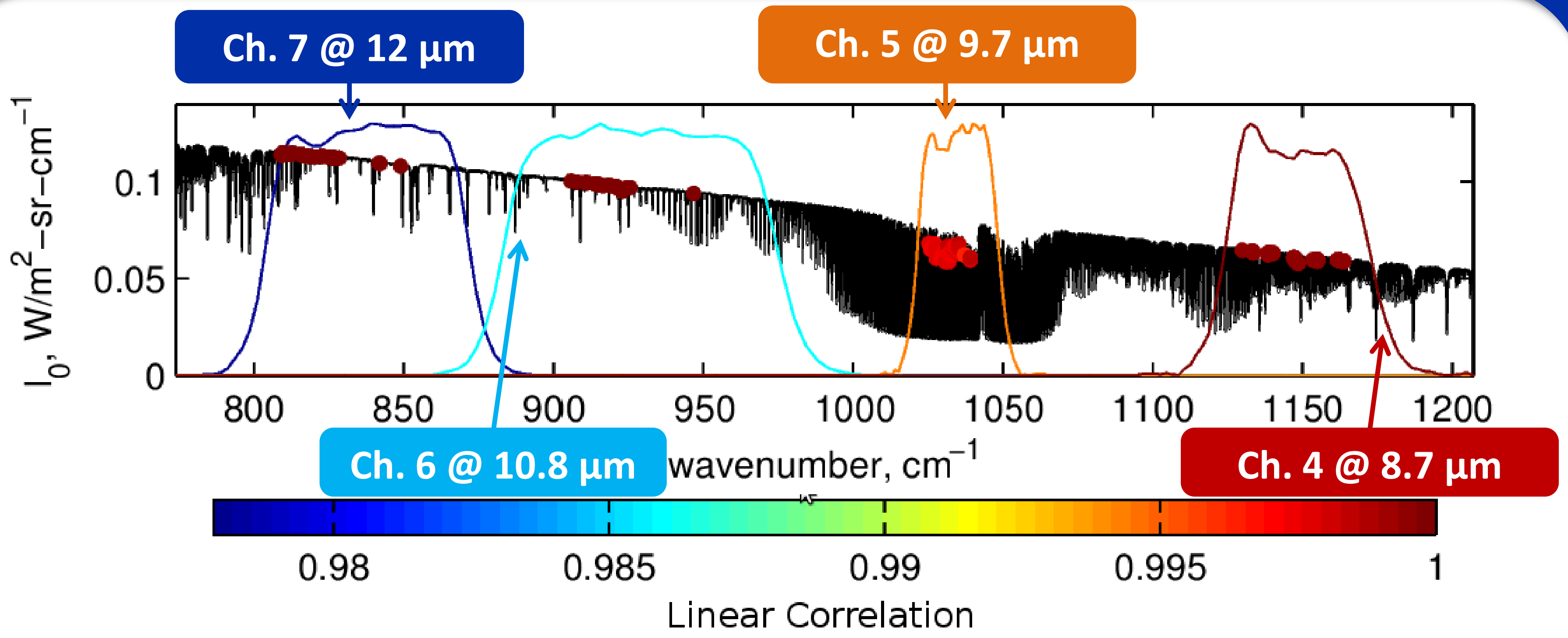
Received: 12-V-2015 – Accepted: 21-I-2016 – **Original version**
Correspondence to: sara.venafra@unibas.it

- Application to SEVIRI window channels, for the retrieval of Ts and ε

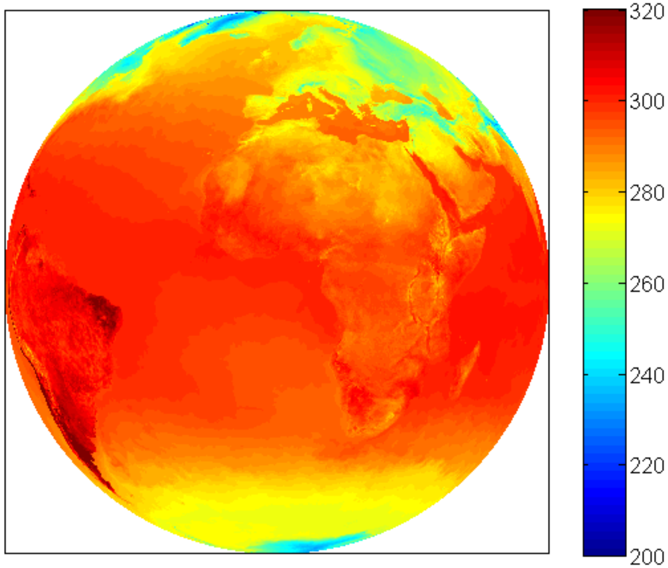
  Masiello, G. et al. 2013, Atmos. Meas. Tech., doi:10.5194/amt-6-3613-2013
  Masiello, G. et al. 2015, Atmos. Meas. Tech., doi:10.5194/amt-8-2981-2015
  Blasi, M.G. et al. 2016, Tethys, doi:10.3369/tethys.2016.13.01

SEVIRI channels used in this analysis

- To retrieve Surface Temperature and emissivity we used IR SEVIRI window Channels ($n_l = 4$)
- 4 @ 8.7 µm, ($n_p = 30, n_c = 9$)
- 5 @ 9.7 µm, ($n_p = 40, n_c = 14$)
- 6 @ 10.8 µm, ($n_p = 20, n_c = 5$)
- 7 @ 12 µm , ($n_p = 30, n_c = 6$)



Background Information, Atmospheric State



ECMWF, Surface temperature

ECMWF Operation Analysis from MARS platform.

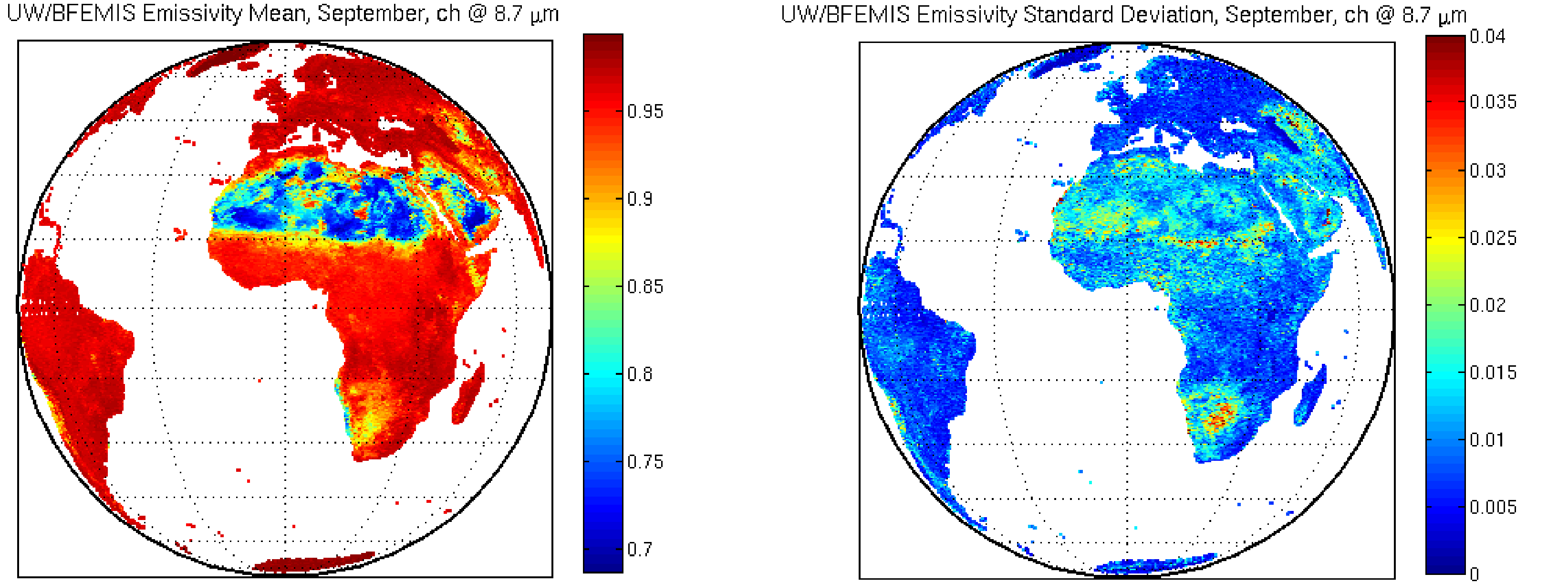
High spatial Resolution (0.125x0.125)

- 60/91/137 Pressure levels

- ST, Surface Temperature
- SP, Surface Pressure
- TCC, Total Cloud Cover

- T, Temperature
- Q, Specific Humidity
- O3, Specific Ozone

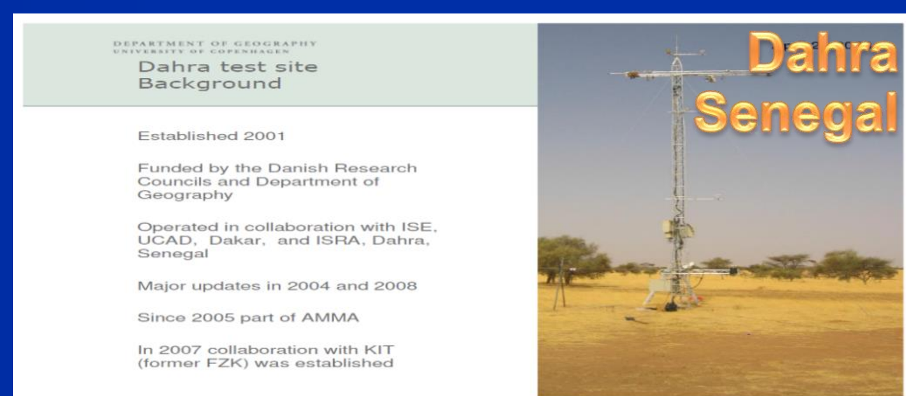
Background Information, Emissivity



UW/BFEMIS, database, Monthly mean and covariance computed for the 14 years period 2003-2016.

Validation Stations: Acknowledgements

- **Isabel Trigo**, Instituto Portugues do Mar e da Atmosfera IP, Land SAF, Lisbon, Portugal
- **Frank M. Göttsche**, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

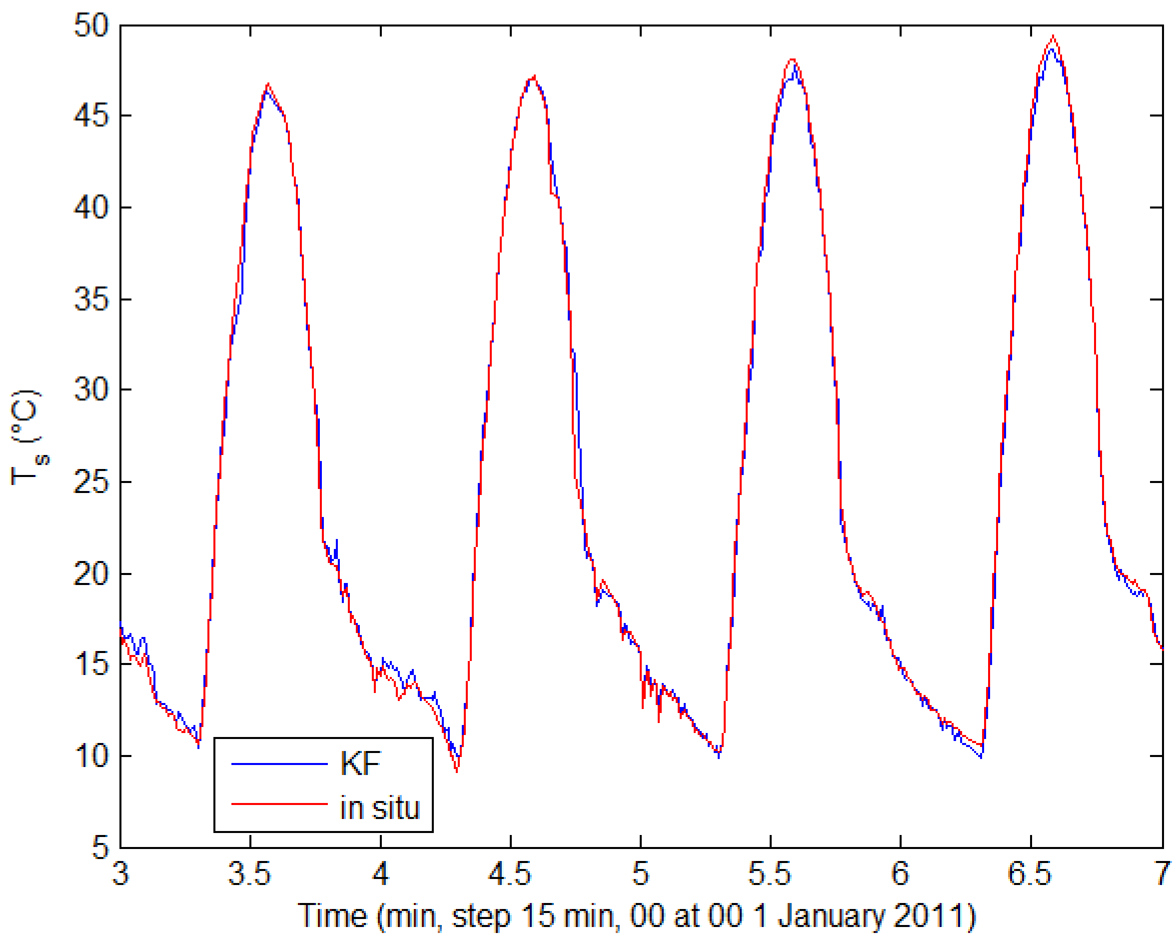


Comparison with in situ measurements

	Mean difference with in situ data (°C)	Standard deviation of the difference (°C)
Dahra, Jan.-to Oct. 2011	-0.70	0.96
Evora, Jan. to Dec. 2010	+0.91	1.62
Gobabeb, Jan. to Dec. 2010	+0.86	1.18

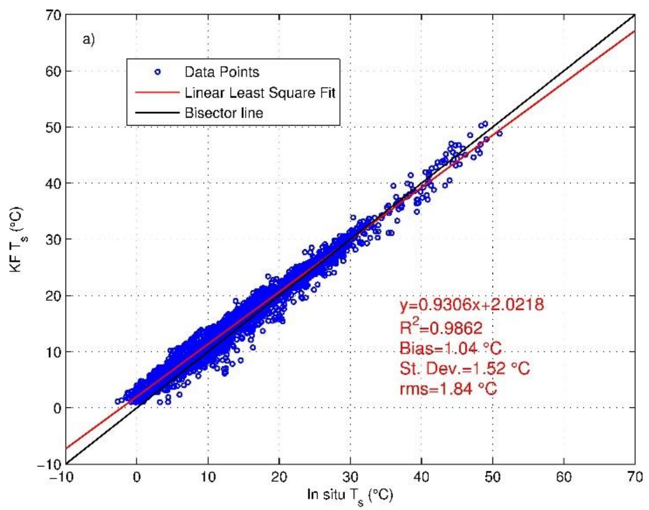
- Summary of the Results from the three LSA SAF validation stations
- Comparison with in situ Surface Temperature

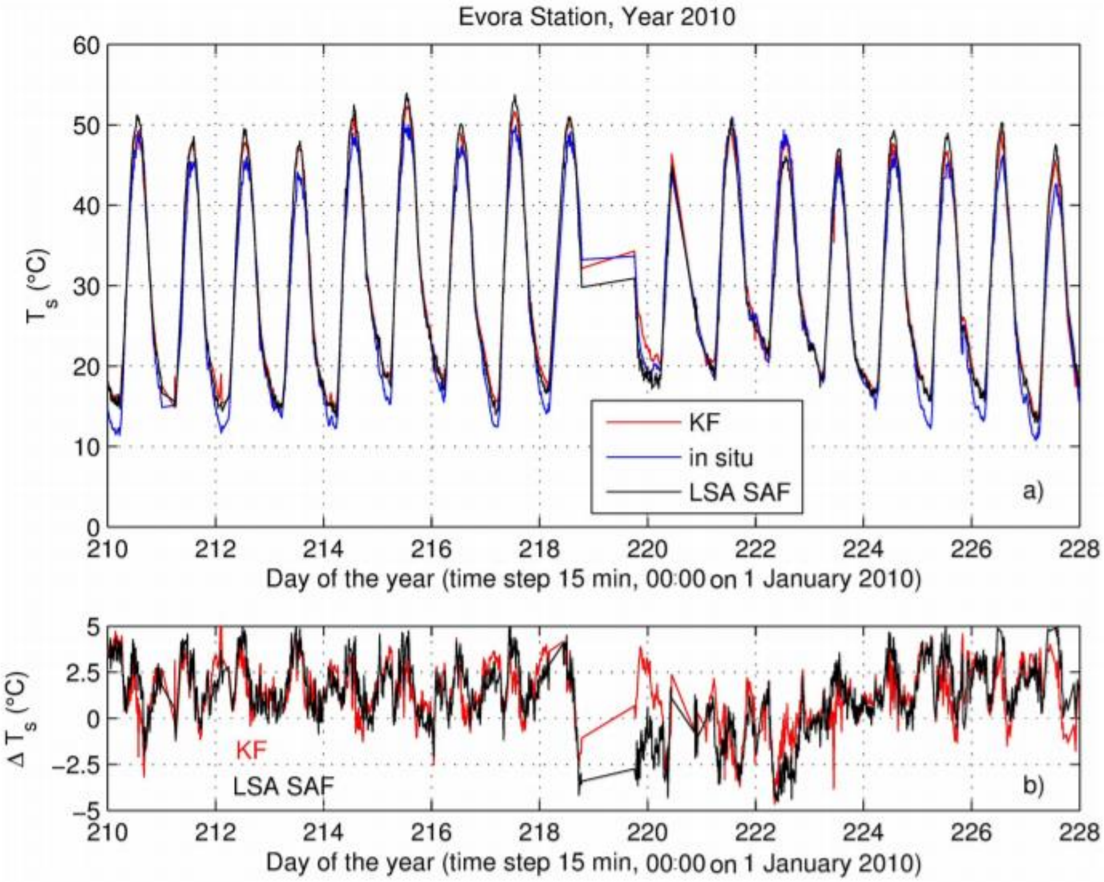
Comparison with in situ measurements: Dahra



- An example from Dahra station (Time series of 4 days – step 15 min)

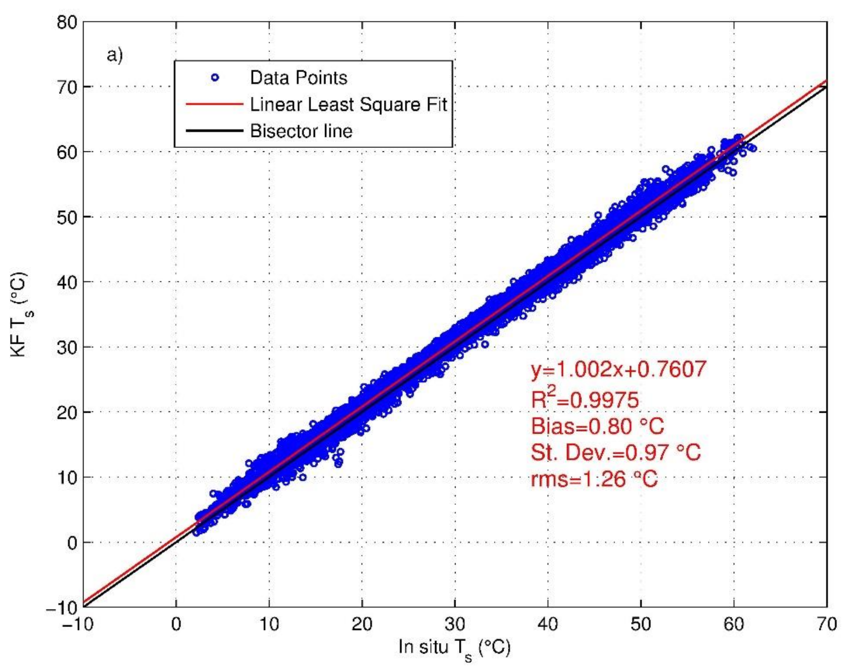
Comparison with in situ measurements: Evora

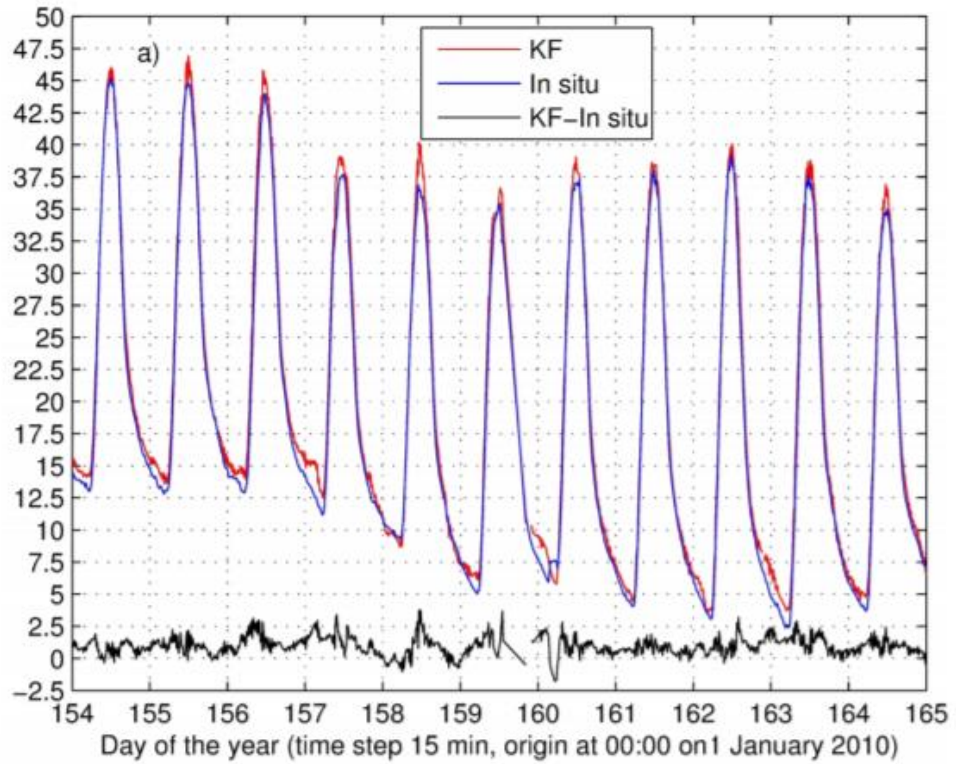




- Evora station. 1 year Scatter plot (Left). 17 days long time serie with 15 min step (Right)

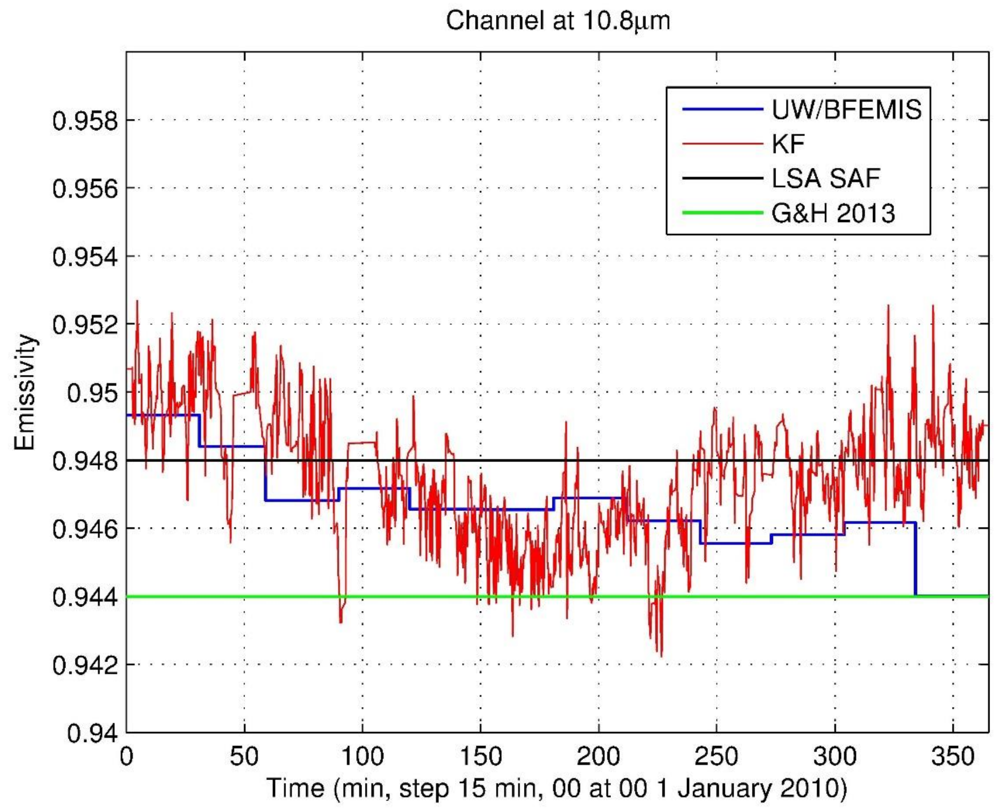
Comparison with in situ measurements: Gobabeb





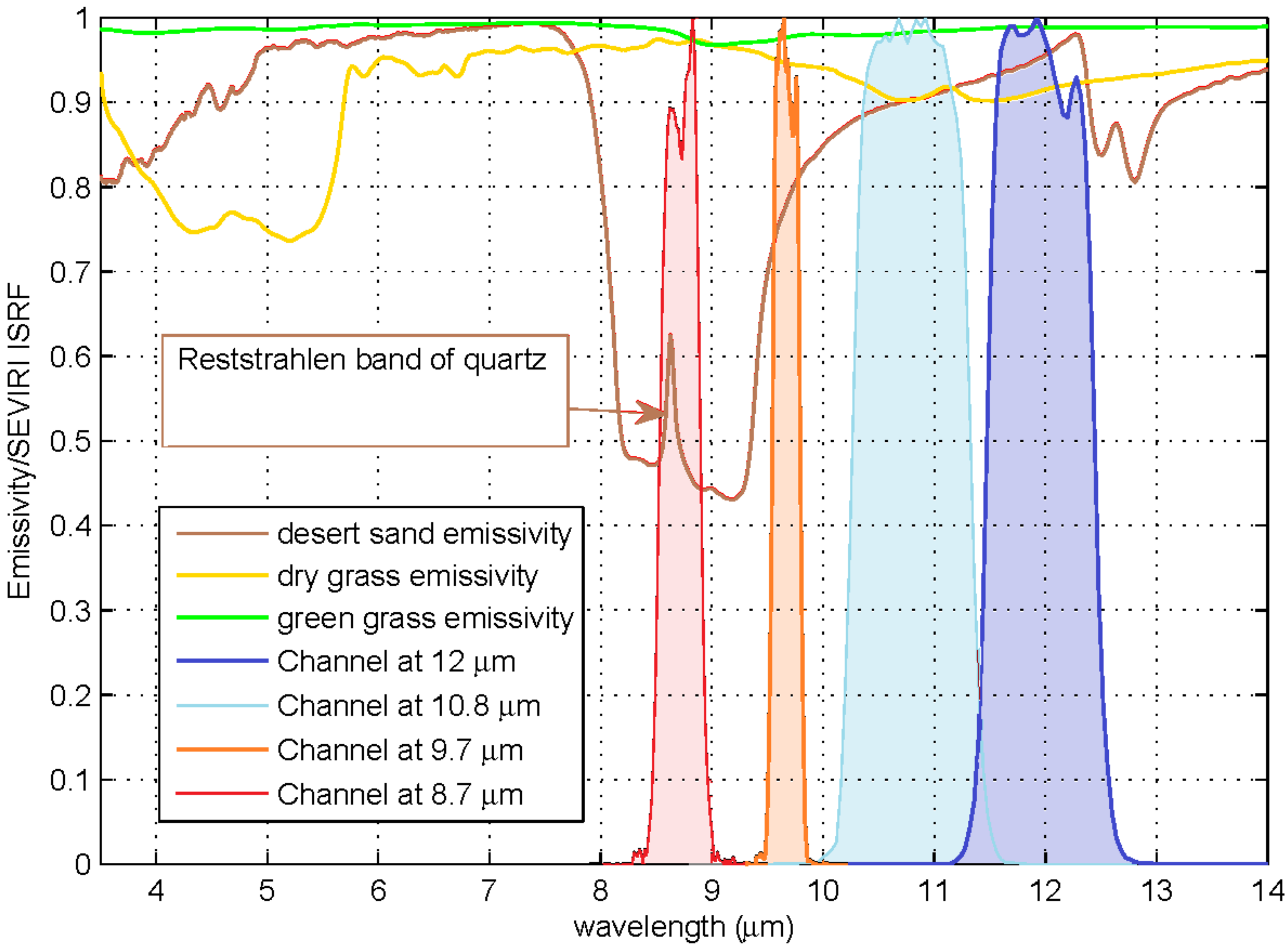
- Gobabeb station. 1 year Scatter plot (Left). 11 days long time serie with 15 min step (Right)

Comparison with in situ measurements: Gobabeb

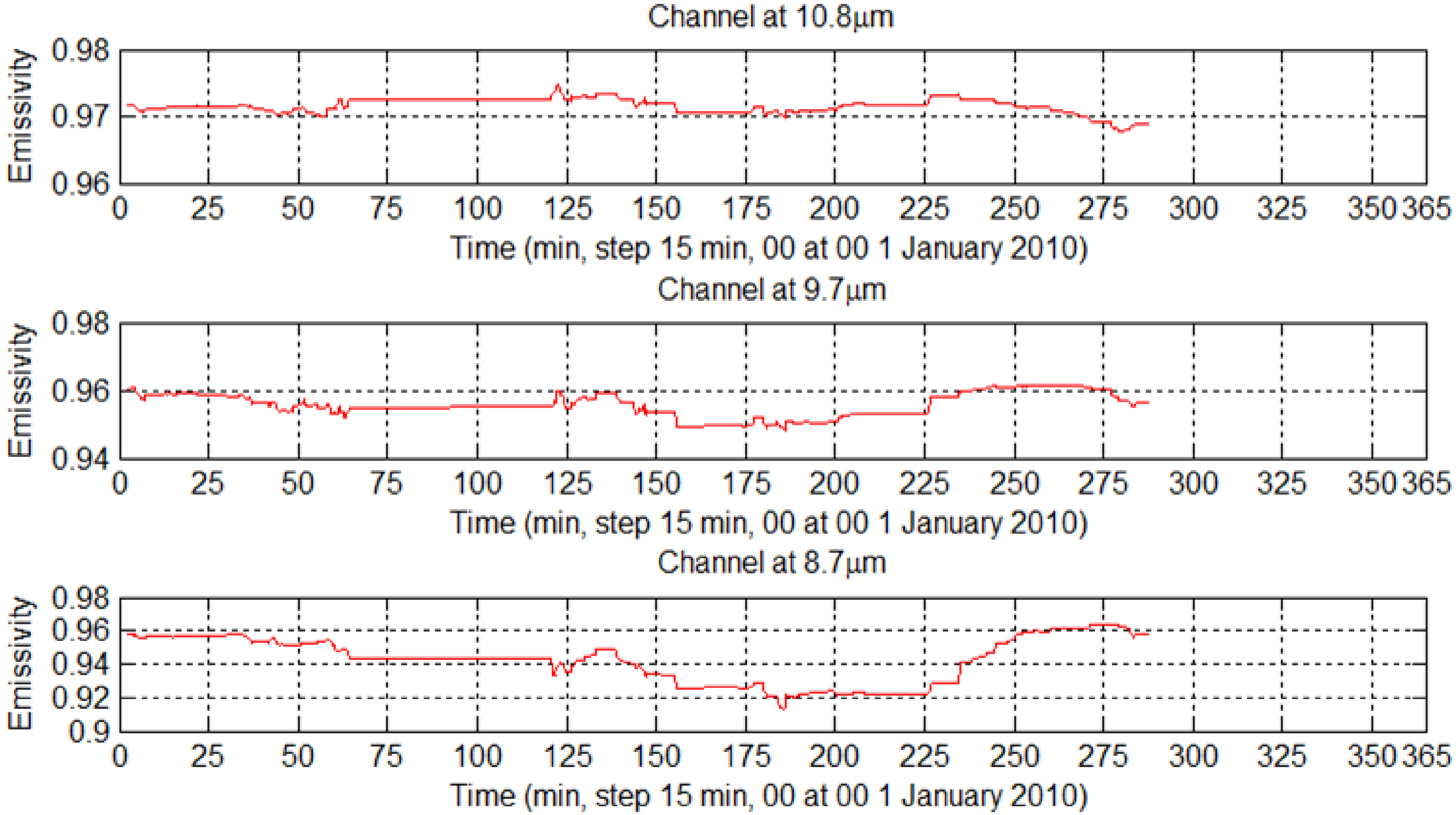


- Gobabeb station. ε@10.8 - 1 year long time series with 15 min step

Land cover change detection with IR SEVIRI channels

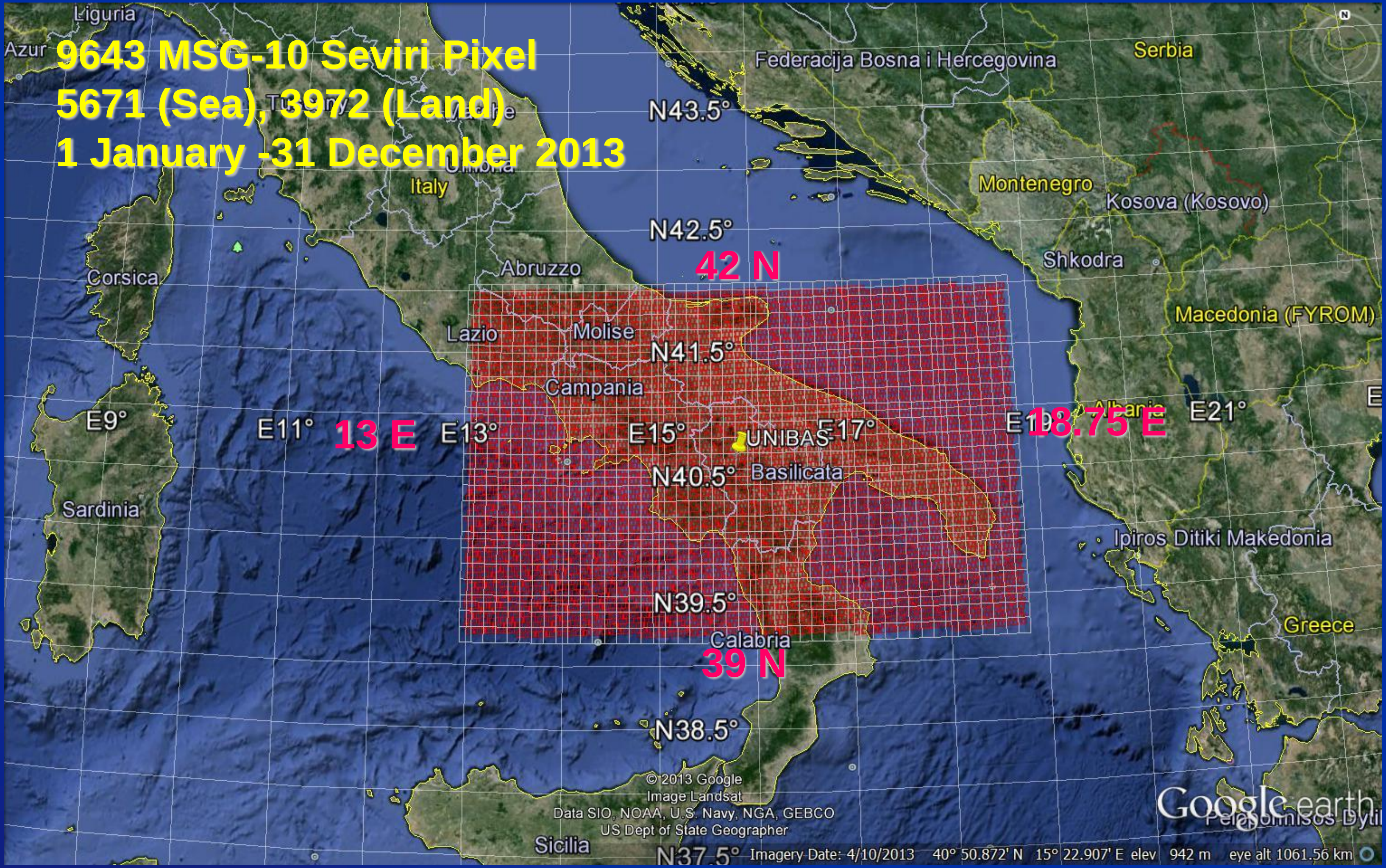


Land cover change detection, an example: Dahra



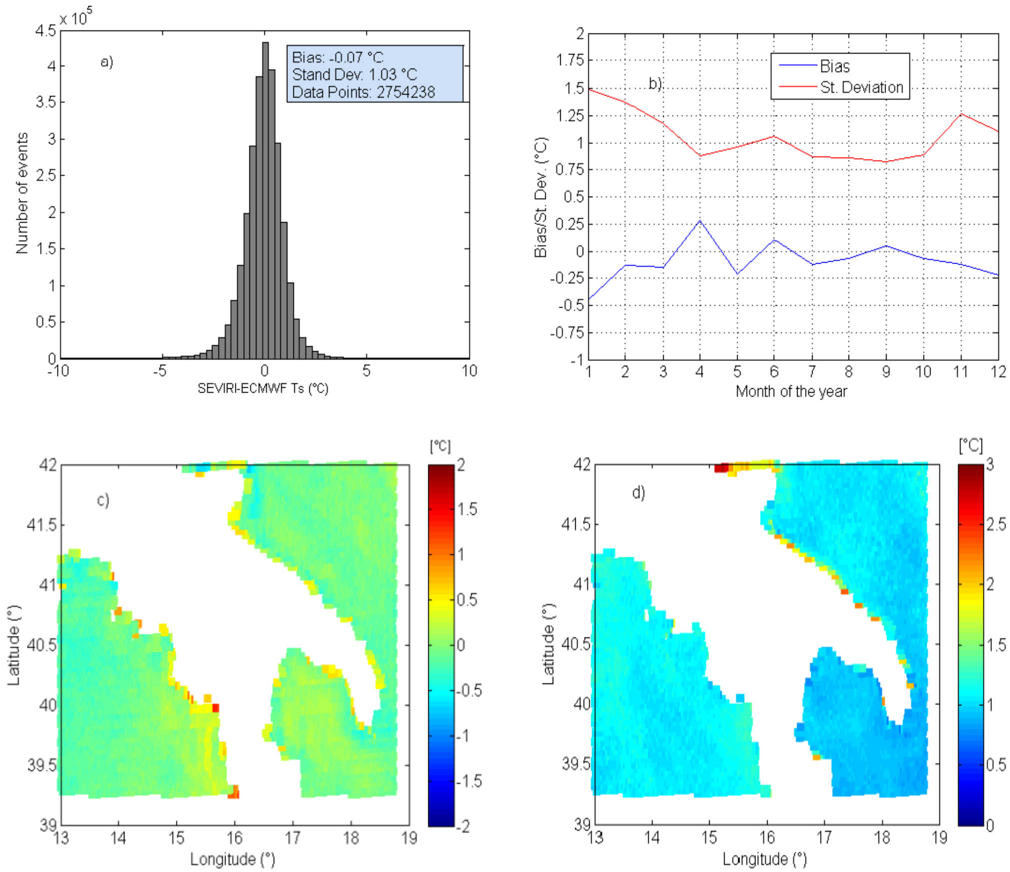
1. Introduction
2. Methodology
3. Results
4. Conclusions

Validation for the Sea



- The scheme works for the SEVIRI full disk
- The case study shown here is an area surrounding Basilicata Region, including Mediterranean Sea (Tyrrhenian, Ionian and Adriatic Seas)

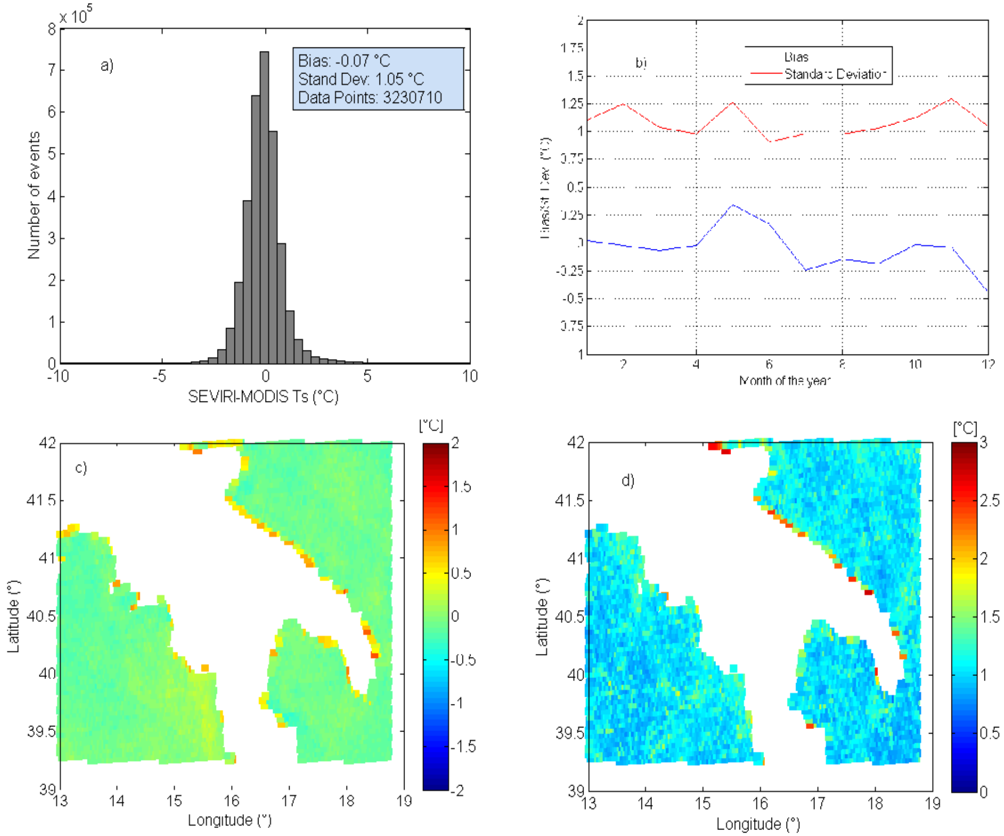
Comparison with ECMWF



Bias -0.07 °C
Std 1.03 °C

- Comparison with ECMWF data show excellent agreement (statistics based on 2,754,238 data points, 1 year)

Comparison with MODIS

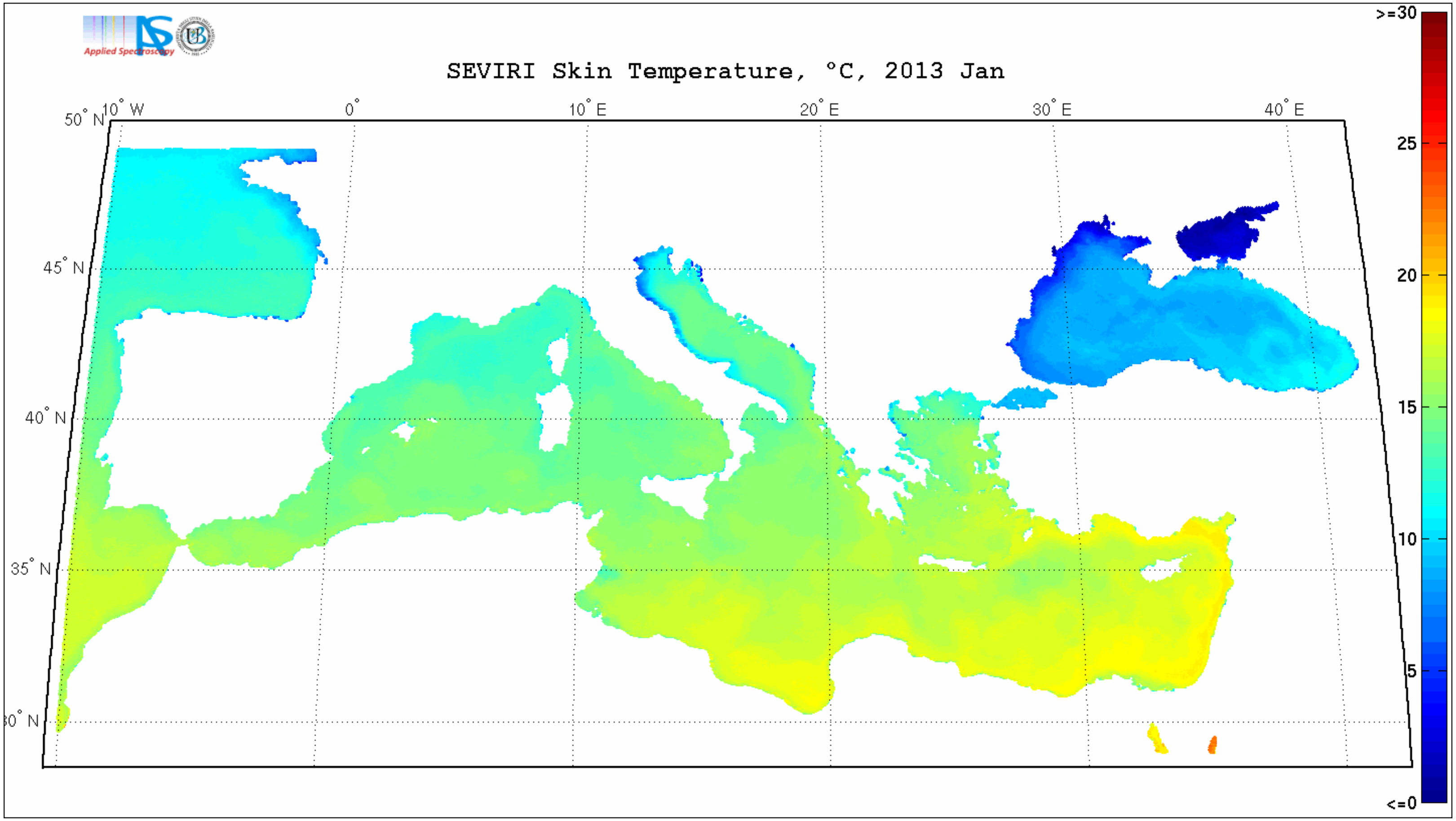


Bias 0.07 °C
Std 1.05 °C

- Comparison with MODIS (statistics based on 3,230,710 data points 1 year)

4 Years of Continuous Retrieved Skin Temperature

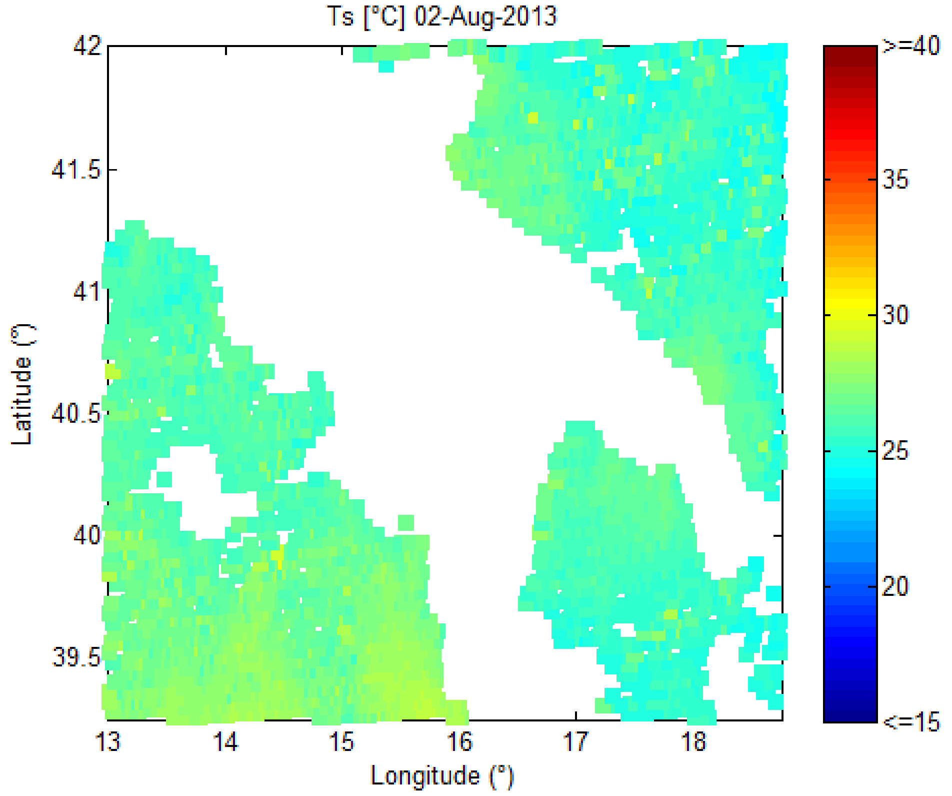
- The animation shows Evolution of Sea Skin Temperature in the period 2013-2016
- Each Frame represents monthly mean.



http://www2.unibas.it/gmasiello/assite/rep/Med_2013-2016_T.gif

Retrieved Skin Temperature, 1 Day of August

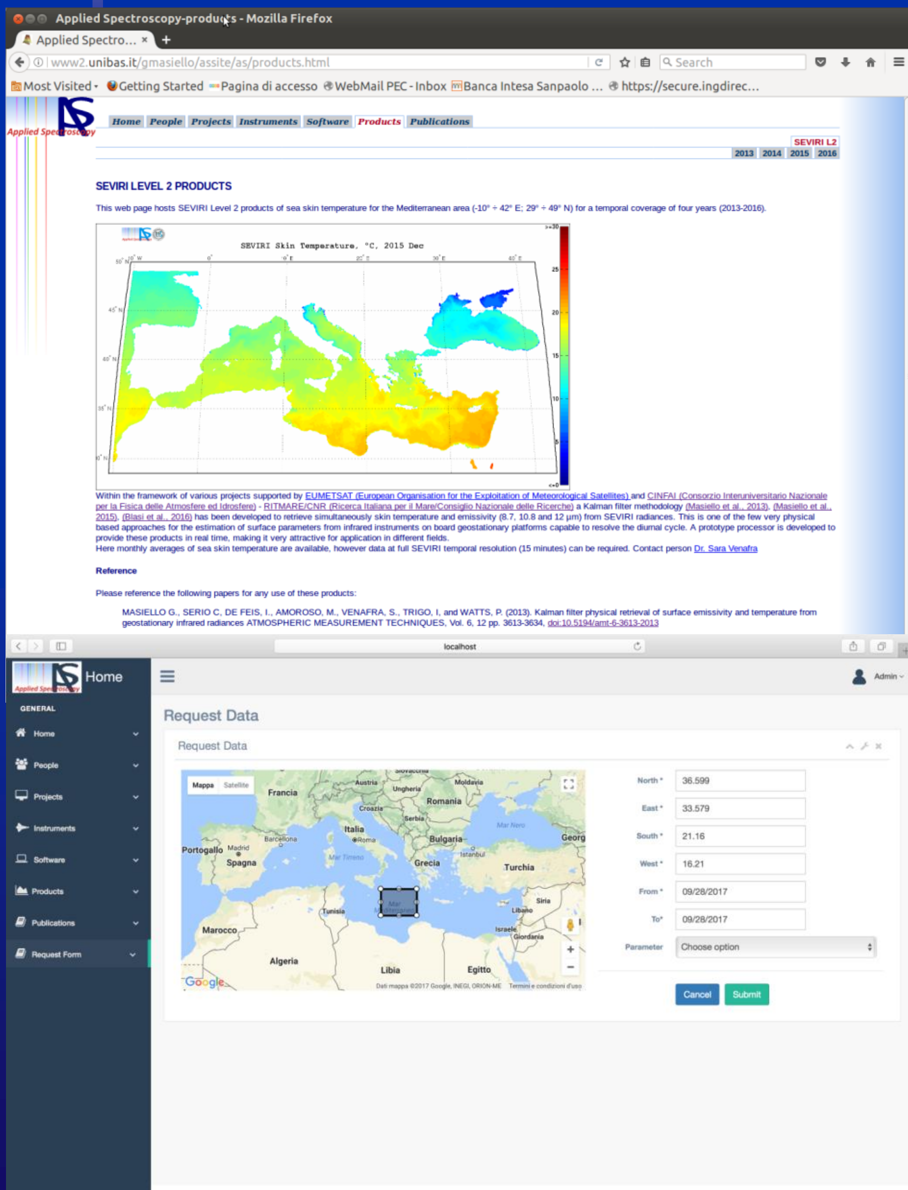
- The animation shows Evolution of Surface Temperature for the 2 of August 2013 at the temporal resolution of SEVIRI (15')



http://www2.unibas.it/gmasiello/assite/basilicata_Aug_2013.gif

Current and Future Data Availability

- The Monthly mean data are freely available at web site
- http://www2.unibas.it/gmasiello/assite/as/products.html

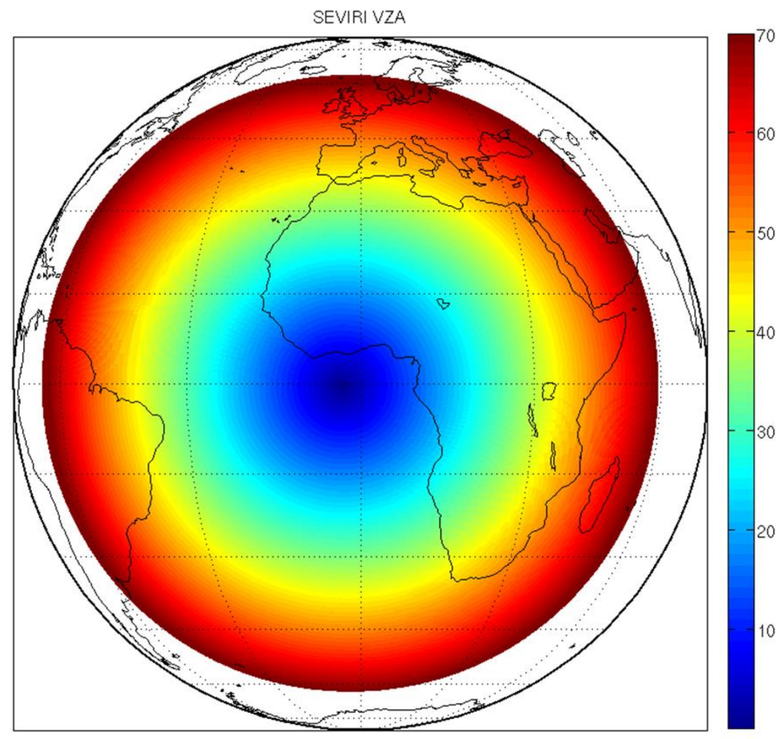


- At the moment they are organized in compressed ASCII files (1 per month)
- We are processing SEVIRI data for 2017 (Results will be available on line as soon as possible)
- We plan to process SEVIRI data back to 2003
- We are implementing a new web portal that simplify data request enabling download of the full time resolution results. (Master Thesis of A. Coviello)

Applications to Full Disk

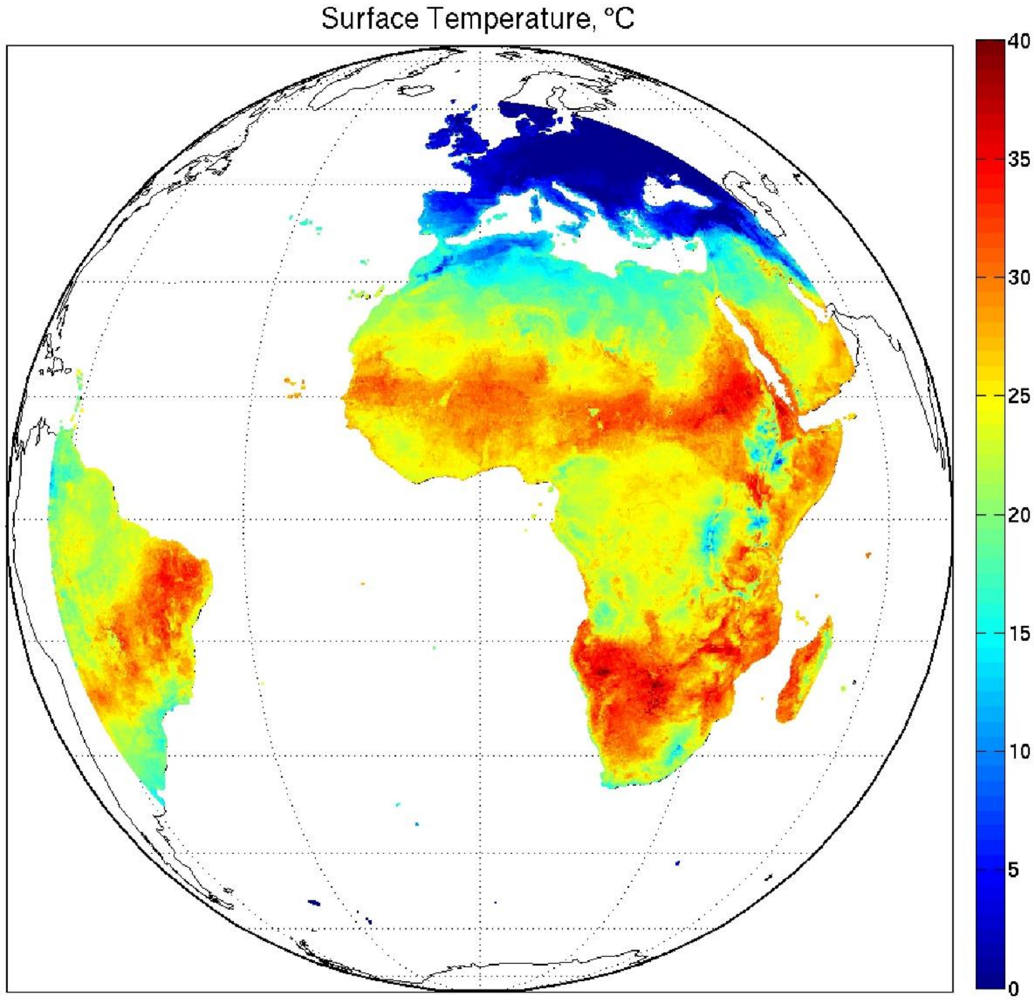
- The scheme works for the SEVIRI full disk

- **Full Disk (VZA<=70°):**
- Total 3,545,871 pixels
- 3,488,328 Land pixels
- 57,543 In Land Water pixels



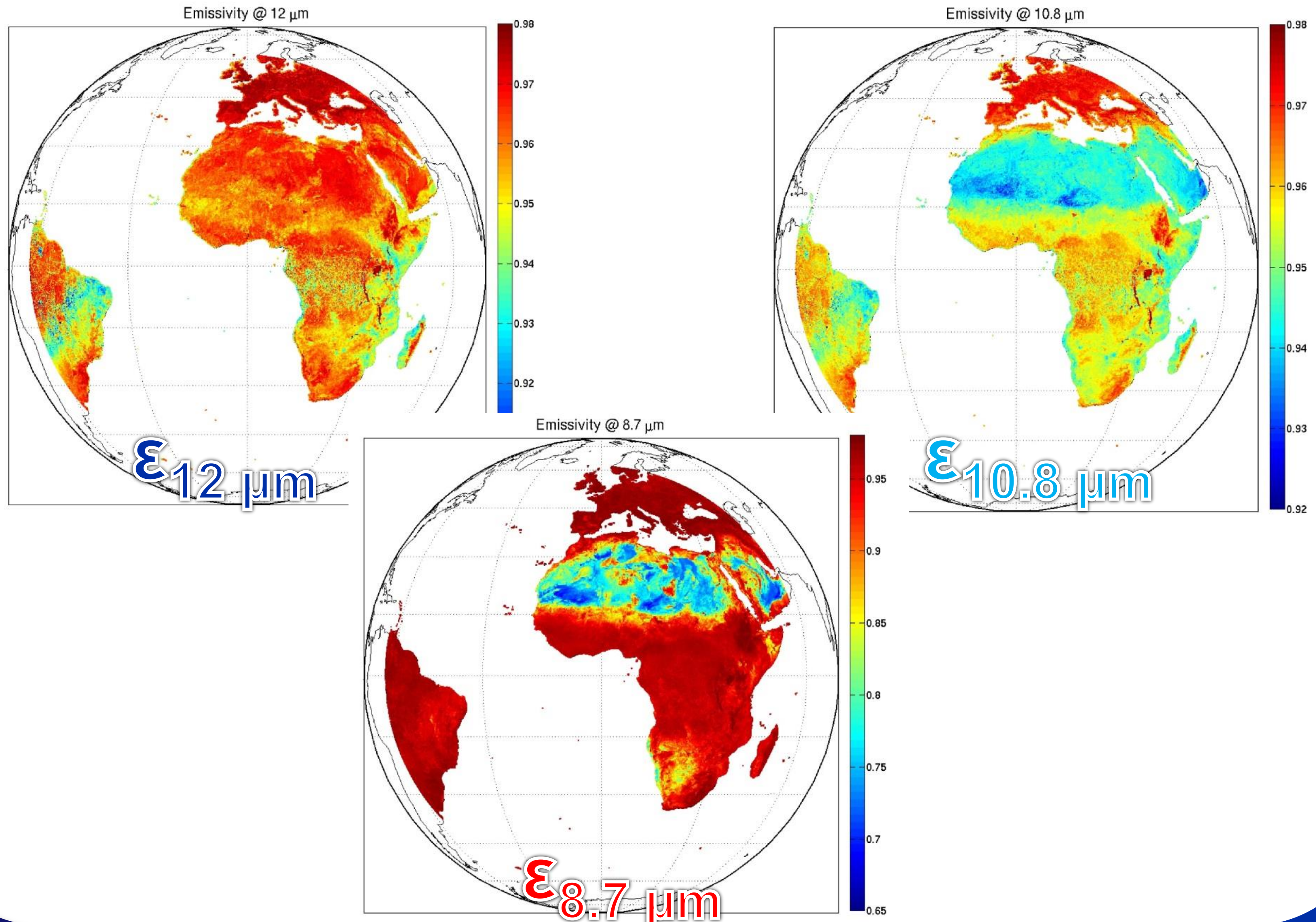
November 2007 surface temperature

- Monthly mean surface temperature



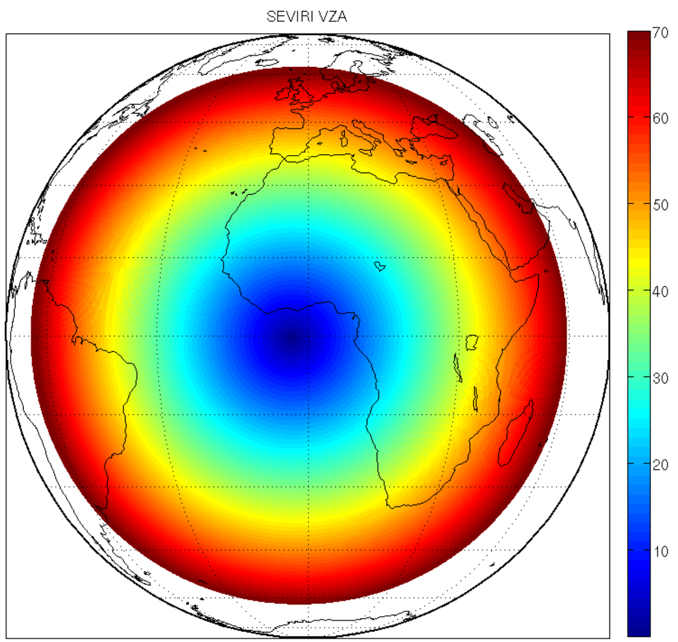
November 2007 Emissivity

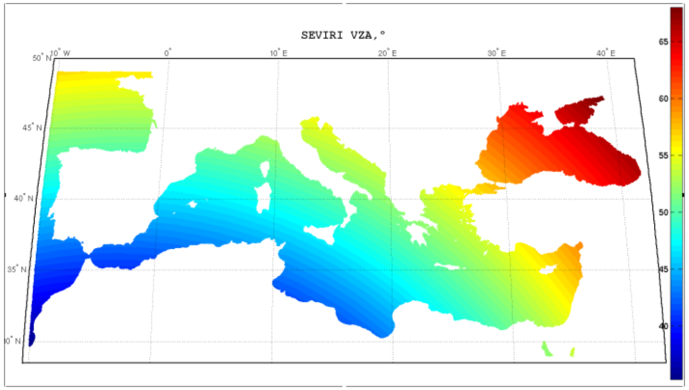
- Monthly mean surface emissivity



Computational Performances

- The code can run from the level of the single pixel up to the SEVIRI full disk scale





- **Full Disk (VZA<=70°):**
- Total 3,545,871 pixels
- 3,488,328 Land pixels
- 57,543 In Land Water pixels
- A single SEVIRI FD run will take about 30 min exploiting 8 threads and considering all pixels as clear sky (Ifort Compiler)
- *Integrated and tested on IPMA LSA-SAF virtual machine for full disk retrieval of surface temperature and emissivity.*

- **Mediterranean Sea:**
- Total 225962 pixels
- A single SEVIRI Mediterranean Sea run will take about 8 min exploiting 1 thread and considering all pixels as clear sky (Ifort Compiler)

Conclusions

- The Kalman filter (KF) retrieval system is one of the first physically based schemes for the simultaneous retrieval of surface emissivity and temperature.
- The KF retrieval is unique in its capability to exploit the time continuity of geostationary infrared observations.
- The SEVIRI KF retrieval is fully characterized in terms of its variance-covariance structure. The theoretical precision is better than 0.2 K for sea and land surface.
- Potentially, the scheme can accommodate time-spatial constraints in case they are available. For now we use a simple *persistence model* for the state equation.
- Comparison with in situ, ECMWF, polar satellite observations shows a very good agreement for temperature.
- The KF methodology developed for SEVIRI is robust even at the full time resolution of 15 minutes
- The algorithm can be specialized for land or sea or both and a land-based version has been integrated and tested on IPMA LSA-SAF virtual machine for full disk retrieval of surface temperature and emissivity.