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Hyperspectral Observations of Land Surfaces: Temperature & Emissivity

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Assimilation of Hyper-spectral Geostationary Satellite Observations, Reading 22-25 May 2017

Outline

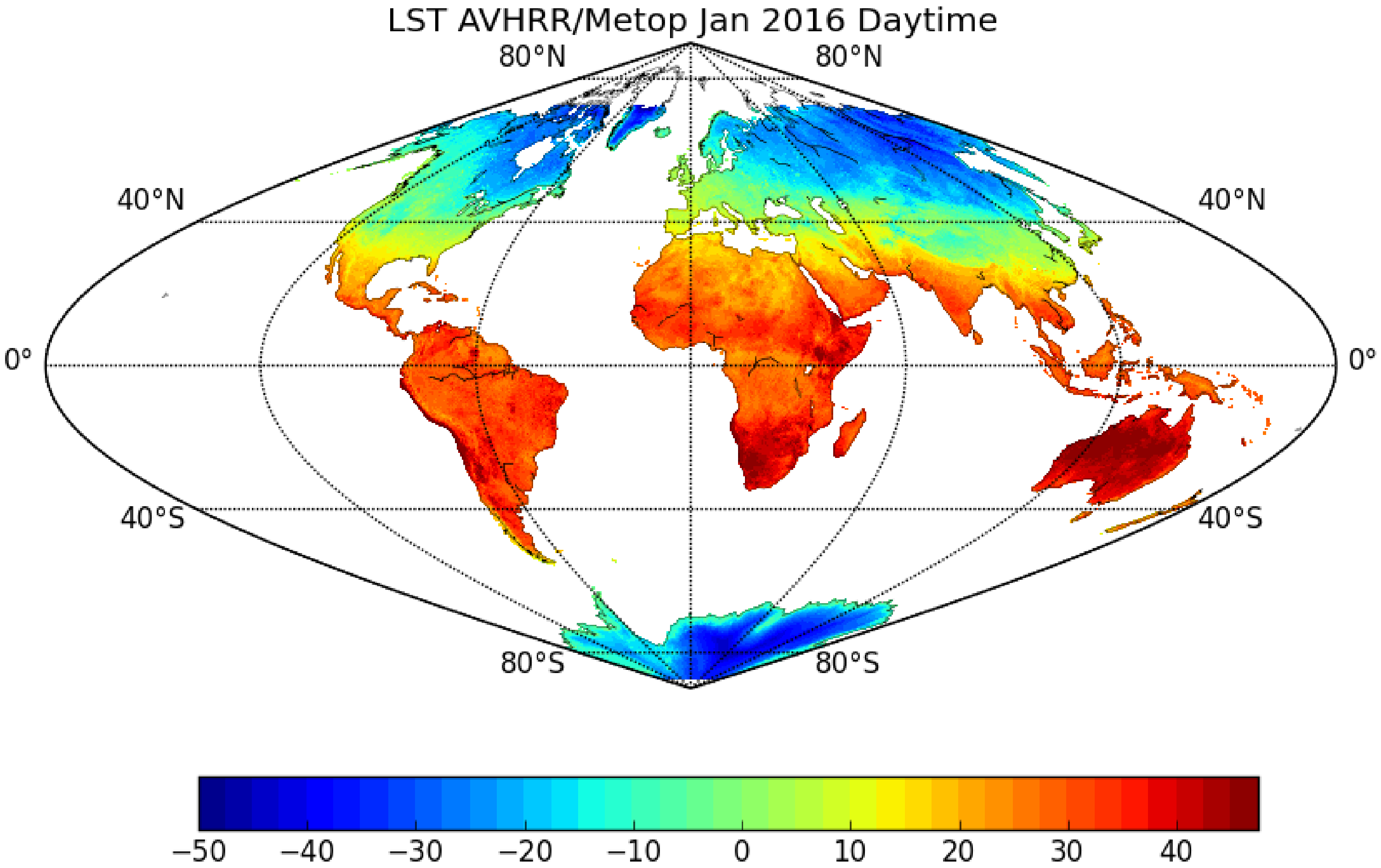
Land Surface Temperature

- Products & Requirements
- Validation
- Sources of Uncertainty - Emissivity
- Use of Hyperspectral observations to address the above
  - Retrieval of IASI emissivity spectrum and LST
- Concluding Remarks

Land Surface Temperature

Land Surface Temperature

- Aggregated radiometric surface temperature of the ensemble of components within the sensor FOV
- LST is important for
  - ✓ evaluating land surface & land-atmosphere interaction
  - ✓ constraining surface energy budgets (& model parameters)
  - ✓ providing observations of surface temperature change both globally and in key regions



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Land Surface Temperature

Land Surface Temperature – remote sensing products

- Most estimated from TOA brightness temperature within Thermal Infrared
  - ✓ Clear-Sky only
  - ✓ Given the high variability of LST, user requirements value:
    - spatial resolution – from high (~50 m) to low (~5 km) resoltutions
    - Temporal frequency – from 15 min (10 min) to 16 days

EUMETSAT Satellite Applications Factility on Land Surface Analysis (LSA-SAF)

- AVHRR/Metop: global, daytime & night-time fields, 1 km x 1 km
- SEVIRI/Meteosat: 15-min, 3 km (nadir)

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Land Surface Temperature - SEVIRI

1 day/ 15 min

SEVIRI LST

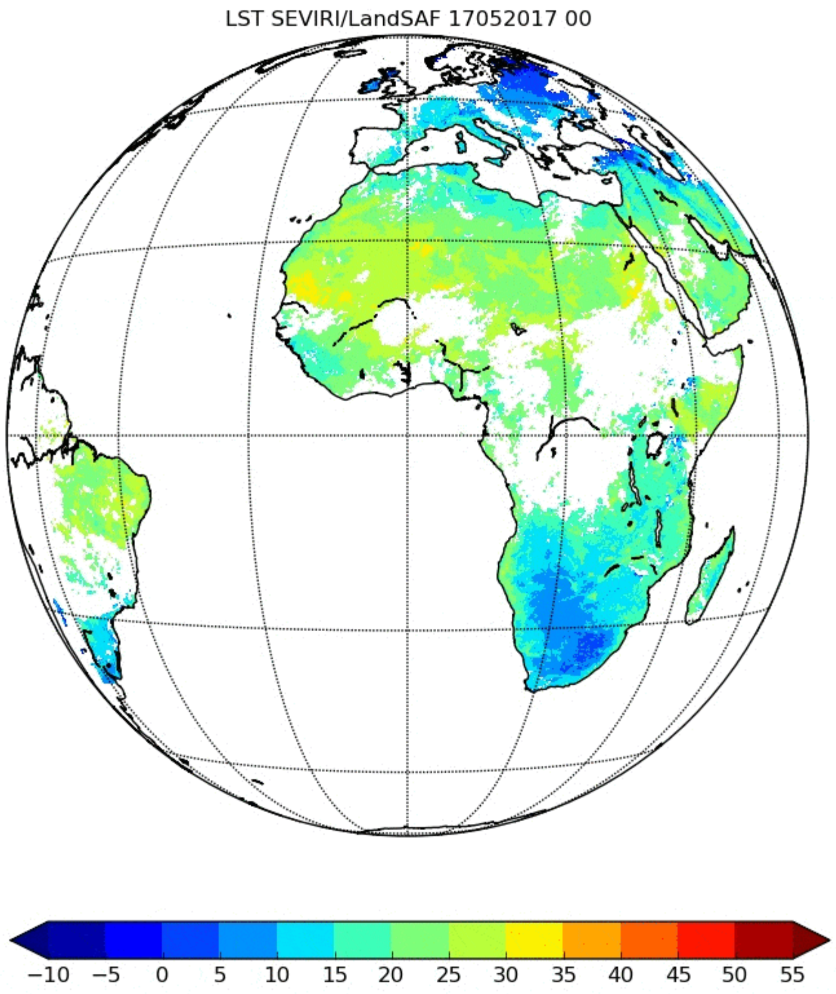
Standard Split-window algorithm

LST = f ($Tb_{10.8}$, $Tb_{12.0}$, $\varepsilon_{10.8}$, $\varepsilon_{12.0}$, …)

- Semi-empirical: simplification of Rad Transf Eq
- Atmospheric correction: [$Tb_{10.8} - Tb_{12.0}$], View angle, TCWV forecasts
- $\varepsilon_{10.8}$, $\varepsilon_{12.0}$ assigned depending on land cover & Fraction of Vegetation Cover (FVC)

✓ Similar approach followed for AVHRR

✓ Efficient, accurate, stable



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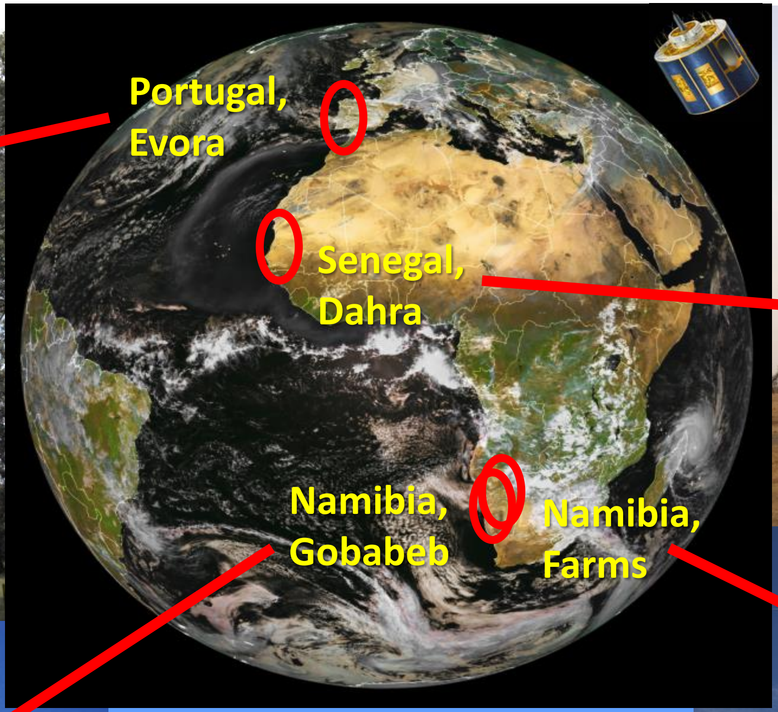
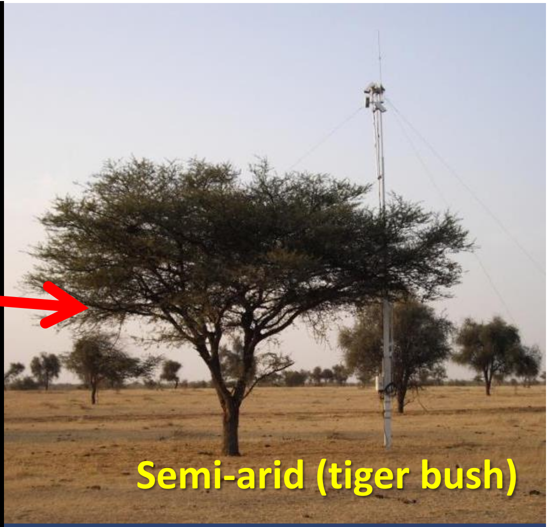
Land Surface Temperature - Validation

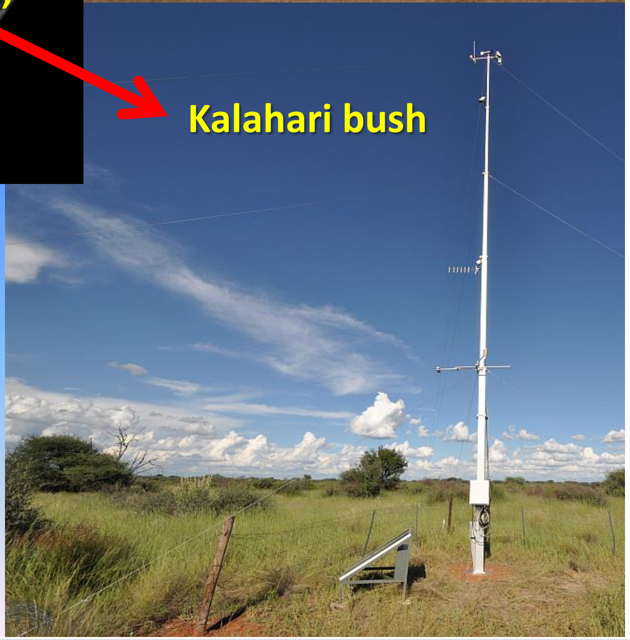
KIT Validation Sites

KIT Karlsruher Institut für Technologie





- Large, **homogeneous** sites
- Well **characterised**
- Different climates & biomes
- **Dedicated** to LST validation



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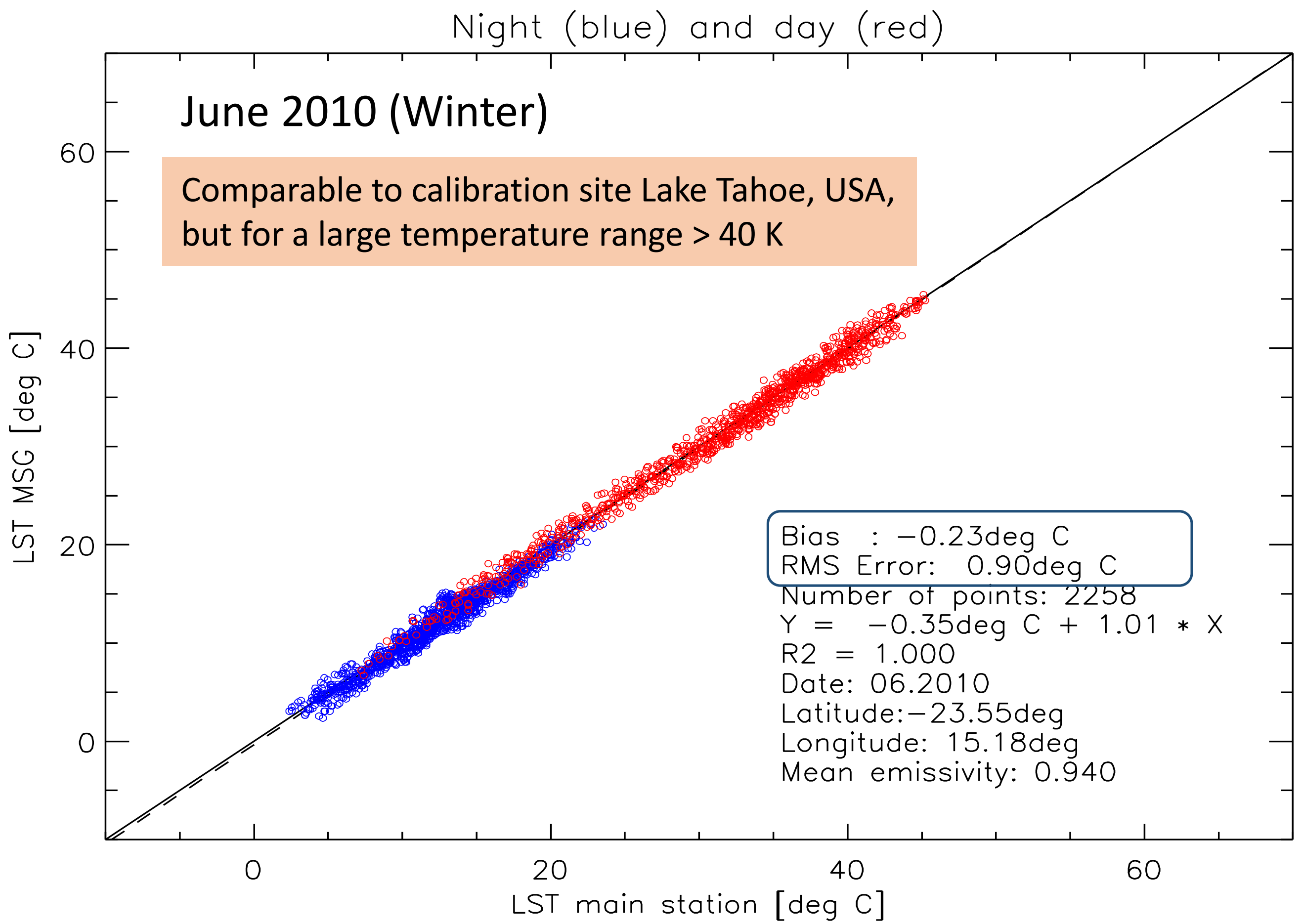
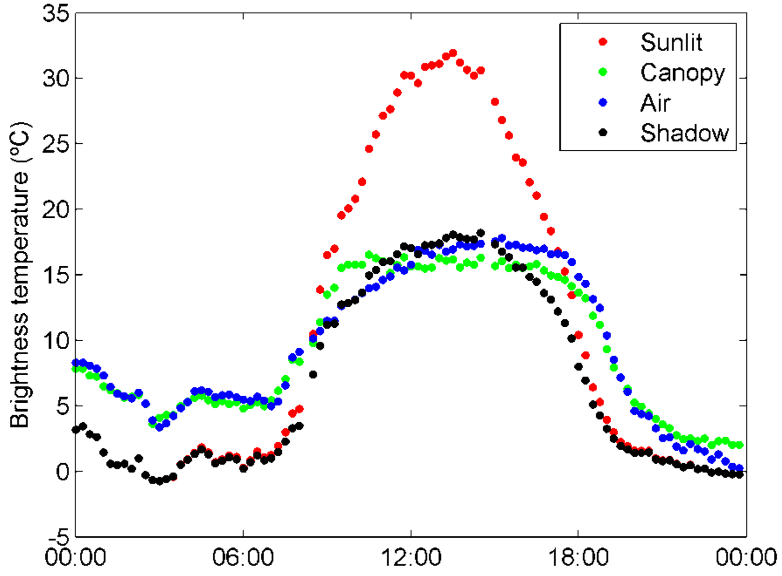
Gobabeb Ground LST versus SEVIRI/MSG LST

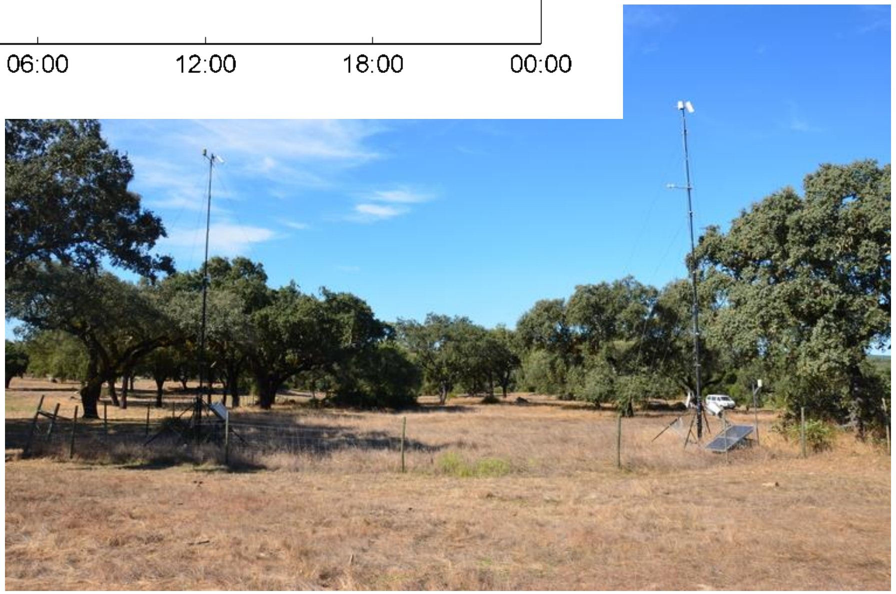


Göttsche, F.-M., F.S. Olesen, I.F. Trigo, A. Bork-Unkelbach, and M.A. Martin (2016). Long Term Validation of Land Surface Temperature Retrieved from MSG/SEVIRI with Continuous in-Situ Measurements in Africa. Remote Sensing, 8(5), 410, 1 -27

Evora LST versus SEVIRI/MSG LST



Radiometric temperature in a summer day



- High surface heterogeneity
- Upscaling needs to take into account distribution of surface elements and ….
- … viewing & illumintation geometries

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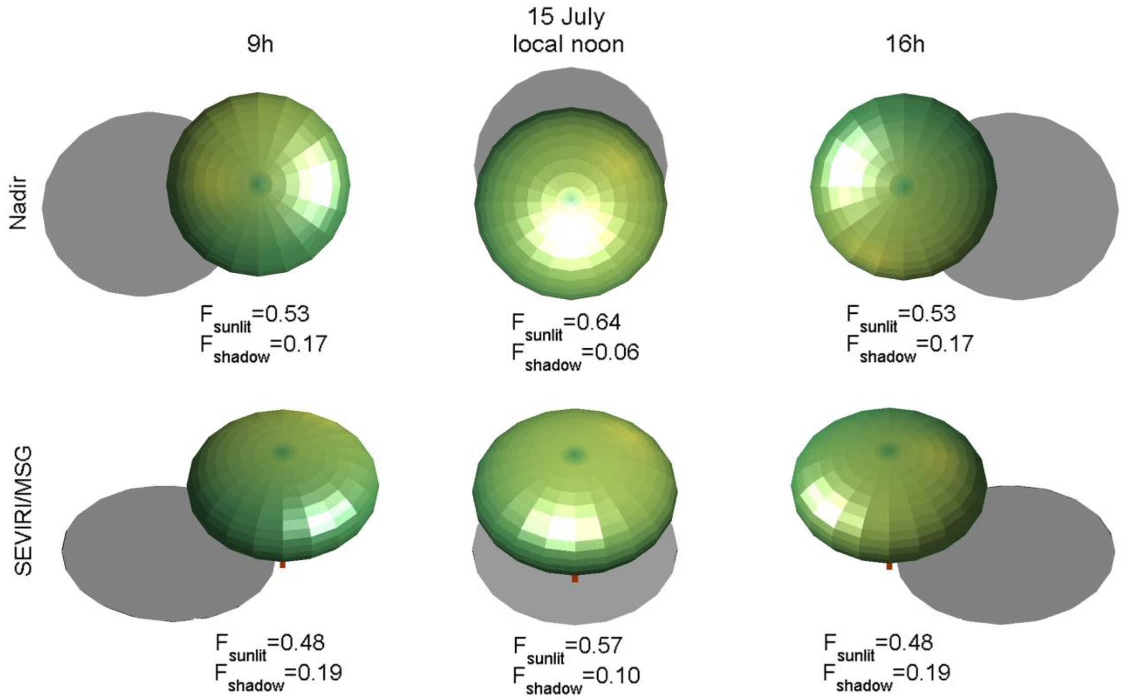
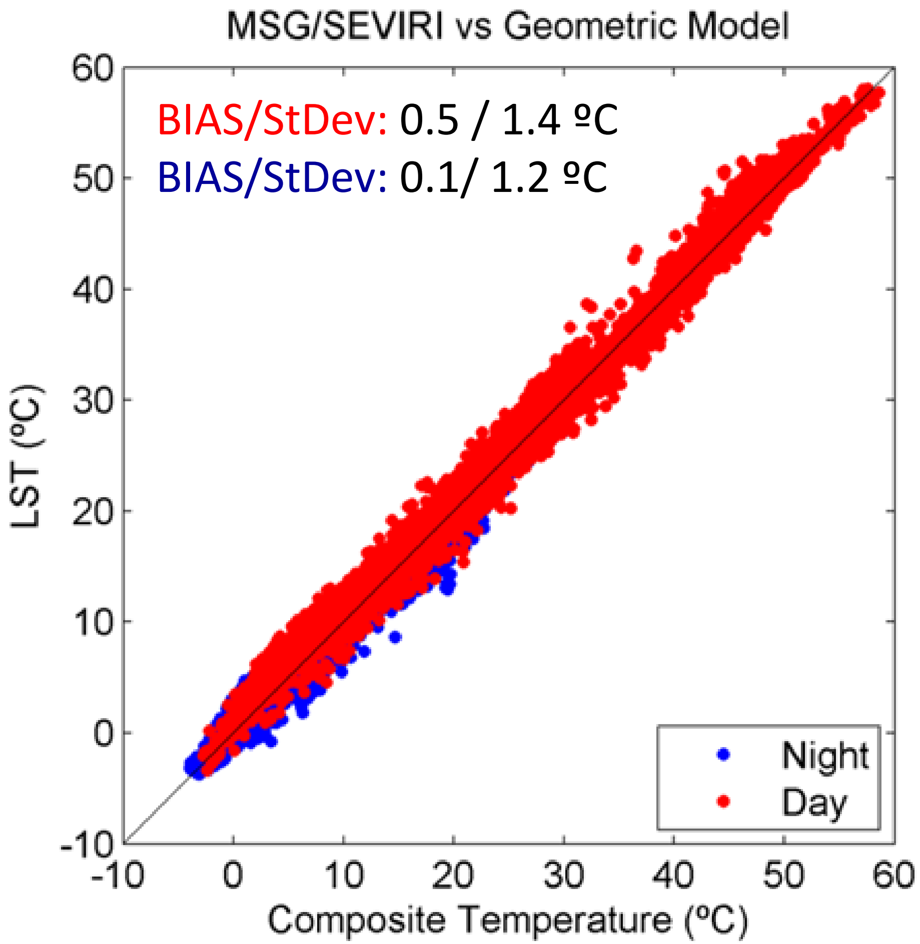
Evora LST versus SEVIRI/MSG LST

Geometric model: shapes of objects seen by the sensor **+** **Boolean model**: overlap probabilities, i.e., actual fraction of end-members





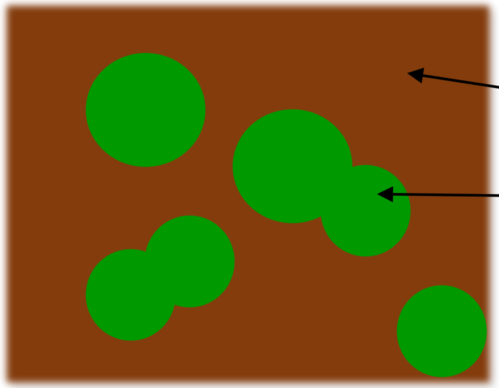
Ermida, S. L., I. F. Trigo, C. C. DaCamara, F. M. Göttsche, F. S. Olesen, G. Hulley, 2014: Validation of remotely sensed surface temperature over an oakwood landscape – The problem of viewing and illumination geometries. Remote Sens. Env., DOI:10.1016/j.rse.2014.03.016

Land Surface Temperature - SEVIRI

Emissivity Estimation:

- ✓ Assumes pixel <u>dominant landcover is known</u>
- ✓ Pixel emissivity can be estimated

Pixel MSG



$$\varepsilon = \varepsilon_{veg}\,\boxed{FVC} + \varepsilon_{ground}\,(1\text{-}FVC) + \boxed{\delta\varepsilon}$$

LSA SAF Product
↑
Sfc Reflectances VIS

- Non-accounted effects (multiple reflections at sfc)
- Variability of bare ground/ vega within pixel

Land Surface Temperature & Emissivity - SEVIRI

Channel Emissivity per VEGETATION / SOIL classes

$$\varepsilon_{C\text{-}VEGA/SOIL} = \frac{\int_{\lambda 1}^{\lambda 2} f_\lambda \varepsilon_\lambda B_\lambda \, d\lambda}{\int_{\lambda 1}^{\lambda 2} f_\lambda B_\lambda \, d\lambda}$$

Emissivity at λ

- Vegetation types
- Soil types

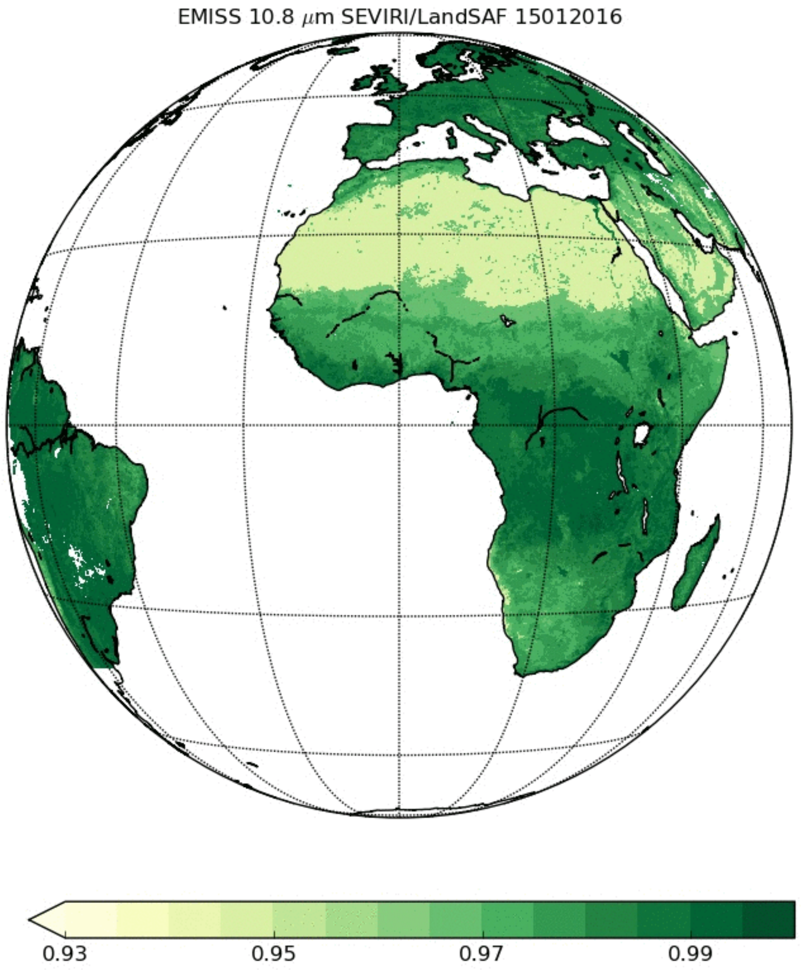
←(Spectral Libraries)

Channel response function

Trigo et al. (2008) in *IEEE Trans Geosc Remote Sens.*, Doi: 10.1109/TGRS.2007.905197

Land Surface Temperature & Emissivity - SEVIRI

Surface Emissivity IR10.8: 2016

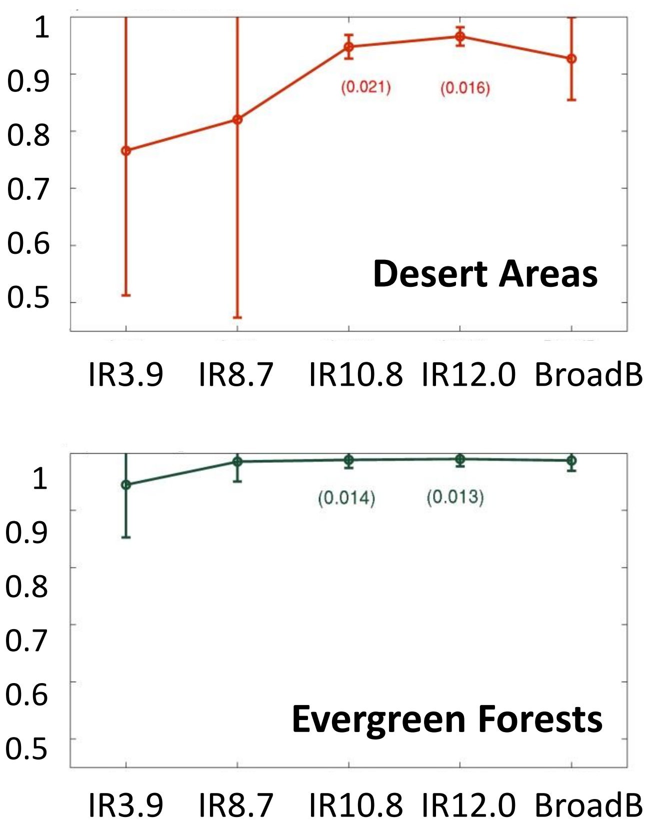


Emssivity: Vegetation cover & Land Cover

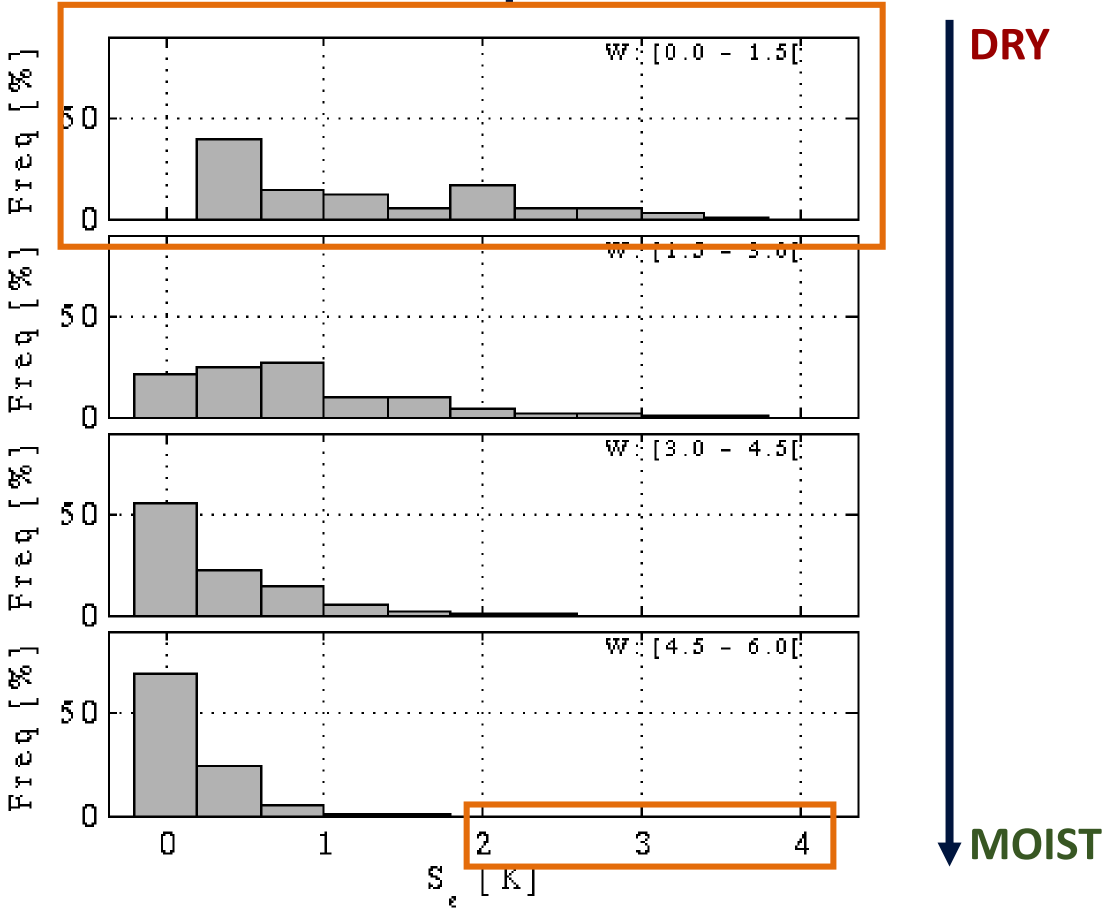
- ✓ Captures well vegetation dynamics
- ✗ Highly dependent on errors in Land cover classification
- ✗ Fails in representing spatial variability over desert regions

SEVIRI LST: Sensitity to Surface Emissivity

Emissivity uncertainty



EMISSIVITY uncertainty in channels 10.8 & 12.0: Impact on LST



Freitas et al (2010) in TGRS

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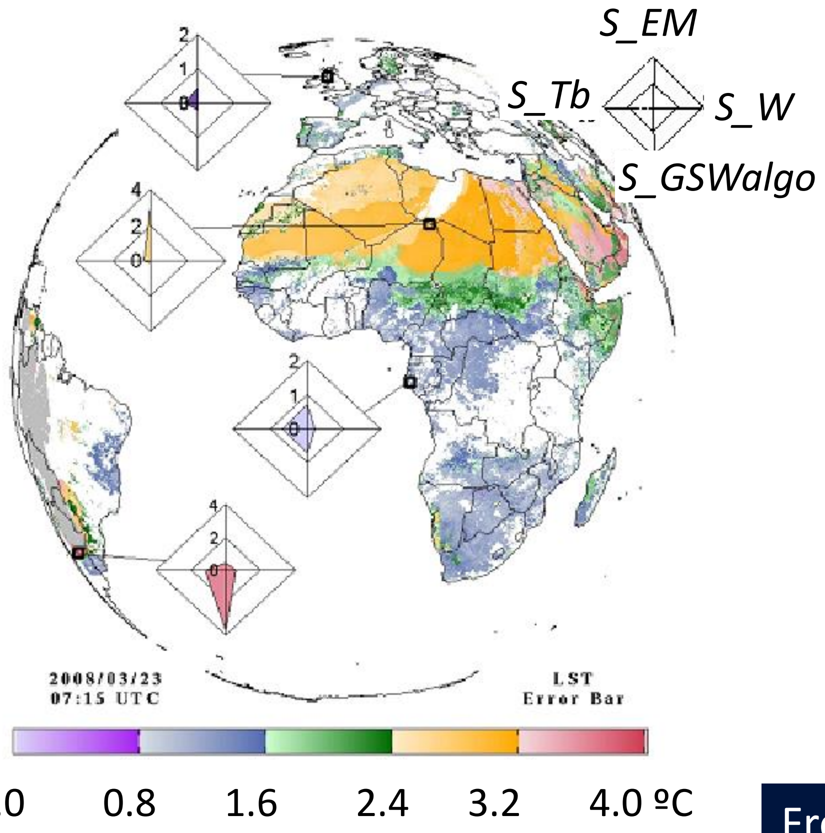
SEVIRI LST: Uncertainty Budget

LST uncertainty (provided with NRT LST product)



Uncertainty estimated taking into account:

- Uncertainty of the GSW algorithm
- Propagation of input uncertainties:
  - Emissivity
  - Sensor noise
  - TCWV ECMWF forecasts

Land Surface Emissivity is the main source of LST errors over deserts & sparsely vegetated areas under dry atmospheric conditions

Freitas, S. C., Trigo, I. F., Bioucas-Dias, J. M., Goettsche, F.-M., 2010: Quantifying the Uncertainty of Land Surface Temperature Retrievals From SEVIRI/Meteosat, *IEEE Trans. Geosci. Remote* Sens. DOI: 10.1109/TGRS.2009.2027697

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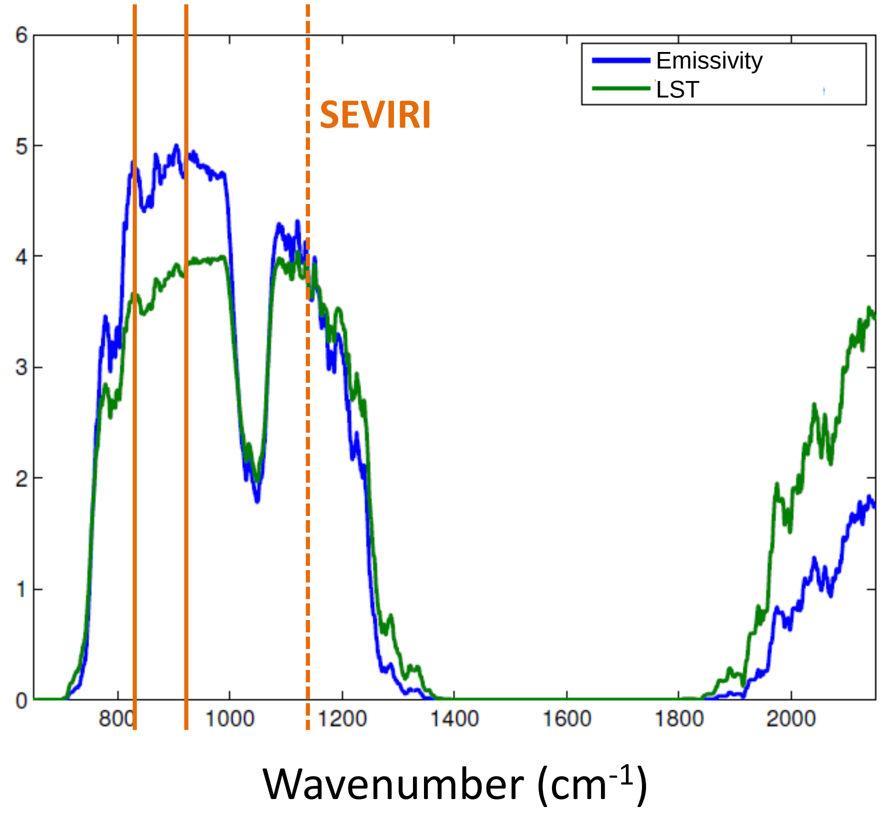
Hyper-sepctral observations: IASI

Sensitivity of IASI Spectra [in K] to:

- 5 K in LST
- 0.1 in surface Emissivity



- ✓ High sensitivity to both LST & Emissivity
- ✓ Simultaneous retrieval may contribute to significantly increase accuracy and ….
- ✓ … improve a priori knowledge of surface emissivity for sensors with lower spectral resolution

Hyper-sepctral observations: IASI

Physical Retrieval of LST & Emissivity

Methodology developed by Paul et *al*. (2012)

- Emissivity 1st guess:
  - MODIS 6 bands + land-cover classification + spectral libraries ⇒ **Emissivity spectra Database**
  - PCA used for compression: emissivity spectra represented by limited number of spectral features

- Physical retrieval:
  - Retrieve *P* emissivity Principal Components & LST
  - The full emissivity spectra can be estimated from the above

Paul, M., F. Aires, C. Prigent, I. F. Trigo, and F. Bernardo, 2012: An innovative physical scheme to retrieve simultaneously surface temperature and emissivities using high spectral infrared observations from IASI, *J. Geophys. Res.*, **117**, D11302, doi:10.1029/2011JD017296.

Hyper-sepctral observations: IASI

Principal Component Analysis

Represent the full spectrum by:

$(\varepsilon_1, \ldots . \varepsilon_N) \approx PC\,.EV + \bar{\varepsilon}$ with N = 8461 (number of IASI channels)

PC – vector with P principal components, $P < N$

EV – eigenvector matrix considering only P components (P x N)

$\bar{\varepsilon}$ mean emissivity spectrum

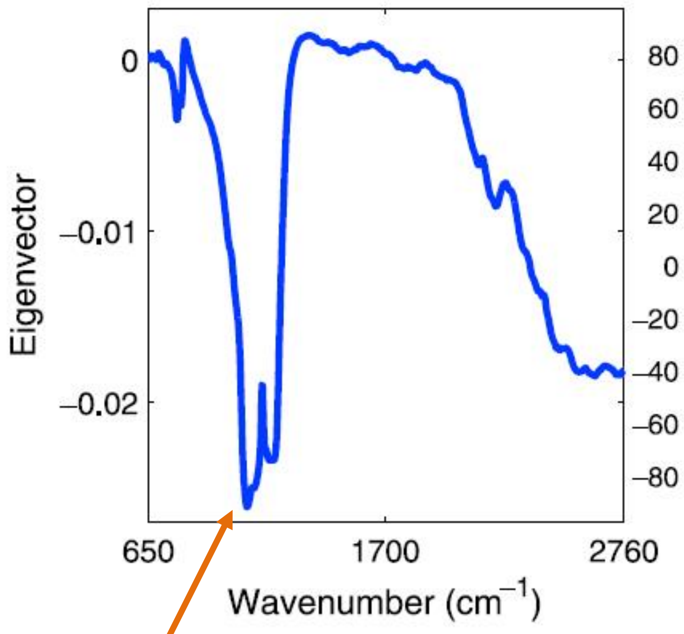
PCA ⇨ Global database spectral emissivity [land-cover & spectral libraries]

***P* = 10** explains 99.98% total emissivity variance.

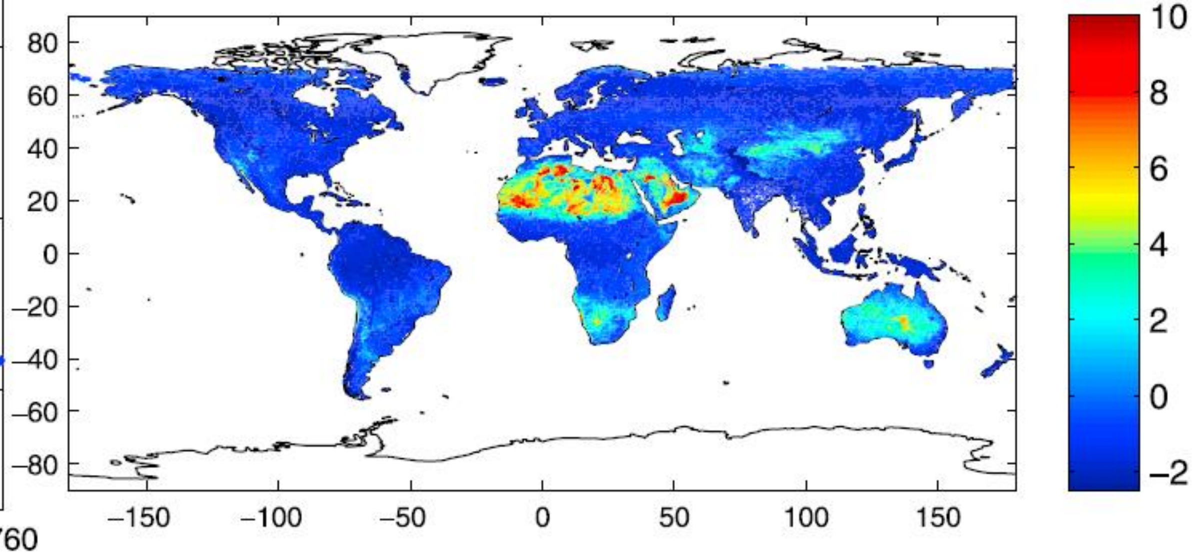
NN interpolator trained with EM Database: *P* PCs from MODIS 6 band Emissivities

Hyper-sepctral observations: IASI

EV_1



Spatial Distribution of the 1st PC



- Silicate absorption band
- High values of the 1st PC over desert areas

Paul et al. (2012)

IASI LST & EM Retrieval

Physical retrieval

- Retrieve ***P*** emissivity Emissivity Principal Components & LST
- … Using ***n*** IASI channels

Solving the equation [RTE + *P* PC for representation of emissivity spectra]:

$$\left(\boldsymbol{PC_1}, \ldots, \boldsymbol{PC_P}, \Delta\boldsymbol{T}\right) \cdot \underbrace{\begin{pmatrix} ev_{1,1} & \ldots & ev_{1,n} \\ & \ddots & \\ ev_{P,1} & \ldots & ev_{P,n} \\ F_1'(T_{fg}) & \ldots & F_N'(T_{fg}) \end{pmatrix}}_{\boldsymbol{M}} = -\bar{\varepsilon} + F\left(T_{fg}\right)$$

$$\left(\boldsymbol{PC_1}, \ldots, \boldsymbol{PC_P}, \Delta\boldsymbol{T}\right) = -\bar{\varepsilon} + F\left(T_{fg}\right)\Delta\mathrm{T} \,.\, M^{+}$$

$\Delta\boldsymbol{T}$ = LST – T_{fg} (First Guess for LST)

For wavelenght *i*, $F_i(T) = A_i\,/B_i(T)$, where:
- *A* depends only on TOA observations & First Guesses
- $B_i(T)$ is the Planck function

IASI LST & EM Retrieval

Physical retrieval

Assumptions:

- Atmospheric transmittance / emission is known!

  NWP Profiles (T, q, O3) + RTTOV

- Function *F* can be linearized around T_{fg}

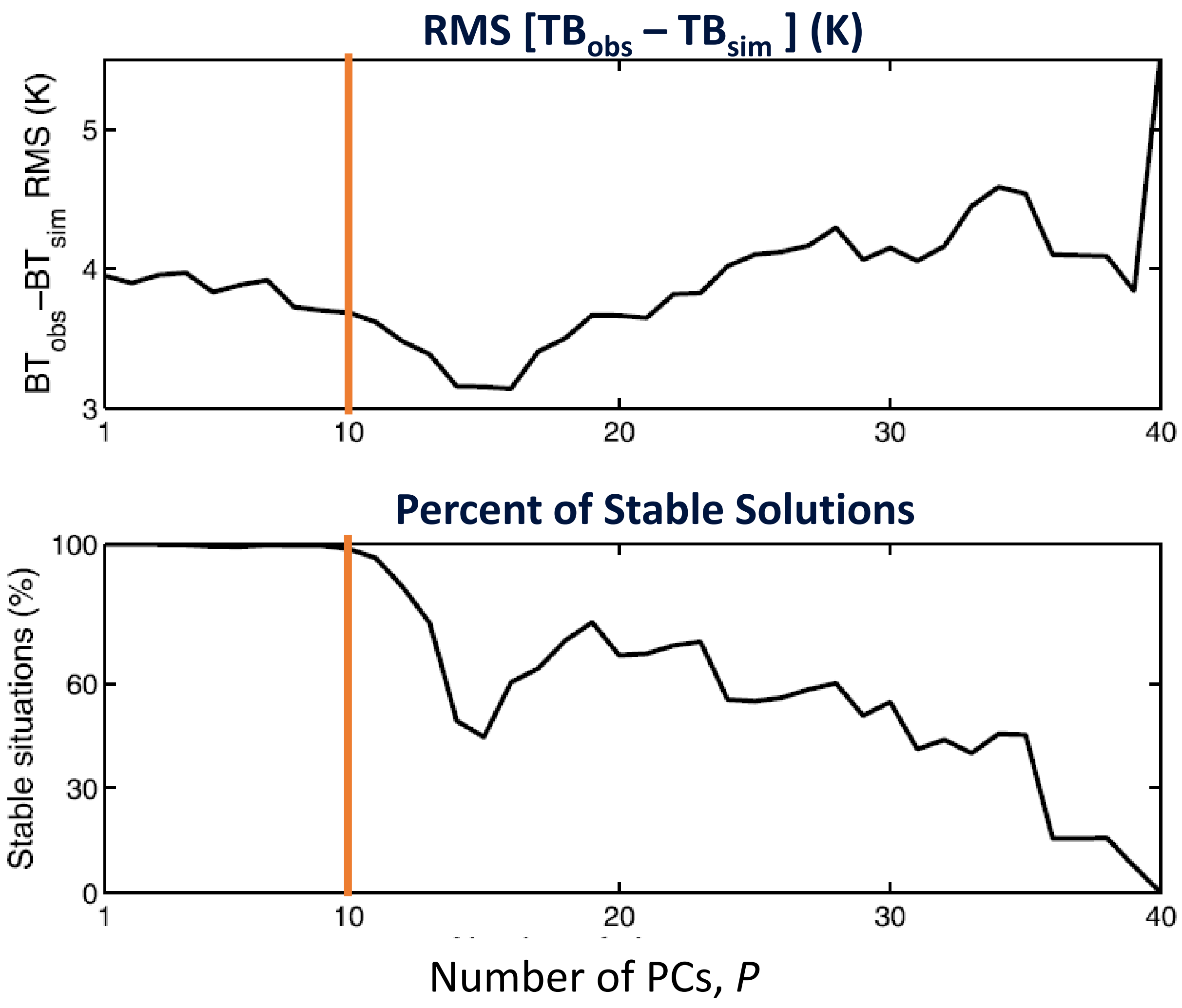
Choice of ***P*** Principal Components and ***n*** channels:

- ***n*** restricted to window channels with lowest chance of being (too much) affected by the atmosphere ⇨ ***n* = 512** with highest transmittance, τ, & lowest τ gradient in spectra space;
- ***P*** optimum value ⇨ balance between degrees of freedom & accuracy RMS[$BT_{obs} – BT_{retrieved}$]

  ***P* = 10**

Each retrieval considers 512 observations & 11 unknowns [10 PCs + LST]

IASI LST & EM Retrieval



- ➢ Unstable solutions, $|\Delta T|$> 20 K, are filtered out!

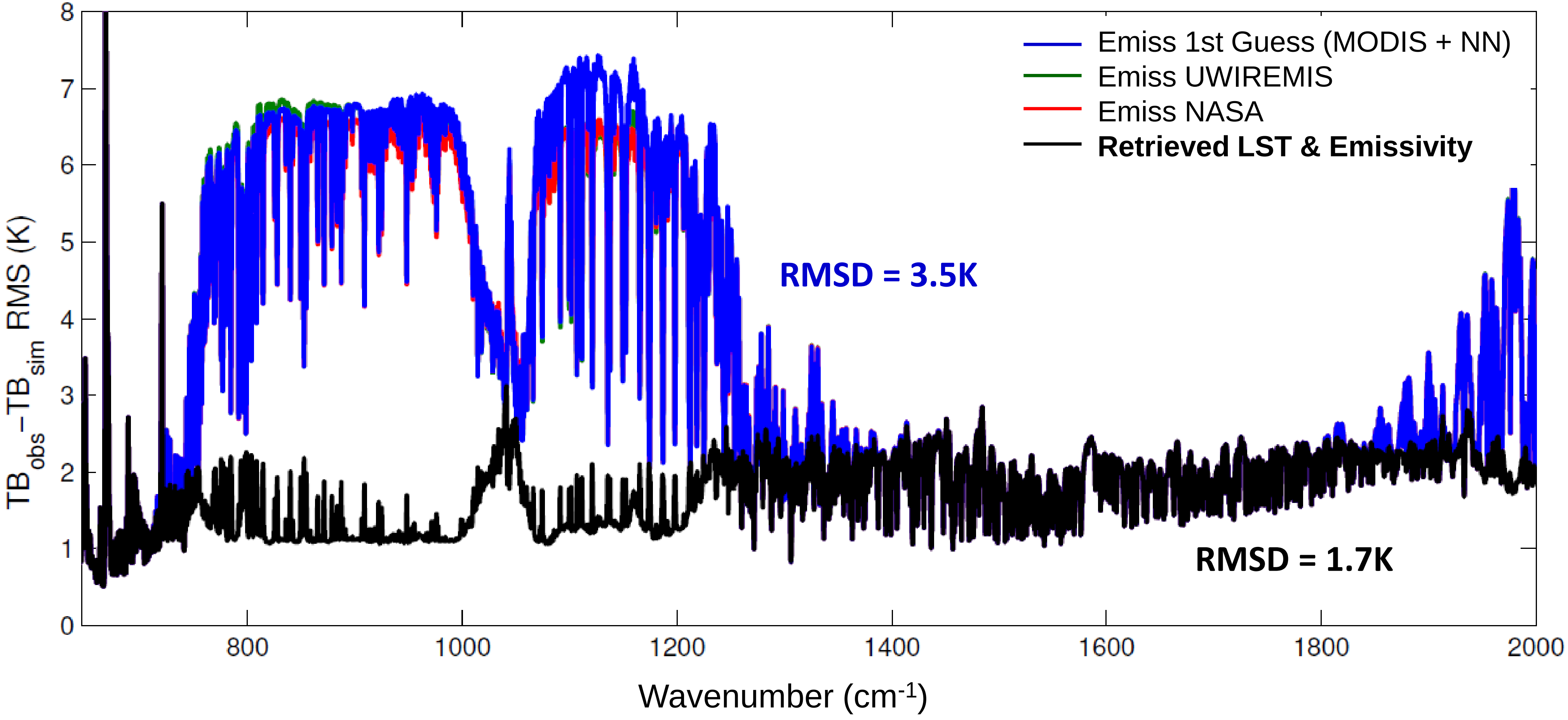
Number of PCs *P* = 10

- ➢ Acceptable accuracy
- ➢ Limits the % of unstable solution

Too many PCs $\rightarrow$ too many degrees of freedom

IASI LST & EM Retrieval

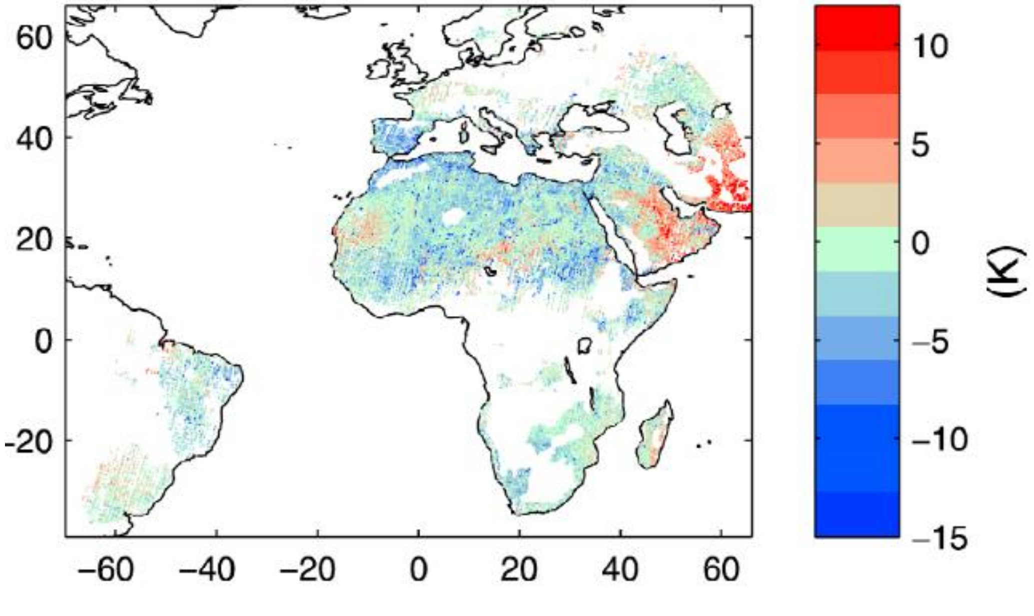
Statistics over 4 weeks: Jan, Apr, Jul, Oct 2008



IASI LST & EM Retrieval versus SEVIRI LST

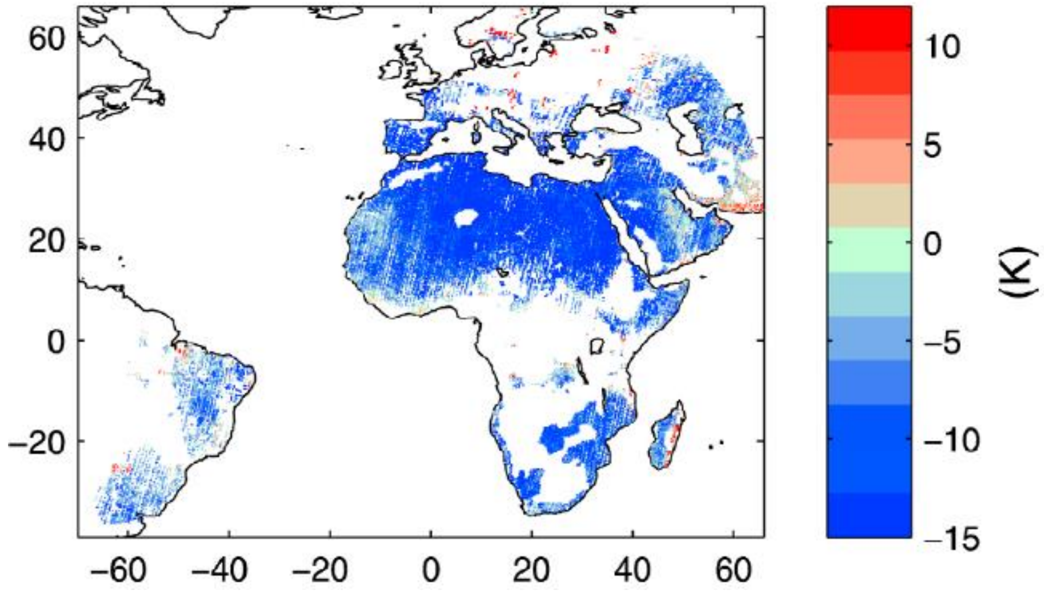
Statistics over 4 weeks: Jan, Apr, Jul, Oct 2008

IASI LST – SEVIRI LST



First Guess Ts

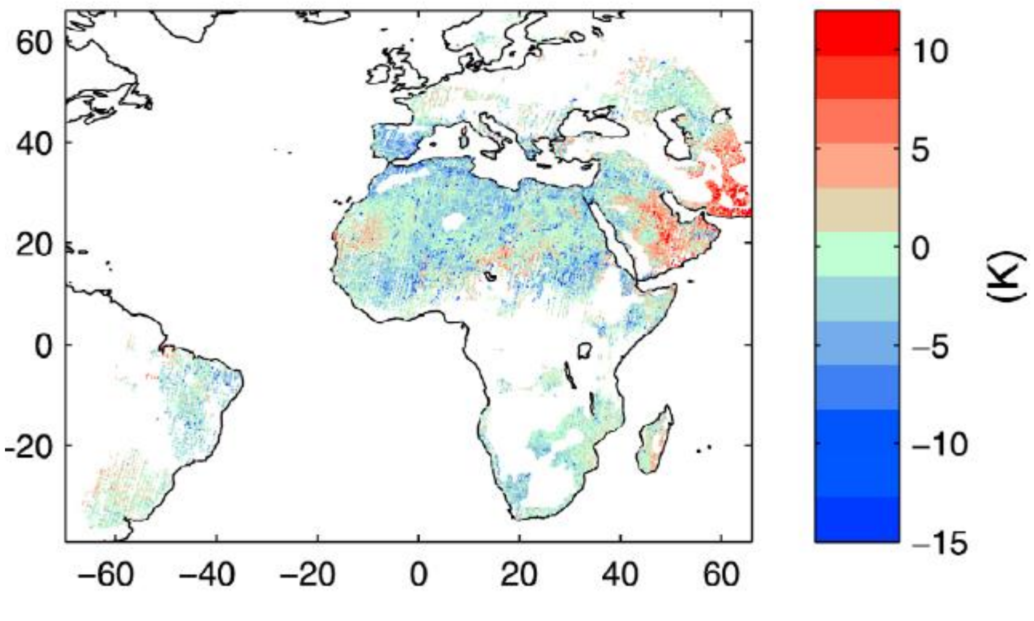
ECMWF Tskin – SEVIRI LST



IASI LST & EM Retrieval versus SEVIRI LST

Statistics over 4 weeks: Jan, Apr, Jul, Oct 2008

IASI LST – SEVIRI LST



Comparison against SEVIRI LST	Bias (K)	StDev (K)
ECMWF Tskin (ERA)	-6.0	6.3
IASI LST	2.3	3.5

Correlations		
	ERA vs SEVIRI	0.78
	ERA vs IASI	0.83
	IASI vs SEVIRI	0.94

Concluding Remarks

Land Surface Temperature

- ➢ Regularly retrieved from (IR) imagers; split-windows proves to be efficient & stable
  - AVHRR: night-time and daytime LST; ~ 1km spatial resolution
  - SEVIRI: 15 min LST; 3km nadir
  - …
- ➢ Validation with ground measurements
  - Gobabeb (Namibia) gravel plain: Bias < 0.25K & RMSE < 1.0K
  - Evora (Portugal) savanna-like: Bias ~ 0.5K & RMSE ~1.5K
- ➢ However, emissivity is a major source of LST uncertainty in arid regions (2.5K or more)
- ➢ There are other methods under testing / used for direct retrieval of LST & EM from IR imagers
  - Feasibility study ongoing: Kalman Filter (logit of SEVIRI emissivity & LST); sensitive to EM 1st guess!

Masiello, et al. (2015), in Atmos. Meas. Tech., 8, 2981–2997, doi: 10.5194/amt-8-2981-2015

- ➢ Better characterization of Land Surface Emissivity would benefit all the above!

Concluding Remarks

IASI: LST & Emissivity Spectra Physical Retrieval:

- 1st guess: Emissivity spectra based on MODIS & spectral libraries; Tskin (ERA-40)
- Estimates P=10 Emissivity PCs & ΔT [LST – Tskin], assuming atmosphere is known
  - Only 512 window channels are considered
  - “Unstable solutions” ΔT > 20 K are filtered out
- Verification via comparison:
  - Between simulated radiance spectra & IASI observations
  - Retrieved IASI LSI, 1st Guess & LSA-SAF
- **Such method may be used to derive a emissivity spectra climatologies – to be used in land (or atmospheric profiles) retrievals**
- **To be solved/ checked:**
  - **Improve atmospheric profiles**
  - **Downscalling/ rescalling emissivity**
  - **Emissivity dependence on zenith angle**

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