Assessment of Land Surface Temperature methods for future high resolution thermal missions

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Assessment of LST algorithms for LSTM and TRISHNA missions

- Algorithms
- LIAISE campaign
- Synthetic images
- LSTM & TRISHNA algorithms validation
- ET estimation
- Conclusions

Algorithms

Split-window

- Three different SW structures proposed
- *Becker. F & Li. Z. (BL); Wan Z, Dozier (GSW) & J. A. Sobrino & N. Raissouni (SOB)*

$$T_s = A_0 + P\frac{T_i + T_j}{2} + M\frac{T_i - T_j}{2}$$
$$A_0 = a_0 + a_1 w$$
$$P = a_2 + (a_3 + a_4 w\cos\theta)(1-\varepsilon) - (a_5 + a_6 w)\Delta\varepsilon$$
$$M = a_7 + a_8 w + (a_9 + a_{10} w\cos\theta)(1-\varepsilon) - (a_{11} + a_{12} w)\Delta\varepsilon$$

Becker. F & Li. Z. Surface temperature and emissivity at various scales: Definition, measurement and related problems[J]. Remote sensing reviews, 1995, 12(3-4): 225-253.

$$T_s = a_0 + (a_1 + a_2\frac{1-\varepsilon}{\varepsilon} + a_3\frac{\Delta\varepsilon}{\varepsilon^2})\frac{T_i + T_j}{2} + (a_4 + a_5\frac{1-\varepsilon}{\varepsilon} + a_6\frac{\Delta\varepsilon}{\varepsilon^2})\frac{T_i - T_j}{2}$$

Wan Z, Dozier J. A generalized split-window algorithm for retrieving land-surface temperature from space[J]. IEEE Transactions on geoscience and remote sensing, 1996, 34(4): 892-905.

$$T_S = T_i + a_0 - a_1(T_i - T_j) + a_2(T_i - T_j)^2 + (a_3 + a_4 w)(1-\varepsilon) + (a_5 + a_6 w)\Delta\varepsilon$$

J. A. Sobrino & N. Raissouni. Toward remote sensing methods for land cover dynamic monitoring: Application to Morocco, International Journal of Remote Sensing, 2000, 21:2, 353-366

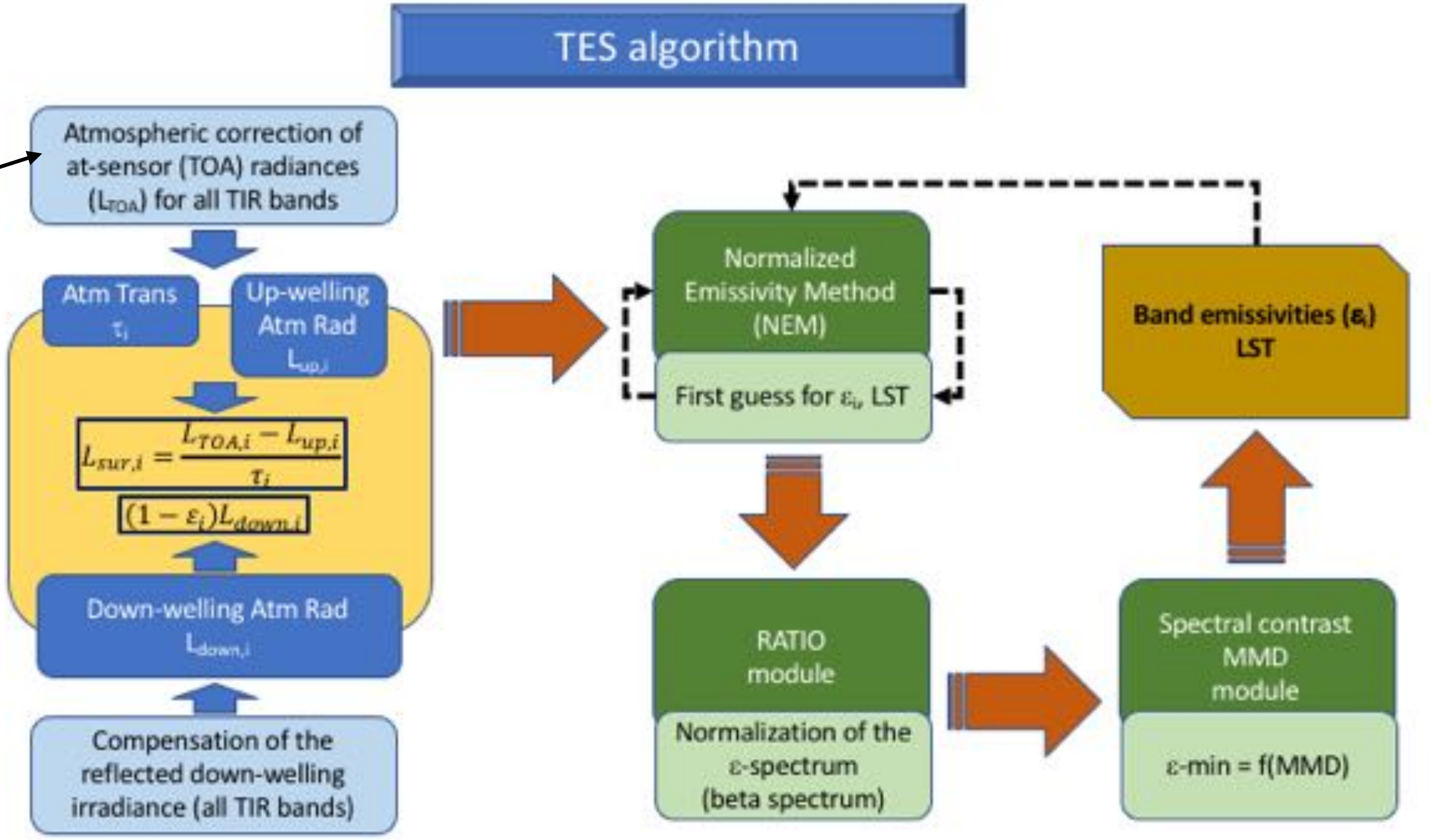
Algorithms

Temperature Emissivity Separation (TES)

Gillespie et al., (1998)

- Starting from RTE:

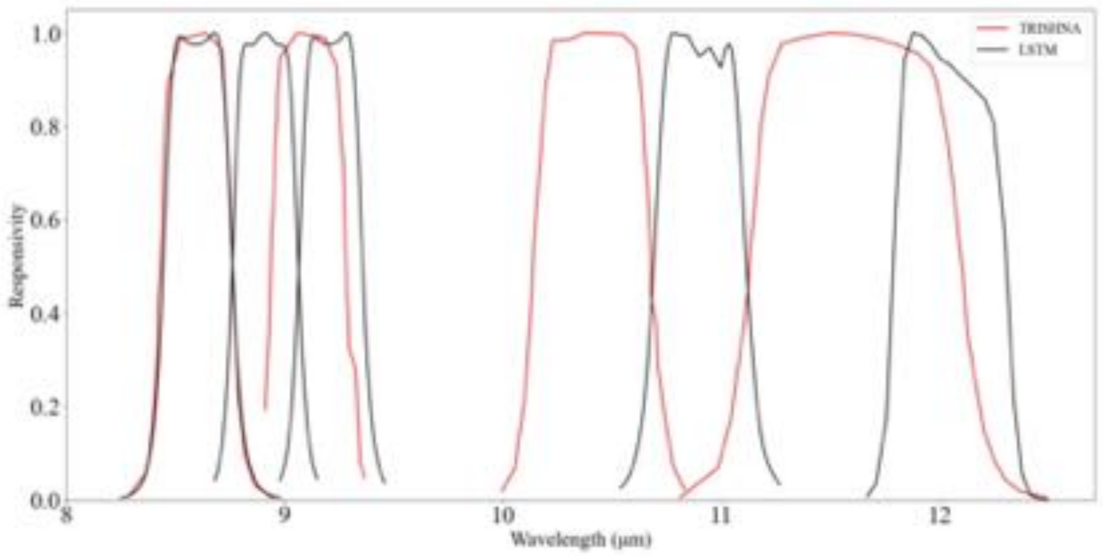
$$L_i^{at-sensor} = \left[\varepsilon_i B_i(Ts) + (1-\varepsilon_i) L_i^{\downarrow} \right] \tau_i + L_i^{\uparrow}$$



- LST and Land Surface Emissivity (LSE) can be estimated simultaneously

Instrument Spectral Response Functions (ISRF)

LSTM and TRISHNA filter functions



Thomas H.G. Vidal et al., (2022)

LSTM and TRISHNA spatial resolution

	TRISHNA	LSTM
NADIR	57 m	37 m
Max scan angle	90 m	50 m

LSTM Mission Requirement Document

MR- OBS-025	The mission shall measure TOA radiance with 3 (threshold) to 5 (goal) spectral bands in the TIR spectral range (8 - 12.5 μm) for the primary mission objective, as specified in Table 4.1 below.

MR- OBS-030	The centre and spectral width of the TIR spectral bands shall be met within the tolerance (e.g. manufacturing tolerances, variations within the FOV, evolution over lifetime) and knowledge specified in Table 4.1.

Note 1: TIR-1 has been recommended to be prioritized of the two goal bands in the case of a four-band scenario

Note 2: The spectral tolerance of TIR bands could be relaxed to 20 nm and knowledge to 7 nm if required

Note 3: Thresholds and goals of spectral bandwidth will need to be further studied.

Band #	Goal /Threshold	Centre λ_{centre} (μm)	Spectral width Δλ (μm)	Tolerance λ_{centre} (± nm)	Tolerance Δλ (± nm)	Knowledge λ_{centre} (± nm)	Knowledge Δλ (± nm)
TIR-1	G	8.6	0.18 (G)/0.30 (T)	10	10	5	5
TIR-2	G	8.9	0.18 (G)/0.30 (T)	10	10	5	5
TIR-3	T	9.2	0.18 (G)/0.30 (T)	10	10	5	5
TIR-4	T	10.9	0.40 (T)	10	10	5	5
TIR-5	T	12.0	0.47 (T)	10	10	5	5

Table 4.1: TIR spectral bands. Tolerance includes manufacturing tolerance, evolution over lifetime, variation of the field of view, etc.

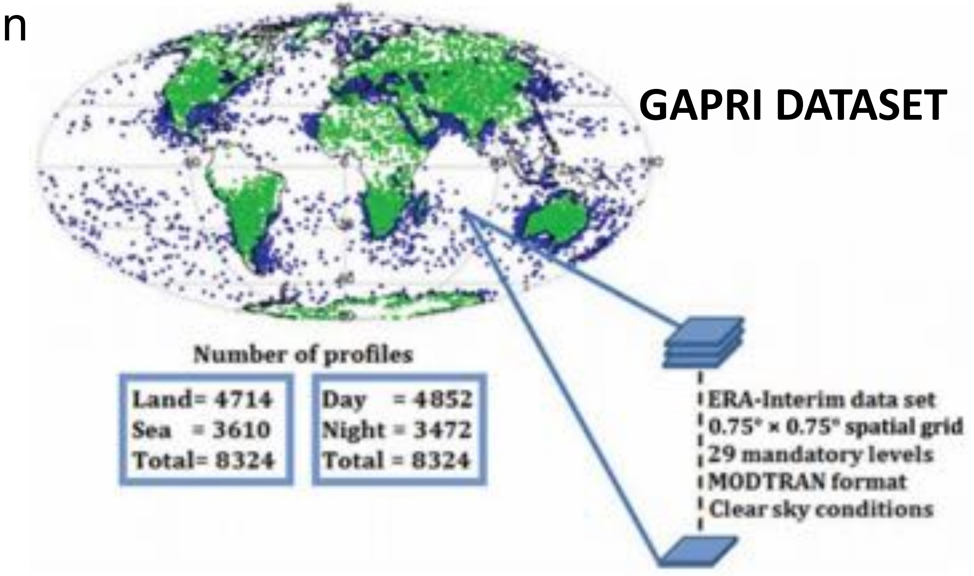
SW COEFFICIENTS ESTIMATION

Modtran simulations

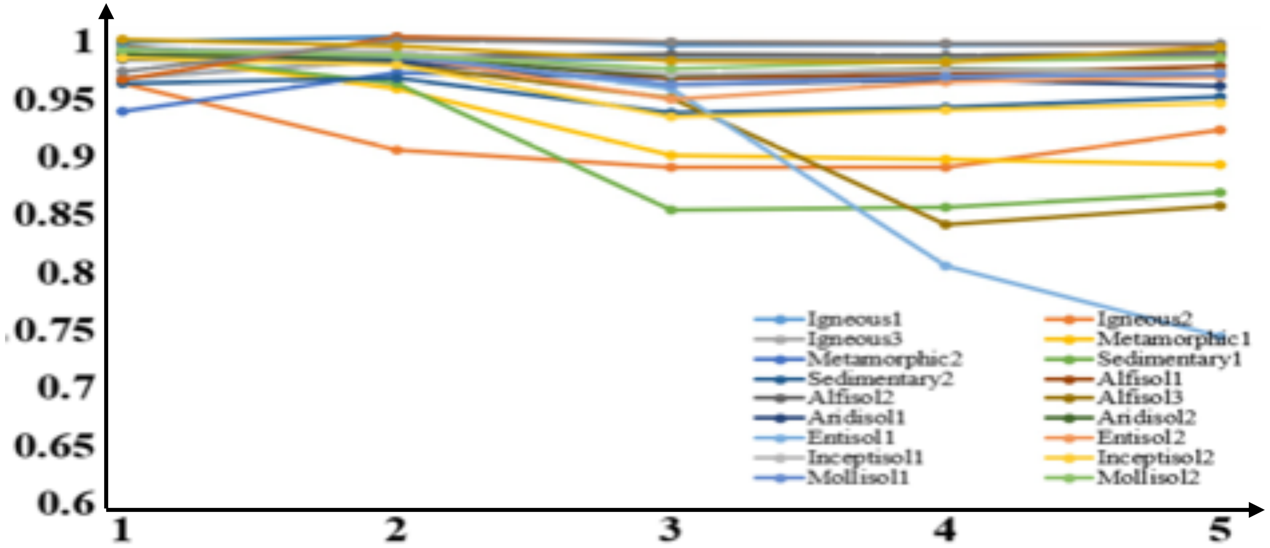
- with Global Atmospheric Profiles derived from Reanalysis Information (GAPRI) (Mattar et al., 2015)
- Emissivity from ECOSTRESS library
- Surface temperature simulation range [T_0-15, T_0-10, T_0-5, T_0, T_0+5, T_0+10, T_0+15 K]

Simulations: More than 7 million cases

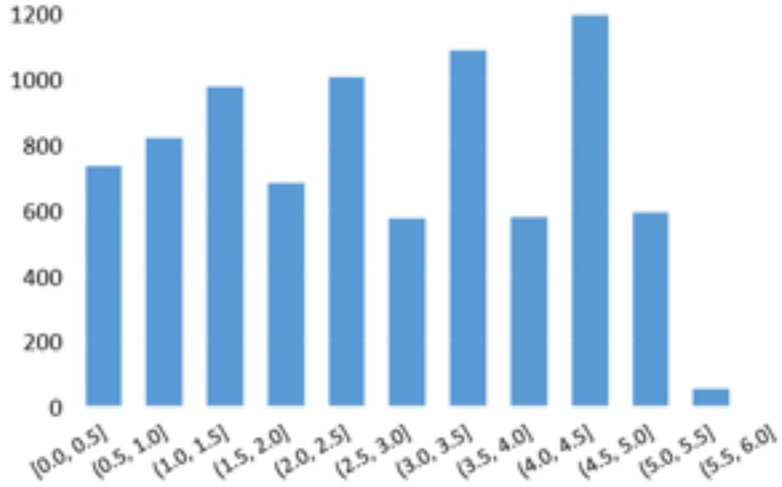
GAPRI DATASET



ECOSTRESS emissivity for LSTM TIRS channels



WV DATASET DISTRIBUTION



SW COEFFICIENTS ESTIMATION

- **Fitting coefficients for LSTM TIRS channels 4 (10.9 μm) and 5 (12.0 μm)***

SW algorithm	a0	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12
BL-1995	-7.1391	-0.2757	1.0256	0.2156	-0.0275	0.4621	-0.0732	4.1042	0.5355	-2.7713	0.9951	1.424	-0.3734
GSW-1996	-7.8407	1.0338	0.0743	-0.095	3.2518	-7.283	8.9925						
SOB-2000	-0.772	2.6207	0.0548	49.202	-4.8838	-172.77	29.664						

- **Fitting coefficients for TRISHNA TIRS channels 3 (10.4 μm) and 4 (11.6 μm)***

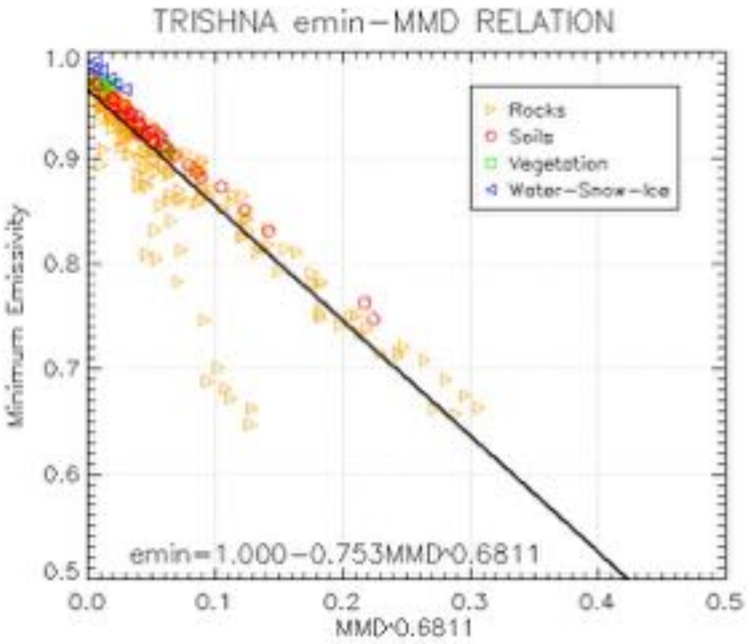
SW algorithm	a0	a1	a2	a3	a4	a5	a6	a7	a8	a9	a10	a11	a12
BL-1995	-44.4917	-0.3157	1.1822	0.1581	0.0389	0.4509	0.0427	5.5439	0.3229	-5.5226	0.2721	0.5224	-0.4493
GSW-1996	-39.5252	1.1645	0.127	-0.5212	6.8865	2.5066	0.1866						
SOB-2000	2.1723	0.0294	6.0919	21.9485	6.5685	-124.59	-6.8636						

*best combinations of channels to estimate the LST from a SW algorithm

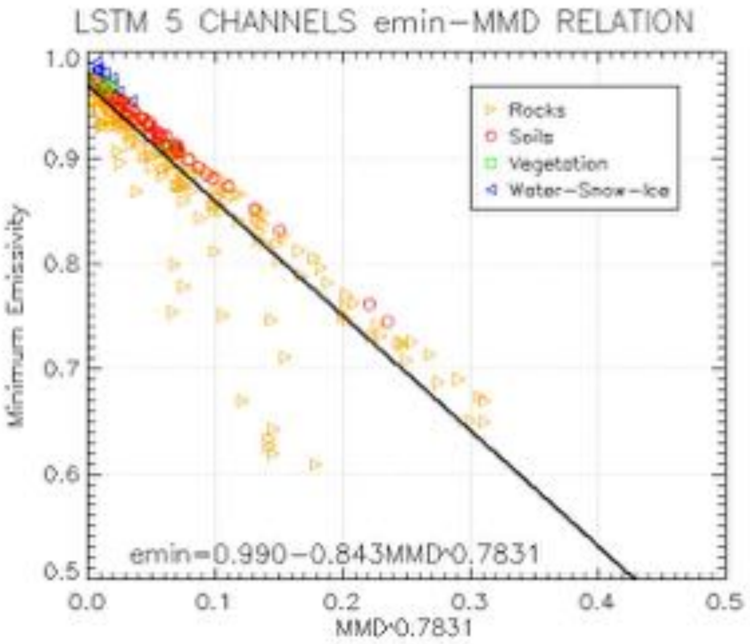
TES COEFFICIENTS ESTIMATION

- Use of ECOSTRESS spectra library
- εmin-MMD: minimum value of the emissivity spectrum estimated as an empirical relationship of the Maximum Minimum Difference (MMD ≡ spectral contrast) for 3 TIRS Channel configurations TRISHNA (4), LSTM (5), LSTM (3)

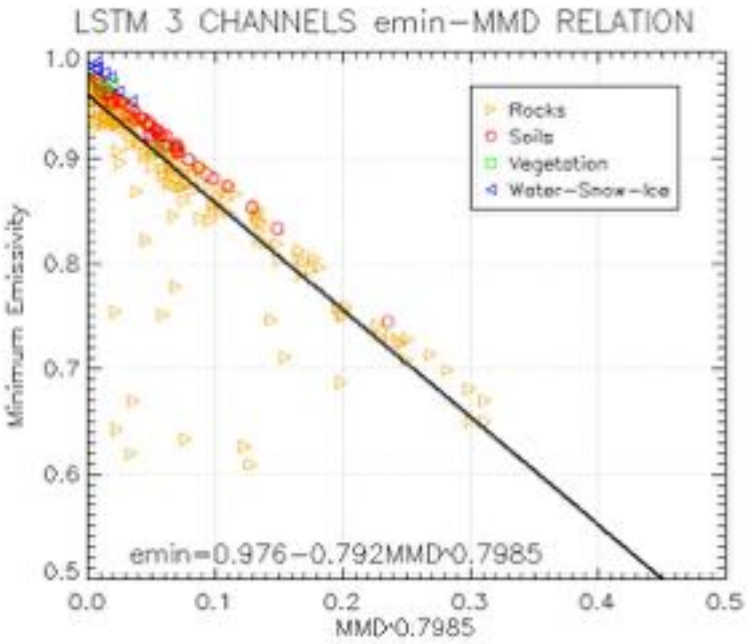
TRISHNA
ALL CHANNELS



LSTM-5
ALL CHANNELS



LSTM-3
{TIRS 3, TIRS 4, TIRS 5}



OVERVIEW

- Algorithms
- LIAISE campaign
- Synthetic images
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LIAISE CAMPAIGN 2021

STUDY AREA (LLEIDA, SPAIN 2021)
AIRPLANE FLIGHTS (TASI/CASI) 17th - 19th - 22th - 24th and 29th JULY, 2021

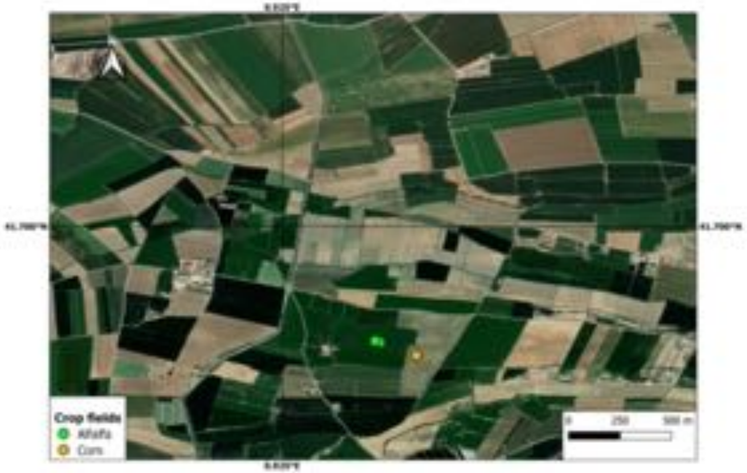
- Airborne data acquired in two different locations at different overpass times.

- Flight characteristics:
  - ➢ Flight Height 3,300 m.
  - ➢ Pixel size: 4.0 m
  - ➢ Flight pass time 10-15 UTC

- Airborne images obtained with a TASI-600 sensor, a pushbroom hyperspectral thermal sensor system.
  - Spectral bands: 32, but 24 used for LST retrieval
  - Range from 8 to 11.5 microns

- TES outputs (LST & LSE) validated against in situ measurements.

CORN location 17 JULY, 2021



Alfalfa location 19-22-24 JULY, 2021

TASI LST Validation

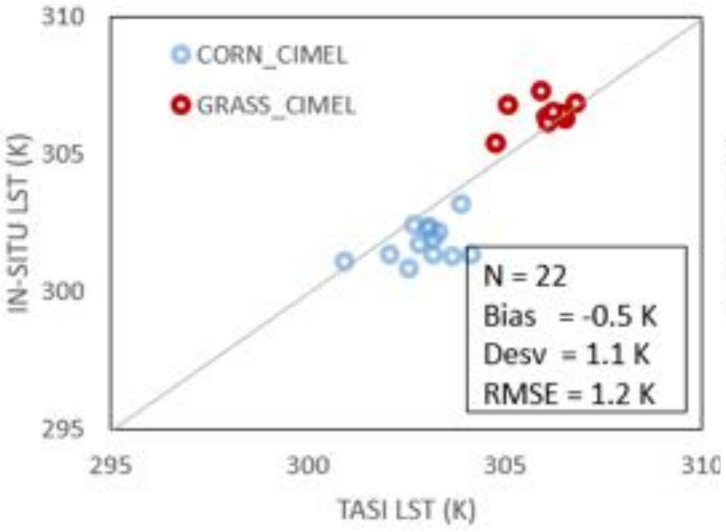
In situ measurements used for validation of TASI TES outputs (LST & LSE)

- Multiband radiometers for surface characterization (calibrated with desviations below 0.3 K).
- Diffuse reflectance plate to address atmospheric downward effects.
- Broadband sensor 8-14 μm, installed in a fixed station for continuous measurements.

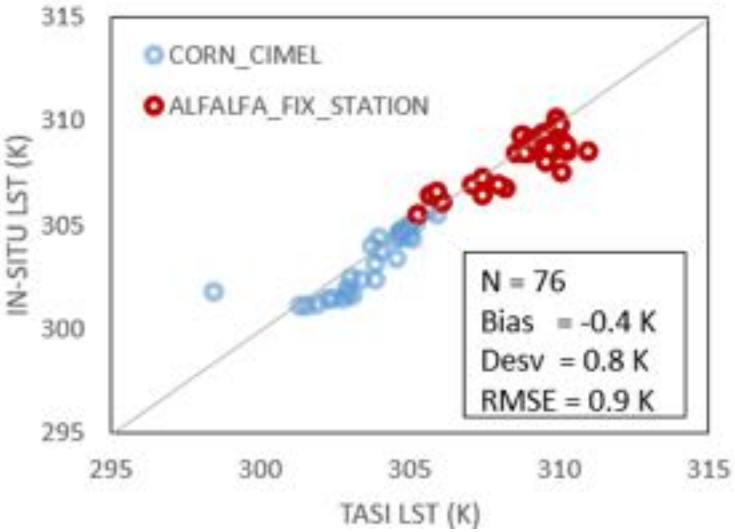
- LST validation 1.2 K (17 July), 0.9 K (19 July)

TASI LST validation

17 July



19 July



SINGLE BAND RADIOMETER

Apogee SI-400

MULTI BAND RADIOMETER

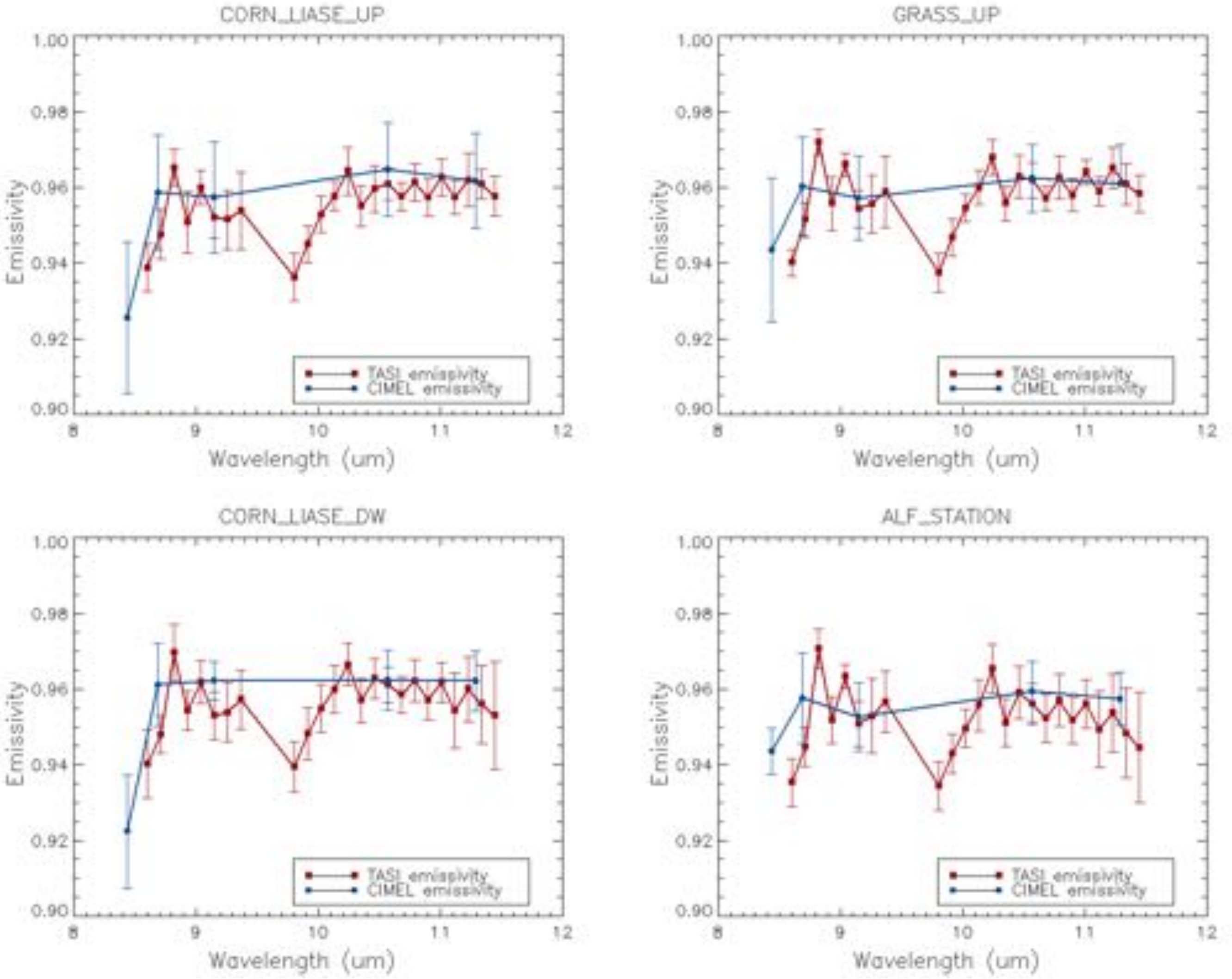
DIFFUSE REFLECTANCE PLATE

Infragold Labsphere

TASI LSE Validation

17 July

19 July



- In situ and TASI emissivities from TES
- Comparison of most similar TASI bands to CIMEL bands: differences below 0.01 are retrieved for CIMEL bands 9.15, 10.57 and 11.29 µm and 0.02 for band 8.69 µm.

EMISSIVITY [CIMEL – TASI]	CIMEL WAVELEGTH (µm)			
	8.69	9.15	10.57	11.29
GRASS_1707	0.020	0.003	0.001	-0.004
CORN_1707	0.020	0.005	0.004	0.000
ALFALFA_1907	0.007	-0.007	-0.004	0.000
CORN_1907	0.017	0.010	0.000	0.004
BIAS	0.016	0.003	0.000	0.000
DEVIATION	0.006	0.007	0.003	0.003
RMSE	0.017	0.008	0.003	0.003

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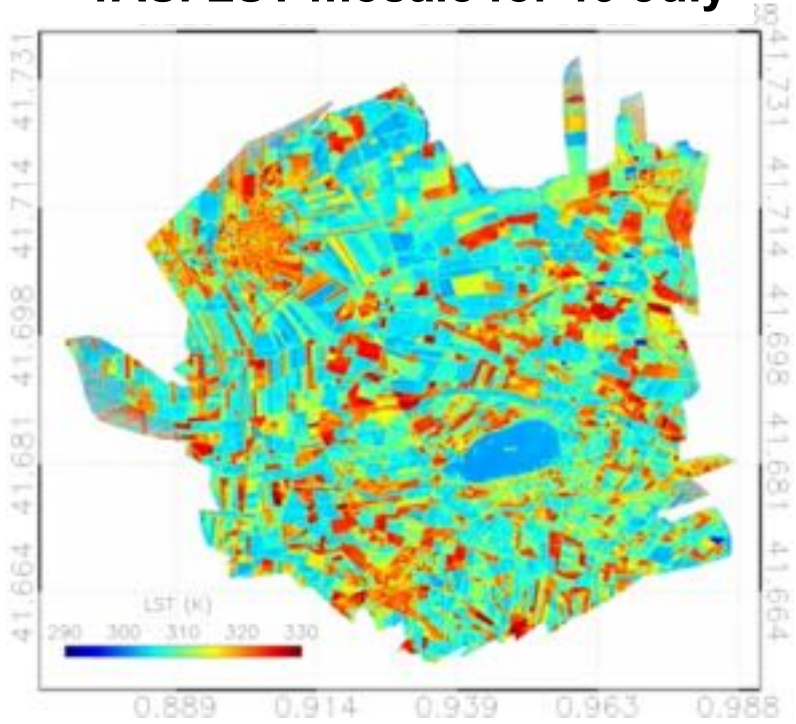
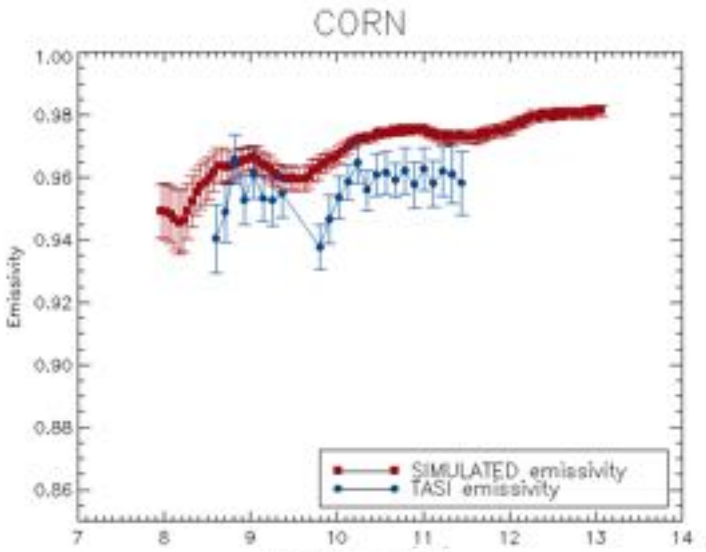
Synthetic Images

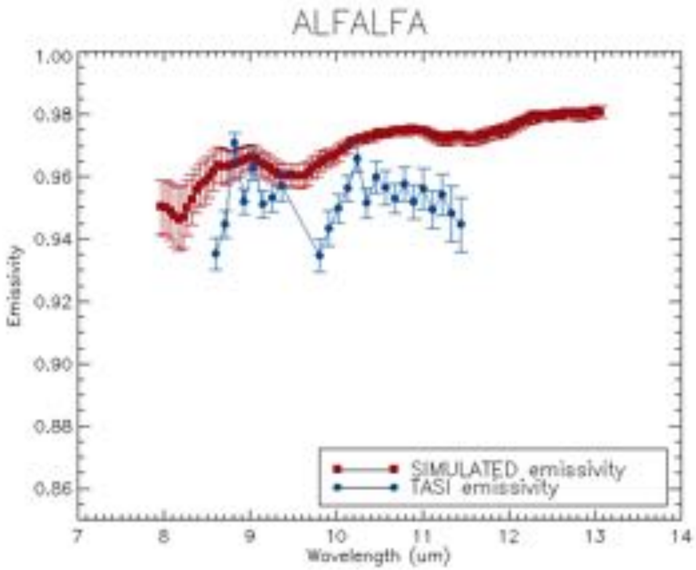
- From TASI level 2 images (LST and LSE), synthetic images are generated.
- ECOSTRESS library used to create LSE data from 8-13 μm as TASI can not provide values above 11.5 μm.
- TASI emissivities compared to most similar ECOSTRESS samples for Simulated LSE retrieval.

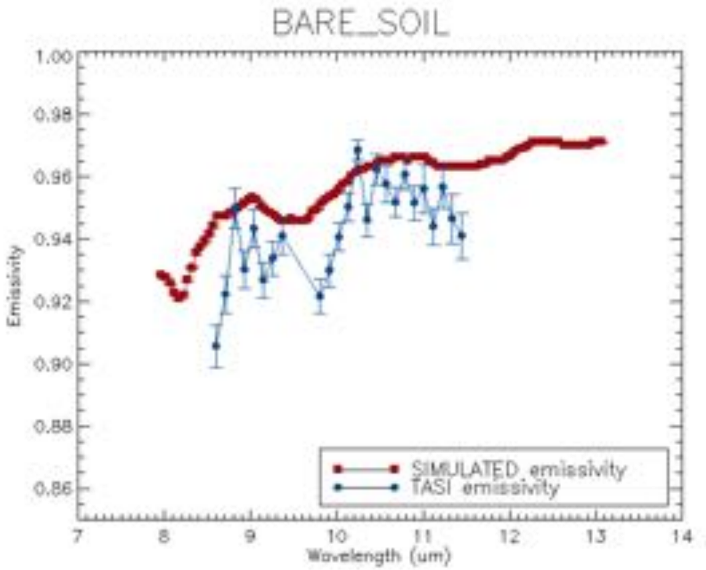
TASI LST mosaic for 19 July



Simulated LSE data for Corn, Alfalfa and bare soil







Synthetic Images

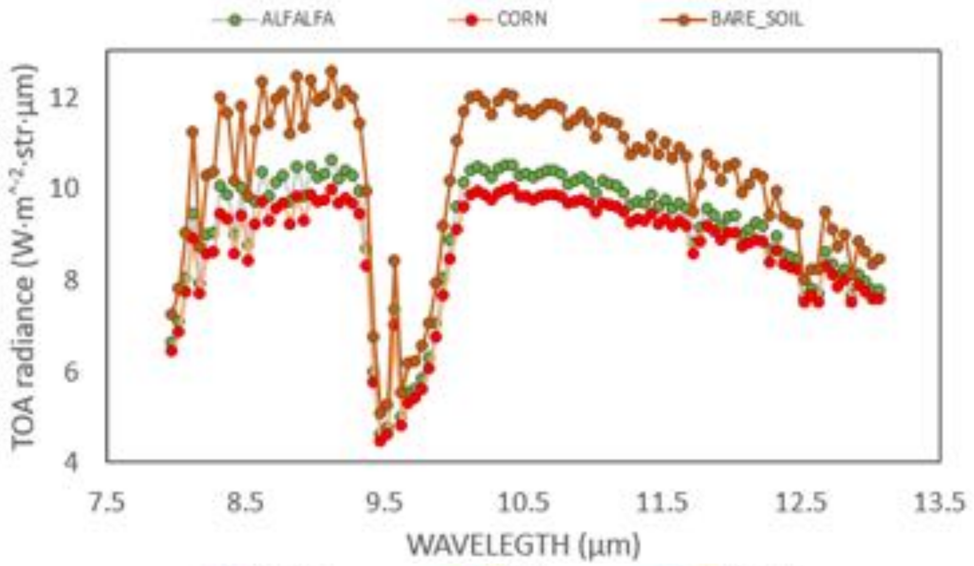
- TASI LST images + Simulated emissivity + Atmospheric parameters
  - Transmissivity, upward and downward radiance retrieved from ECMWF profiles ingested to MODTRAN

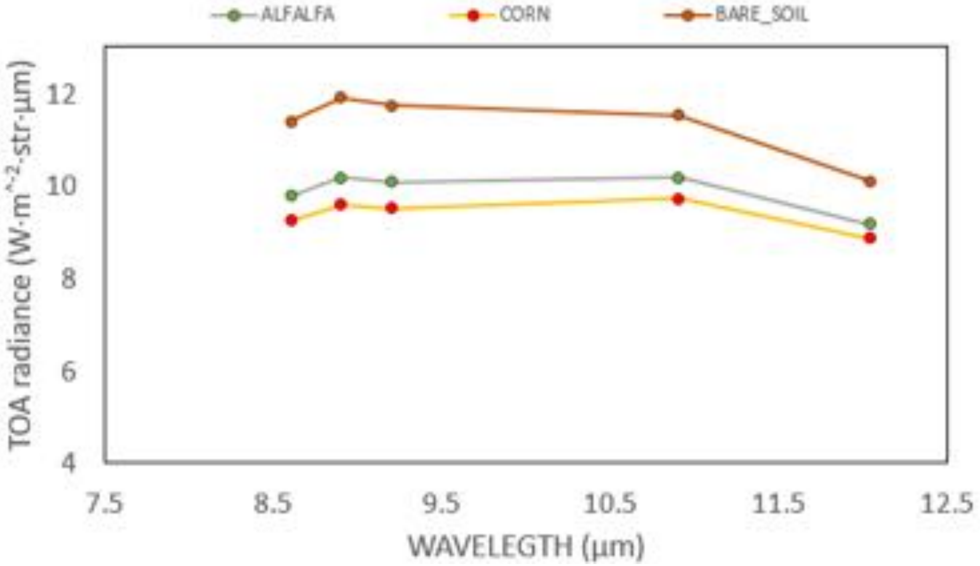
- Creation of TOA radiances by the application of inverse RTE and Planck's law
  - Spectral resolution of 0.02 μm

$$L_i^{at-sensor} = \left[\varepsilon_i B_i(Ts) + (1-\varepsilon_i) L_i^{\downarrow} \right] \tau_i + L_i^{\uparrow}$$

$$T_S = {c_2} \Big/ {\lambda \ln\left[\frac{c_1}{\lambda^5 B_i(T_S)} + 1\right]}$$

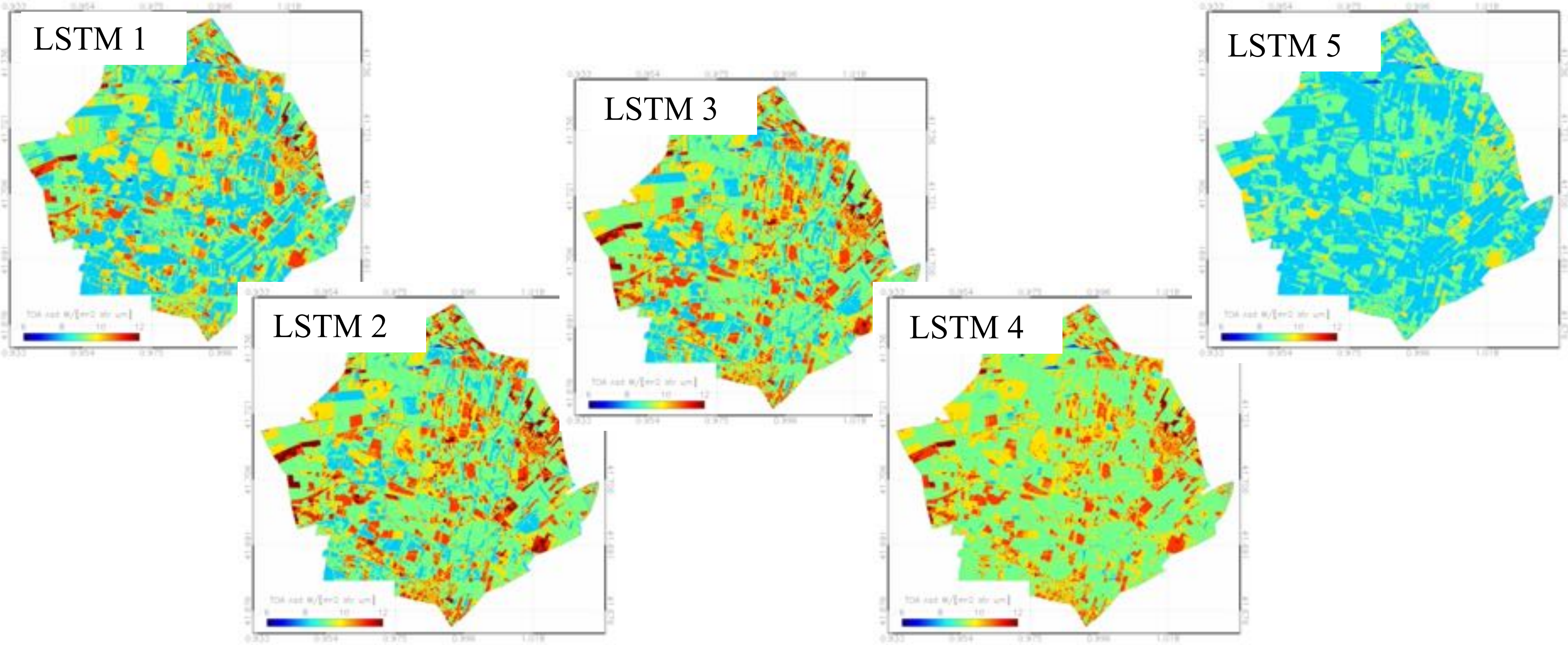
- Application of LSTM filter functions to TOA radiances





Synthetic Images

Example:LSTM synthetic images for the 5 TIRS channels retrieved from the LIAISE campaign on July 19



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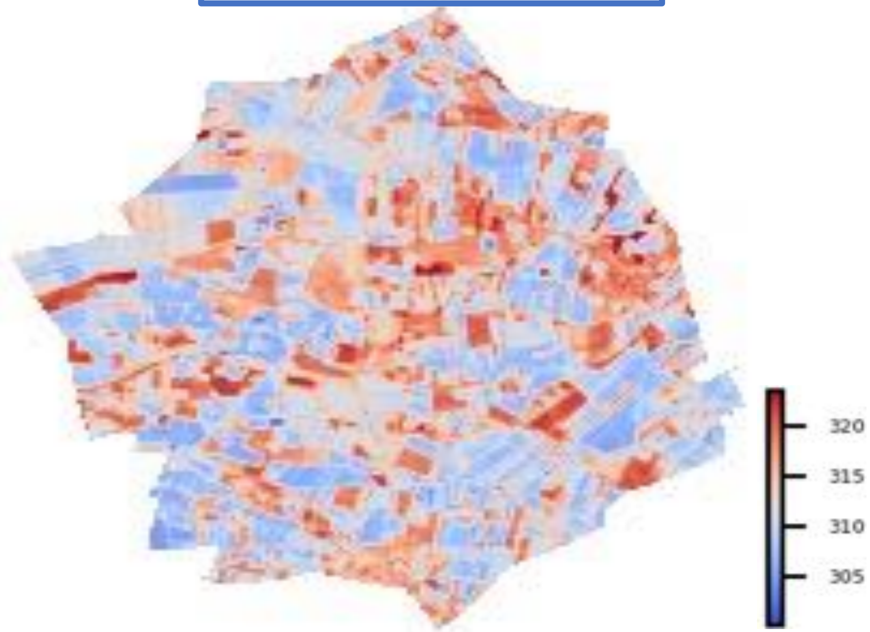
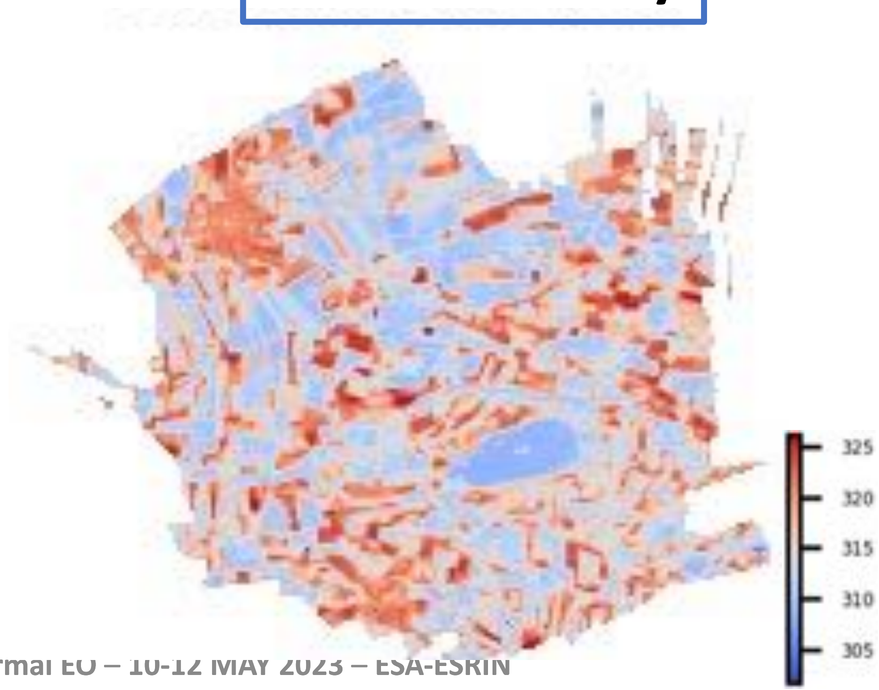
Algorithms validation

- TES algorithm applied to LSTM and TRISHNA validated againts the TASI LST retrieved by TES
  - **TASI LST images are our ground truth**
- LSE from TES algorithm validated against simulated emissivity images.
  - **Simulated LSE images are our ground truth**
- Validation of SW algorithms applied to LSTM and TRISHNA with inputs of simulated LSE images
- Validation of SW algorithms applied to LSTM and TRISHNA with inputs of TES LSE images
  - **TASI LST images are our ground truth**

TASI LST 17 July



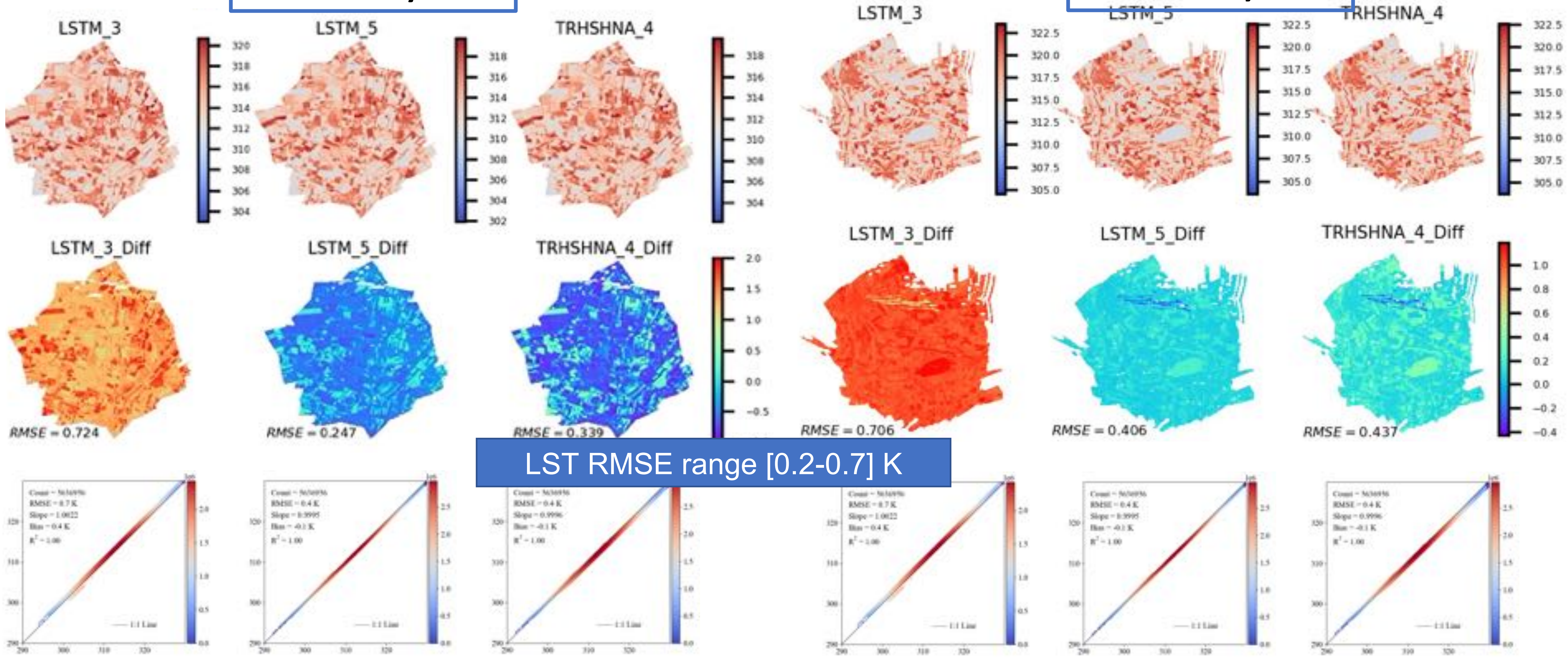
TASI LST 19 July



TES Validation of Synthetic images for LST

17 July

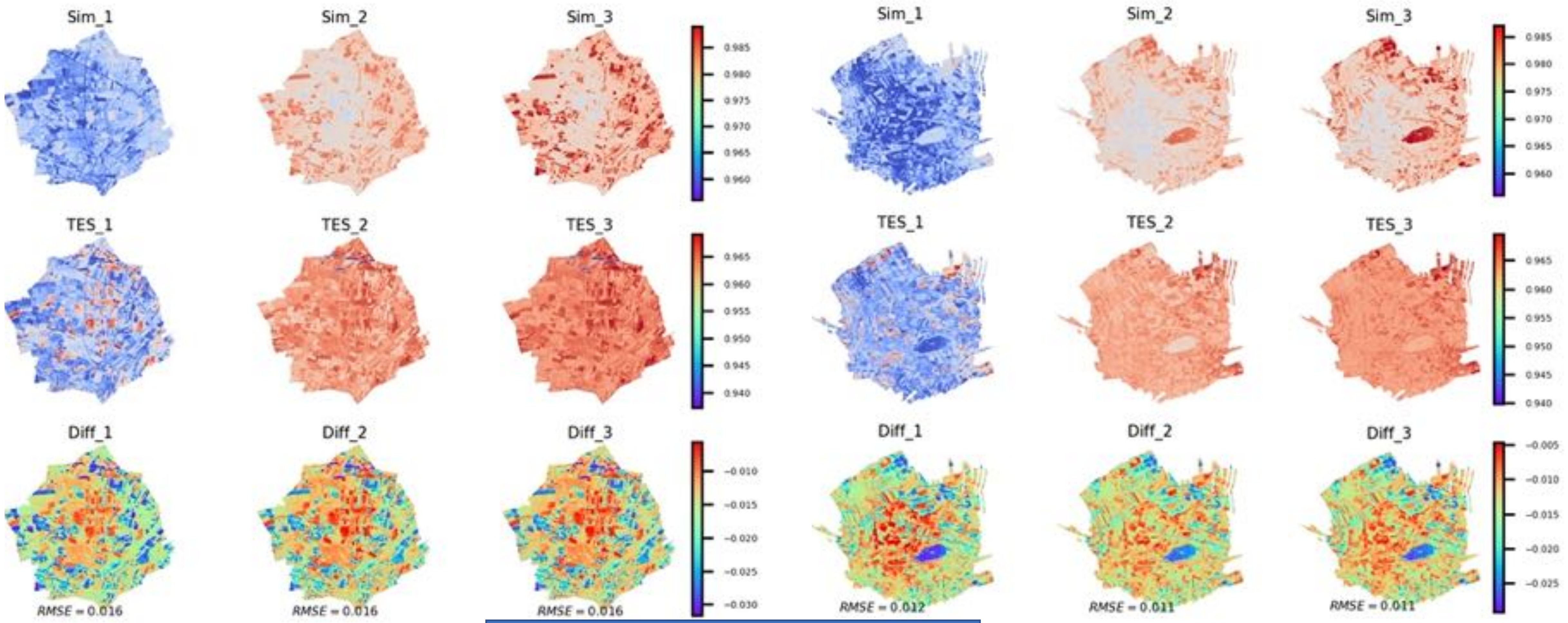
19 July



LST RMSE range [0.2-0.7] K

TES Validation of Synthetic images for LSE LSTM 3 bands

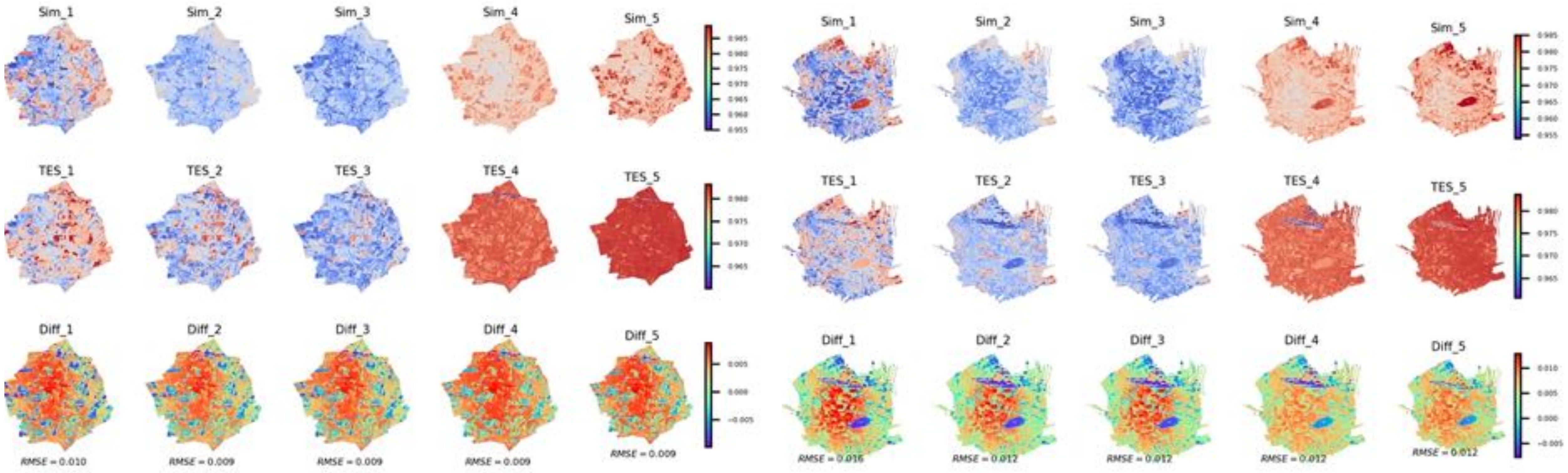
17 July | **19 July**



LSE RMSE range [0.011-0.016]

TES Validation of Synthetic images for LSE LSTM 5 bands

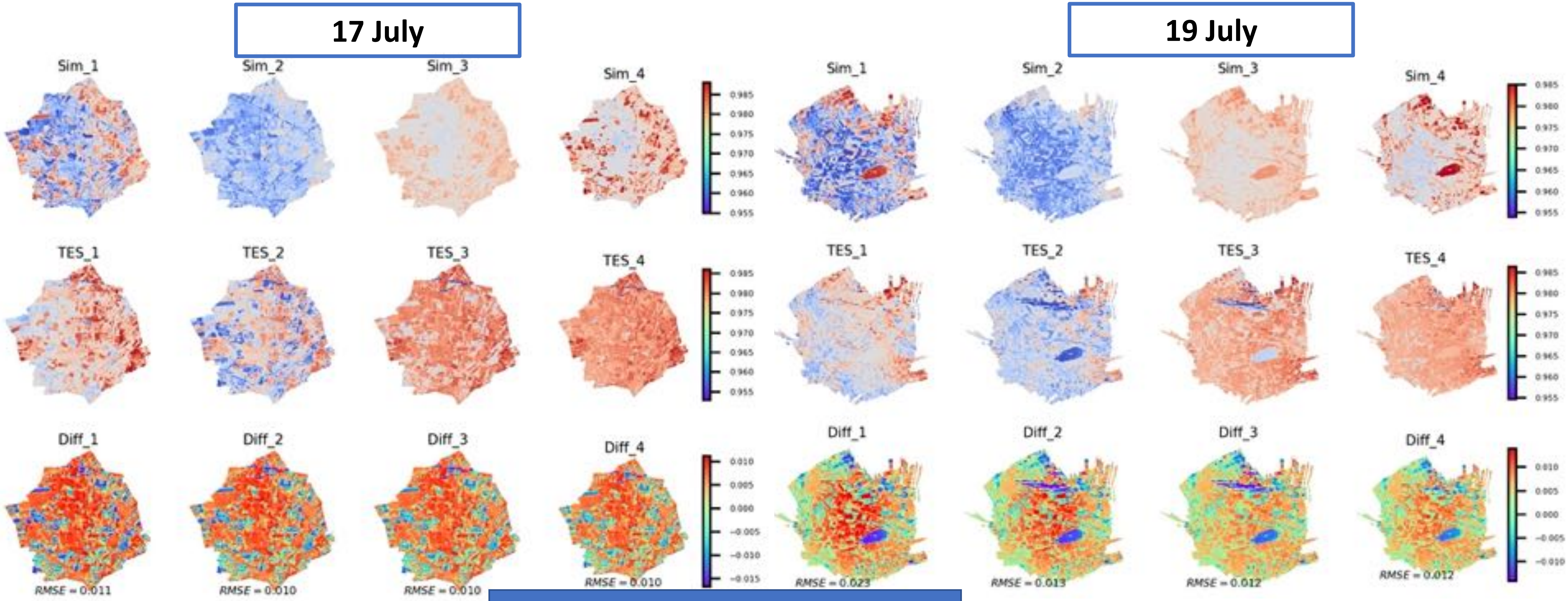
17 July | **19 July**



LSE RMSE range [0.009-0.012]

- Slightly better results than for the 3-band configuration

TES Validation of Synthetic images for LSE TRISHNA 4 bands



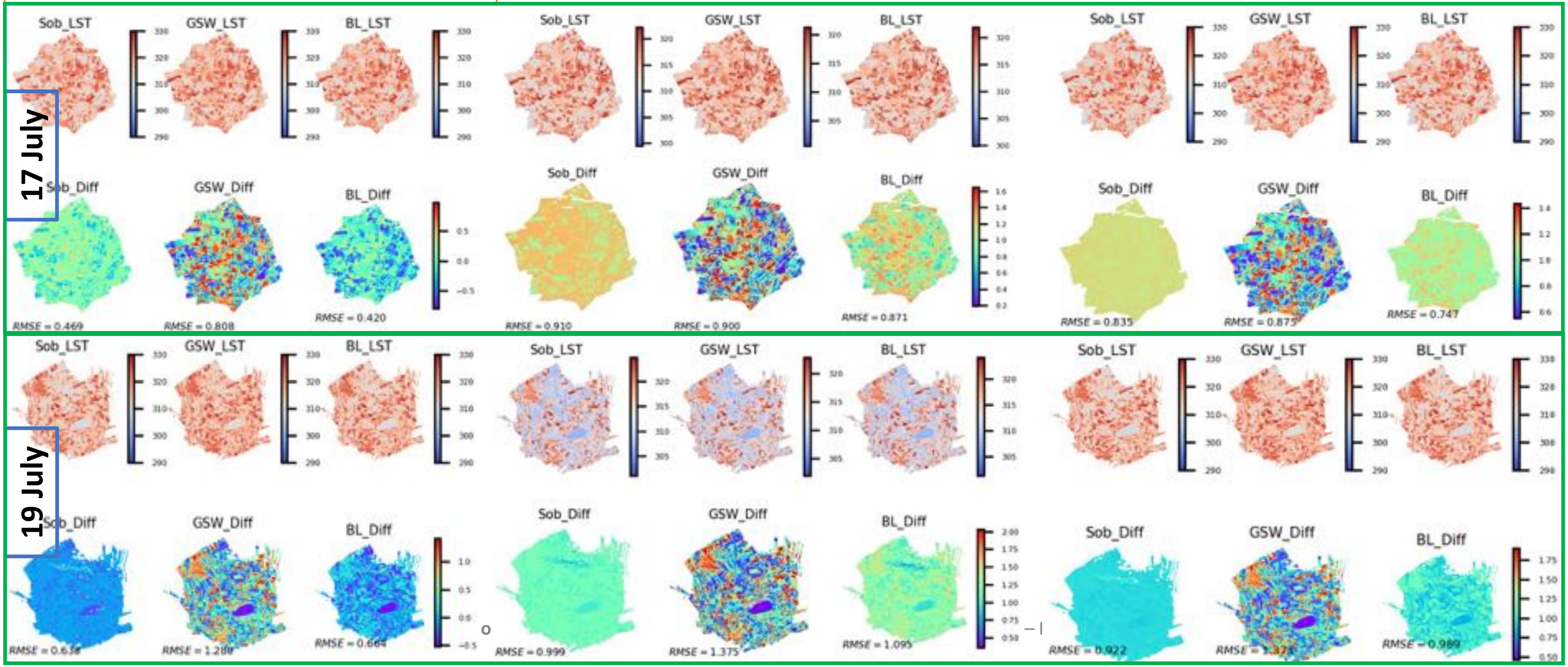
LSE RMSE range [0.010-0.023]

- TRISHNA TIRS 1 (8.6 μm) show the highest RMSE (0.023)
- In general, bands from 10 μm to 12 μm show better results in LSTM 5 and TRISHNA configurations than in LSTM 3 bands.

SW Validation of Synthetic LSTM images

- Validations of SW against the ground truth image for LSTM sensor range [0.7, 1.4] K
- Minimal variations (below 0.1 K) when LSE is ingested from TES algorithm results.

LSE from simulated LSTM data or ground truth	LSE from TES LSTM 3 channels	LSE from TES LSTM 5 channels

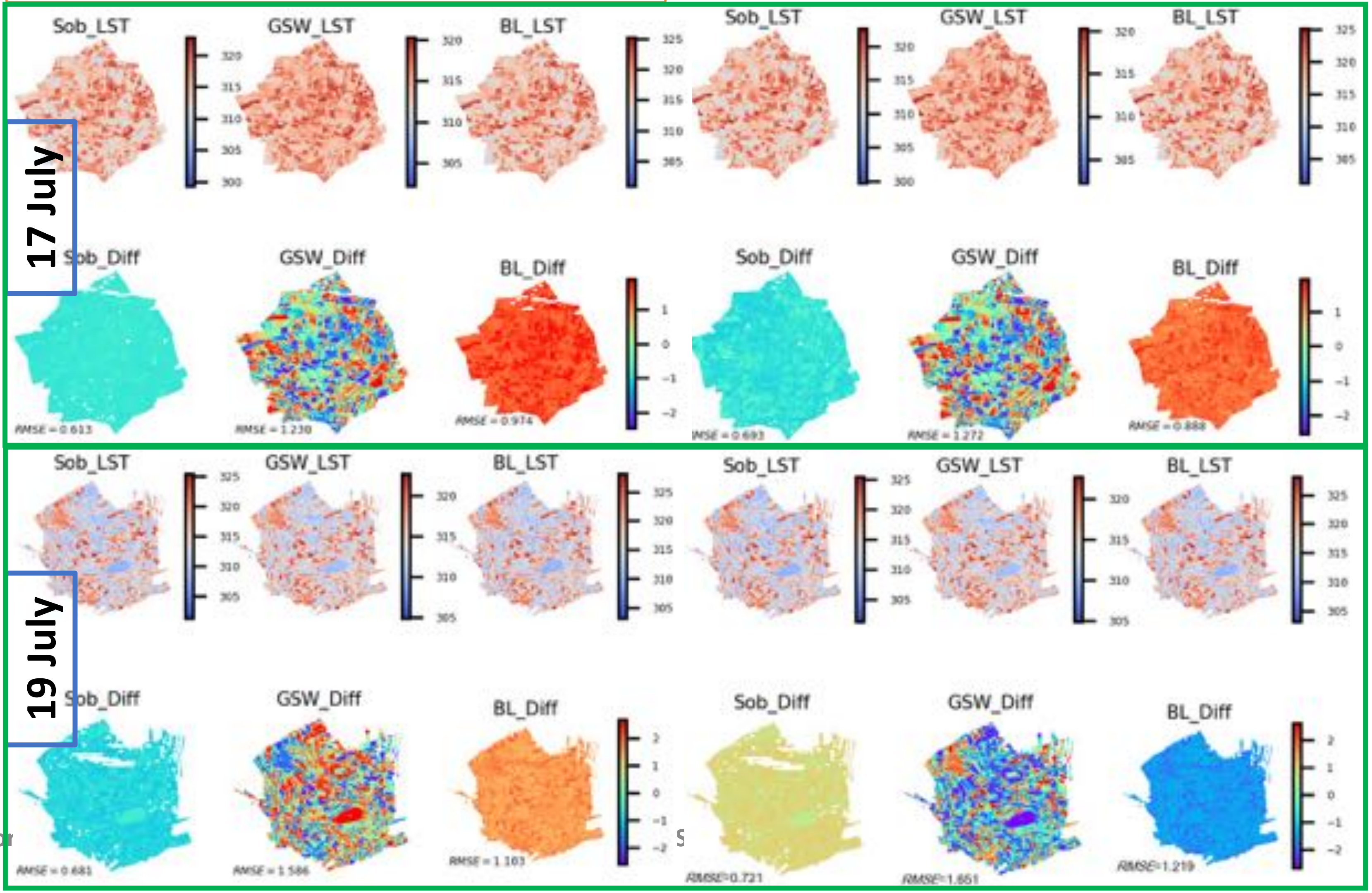


SW Validation of Synthetic TRISHNA images

- Minimal variations (below 0.1 K) when LSE is ingested from TES algorithm results.

LSE from simulated TRISHNA data or ground truth

LSE from TES TRISHNA channels



SW validation summary

- results for day 17 and 19 July

	TRISHNA			TRISHNA TES input			LSTM			LSTM 3 TES input			LSTM 5 TES input		
SW	SOB	GSW	BL	SOB	GSW	BL	SOB	GSW	BL	SOB	GSW	BL	SOB	GSW	BL
Bias (K)	-0.4	-0.2	-0.7	-0.3	-0.2	0.7	0.5	0.6	0.6	0.7	0.7	0.6	0.3	0.3	0.4
RMSE (K)	0.7	1.4	1.1	0.7	1.4	1.0	0.8	1.0	0.7	0.8	1.1	0.8	0.7	1.1	0.7

- In general, similar performance for LSTM and TRISHNA synthetic images
- SOB SW shows similar results for LSTM and TRISHNA
- higher RMSE for GSW in all cases

SW validation summary

- results for day 17 and 19 July

	TRISHNA			TRISHNA TES input			LSTM			LSTM 3 TES input			LSTM 5 TES input		
SW	SOB	GSW	BL	SOB	GSW	BL	SOB	GSW	BL	SOB	GSW	BL	SOB	GSW	BL
Bias (K)	-0.4	-0.2	-0.7	-0.3	-0.2	0.7	0.5	0.6	0.6	0.7	0.7	0.6	0.3	0.3	0.4
RMSE (K)	0.7	1.4	1.1	0.7	1.4	1.0	0.8	1.0	0.7	0.8	1.1	0.8	0.7	1.1	0.7

- In general, similar performance for LSTM and TRISHNA synthetic images
- SOB SW shows similar results for LSTM and TRISHNA
- higher RMSE for GSW in all cases
- No important differences when TES emissivity inputs are applied to SW instead of simulated emissivity values.

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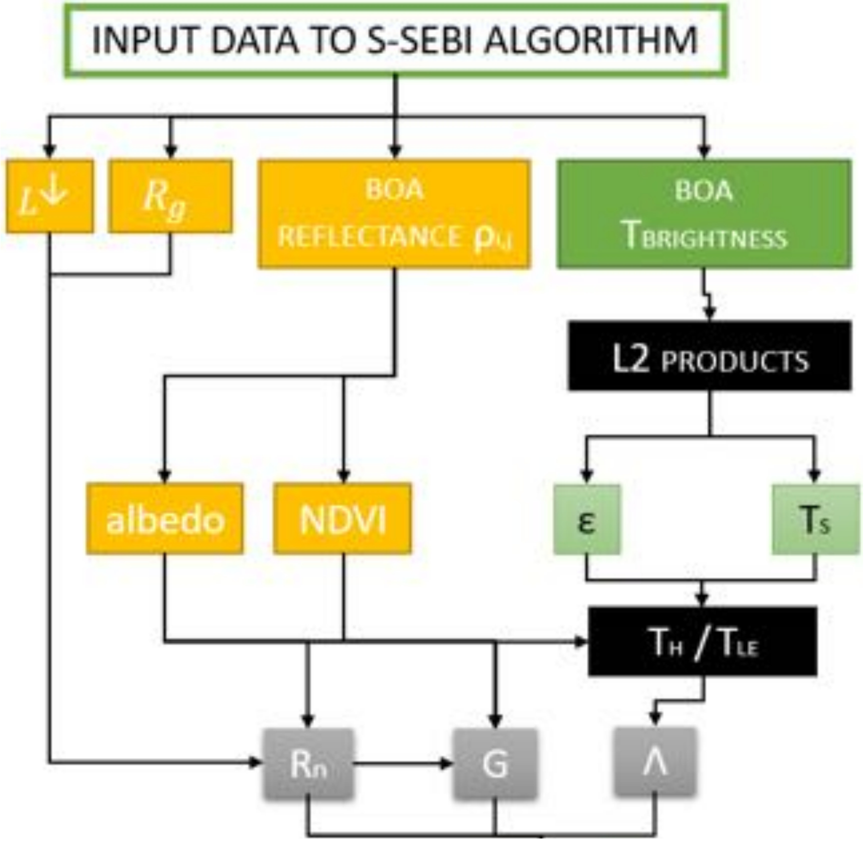
ALGORITHM: S-SEBI

SIMPLIFIED SURFACE ENERGY BALANCE INDEX (S-SEBI)



Sobrino et al, (2020)

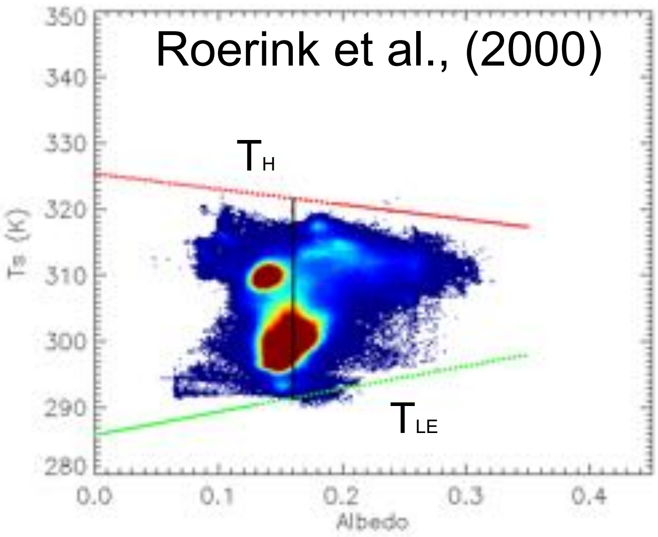
ENERGY BALANCE EQUATION

$$R_n = G + H + LE \rightarrow LE = \Lambda(R_n - G)$$

- Evaporative fraction

$$\Lambda = \frac{T_H - T_S}{T_H - T_{LE}}$$

T_H: Min LE temperature
T_{LE}: Max LE temperature



- Conversion to daily values

$$LE_d = 24 \times 3600 \frac{\Lambda R_n C_{di}}{\lambda}$$

- G_d=0 (Seguin and Itier, 1983)
- Λ constant (Farah et al., 2004).

S-SEBI input data

CASI BANDS (1.6 m)

Band number	Wavelength (nm)
26	560.16
41	667.12
42	674.25
47	709.90
53	752.68
57	781.20
66	845.36

ALBEDO (α) ALGORTIHM

$$\alpha = 0.174969b_{26} - 0.146507b_{42} + 0.781783b_{47} - 0.510578b_{53} + 0.529190b_{57} + 0.016090$$

SOLAR RADIATION (Rg)

Retrieved from ECMWF

EMISSIVITY (ε)

$$\bar{\varepsilon} = \frac{\sum_{i=1}^{n} \varepsilon_i}{n}$$

LAND SURACE TEMPERATURE (LST)

RETRIEVED BY TES ALGORITHM

Spatial resampling of LST, LSE and albedo at sensor theoretical nadir spatial resolution

ET RESULTS PROVIDED FOR:

TASI 24 channels
spatial resolution 4 m

LSTM (3 & 5 channels configuration)
spatial resolution 40 m

TRISHNA 4 channels
spatial resolution 60 m

Instantaneous ET: TASI and Synthetic LSTM and TRISHNA images

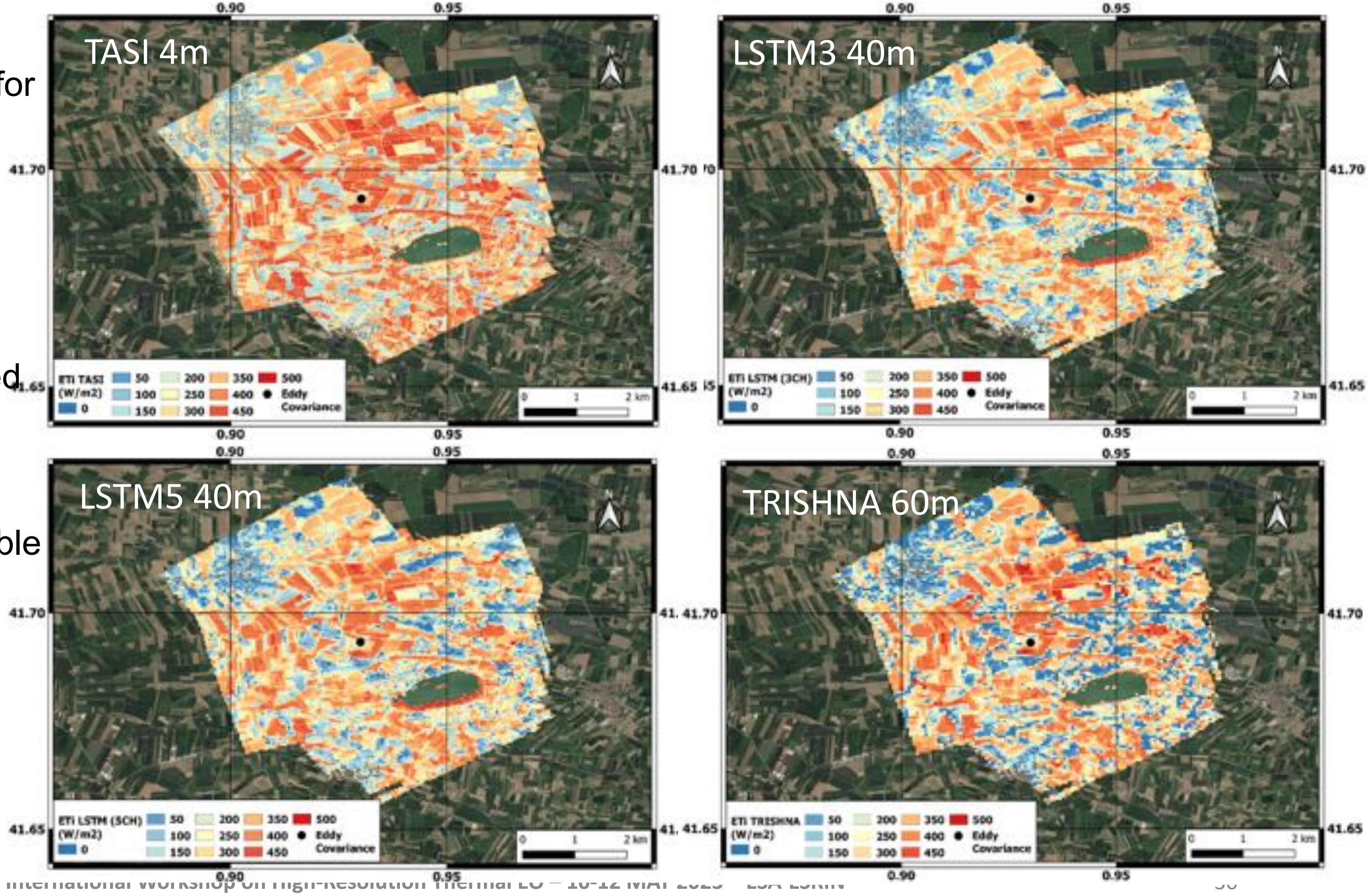
Instantaneous ET estimated for days:

- 19/07/2021
- 22/07/2021
- 24/07/2021
- 29/07/2021

Validation of results performed against Eddy Covariance on 41.693228N, 0.930067E

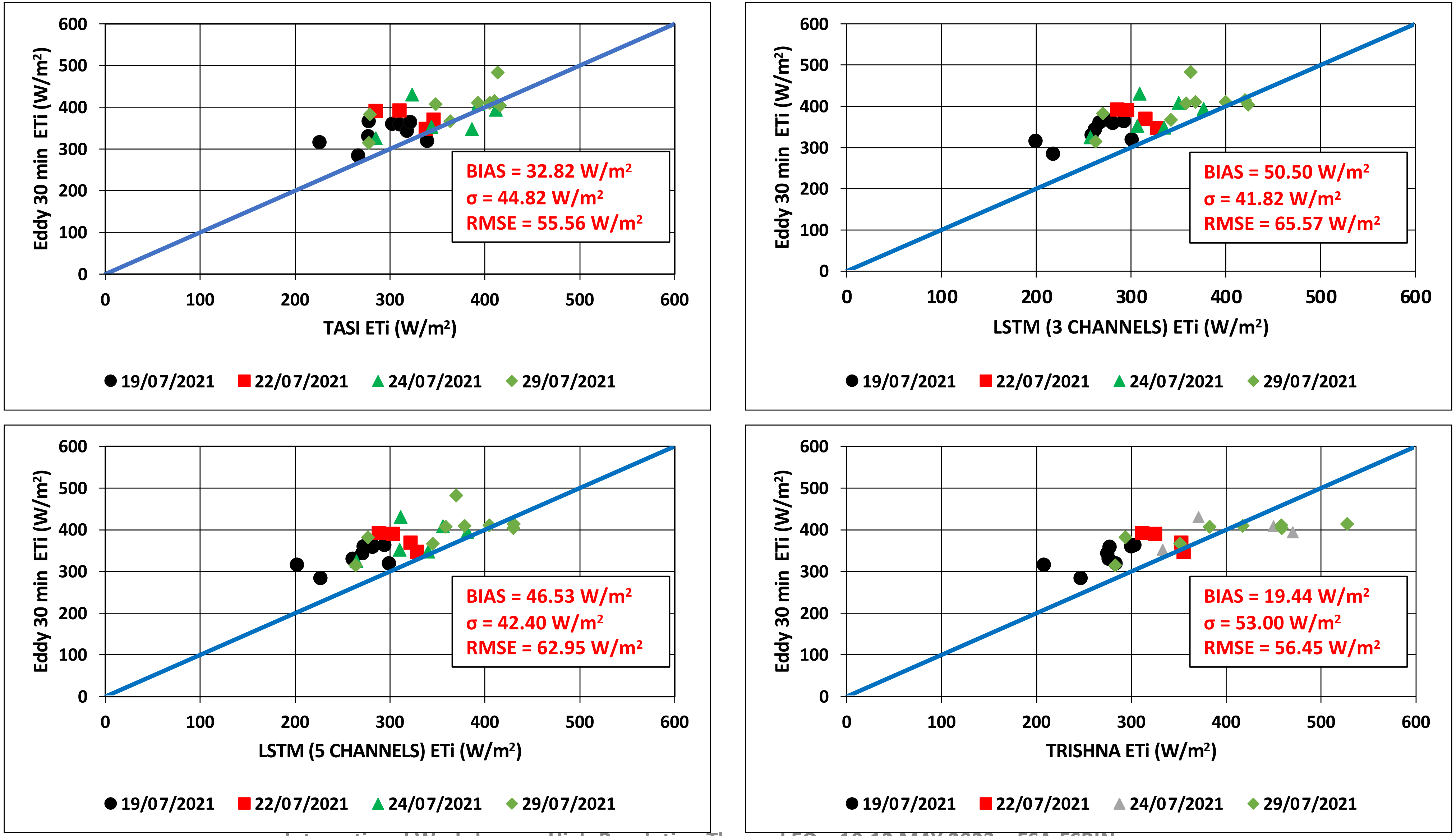
Eddy Covariance data available every:

- 10 min
- 30 min



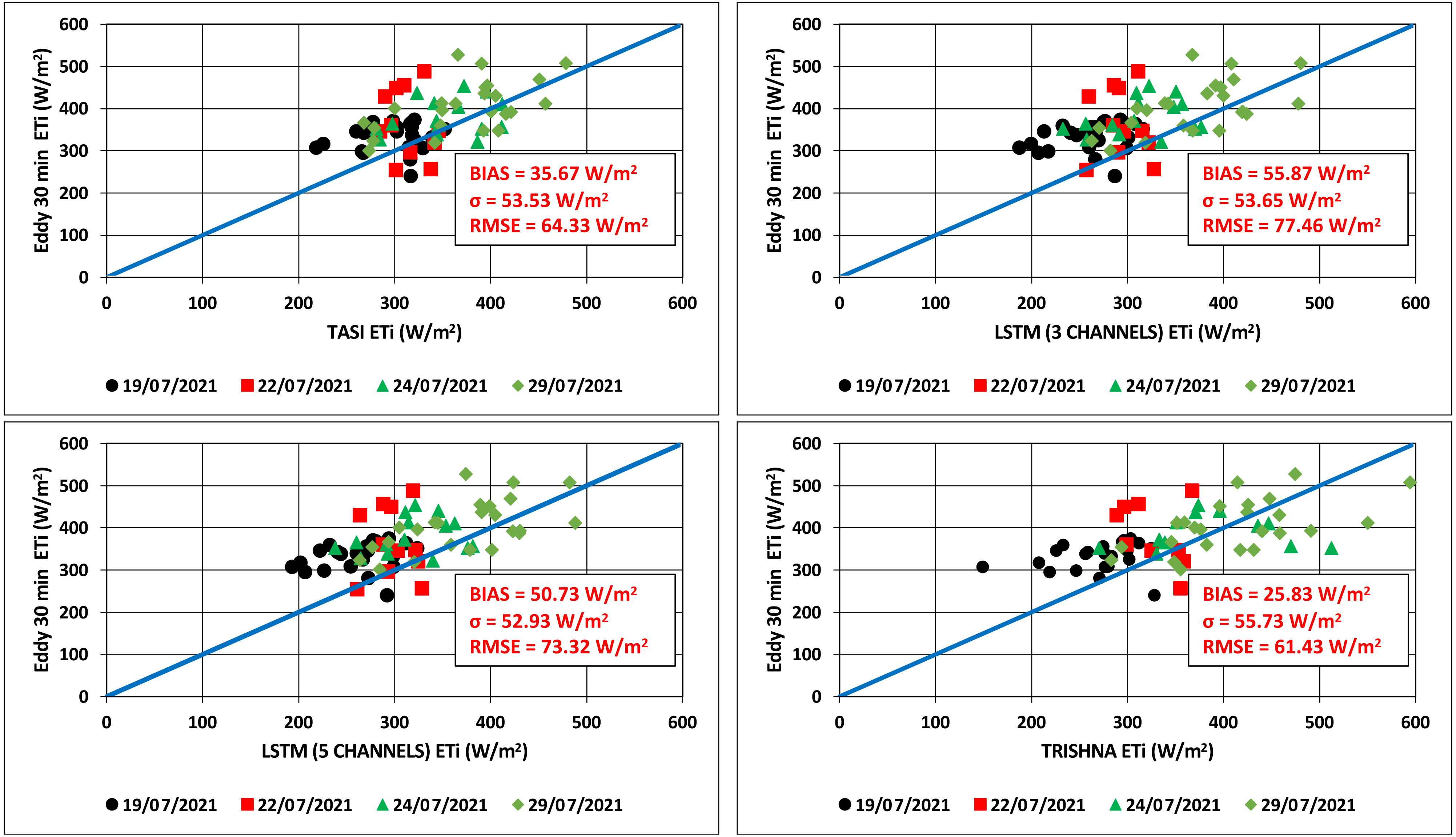
Instantaneous ET

SCATTER PLOTS (EDDY 30 min; N = 27)



RESULTS: Instantaneous ET

SCATTER PLOTS (EDDY 10 min; N = 71)



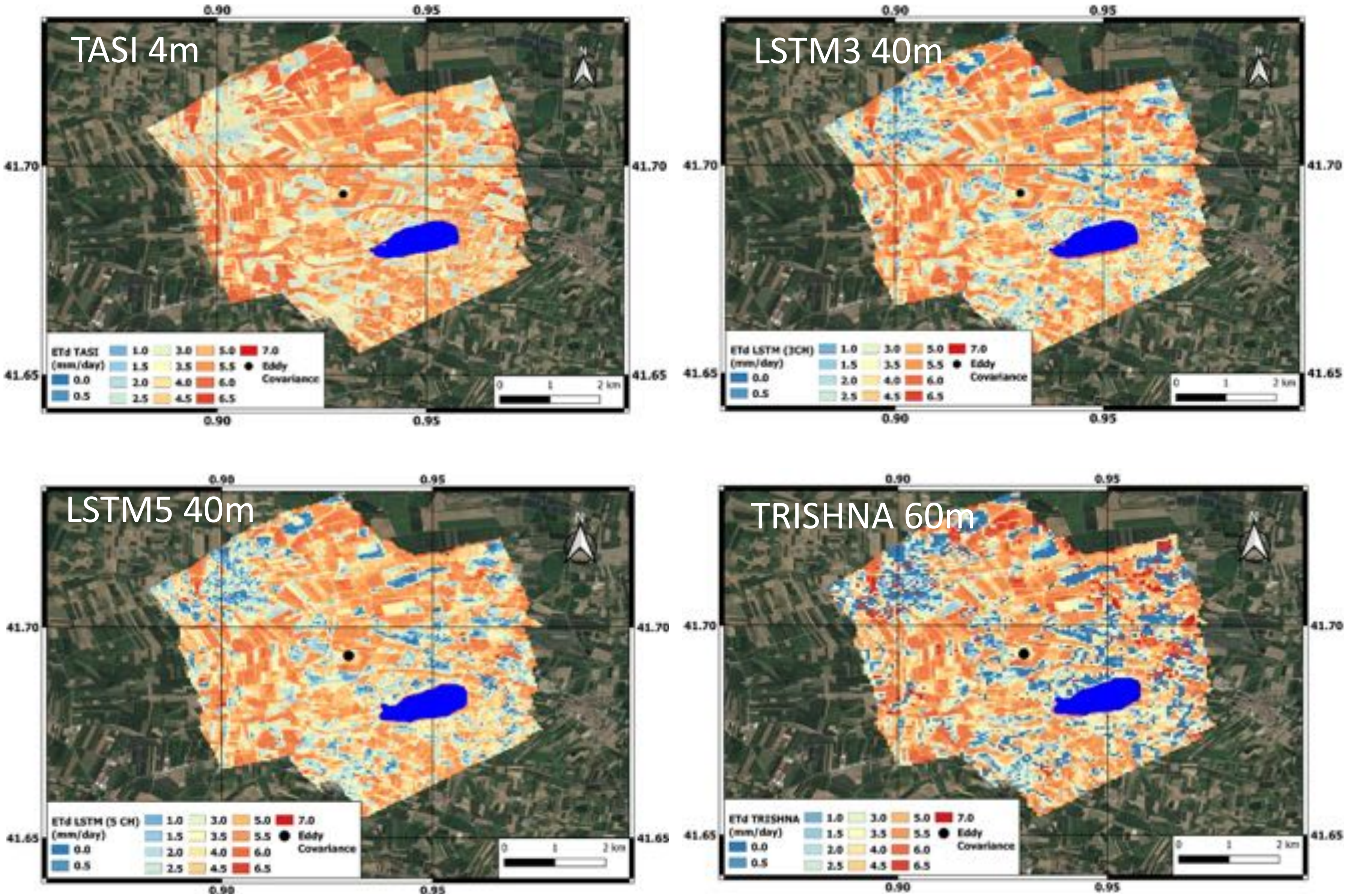
Daily ET

Daily ET estimated for days:

- 19/07/2021
- 22/07/2021
- 24/07/2021
- 29/07/2021

Validation of results performed against Eddy Covariance on 41.693228N, 0.930067E

Eddy Covariance data converted to daily values (mm/day)



Daily ET

- All flights data from 10:30 to 14:30 UTC have been considered for conversion to daily ET values.
  - Standard deviation for average value is included in the table with typical values from 0.2-0.6 mm/day.

- Average value was used for comparison against Eddy Covariance daily ET.

- Validation results show RMSE below 0.4 mm/day

Eddy minus S-SEBI	Differences between Eddy covariance ETd (mm/day) and TASI, LSTM (3 channels, LSTM 5 channels and TRISHNA synthetic images				
	TASI	**LSTM (3 CHANNELS)**	**LSTM (5 CHANNELS)**	**TRISHNA**	**Eddy ETd**
19/07/2021	-0.56 ± 0.20	-0.17 ± 0.27	-0.07 ± 0.28	-0.11 ± 0.41	4.26
22/07/2021	-0.20 ± 0.24	-0.07 ± 0.41	0.20 ± 0.61	-0.32 ± 0.34	5.17
24/07/2021	-0.05 ± 0.29	0.43 ± 0.27	0.54 ± 0.28	-0.36 ± 0.49	5.36
29/07/2021	0.06 ± 0.25	0.01 ± 0.30	0.13 ± 0.30	-0.49 ± 0.58	5.45
BIAS	-0.19	0.05	0.20	-0.32	
σ	0.27	0.26	0.25	0.16	
RMSE	0.33	0.27	0.32	0.36	

CONCLUSIONS

- Different SW algorithms and εmin-MMD relation was estimated for LSTM & TRISHNA filters and were proposed for both missions.

- Synthetic LSTM and TRISHNA images of LST were retrieved using validated TASI data, ECOSTRESS emissivity spectrums and ECMWF atmospheric profiles.

- TES LST validation has shown good results for all sensors and configurations (below 1 K). When more channels are introduced in TES algorithm, better results are achieved.
  - ✓ Emissivity values show minimum differences of 0.01 independently of channels and sensor considered.

- SW validation shows, in general, uncertainties higher than TES algorithm and not important differences when LSE input comes from TES algorithm instead of simulated LSE data.

- S-SEBI algorithm validation has shown results between 55-75 W/m^2 with not significant improvement when different sensor or algorithm is considered.

- Conversion to daily ET values provide good agreement against in situ data, been RMSE values lower than 0.4 mm/day.