11th Advanced Training Course on Land RS

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Thermal Infrared Remote Sensing of Land Surface Temperature

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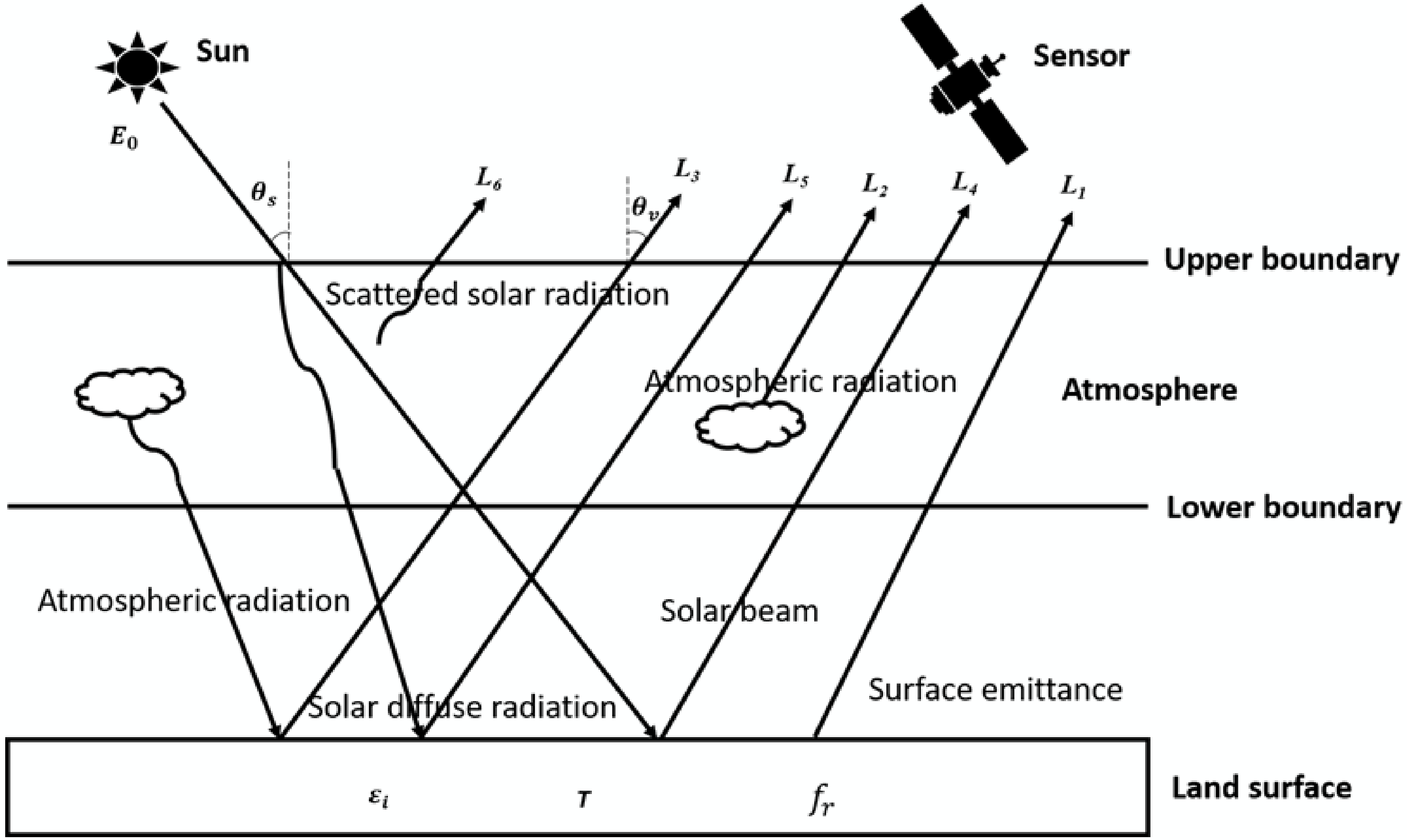
22/11/2022

Contents

1. Thermal Infrared Radiative Transfer Process



1) surface thermal emittance L1

$$L_1 = \tau_v(\lambda,\mu)\varepsilon(\lambda,\mu)B(\lambda,T)$$

2) thermal path radiance L2

3) reflected atmospheric downwelling radiance by the surface L3

$$L_3 = \tau_v(\lambda,\mu)\int_0^{2\pi}\int_0^1 \mu' f_r(\mu;\mu',\varphi')\, L_t^{\downarrow}(\lambda,-\mu',\varphi')d\mu' d\varphi'$$

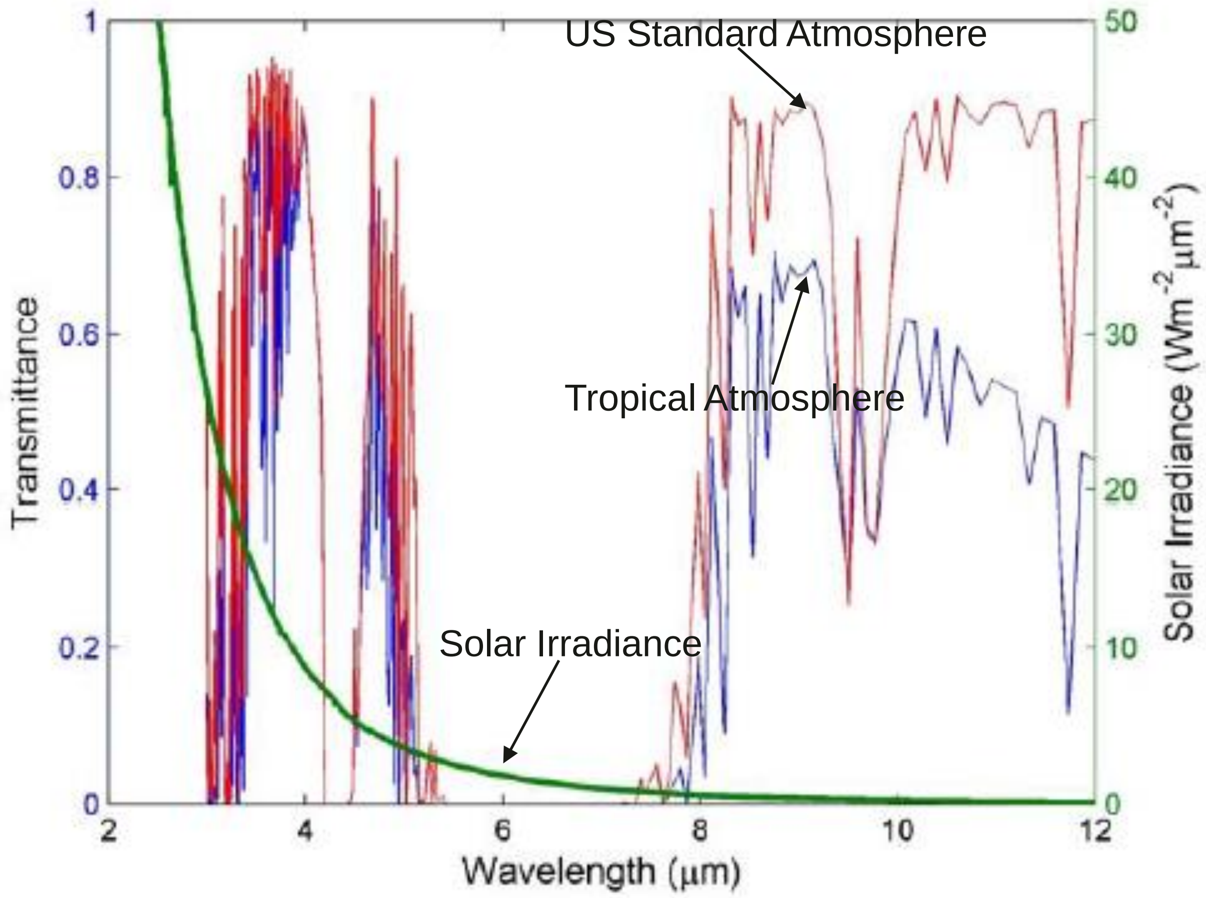
~~4)~~ reflected solar beam by the surface L4

~~5)~~ reflected solar diffuse radiation by the surface L5

~~6)~~ path radiance resulting from scattering of solar radiation L6.

$$L_\lambda = \tau_\lambda\left(\varepsilon_\lambda B(T,\lambda) + (1-\varepsilon_\lambda)L_a^{\downarrow}\right) + L_a^{\uparrow}$$

Atmospheric Attenuation



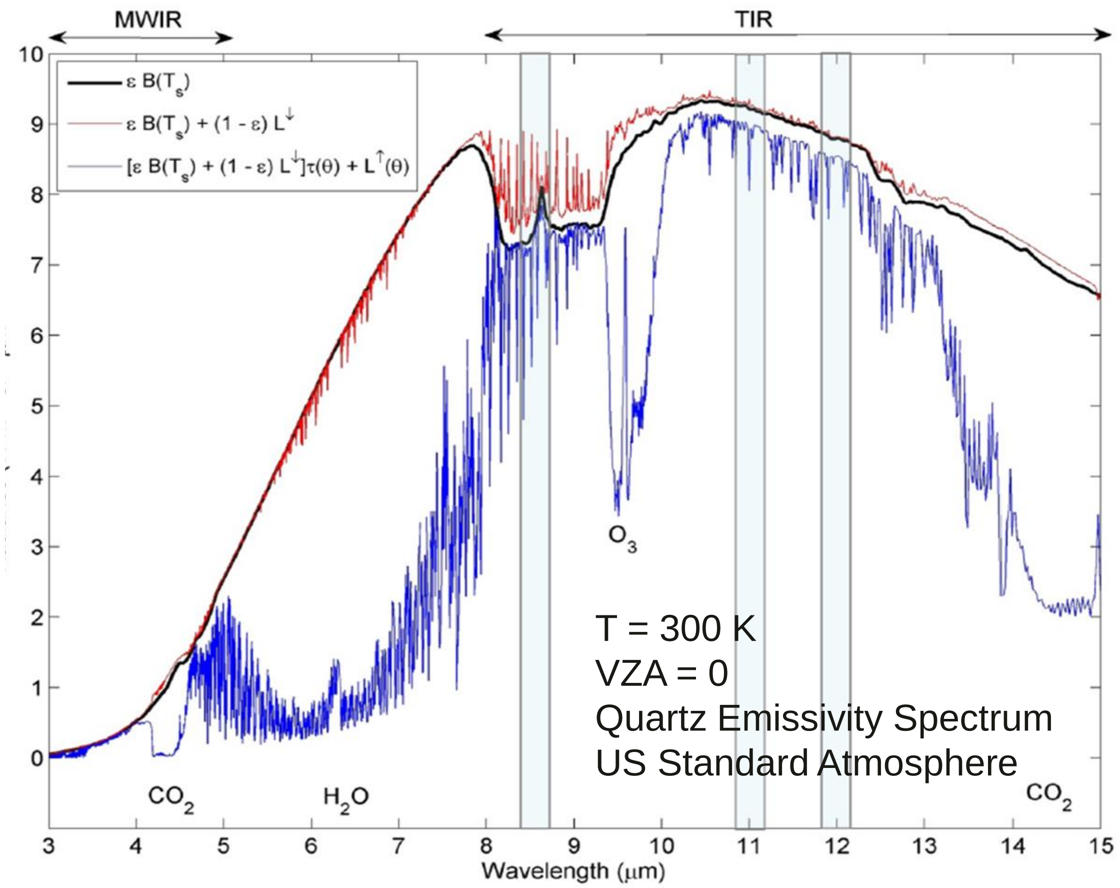


Figure Courtesy of Hulley et al. (2016, MxD21 ATBD C6)

Planck Function: Blackbody Spectral Emittance

$$B_\lambda = \frac{C_1}{\lambda^5 \left[\exp\left(\frac{C_2}{\lambda T} \right) - 1 \right]}$$

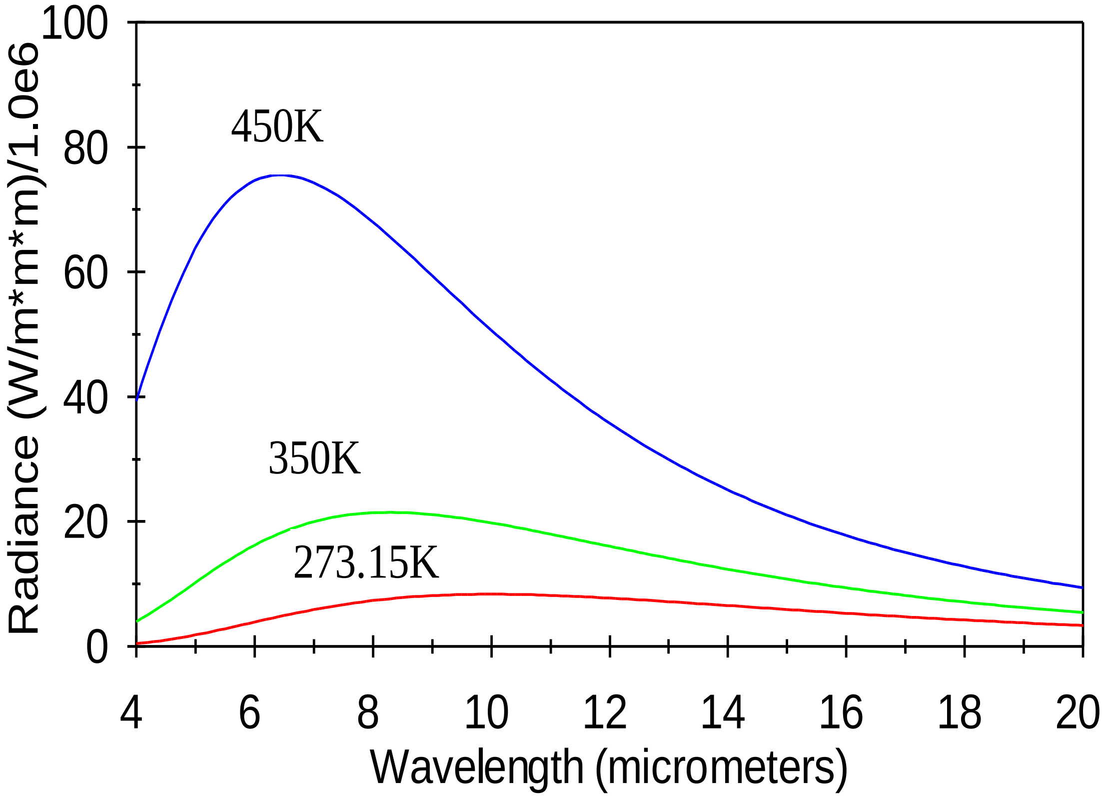
B_λ = Blackbody spectral emittance

λ = Wavelength

T = Temperature

C_1 = First radiation constant

C_2 = Second radiation constant



As surface temperature increases, the peak of surface-emitting radiance shifts to a shorter wavelength

Land Surface Temperature and Emissivity Definition

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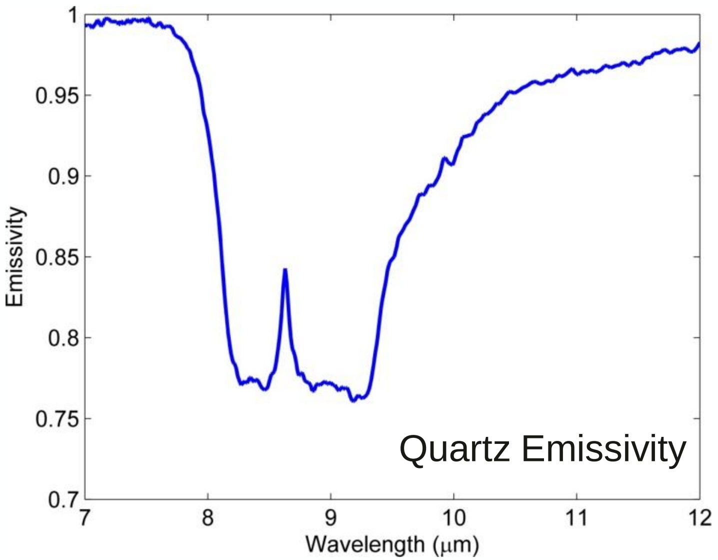
❑ Land Surface Temperature (LST, *Ts*)

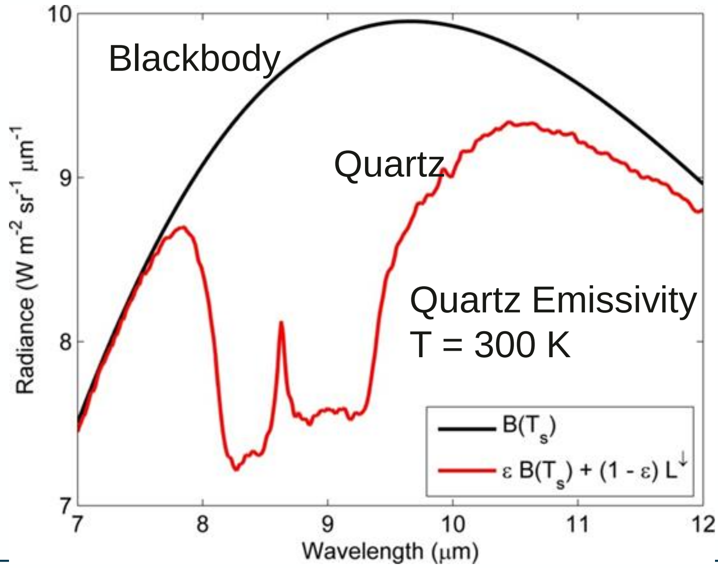
Land surface temperature is radiative temperature. It is the temperature of a layer of a medium of depth equal to the penetration depth of the electromagnetic radiation at the given wavelengths. LST is an approximation of thermodynamic and aerodynamic temperatures, but has a different conotation.



❑ Land Surface Emissivity (LSE, *ε*)

Materials are not perfect blackbodies, but instead emit radiation in accordance with their own characteristics. The ability of a material to emit radiation can be expressed as the ratio of the spectral radiance of a material to that of a blackbody at the same temperature. This ratio is termed spectral emissivity.

$$\varepsilon_\lambda = \frac{M(T,\lambda)}{M_B(T,\lambda)} \quad \Longrightarrow \quad M(T,\lambda) = \varepsilon_\lambda . M_B(T,\lambda)$$

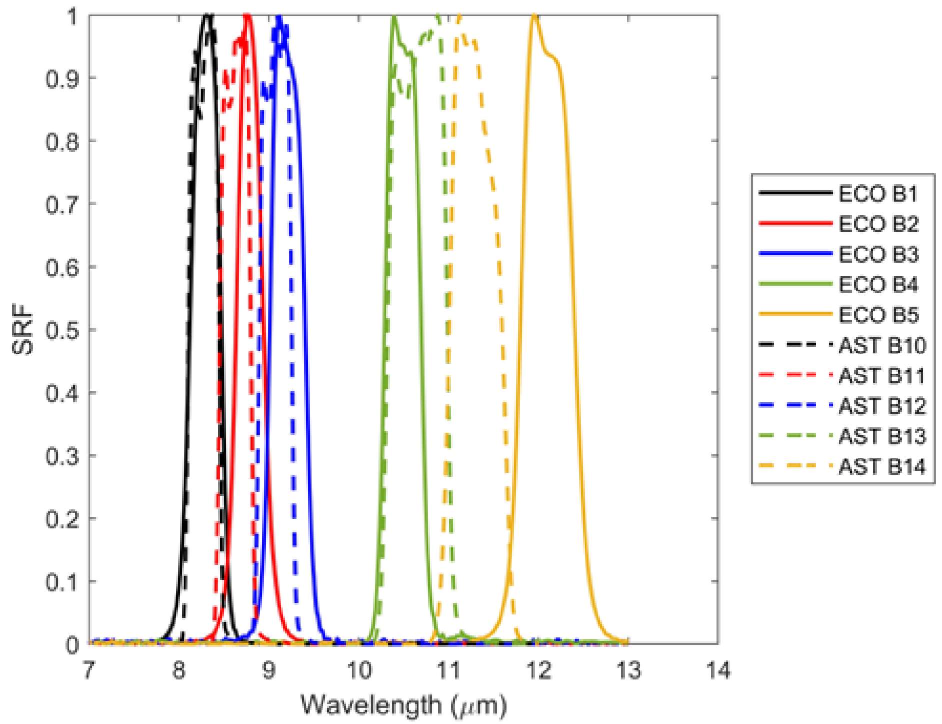


2. Land Surface Temperature Retrieval Algorithms

$$L_\lambda = \tau_\lambda\left(\varepsilon_\lambda B(T,\lambda) + (1-\varepsilon_\lambda)L_a{}^{\downarrow}\right) + L_a{}^{\uparrow}$$

⇓ Spectral Convolving using Spectral Response Function

$$L_i = \tau_i\left(\varepsilon_i B_i(T) + (1-\varepsilon_i)L_{a,i}{}^{\downarrow}\right) + L_{a,i}{}^{\uparrow}$$



- **Ill-posed inversion problem**
  N observations < N + 1 unknowns (N emissivities + 1 temperature)

- **Atmospheric correction**
  Challenging to estimate three atmospheric parameters in the thermal radiative transfer equation with high accuracy

Two Major Categories of LST Retrieval Algorithms

Various algorithms have been proposed to estimate LST for different sensors based on different assumptions and approximations for the radiative transfer equation (RTE) and LSE

1. If ε is known a priori, to retrieve Ts

- Single channel algorithm
- Split window algorithm
- Dual window algorithm
- Dual angle algorithm

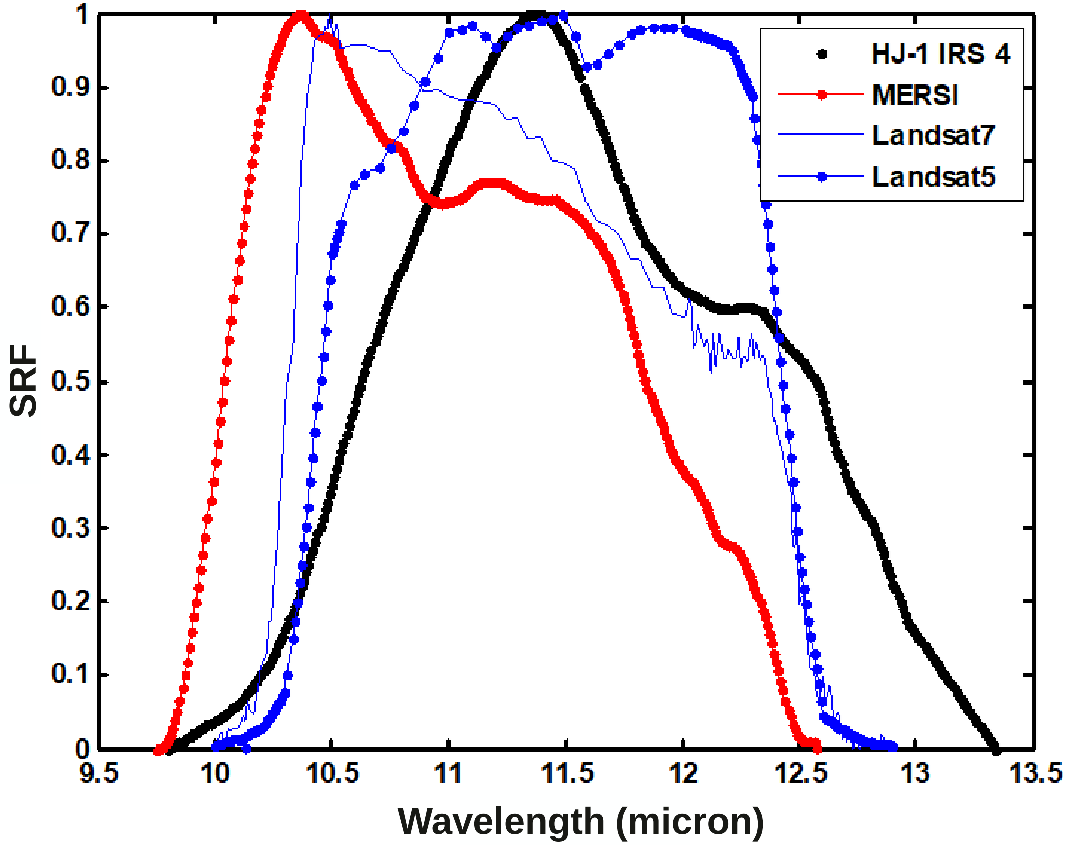
2. If ε is unknown, to retrieve both ε and Ts

- Simultaneous retrieval of ε and Ts with known atmospheric information
- Simultaneous retrieval of ε and Ts with unknown atmospheric information

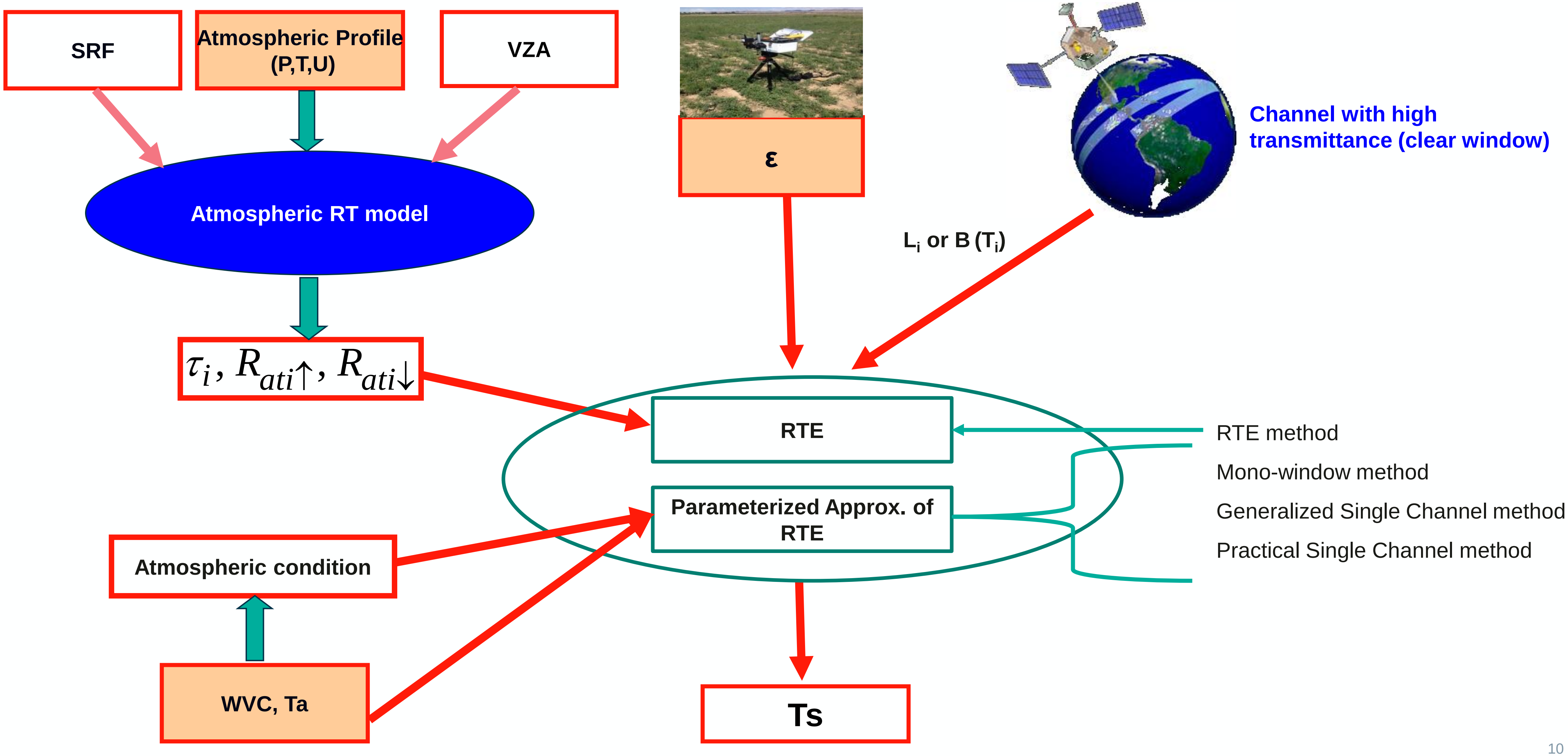
2.1 Single Channel Algorithm

Single-channel algorithm is used for satellite data with only one thermal channel, such as Landsat TM, ETM+, and HJ-1 IRS data.

Satellite	Thermal band Spatial resolution
Landsat TM	120m
Landsat ETM+	60m
CBERS IRMSS	96m
HJ-1B IRS	300m
FY-3 MERSI	250m



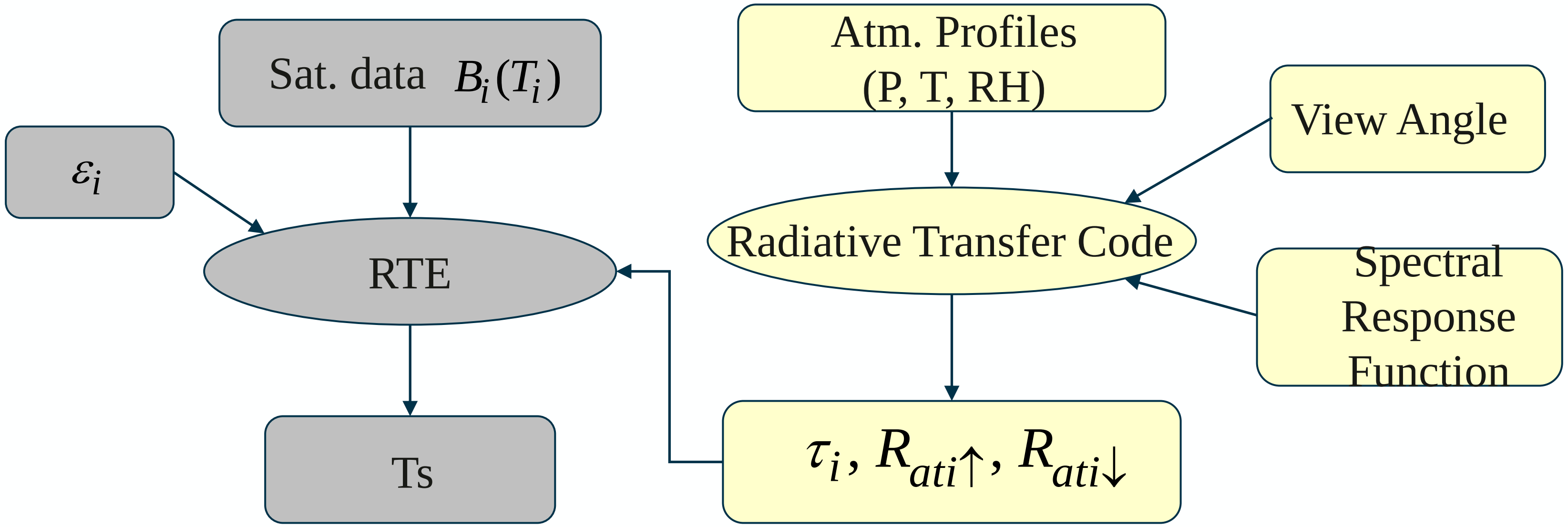
2.1 Single Channel Algorithm



2.1.1 RTE Method

- It takes the radiance measured by satellite in one TIR channel and corrects for residual atmospheric absorption and emission based on an atmospheric RT model that requires inputs of atmospheric profiles (P, T, RH)
- LST is derived by inverting the physical radiative transfer equation

$$T_{si} = B_i^{-1}\left(\frac{(B_i(T_i) - R_{at_i}\uparrow)/\tau_i - (1-\varepsilon_i)R_{at_i}\downarrow}{\varepsilon_i}\right)$$



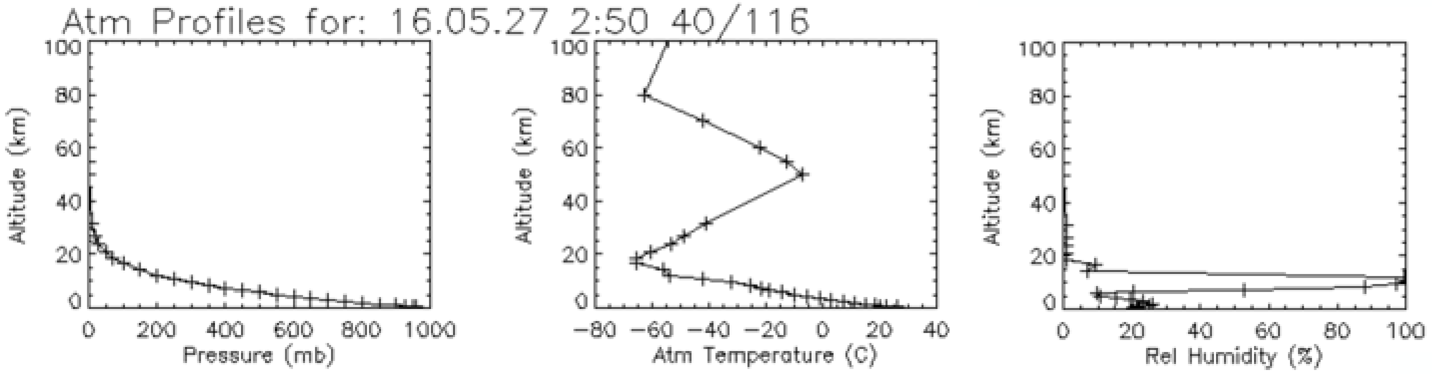
Atmospheric Parameter Estimation

❑ NASA Online Tool

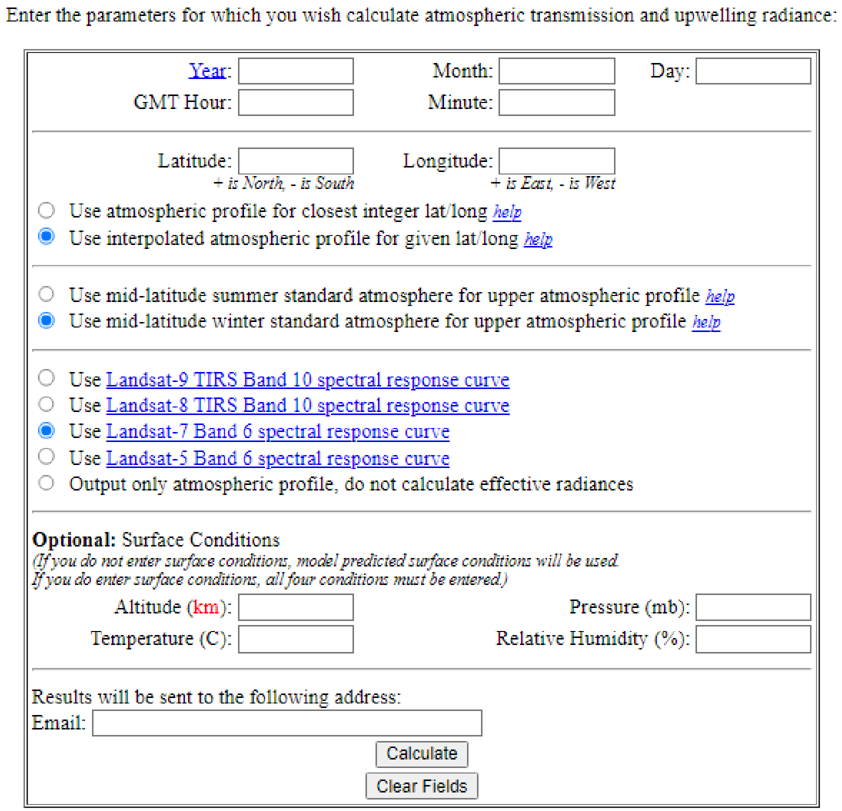
Atmospheric Correction Parameter Calculator (Barsi et al., 2003), https://atmcorr.gsfc.nasa.gov/

❑ MODTRAN + Atmospheric Profiles

- NOAA NCEP
- NASA MERRA
- ECMWF ERA5
- MODIS MOD07



t = 0.93
Lu = 0.53
Ld = 0.95


Enter the parameters for which you wish calculate atmospheric transmission and upwelling radiance:

Year: Month: Day:
GMT Hour: Minute:

Latitude: Longitude:
+ is North, - is South + is East, - is West

- Use atmospheric profile for closest integer lat/long help
- Use interpolated atmospheric profile for given lat/long help

- Use mid-latitude summer standard atmosphere for upper atmospheric profile help
- Use mid-latitude winter standard atmosphere for upper atmospheric profile help

- Use Landsat-9 TIRS Band 10 spectral response curve
- Use Landsat-8 TIRS Band 10 spectral response curve
- Use Landsat-7 Band 6 spectral response curve
- Use Landsat-5 Band 6 spectral response curve
- Output only atmospheric profile, do not calculate effective radiances

Optional: Surface Conditions
(If you do not enter surface conditions, model predicted surface conditions will be used.
If you do enter surface conditions, all four conditions must be entered.)

Altitude (km): Pressure (mb):
Temperature (C): Relative Humidity (%):

Results will be sent to the following address:
Email:

Calculate
Clear Fields

2.1.1 RTE Method

- The accurate determination of Ts using this type of method requires
  - A good quality of radiative transfer code
  - A good knowledge of surface emissivity
  - Accurate atmospheric profiles
  - Correct consideration of topographic effects

- Drawbacks
  - Requirement of additional information (i.e., atmospheric profiles), which is usually not available with sufficient spatial density or at the satellite overpass time
  - Running the atmospheric RTE code (e.g., MODTRAN) is time-consuming

2.1.2 Mono Window Method

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- In order to avoid the dependence on in-situ atmospheric profiles and to simplify the retrieval process, Qin et al.(2001) developed a mono-window algorithm for retrieving LST from Landsat TM6.

- This algorithm requires the knowledge of the atmospheric transmissivity (τ) and the atmospheric mean temperature (Ta).

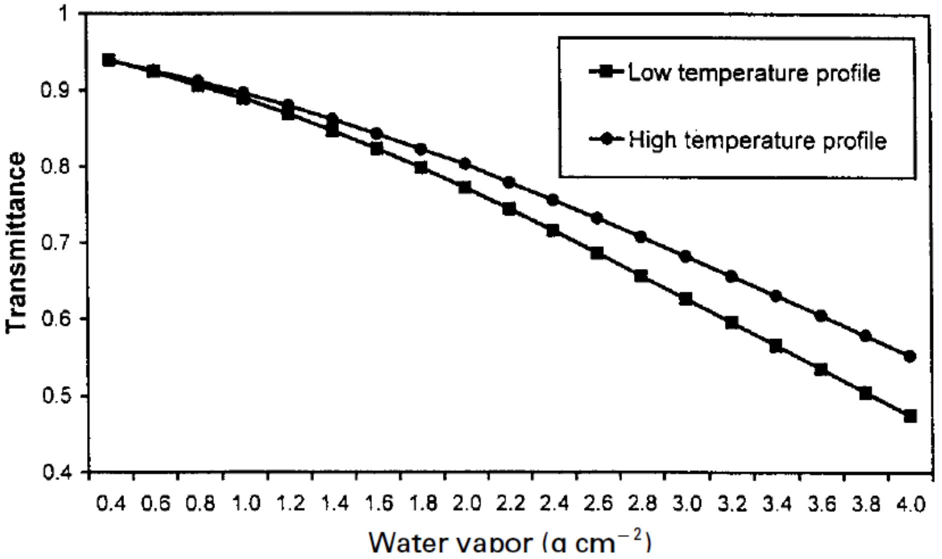
$$T_s = \frac{1}{C}[a(1-C-D)+(b(1-C-D)+C+D)T_{sat}-DT_a] \qquad C=\varepsilon\tau \qquad D=(1-\tau)[1+(1-\varepsilon)\tau]$$

Mid-latitude Summer	$T_a = 16.0110 + 0.9262 T_0$	$\tau = 0.974290 - 0.08007 w$
Mid-latitude Winter	$T_a = 19.2704 + 0.91118 T_0$	$\tau = 0.982007 - 0.09611 w$

2.1.2 Mono Window Method

- In order to get τ and T_a, simulated data computed from LOWTRAN 7 code were used to fit τ versus atmospheric water vapor content (W) and Ta versus near-surface air temperature (T_0). In this way, the algorithm uses W and T_0 as input data.

- The relationships between τ and W depend on not well-defined "high" and "low" air temperature values. Whereas relationships between T_a and T_0 are given for certain standard atmospheres in LOWTRAN 7, which are not suitable for most cases.



2.1.3 Generalized Single Channel Method

- A linear relationship between TOA radiance and surface temperature can be built based on the Taylor's approximation around a certain temperature value (T0) of the RTE

$$B(\lambda,T_s)=B(\lambda,T_o)+\left[\frac{\partial B(\lambda,T_s)}{\partial T_s}\right]_{\lambda,T_s=T_o}(T_s-T_o)=\alpha(\lambda,T_o)+\beta(\lambda,T_o)T_s$$

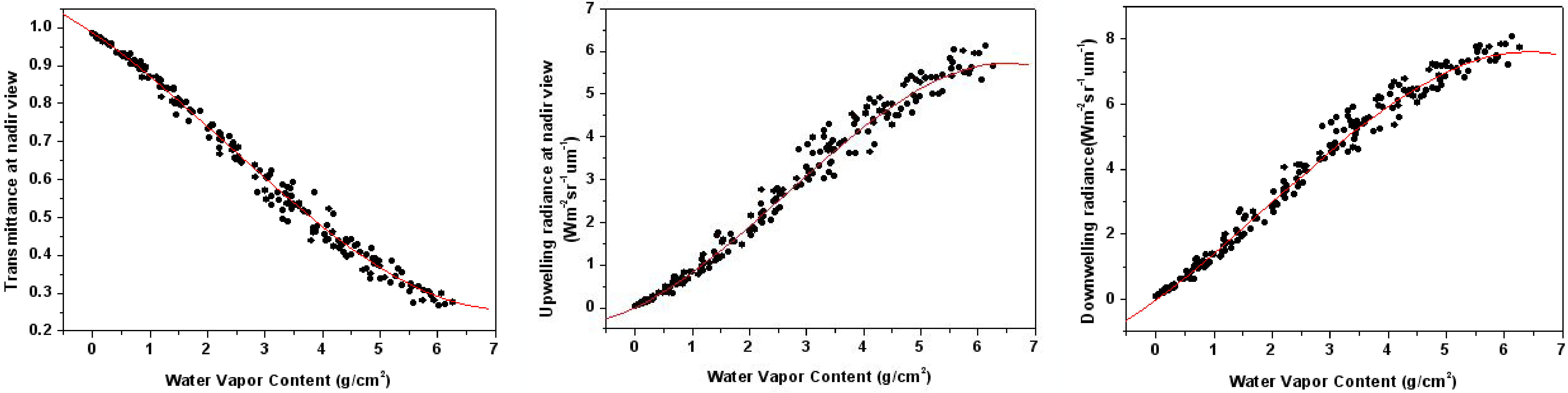
$$T_s=\gamma\left\{\frac{1}{\varepsilon}[\varphi_1(\lambda,\mathrm{w})L_\lambda^{sensor}+\varphi_2(\lambda,\mathrm{w})]+\varphi_3(\lambda,\mathrm{w})\right\}+\delta$$

$\varphi_1(\lambda,\mathrm{w}),\varphi_2(\lambda,\mathrm{w}),\varphi_3(\lambda,\mathrm{w})$ are the atmospheric functions, dependent only on *w* (water vapor content)

$$\gamma=\frac{1}{\beta}\qquad \delta=-\frac{\alpha}{\beta}\qquad \alpha=B(T_0)\left[1-\frac{c_2}{T_0}\left(\frac{\lambda^4}{c_1}B(T_0)+\frac{1}{\lambda}\right)\right]\qquad \beta=\frac{c_2B(T_0)}{T_0^2}\left[\frac{\lambda^4B(T_0)}{c_1}+\frac{1}{\lambda}\right]$$

$$\psi_1=\frac{1}{\tau}\qquad \psi_2=-L^{\downarrow}-\frac{L^{\uparrow}}{\tau}\qquad \psi_3=L^{\downarrow}$$

2.1.3 Generalized Single Channel Method



$$\psi_1 = 0.14714w^2 - 0.15583w + 1.1234$$

$$\psi_2 = -1.183w^2 - 0.3760w - 0.52894$$

$$\psi_3 = -0.0455w^2 + 1.8719w - 0.39071$$

$$\begin{bmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} w^2 \\ w \\ 1 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.14714 & -0.15583 & 1.1234 \\ -1.1836 & -0.37607 & -0.52894 \\ -0.04554 & 1.8719 & -0.39071 \end{bmatrix}$$

2.1.4 Practical Single Channel Method

- The RTE algorithm requires concurrent atmospheric profiles and is computationally intensive due to the running of atmospheric RT model

- The Mono Window algorithm and Generalized Single Channel algorithm have large uncertainties under humid atmosphere due to the linearization of the Planck function

- To mitigate the large retrieval errors under humid atmosphere, the Practical Single Channel method uses a two-step strategy to avoid the linearization of the Planck function

2.1.4 Practical Single Channel Method: Solution 1

$$L_{sen}(\theta) = \varepsilon\tau(\theta)B(T_s) + (1-\varepsilon)\tau(\theta)R^{a\downarrow} + R^{a\uparrow}$$

$$B(T_s) = \frac{K_1}{e^{(K_2/T_S)-1}}$$

$$B(T_s) = R^{a\downarrow} - \left(R^{a\downarrow} + \frac{R^{a\uparrow}}{\tau(\theta)}\right)\cdot\varepsilon + \frac{1}{\tau(\theta)}\cdot\frac{L_{sen}}{\varepsilon}$$

$$T_s = \frac{K_2}{LN(K_1/T_S + 1)}$$

$$R^{a\uparrow} = \int_0^h B(T_z)k\rho\sec\theta\, e^{-\int_z^h k\rho\sec\theta dz}dz = \int_0^h B(T_z)\frac{\partial\tau(z,h,\theta)}{\partial z}dz = \int_{\tau(0,h,\theta)}^1 B(T_z)d\tau(z,h,\theta)$$

$$R^{a\downarrow} = \int_h^0 B(T_z)k\rho\sec\theta'\, e^{-\int_0^z k\rho\sec\theta' dz}dz = \int_h^0 B(T_z)\frac{\partial\tau(0,z,\theta')}{\partial z}dz = \int_{\tau(0,h,\theta')}^1 B(T_z)d\tau(0,z,\theta')$$

$$R^{a\uparrow} = B(T^{a\uparrow})\cdot(1-\tau(0,h,\theta)) = B(T^{a\uparrow})\cdot(1-\tau(\theta))$$

$$R^{a\downarrow} = B(T^{a\downarrow})\cdot(1-\tau(0,h,\theta')) = B(T^{a\downarrow})\cdot(1-\tau(\theta'))$$

2.1.4 Practical Single Channel Method: Solution 2

$$B(T_s) = R^{a\downarrow} - \left(R^{a\downarrow} + \frac{R^{a\uparrow}}{\tau(\theta)}\right) \cdot \varepsilon + \frac{1}{\tau(\theta)} \cdot \frac{L_{sen}}{\varepsilon}$$

$$B(T_s) = \left(1 - \tau(\theta)\right) \cdot B\left(T^{a\downarrow}\right) - \left(\left(1 - \tau(\theta)\right) \cdot B\left(T^{a\downarrow}\right) + \frac{\left(1 - \tau(\theta)\right)}{\tau(\theta)} \cdot B\left(T^{a\uparrow}\right)\right) \cdot \varepsilon + \frac{1}{\tau(\theta)} \cdot \frac{L_{sen}}{\varepsilon}$$

	Linear		Second order Polynomial		Third order Polynomial	
	R^2	RMSE	R^2	RMSE	R^2	RMSE
$R^{a\downarrow}$ vs w	0.9731	0.3082	0.9739	0.3036	0.9806	0.2615
$1/\tau$ vs w	0.8497	0.1365	0.9583	0.0719	0.9603	0.0701
$-\left(R^{a\downarrow} + R^{a\uparrow}/\tau\right)$ vs w	0.9071	1.4764	0.9605	0.9630	0.9606	0.9616
$1 - \tau$ vs w	0.9777	0.0235	0.9809	0.0218	0.9846	0.0196
$(1 - \tau)/\tau$ vs w	0.8497	0.1365	0.9583	0.0719	0.9603	0.0701
$B\left(T^{a\uparrow}\right)$ vs T_n	0.9392	0.4497	0.9492	0.4113	0.9531	0.3948
$B\left(T^{a\downarrow}\right)$ vs T_n	0.9123	0.6987	0.9151	0.6874	0.9170	0.6790

2.2 Split Window Algorithm

- The transmittances in two adjacent atmospheric windows (centred around 11 and 12 µm) are different, which can be utilized to remove the atmospheric effects

BT-based

Linear SW

$$T_S = A_0 + A_1 T_i + A_2 (T_i - T_j)$$

Non-linear SW

$$T_S = A_0 + A_1 T_i + A_2 (T_i - T_j) + A_3 (T_i - T_j)^2$$

Radiance-based

$$B(T_S) = A_0 L_i + A_1 L_j + A_2$$

SW coefficient A_k

$$A_k = f_k(g_i, g_j, \varepsilon_i, \varepsilon_j, WV, VZA)$$

- Constant
- Emissivity
- Emissivity, WVC
- Emissivity, WVC, and VZA

2.2 Split Window Algorithm

- Emissivity-implicit SW algorithm (Sentinel-3 SLSTR)

  One expresses emissivity implicitly using different coefficient sets for different land surface types. Significant uncertainties can be introduced into a surface-type dependent algorithm due to the misclassification in land surface type products and the intra-class variability in emissivity.

$$LST = a_{f,i,pw} + b_{f,i}\left(T_{11} - T_{12}\right)^{\frac{1}{\cos(\theta_v/m)}} + \left(b_{f,i} + c_{f,i}\right)T_{12}$$

- Emissivity-explicit SW algorithm (Generalized SW, MOD11, VIIRS and ABI)

  One incorporates emissivity explicitly as a *priori.* The emissivity explicit algorithm is preferred, which allows for improvements in input emissivity to be directly translated into improved LST accuracy and enables easy incorporation of updated emissivity maps.

$$LST = C + \left(A_1 + A_2\frac{1-\varepsilon}{\varepsilon} + A_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{11}+T_{12}}{2} + \left(B_1 + B_2\frac{1-\varepsilon}{\varepsilon} + B_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{11}-T_{12}}{2} + \mathrm{D}(T_{11}-T_{12})^2$$

2.3 Dual Window Algorithm

- In the absence of two thermal infrared channels, one middle infrared channel and one thermal infrared channel are utilized based on their different atmospheric absorptions, which can be utilized to remove the atmospheric effects.

- Reflected solar middle infrared radiance needs to be removed from the TOA radiance.

- DW algorithms were used for the GOES 12-14 LST retrieval.

Daytime:

$$LST = a_0 + a_1 T_{11} + a_2 (T_{11} - T_{3.9}) + a_3 (T_{11} - T_{3.9})^2 + a_4 T_{3.9} \cos\theta_s + a_5 (1 - \varepsilon_{11})$$

Night-time:

$$LST = a_0 + a_1 T_{11} + a_2 (T_{11} - T_{3.9}) + a_3 (T_{11} - T_{3.9})^2 + a_4 (1 - \varepsilon_{11})$$

2.4 Dual Angle Algorithm

- When observing the land surface from different angles, the transmittances of the observed radiances from different angles are different, which can be utilized to remove the atmospheric effects

Algorithm	Linear: $T_s = T_n + p_1(T_n - T_f) + p_2 + p_3(1-\varepsilon_n) + p_4(\varepsilon_n - \varepsilon_f)$ Nonlinear: $T_s = T_n + q_1(T_n - T_f) + q_2(T_n - T_f)^2 + (q_3 + q_4 WV)(1-\varepsilon_n) + (q_5 + q_6 WV)\Delta\varepsilon + q_0$
Adv.	● Not requiring atmospheric profiles
Disadv.	● More suitable for sea surface temperature （accuracy higher than 0.3 K for AATSR) ● Large uncertainties for land surface retrieval temperature, due to the 3-D structure of land surface and spatial heterogeneity, pixel sizes are different viewing from different angles. In this case, surface compositions are different, which lead to different land surface temperatures viewing from different angles

2.5 LSE Retrieval

- In the previously introduced algorithms, including Single Channel algorithm, Split Window algorithm, Dual Window algorithm, and Dual Angle algorithm, LSE is treated as a *priori* to solve the underdetermined question of LST retrieval.

- LSE retrieval at the satellite scale can be divided into the following major categories

  1) Classification-based method (MOD11)

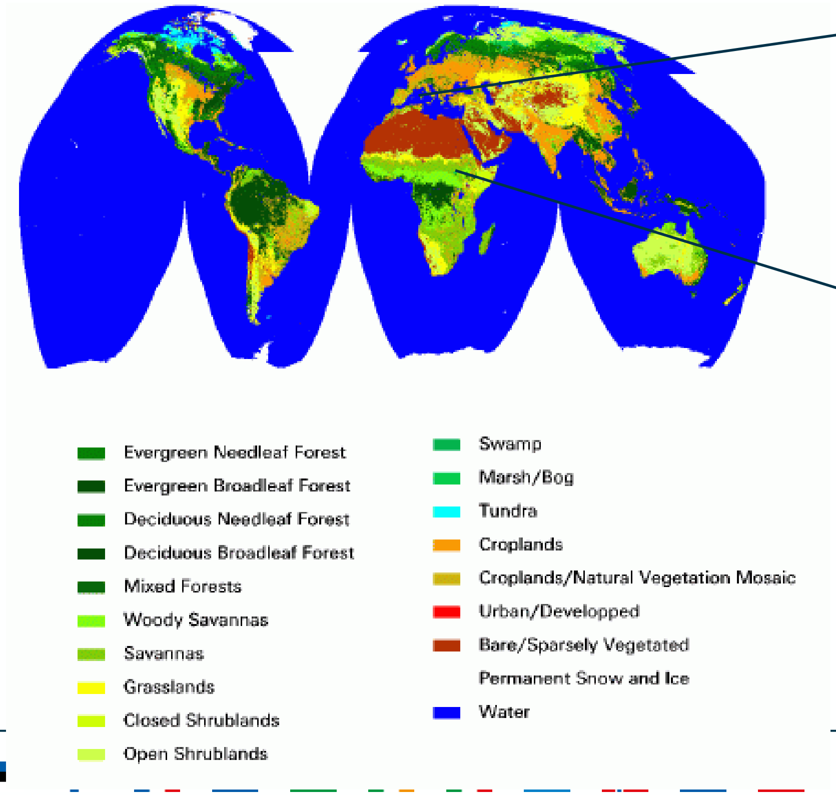
  2) NDVI-based method (Sobrino et al., 2001)

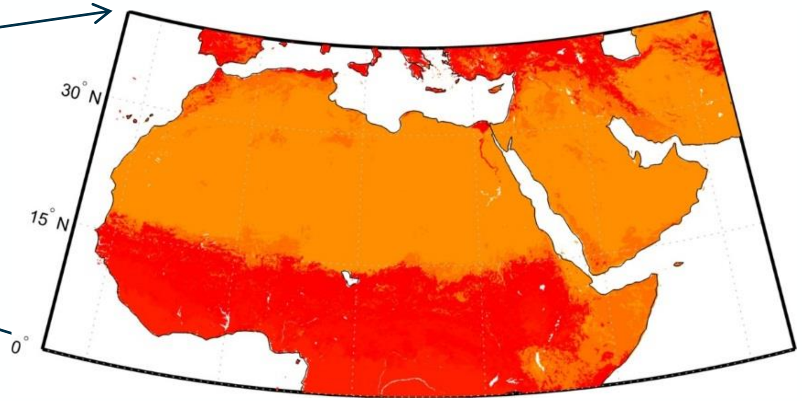
  3) ASTER GED-based method (VIIRS and ABI)

2.5.1 Classification-based emissivity method

- Classification-based emissivity: MODIS LSE product

- Needs: a) land surface classification from VNIR and TIR images
  b) field and laboratory emissivity measurements for each class
  c) emissivity modification based on surface phenology





2.5.2 NDVI-based Method

- NDVI thresholds method (Sobrino et al., 2001)

- For NDVI<0.2 $$\varepsilon_i = a_i + b_i \rho_{red}$$

In this case, the pixel is considered as bare soil and the emissivity is obtained from reflectivity values in the red region.

- For NDVI>0.5 $$\varepsilon_i = \varepsilon_{vi} + d\varepsilon_i$$

Pixels with NDVI values higher than 0.5 are considered as fully vegetated, and then a constant value for the emissivity is assumed, typically 0.99.

- 0.2 <NDVI<0.5 $$\varepsilon_i = \varepsilon_{vi} P_v + \varepsilon_{si}(1 - P_v) + d\varepsilon_i \quad P_v = \left[\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right]^2$$

In this case, the pixel is composed of bare soil and vegetation.

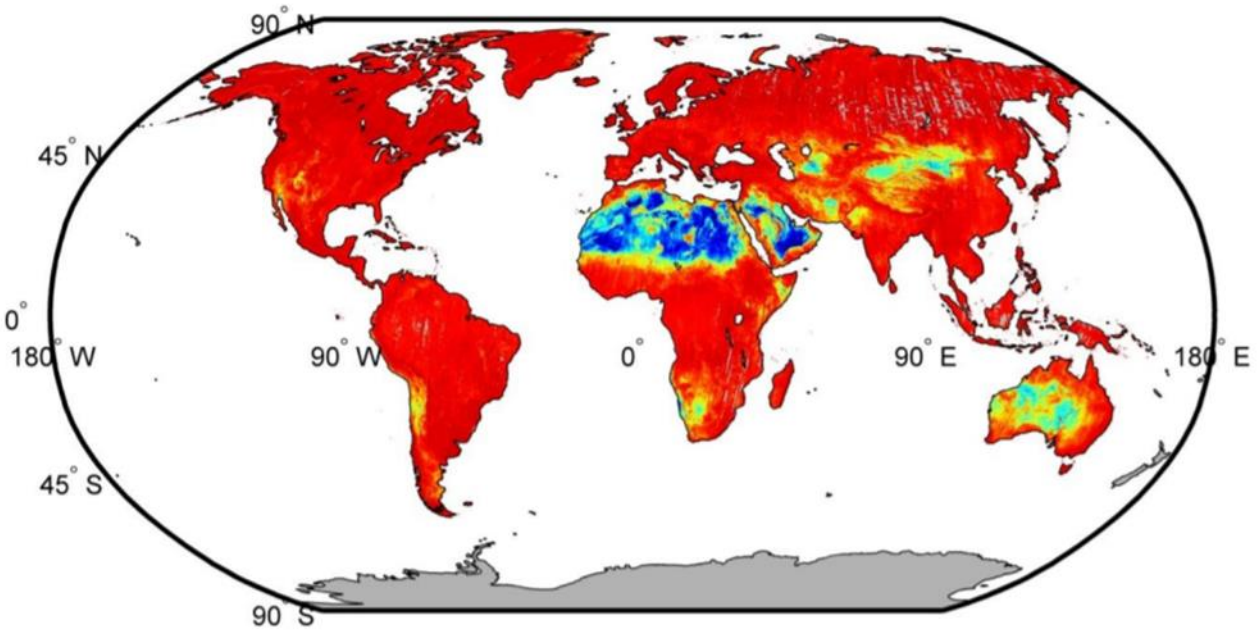
- ***dε*** depicts the effects of the geometrical distribution of natural surfaces and the internal reflections. For plain surfaces, this term is negligible. For heterogeneous and rough surfaces, e.g., forest, this term can reach around 2%.

$$d\varepsilon_i = (1 - \varepsilon_{s,i})\varepsilon_{v,i} F (1 - P_v)$$

2.5.3 ASTER GED-based Method

- ASTER Global Emissivity Dataset (ASTER GED) that was acquired by processing millions of cloud free ASTER scenes from 2000 to 2008.

- The ASTER GEDv3 provides an average emissivity at ~100m and ~1km, while GEDv4 provides a monthly emissivity from 2000 to 2015 at ~5 km spatial resolution in the wavelength range between 8 and 12 μm.



ASTER GED band 12 emissivity resampled from 100 m to 5 km for display purpose (Hulley et al., 2015)

2.6 Simultaneous Retrieval of LST and LSE, Atm. Known

1. Two-temperature method (TTM)

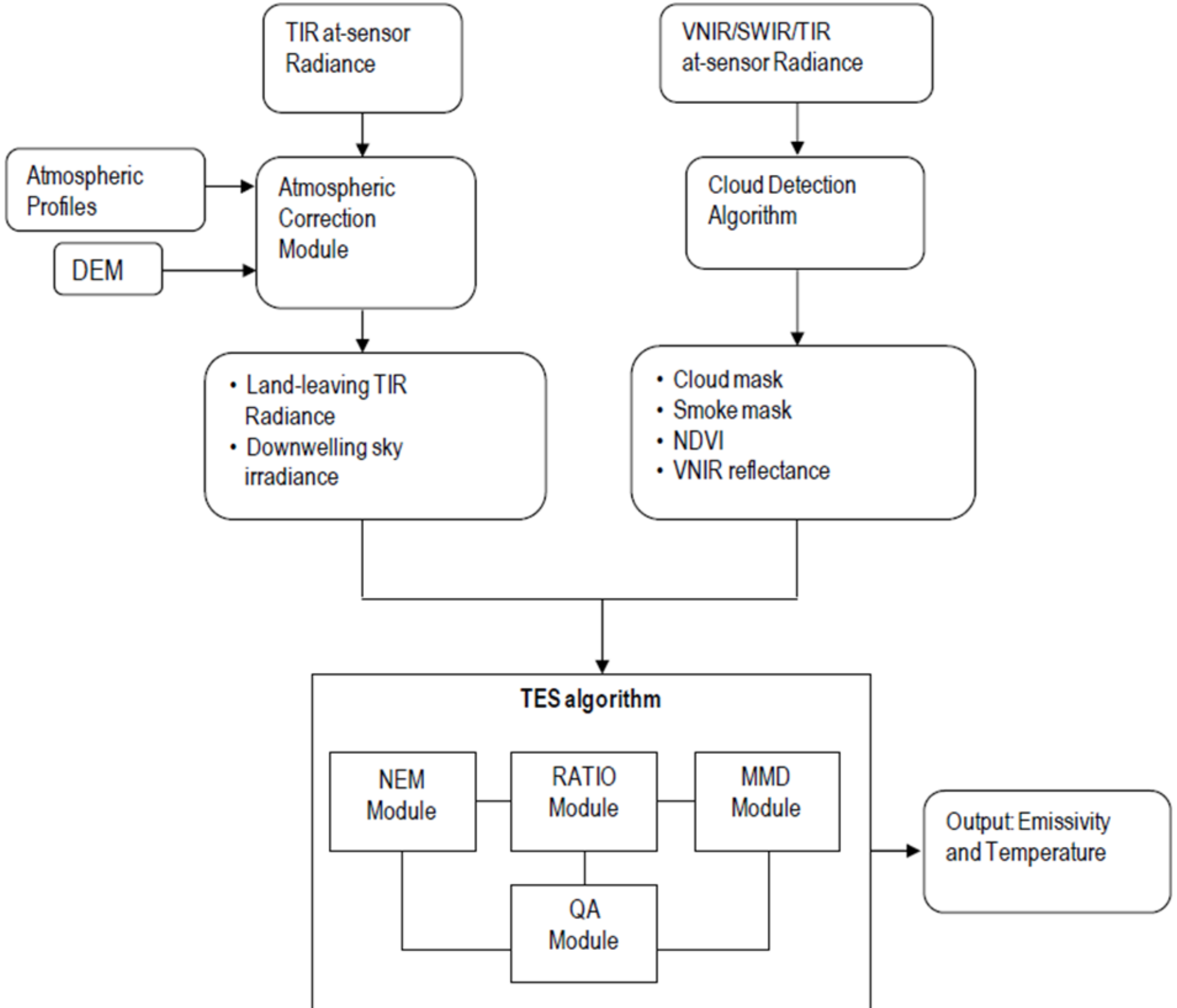
2. Physically-based day/night operational method (D/N), MOD11B1

3. Graybody emissivity method (GBE)

4. Temperature emissivity separation method (TES), ASTER & MOD21

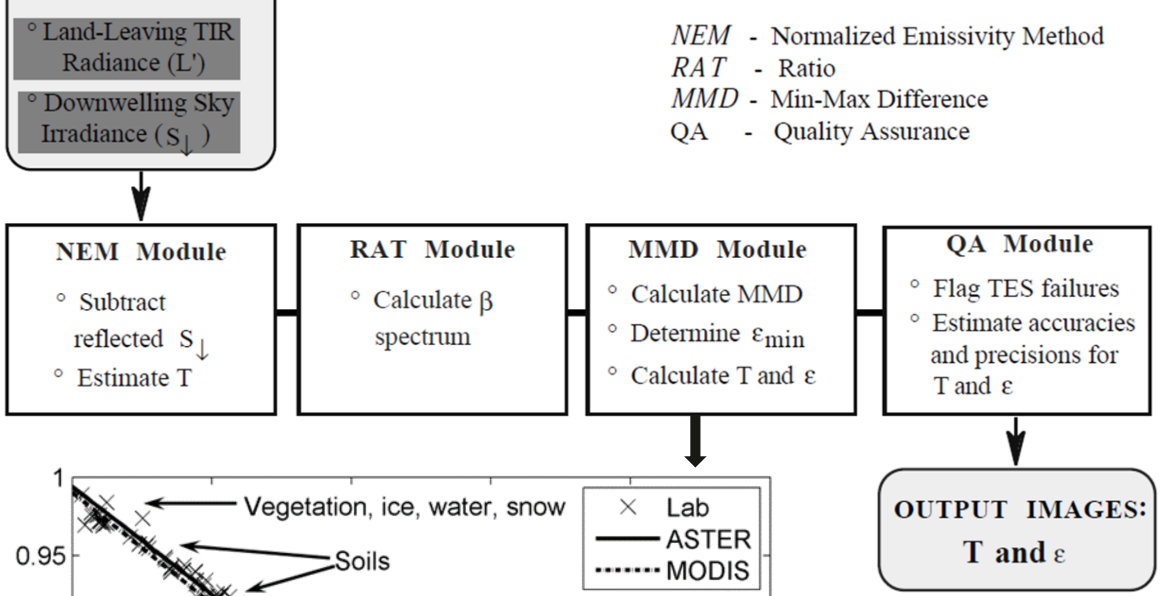
5. Iterative spectrally smooth temperature emissivity separation method (ISSTES)

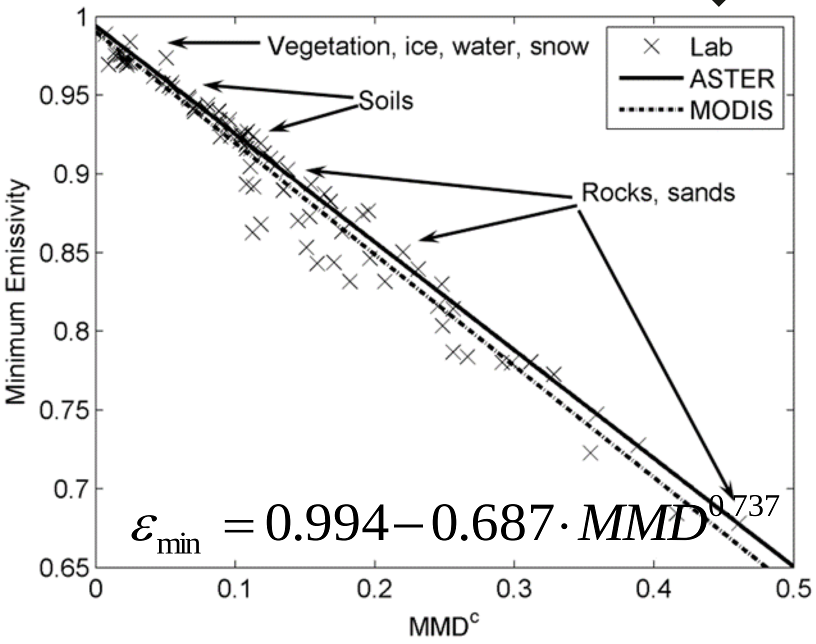
Temperature and Emissivity Separation Method



LST Retrieval Flowchart

TES Algorithm Flowchart





Water Vapor Scaling Method

- Hulley et al.(2012) pointed out that residuals from incomplete atmospheric correction during the conditions of relative high atmospheric water vapor content can be as large as 3 K for LST retrieval from ASTER data based on the results from a wide range of simulated data (atmospheric radiosonde profiles + spectral emissivity library + MODTRAN).

Surface brightness temperature

Observed brightness temperature

Total column water estimate

EMC/WVD equation

$$
\begin{cases}
T_{g,i} = \alpha_{i,o} + \sum_{k=1}^{n} \alpha_{i,k} T_k \\
\alpha_{i,k} = p_{i,k} + q_{i,k} W + r_{i,k} W^2 \; (k = 0,1,..,n)
\end{cases}
$$

Scaling factor

$$
\gamma^{a_i} = \frac{\ln\left[\frac{\tau_i(\gamma_2)^{\gamma_1^{a_i}}}{\tau_i(\gamma_1)^{\gamma_2^{a_i}}} \cdot \left(\frac{B_i(T_{g,i}) - L_i^{\uparrow}(\gamma_1)/(1-\tau_i(\gamma_1))}{L_i - L_i^{\uparrow}(\gamma_1)/(1-\tau_i(\gamma_1))} \right)^{\gamma_1^{a_i} - \gamma_2^{a_i}} \right]}{\ln\left(\frac{\tau_i(\gamma_2)}{\tau_i(\gamma_1)} \right)}
$$

γ is used to modify and improve atmospheric correction terms:

Transmittance: $\tau_i(\gamma) = \tau_i(\gamma_1)^{(\gamma^{a_i} - \gamma_2^{a_i}/\gamma_1^{a_i} - \gamma_2^{a_i})} \cdot \tau_i(\gamma_2)^{(\gamma_1^{a_i} - \gamma^{a_i}/\gamma_1^{a_i} - \gamma_2^{a_i})}$

Path Radiance: $L_i^{\uparrow}(\gamma) = L_i^{\uparrow}(\gamma_1) \cdot \frac{1-\tau_i(\gamma)}{1-\tau_i(\gamma_1)}$

Sky Radiance: $L_i^{\downarrow}(\gamma) = a_i + b_i \cdot L_i^{\uparrow}(\gamma) + c_i \cdot L_i^{\uparrow}(\gamma)^2$

Water Vapor Scaling Method

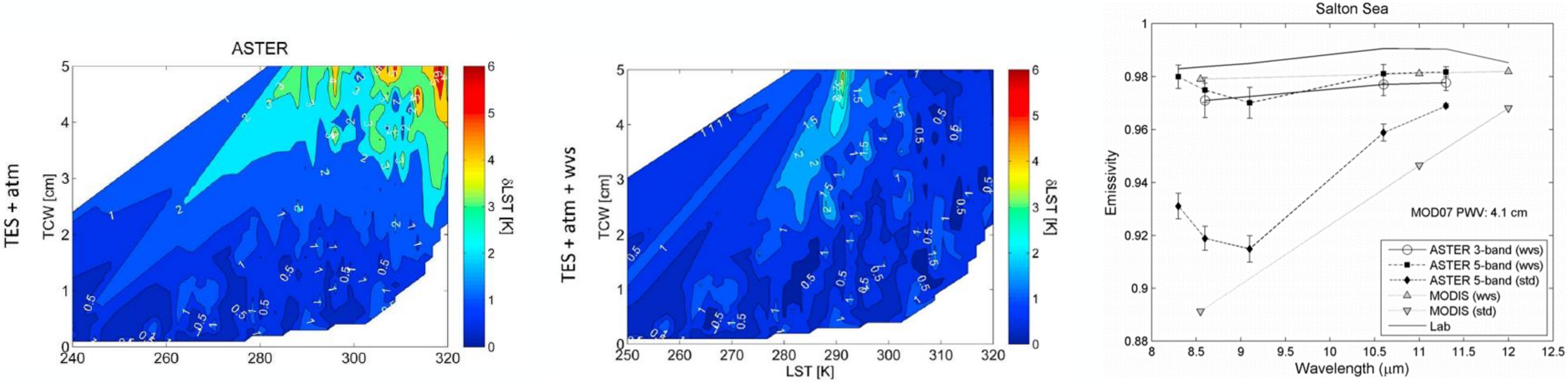


Figure Courtesy of Hulley et al. (2011)

The emissivity of water is high (~0.99) and spectrally flat. The results show a substantial improvement in emissivity accuracy in both magnitude (up to 0.06 for ASTER band 11 and 0.09 for MODIS band 29) and spectral shape when using WVS, as opposed to the STD method.

1. Artificial neural network (ANN) method

- Aires et al. (2002)
- Wang et al. (2010)

The implementation of an ANN depends largely on its architecture and the training data (Mas & Flores,2008). It is difficult to determine the architectures and learning schemes for an ANN.

2. Two-step physical retrieval method (TSRM)

- The measured radiance at the TOA is a function of the surface and atmospheric parameters.
- Ma et al. (2002)
- The first step is to tangent-linearize the atmospheric RTE with respect to the atmospheric temperature humidity profiles, the LST, and the LSEs.
- In the second step, the Newtonian iteration algorithm is utilized with the regularized solution as the initial guess to obtain the final maximum likelihood solution of the atmospheric temperature-humidity profiles, LST, and LSEs.

3. Land Surface Temperature Validation Method

1) Conventional temperature-based method

Compare LST retrievals with in-situ measurements directly

2) Radiance-based method

Adjust LST retrievals to match the TOA radiance through atmospheric radiative transfer models

3) Cross-validation method

Compared LST retrievals with well-validated LST products

3.1 Temperature-based Method

- For the CNR1/4 net radiometer, the LST is estimated from the upwelling and downwelling longwave radiation using the following equation

$$T_s = [\frac{F^{\uparrow} - (1-\varepsilon_b)\cdot F^{\downarrow}}{\varepsilon_b \cdot \sigma}]^{1/4}$$

where T_s is the LST, $F^{\uparrow}$ is the surface upwelling longwave radiation, ε_b is the surface broadband emissivity, σ is the Stefan-Boltzmann's constant (5.67×10^{-8} $Wm^{-2}K^{-4}$), and $F^{\downarrow}$ is the atmospheric downwelling longwave radiation at the surface

- For SI-111 radiometer, the measured radiometric temperatures was corrected for emissivity and the downward sky irradiance effect. If Tr is the radiometric temperature measured by a radiometer, the land surface temperature Ts is given by

$$B(T_s) = [B(T_r) - (1-\varepsilon)L_{sky}]/\varepsilon$$

where B is the Planck function weighted for the spectral response function of the radiometer, ε is the surface emissivity and Lsky is the downward sky irradiance divided by π.

3.2 Radiance-based Method

- LST notoriously difficult to validate
- Accurate radiative transfer model and emissivity measurements required.
- Advantages:
  Application to many sites
  Day and night observations
  Can be used for coarse resolution sensors (at a large, homogeneous site)

Redwood National Forest, CA

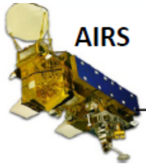
Namib Desert, Namibia

Rice field

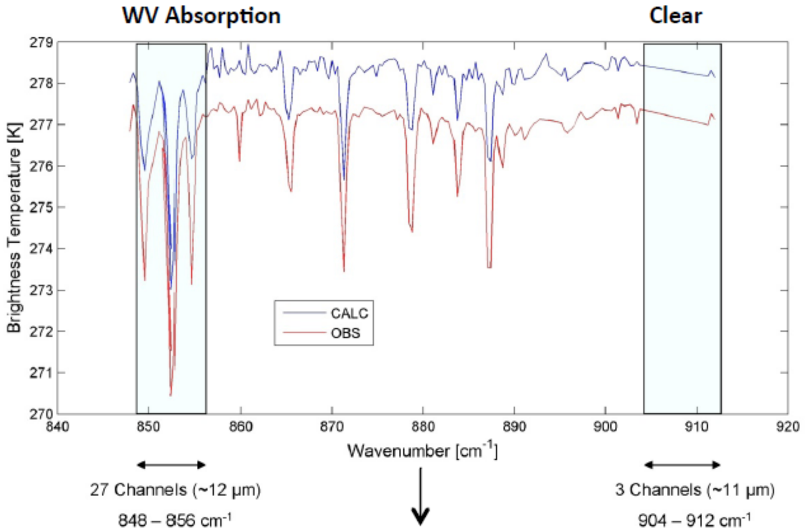
Lake

3.2 Radiance-based Method

Radiance-based LST Validation

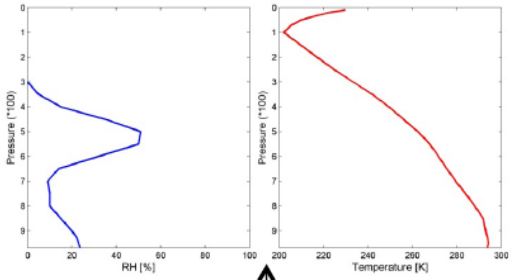


T_b(obs) CCR's →

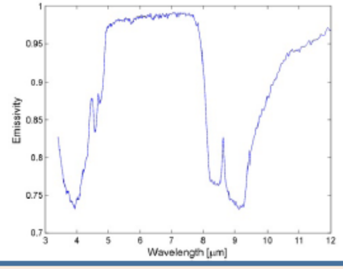


SARTA → T_b(calc) + NEΔT

NCEP (GDAS) Profiles



Lab Field Emissivity



Surface

T_s(AIRS retrieved)

NCEP Profile Quality Test

$\Delta T_b(\text{obs}) = T_{b11}(\text{obs}) - T_{b12}(\text{obs})$

$\Delta T_b(\text{calc}) = T_{b11}(\text{calc}) - T_{b12}(\text{calc})$

$\Delta T_b = \Delta T_b(\text{obs}) - \Delta T_b(\text{calc})$

$-0.5\ K < \Delta T_b < 0.5\ K$

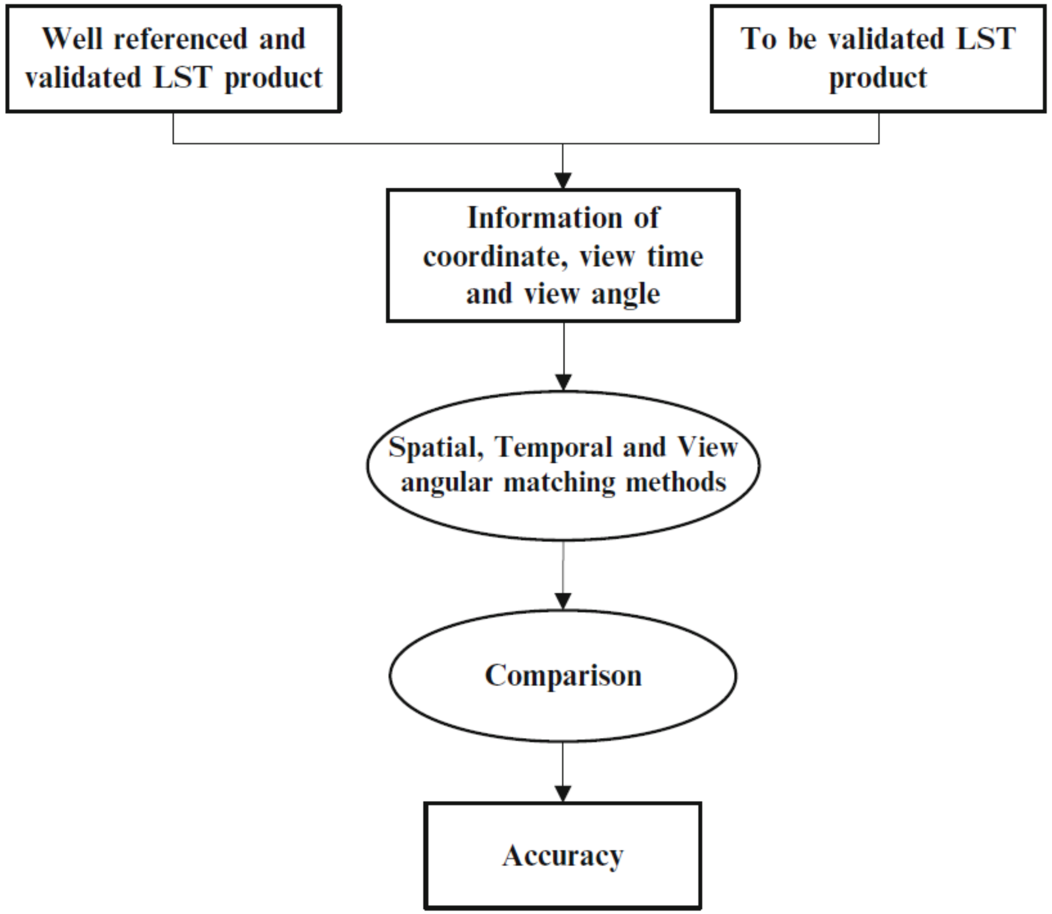
YES → $T_{s'} = T_s \pm 2K$ → SARTA → $T_{b'}$(calc) → $T_{rad} = \text{interp}([T_s\ T_{s'}],[T_{b'}\ T_b],T_b)$ → **Theoretically Correct Surface Temperature**

NO → **QUIT!**

3.3 Cross Validation

- The cross-validation method uses a well-referenced or validated LST product derived from other satellites to compare with the satellite-derived LST to be validated.

- Due to the large spatial and temporal variations in the LST, geographic coordinate matching, temporal matching, and VZA matching have to be performed before the two satellite-derived LST products can be compared.



4. Implementations on Satellite Observations

- **Single Channel algorithms on Landsat**
  How different operational LST retrievals from Landsat based on varying Single Channel algorithms compare with each other?

- **SW, DW, and DA algorithms on Sentinel-3 SLSTR**
  How those algorithms based on the similar theory (combining bands/angles to remove atmospheric effects) compare with each other?

- **SW and TES on ECOSTRESS**
  How SW compares with TES in terms of LST retrieval accuracy?

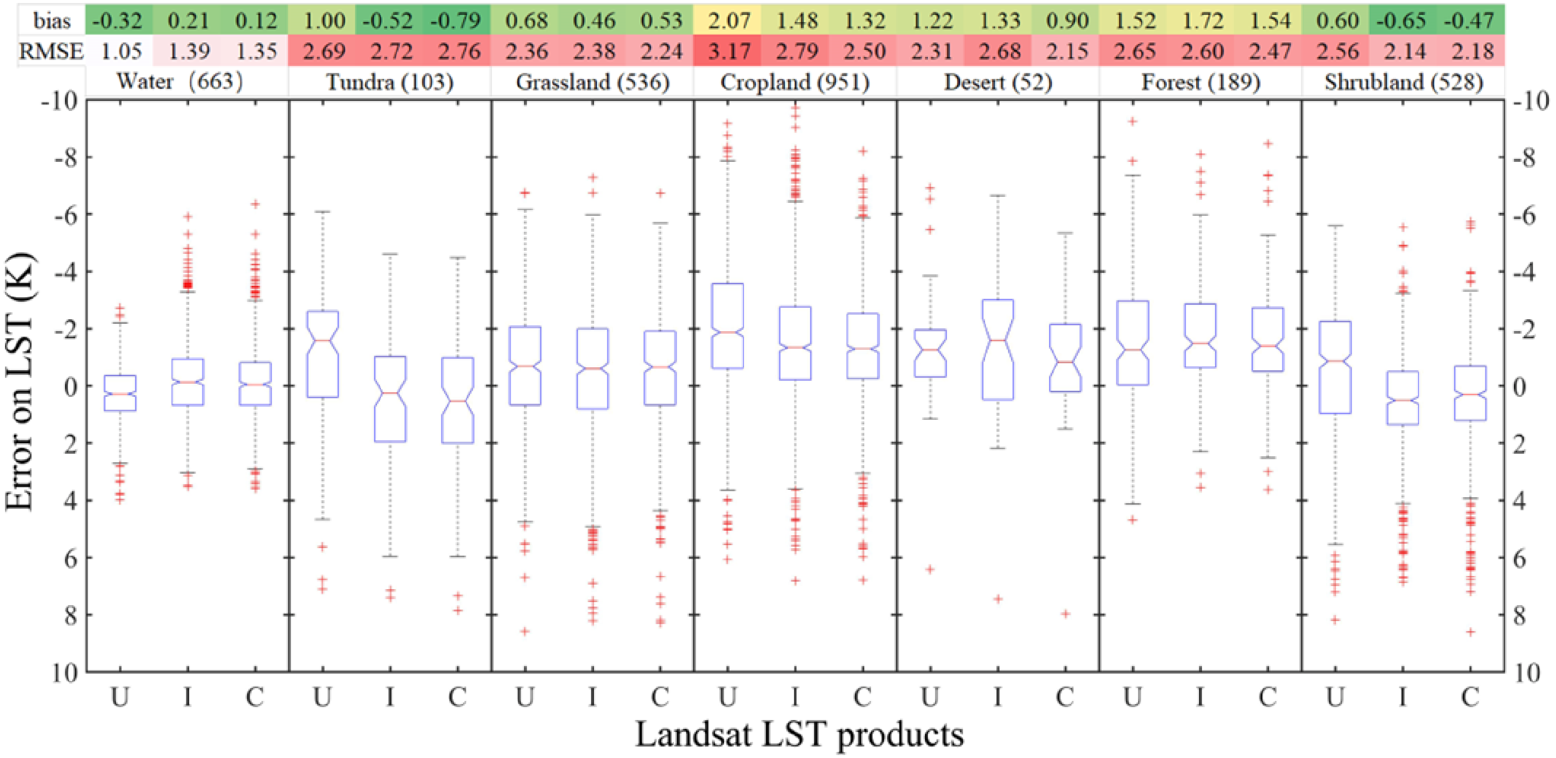
4.1 Single Channel Algorithms on Landsat

Table 6
RMSE (K), MBE (K), and R^2 Between the Retrieved Land Surface Temperature and In Situ Measurements at Seven SURFRAD Stations at PSC_w, $PSC_{w\&Tn}$, and GSC Algorithms

		PSC_w			$PSC_{w\&Tn}$	GSC
SURFRAD site	Number	RMSE	MBE	R^2	RMS	
Bondville	10	1.572	1.146	0.998	1.93	
Boulder	5	1.527	−0.829	0.989	1.55	
Desert Rock	18	1.545	−0.693	0.981	1.44	
Fort Peck	16	1.648	−1.004	0.997	1.48	
Goodwin Greek	7	2.675	2.581	0.994	3.29	
Penn State	5	2.805	1.435	0.945	3.27	
Sioux Falls	10	1.033	−0.310	0.979	0.96	
Total	71	1.772	0.013	0.985	1.91	

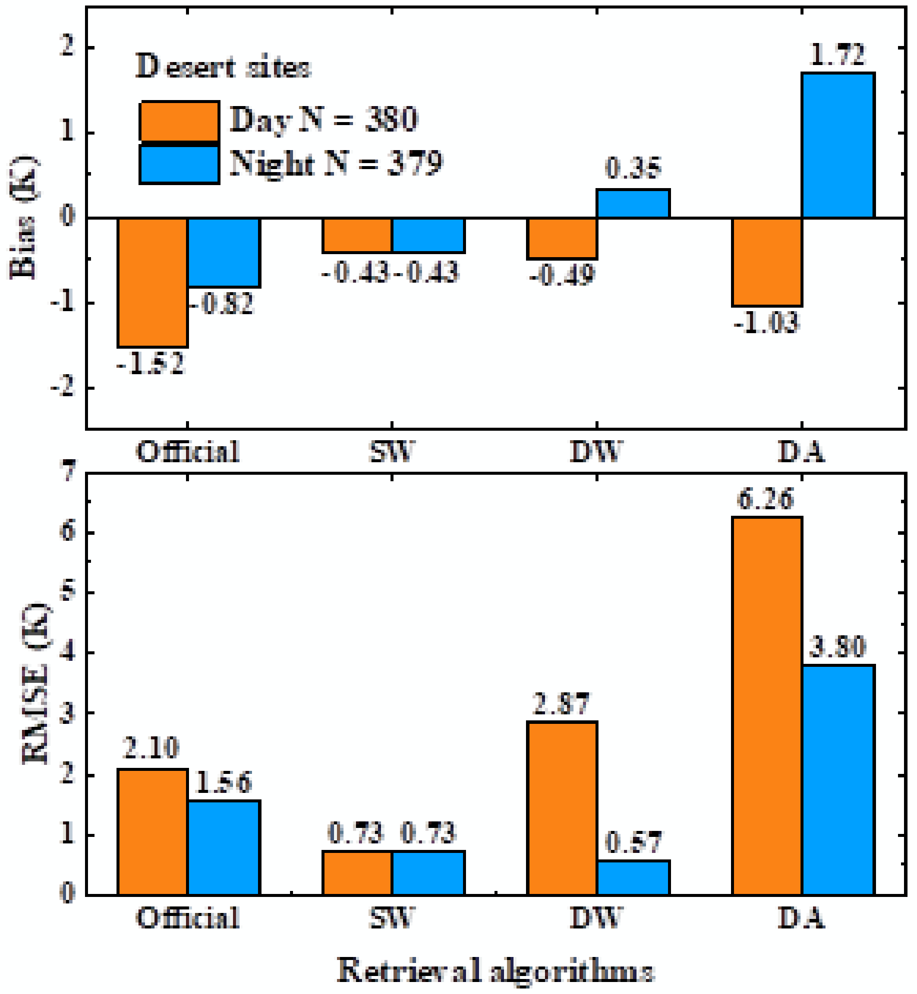
Note. RMSE = root-mean-square error; GSC = generalized s
SURFRAD = surface radiation budget; MBE = mean bias error.

Wang M., Hu T. et al. (2018), J



Wang M., Hu T. et al. (2022), TGRS (under review after revision)

4.2 SW, DW, and DA Algorithms on Sentinel-3 SLSTR



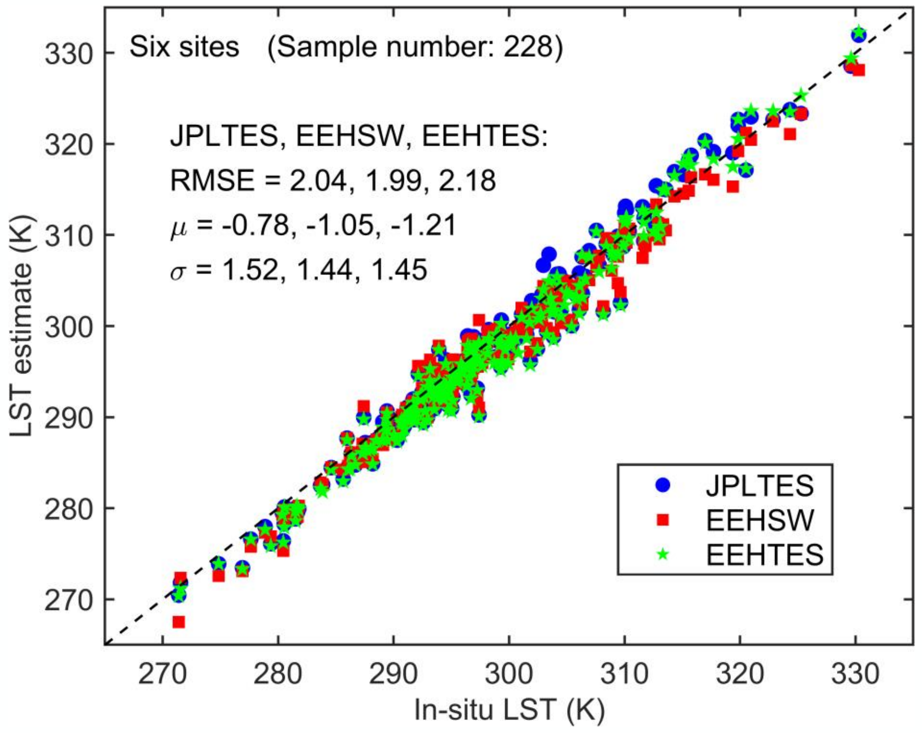
R-based validation over desert

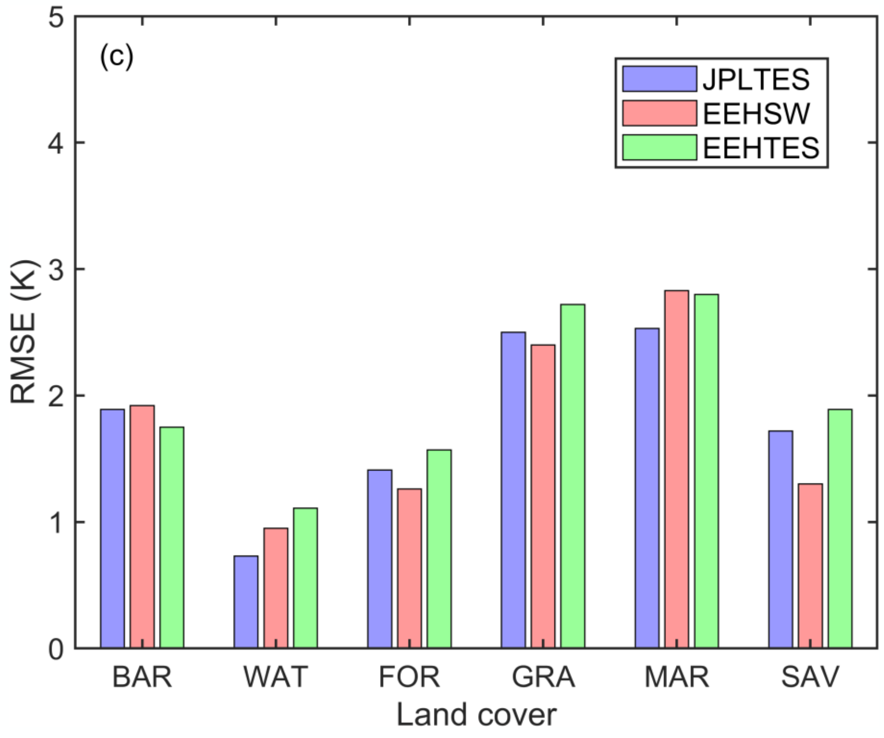
Retrieval Algorithms	Daytime N	Daytime Bias	Daytime STD	Daytime RMSE	Nighttime N	Nighttime Bias	Nighttime STD	Nighttime RMSE	All N	All Bias	All STD	All RMSE
Official	302	1.79	3.06	3.54	267	0.19	2.37	2.37	569	1.04	2.74	2.99
SW		0.83	2.95	3.06		-0.92	2.33	2.50		0.01	2.66	2.80
DW		0.95	3.28	3.41		-0.72	2.55	2.65		0.17	2.94	3.05
DA		-0.11	4.48	4.47		0.19	3.92	3.91		0.03	4.22	4.21

T-based validation using 6 HiWATER sites

Li R., Hu T. et al. (2022), TGRS (under review)

4.3 SW and TES on ECOSTRESS





Hu T. et al. (2022), RSE

Recommended papers for TIR Remote Sensing of LST

- Terminology in thermal infrared remote sensing of natural surfaces, J. M. Norman and F. Becker, 1995, AFM
- Satellite-derived land surface temperature: Current status and perspectives, Zhao-Liang Li et al., 2013, RSE
- A temperature and emissivity separation algorithm for Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images, A. Gillespie et al., 1998, TGRS
- A generalized split-window algorithm for retrieving land-surface temperature from space, Zhengming Wan, J. Dozier et al., 1996, TGRS
- A practical single-channel algorithm for land surface temperature retrieval: application to landsat series data, Mengmeng Wang et al., 2019, JGR-Atmosphere
- Generating consistent land surface temperature and emissivity products between ASTER and MODIS data for earth science research, Glynn Hulley and Simon Hook, 2010, TGRS
- Continental-scale evaluation of three ECOSTRESS land surface temperature products over Europe and Africa: Temperature-based validation and cross-satellite comparison, Tian Hu et al., 2022, RSE

Thank you for listening!

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Luxembourg Institute of Science and Technology
(tian.hu@list.lu)

We are looking for a postdoc who

- has solid knowledge of VSWIR radiative transfer
- is skilled at terrestrial ecosystem process modelling, with a focus on vegetation biochemical process
- has a good understanding of SEB modelling
- can work independently as well as integrate into a team
- has good publication track record
- has good knowledge of SIF (regarded as an asset)
- is expected to start the position in the middle of 2023

Interested to do an internship at LIST?

- The duration is 6 months, with attractive financial subsidies
- The candidate has a Bachelor degree and is conducting his/her Master by Research or PhD study
- The candidate should have a good understanding of thermal infrared remote sensing