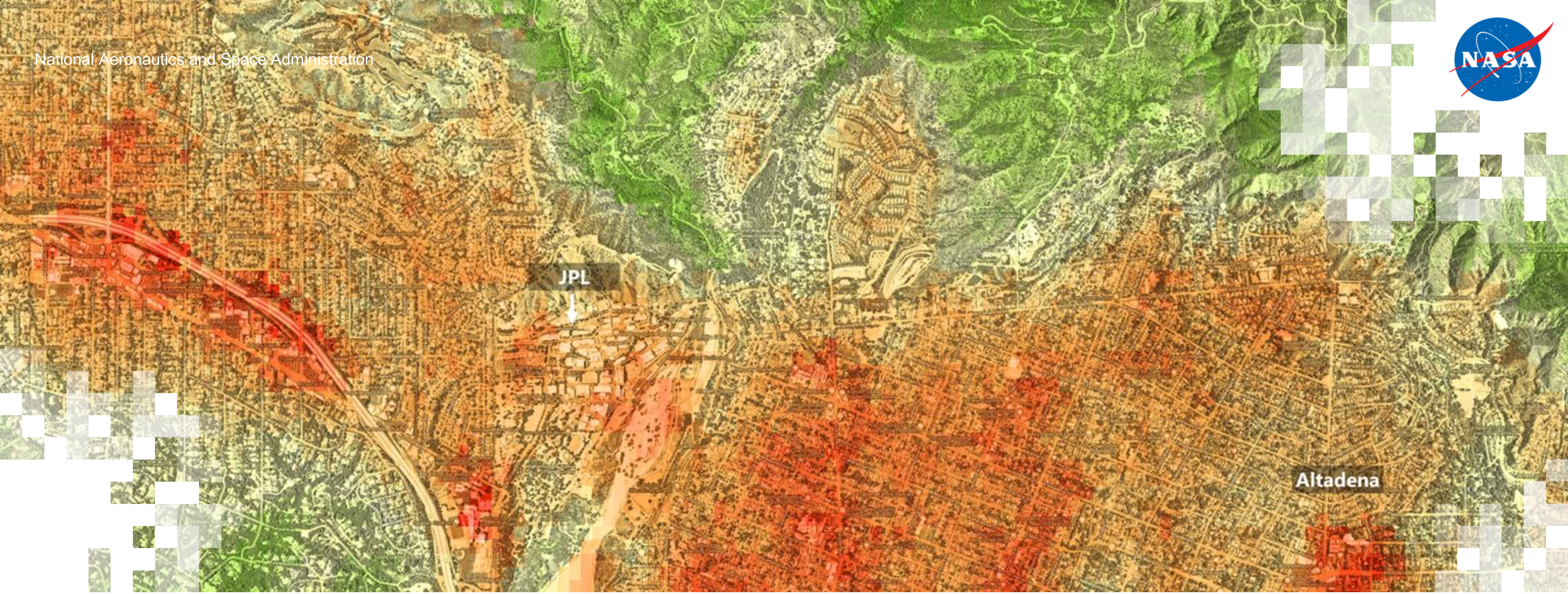
National Aeronautics and Space Administration

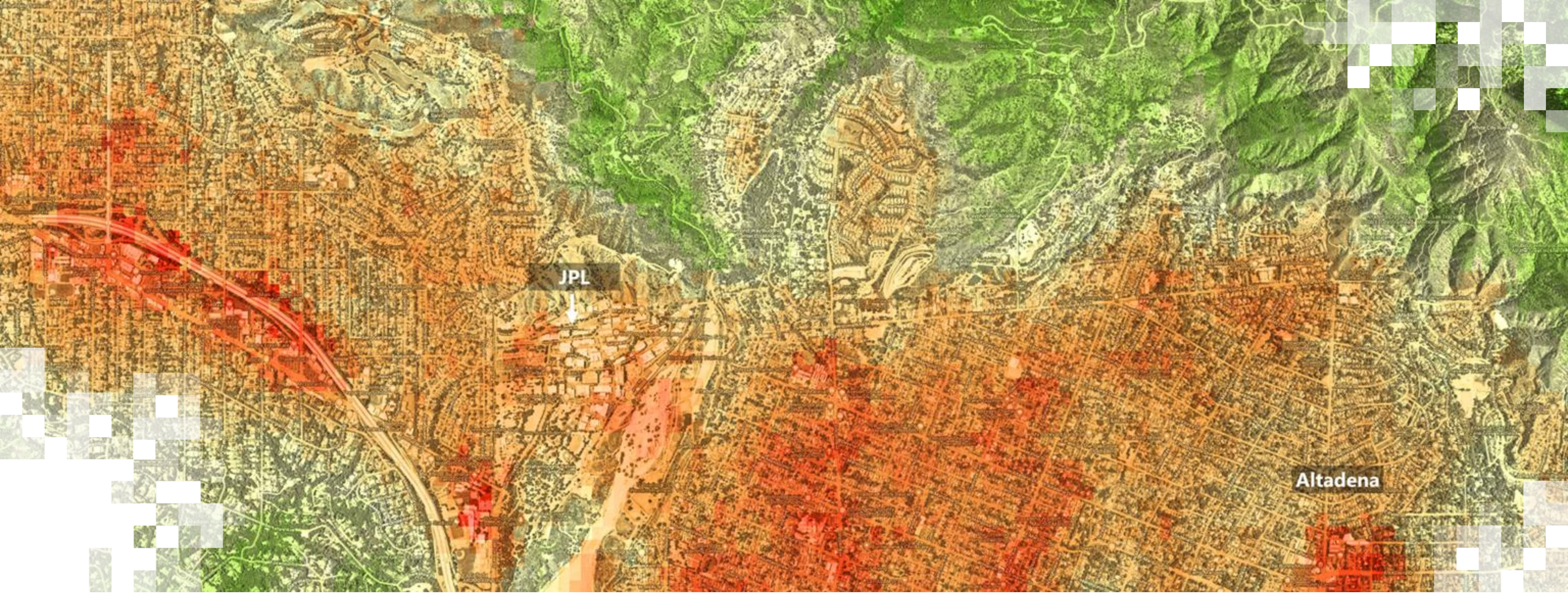


Introduction to Thermal Remote Sensing and Applications in Urban Heat Island Mapping

Part 1: Foundational Concepts of Thermal Remote Sensing

Savannah Cooley, Ph.D. (NASA Ames Research Center, Bay Area Environmental Research Institute),
Glynn Hulley, Ph.D., (NASA Jet Propulsion Laboratory, California Institute of Technology)

May 26, 2026



About ARSET

About ARSET

- **ARSET provides accessible, relevant, and cost-free training on remote sensing satellites, sensors, methods, and tools.**

- Trainings include a variety of applications of satellite data and are tailored to audiences with a variety of experience levels.

AGRICULTURE

DISASTERS

ECOLOGICAL CONSERVATION

HEALTH & AIR QUALITY

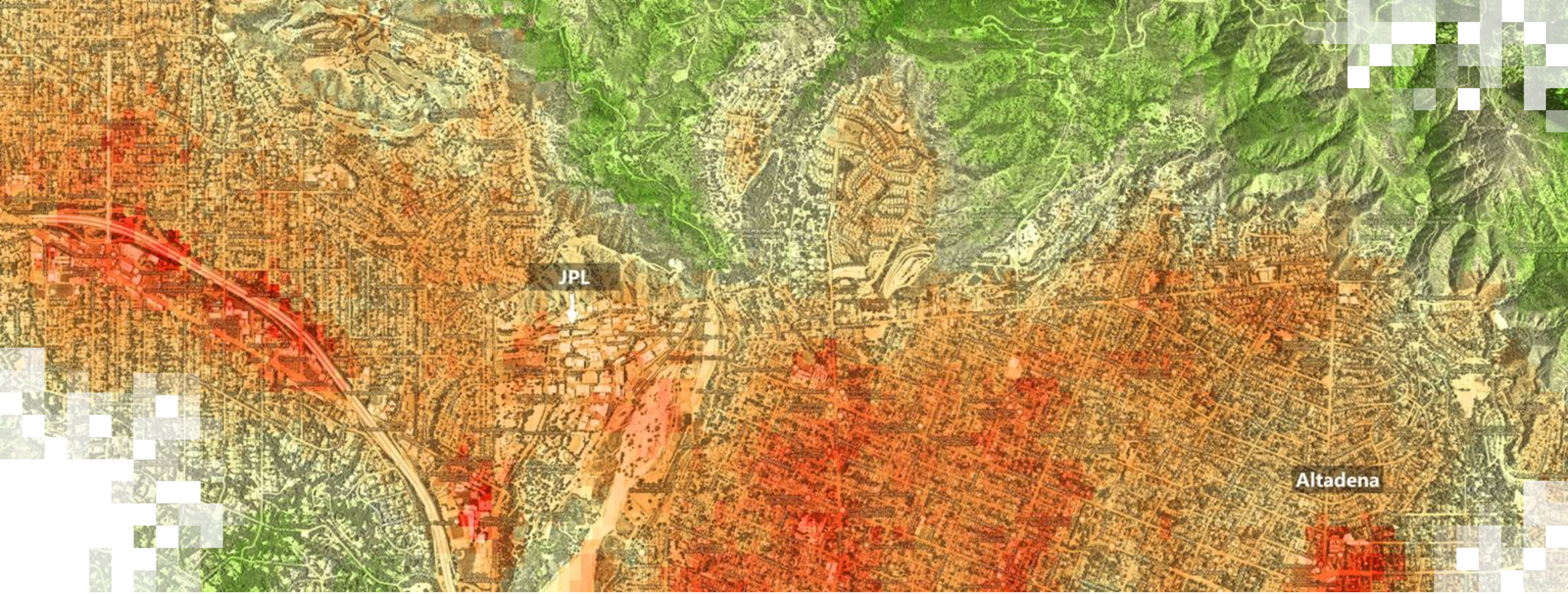
WATER RESOURCES

WILDLAND FIRES

About ARSET Trainings

- Online or in-person
- Live and instructor-led or asynchronous and self-paced
- Cost-free
- Bilingual and multilingual options
- Only use open-source software and data
- Accommodate differing levels of expertise

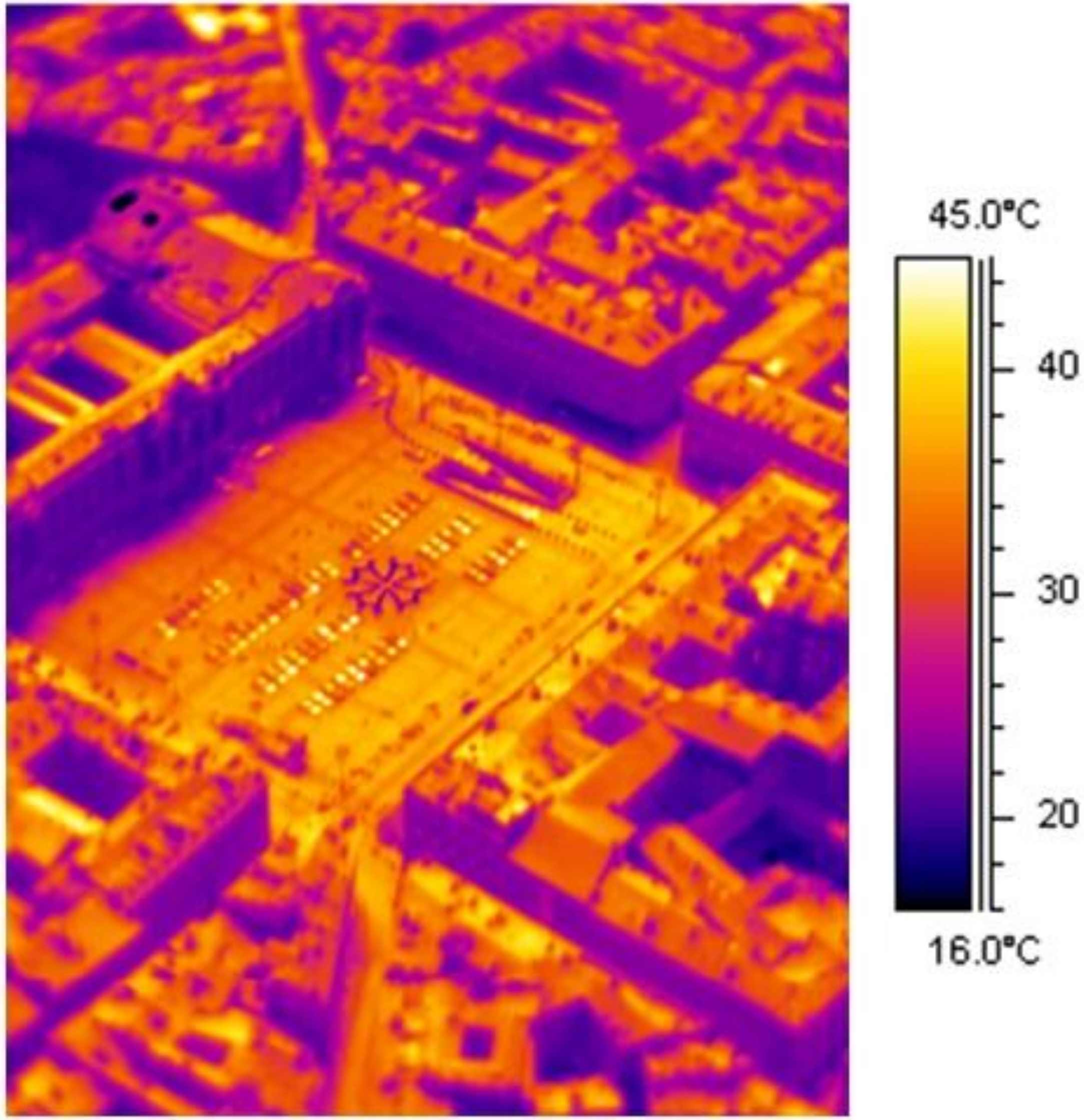
- Visit the ARSET website to learn more.



Introduction to Thermal Remote Sensing and Applications in Urban Heat Island Mapping

Overview

Thermal Infrared 'Vision'



Occitan cross, Toulouse square

Image credit: Jean-Pierre Lagouarde, INRA

Training Learning Objectives

By the end of this training, participants will be able to:

Part 1

- **Identify the fundamental concepts and physical principles** of thermal infrared remote sensing.
- **Define the role of emissivity retrievals** in ensuring the accuracy of satellite-derived land surface temperature products.
- **Distinguish key differences between thermal and optical remote sensing approaches**, including emission vs. reflection, day/night capability, and atmospheric window considerations.
- **Identify applications of thermal remote sensing data** for ecosystems stewardship, agricultural management, climate adaptation and urban planning.
- **Compare the characteristics of current and upcoming thermal missions** in context of their suitability to different application use cases.

Part 2

- **Filter and visualize ECOSTRESS Land Surface Temperature (LST) data** using provided R-based data processing workflows.
- **Downscale native 70m ECOSTRESS LST data to a fine 10m spatial resolution** using a Random Forest machine learning model implemented on an interactive Google Earth Engine (GEE) interface to analyze neighborhood-level urban heat patterns.

Prerequisites

- Fundamentals of Remote Sensing

Suggested Trainings

- For learning about Heat Vulnerability Indices:
  - Satellite Remote Sensing for Measuring Urban Heat Islands and Constructing Heat Vulnerability Indices
- For an introduction to the ECOSTRESS mission:
  - ARSET ECOSTRESS training
- For basics of accessing ECOSTRESS data:
  - LPDAAC tutorials

Training Outline

Session 1

Foundational Concepts in Thermal Remote Sensing

May 26, 2026

11 AM - 1 PM EDT &

2 PM – 3:30 PM EDT

Session 2

Downscaling ECOSTRESS Land Surface Temperature for Urban Heat Island Applications

June 2, 2026

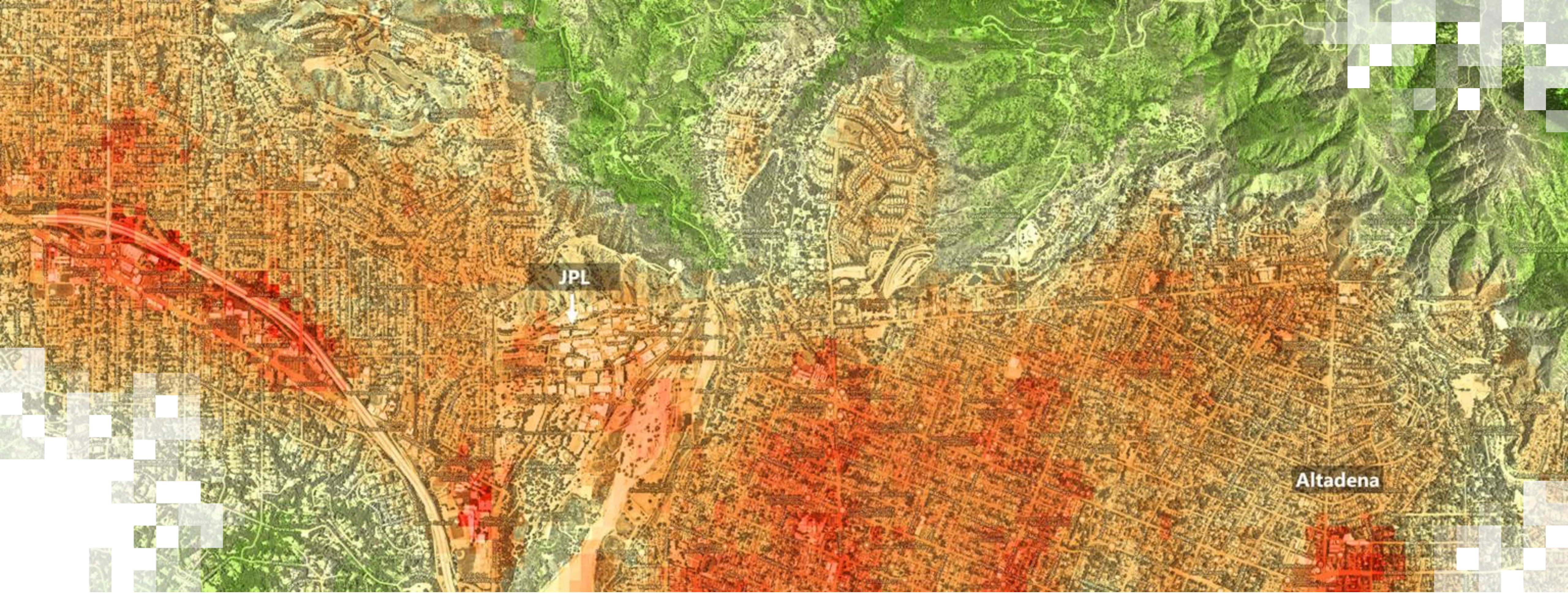
11 AM - 1 PM EDT &

2 PM – 3:30 PM EDT

Homework

Opens June 2 – Due June 16 – Posted on Training Webpage

A certificate of completion will be awarded to those who attend all live sessions and complete the homework assignment(s) before the given due date.



Introduction to Thermal Remote Sensing and Applications in Urban Heat Island Mapping

Part 1: Foundational Concepts in Thermal Remote Sensing

Part 1 – Trainers

Savannah Cooley

Research Scientist

NASA Ames Research Center / BAERI

Glynn Hulley

Research Scientist

NASA Jet Propulsion Laboratory

Part 1 Objectives

By the end of Part 1, participants will be able to:

- **Identify the fundamental concepts and physical principles of thermal infrared remote sensing**.
- **Define the role of emissivity retrievals** in ensuring the accuracy of satellite-derived land surface temperature products.
- **Distinguish key differences** between thermal and optical remote sensing approaches, including emission vs. reflection, day/night capability, and atmospheric window considerations.
- **Identify applications of thermal remote sensing data** for ecosystems stewardship, agricultural management, climate adaptation and urban planning.
- **Compare the characteristics of current and upcoming thermal missions** in context of their suitability to different application use cases.

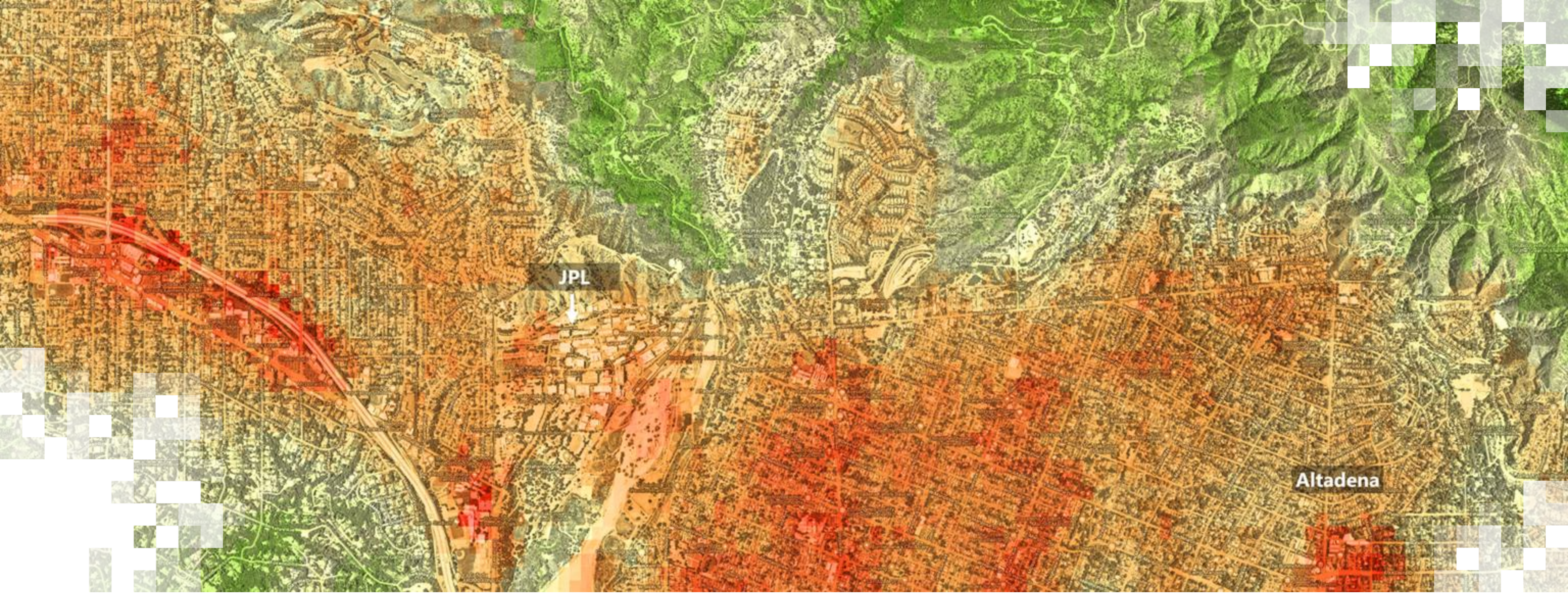
Review of Prior Knowledge

Thermal remote sensing data can be used for…

- A) Detecting visible light reflected from Earth's surface
- B) Estimating land surface temperature (LST)
- C) Measuring surface reflectance in the 5-7 micrometer wavelength range of the electromagnetic spectrum
- D) Mapping soil moisture

How to Ask Questions

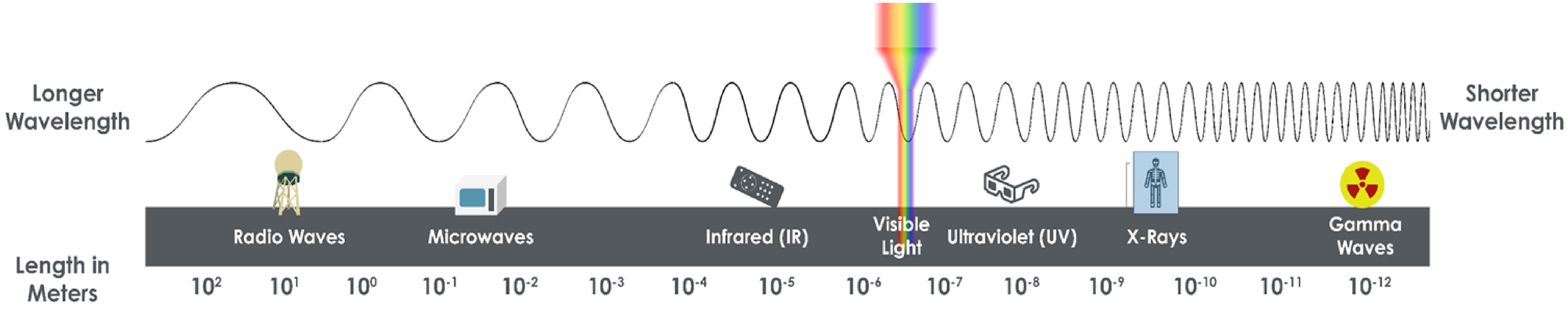
- Please put your questions in the Questions box and we will address them at the end of the webinar.
- Feel free to enter your questions as we go. We will try to get to all of the questions during the Q&A session after the webinar.
- The remainder of the questions will be answered in the Q&A document, which will be posted to the training website about a week after the training.



Part 1: Foundational Concepts in Thermal Remote Sensing

Section 1: The Theoretical Basis of Temperature Measurements

The Electromagnetic Spectrum



Source: Alavipanah et al., 2009

Atmospheric Interferance

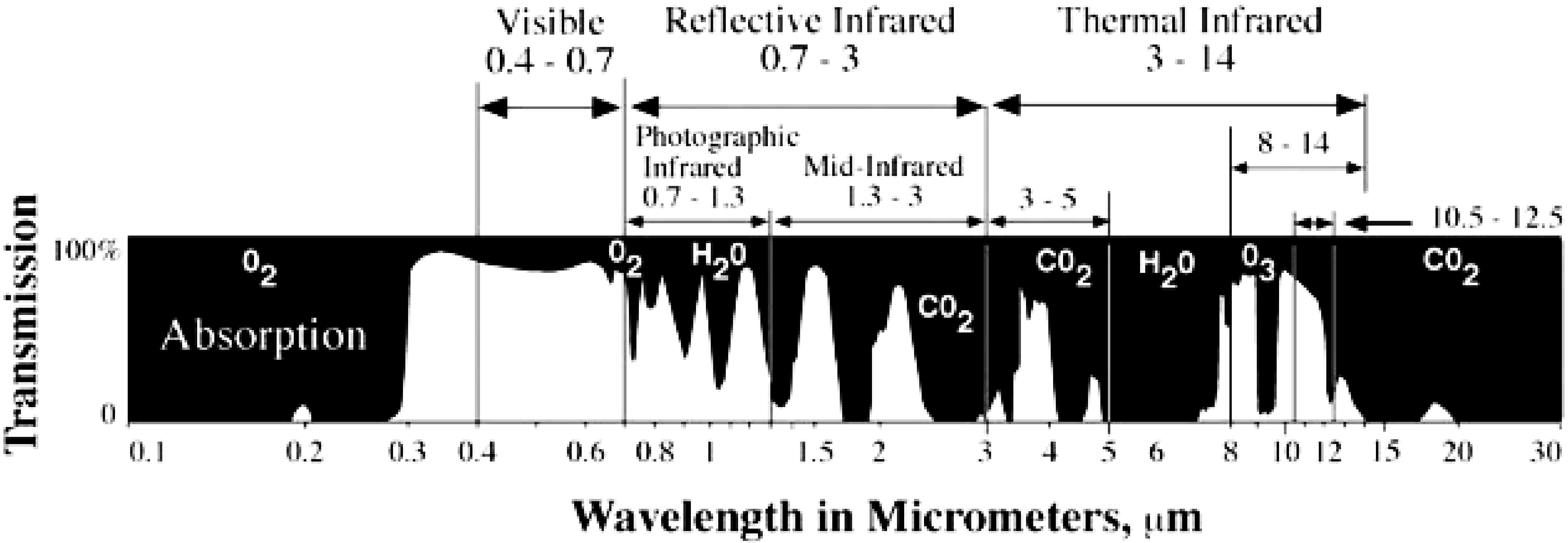
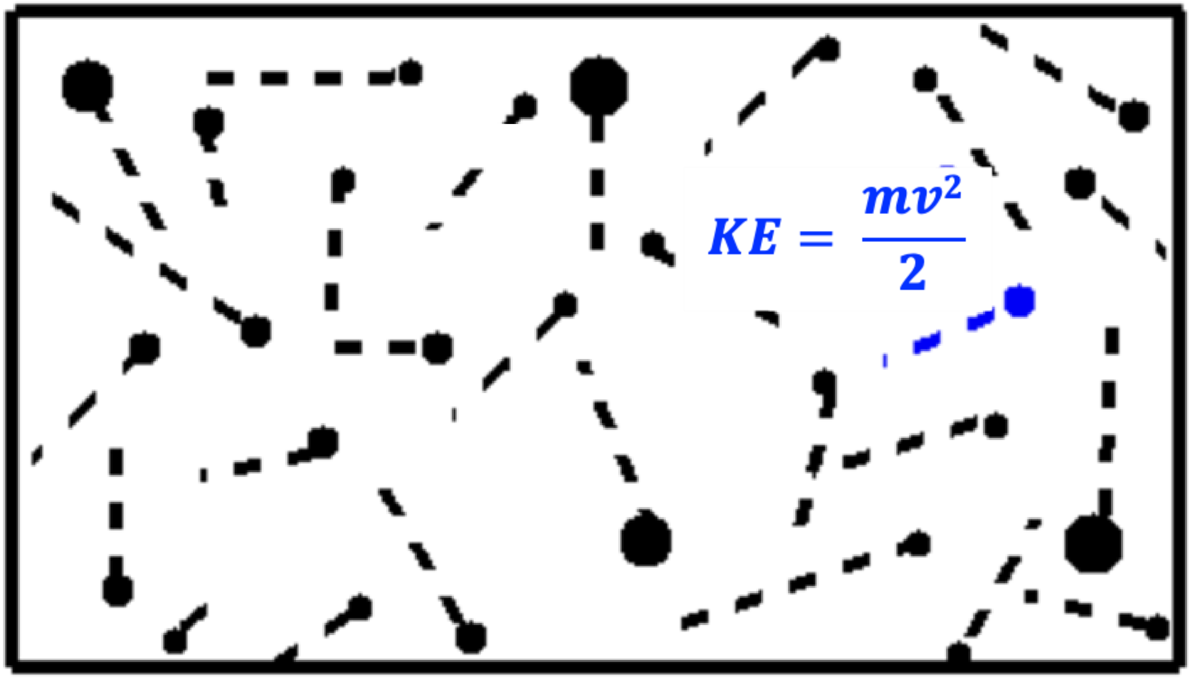


Fig. 1. Atmospheric windows in the electromagnetic spectrum

Source: Alavipanah et al., 2009

What is Temperature?

- **The average kinetic energy (KE) of molecular motion** within a substance



Credit: NASA Glenn Research Center

$$KE = \frac{3}{2} k\, T$$

Where:

KE = Kinetic energy

k = Boltzmann's constant

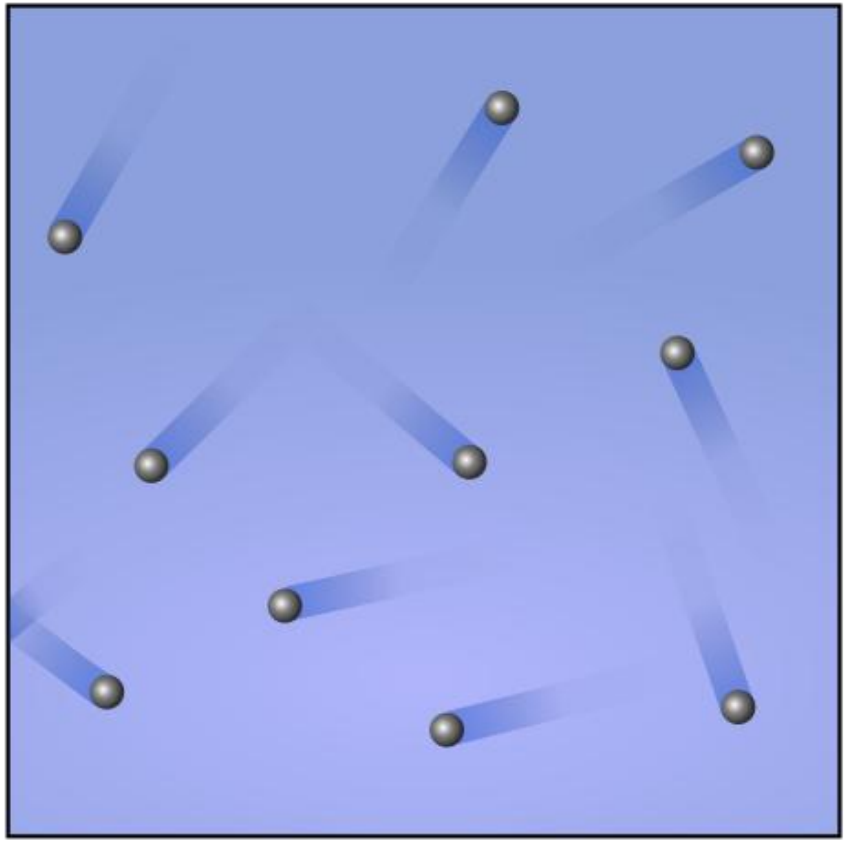
T = absolute temperature

Temperature Scales

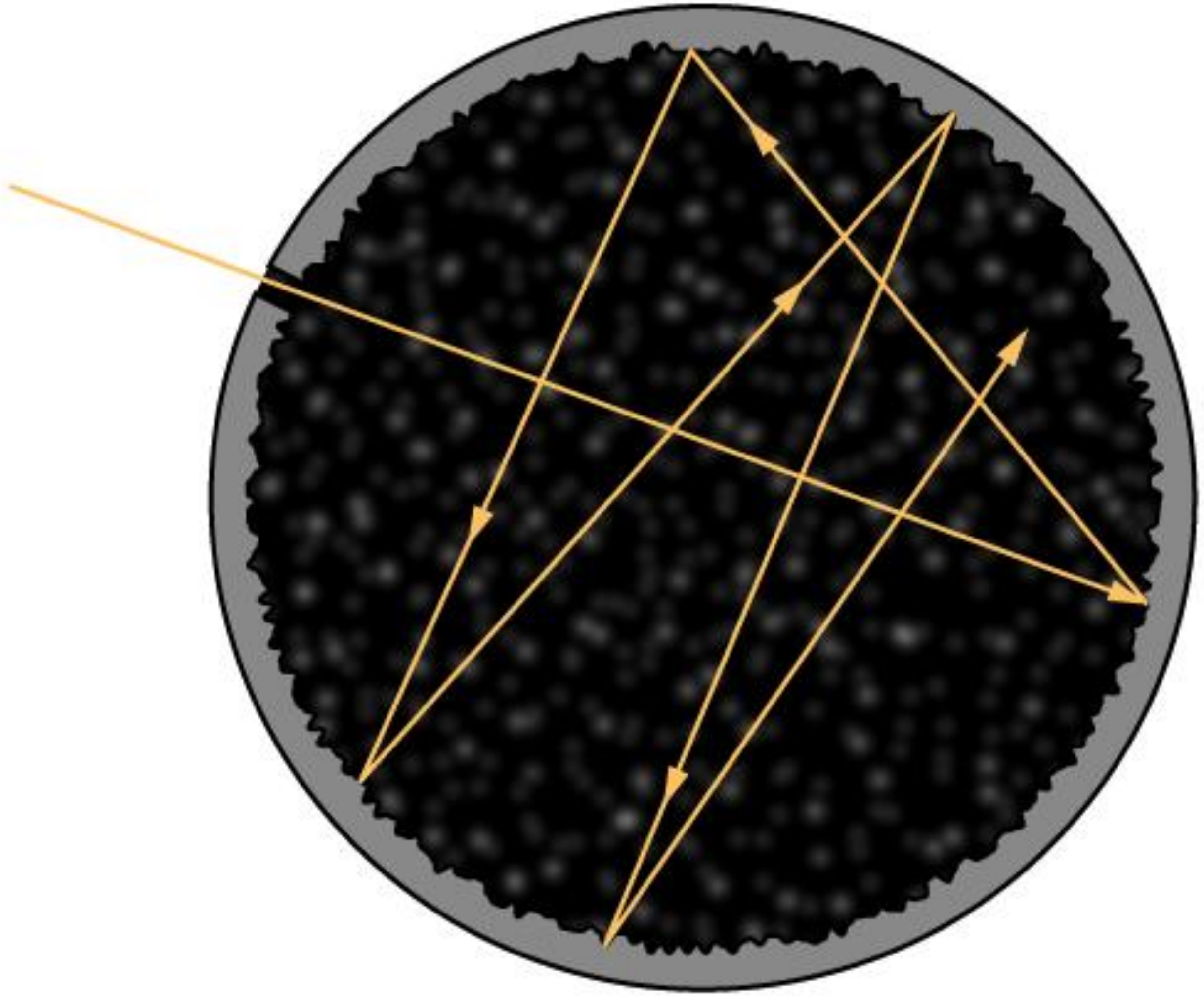
Reference point	Temperature
Absolute zero	0 K = -273.15°C
Water freezing	273 K = 0°C
Typical Earth surface range	250-320 K
Water boiling	373 K = 100°C

From Kinetic Energy to Thermal Radiation

- Molecules above absolute zero are in constant random motion
- The motion causes charged particles to accelerate
- Accelerating charges radiate electromagnetic energy
- The hotter the object, the more vigorous the molecular motion, and therefore the more radiation emitted

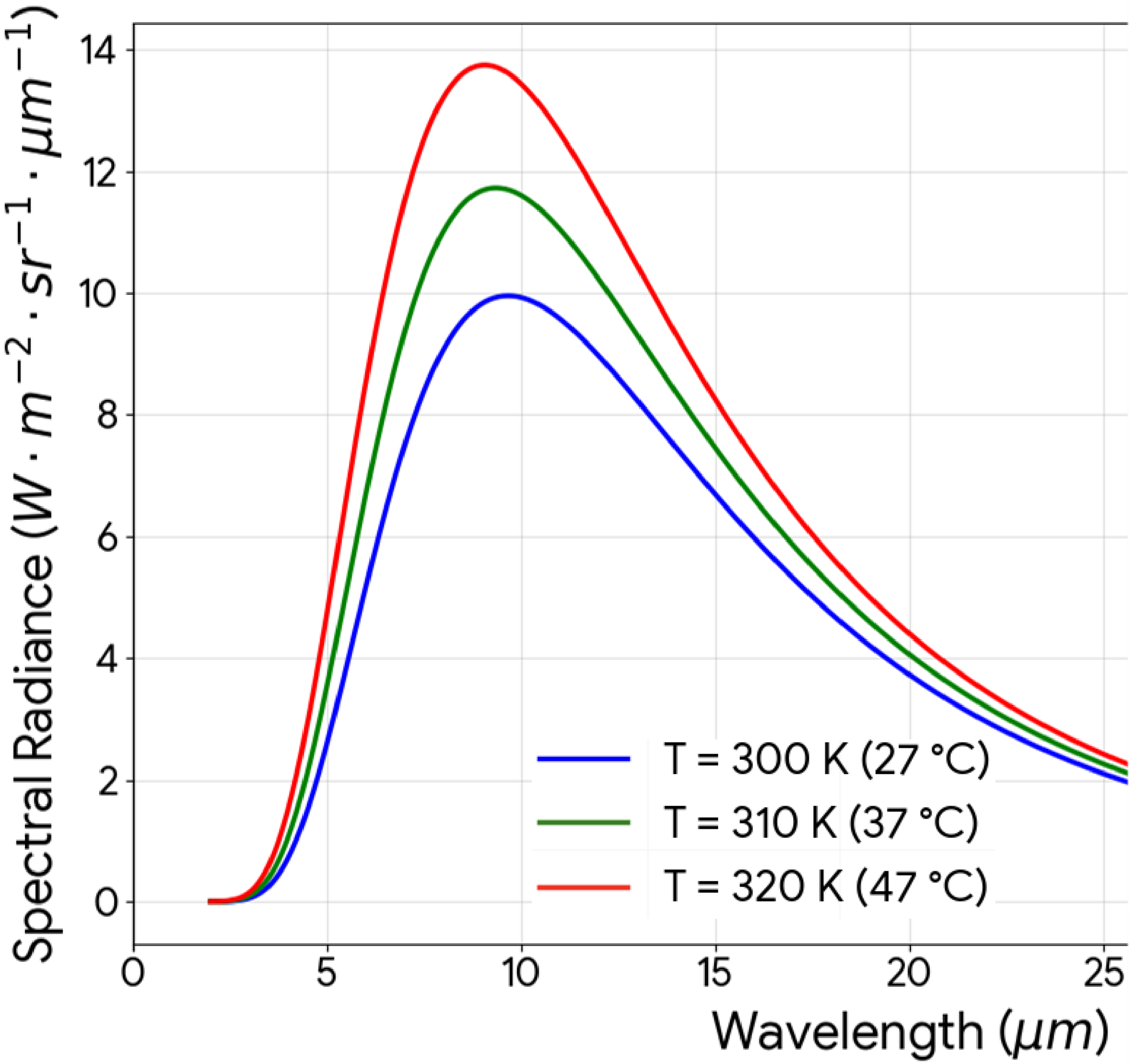


Blackbody Radiation Concept



Credit: Samuel J. Ling, Jeff Sanny, and William Moebs

Planck's Radiation Law



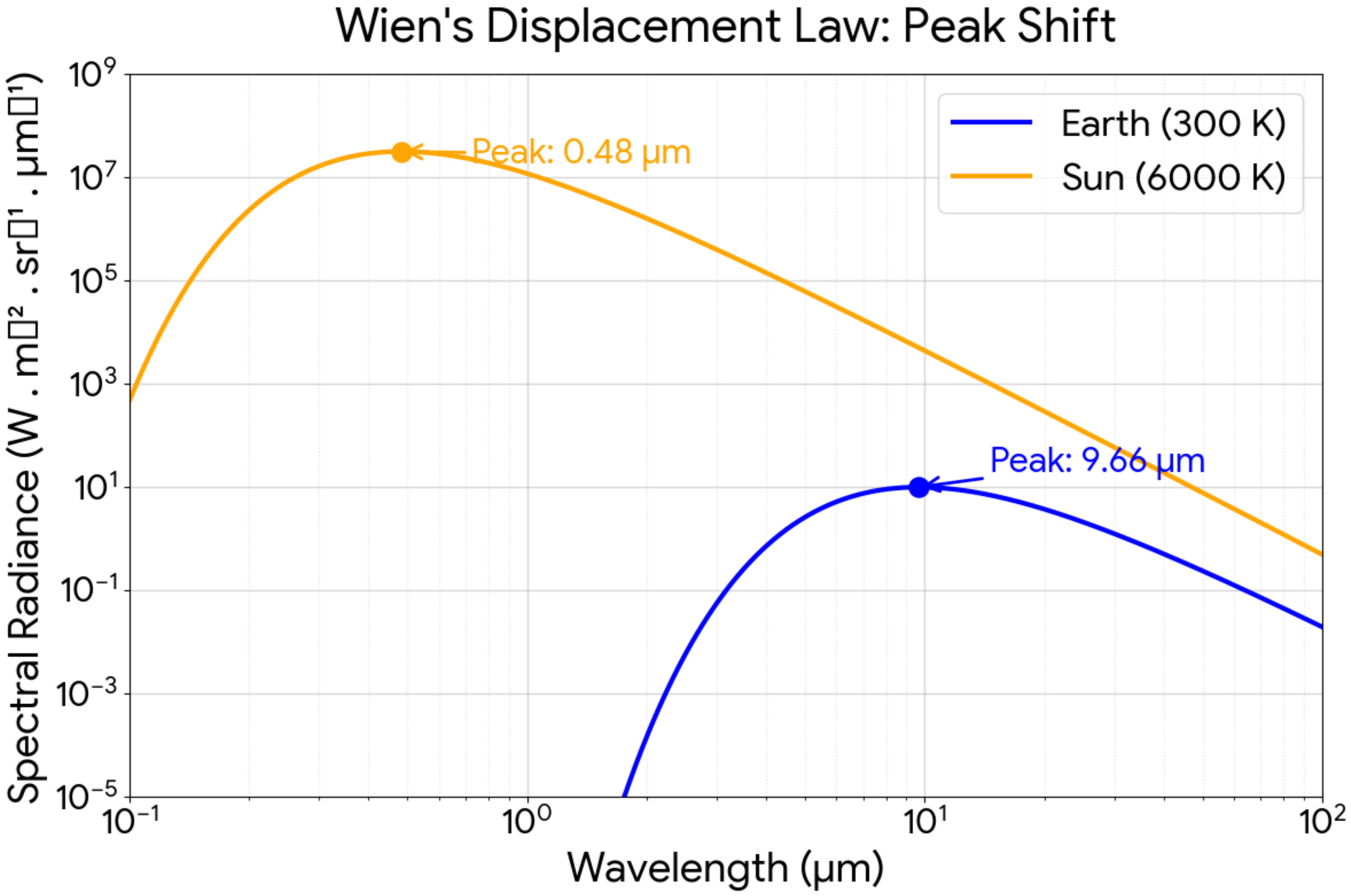
$$B(\lambda, T) = \frac{2hc^2}{\lambda^5}\left(\left(e^{\frac{hc}{\lambda kT}}\right)^{-1} - 1\right)$$

- B (λ,T) is spectral radiance: the power emitted per unit area, per unit solid angle, per unit wavelength (watts/meter$^{2/}$ steradian/ micrometer).
- λ is wavelength (micrometers)
- T is absolute temperature (Kelvin)
- h is Planck's constant, 6.626 x 10^-34 joule-seconds
- c is speed of light, approx. 3 x 10^8 meters per second
- k is Boltzmann's constant, 1.381 x 10^-23 joules per Kelvin
- e is the base of the natural logarithm, approximately 2.718

Wien's Displacement Law

$$\lambda max = \frac{b}{T}$$

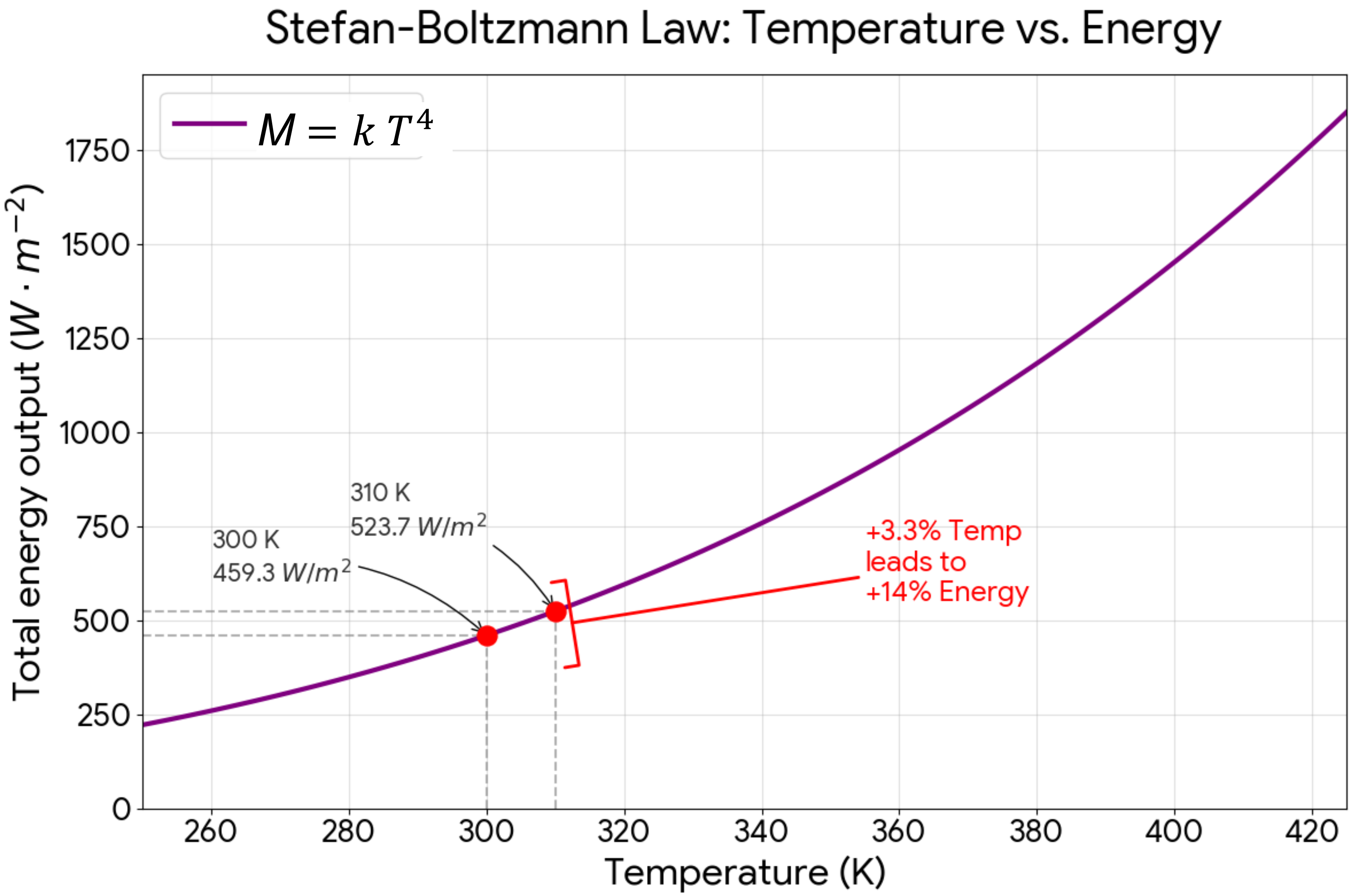
- λmax is the wavelength of peak emission, in micrometers.
- T is the absolute temperature in K.
- b is Wien's displacement constant, equal to 2,898 micrometer-Kelvin. This is a derived constant that comes from finding the maximum of Planck's function



Stefan-Boltzmann Law

$$M = \epsilon\sigma T^4$$

- M (Radiant Exitance): total power emitted per unit area, measured in Watts per square meter
- ϵ (Emissivity): the efficiency factor, ranging from 0 to 1
- σ (Stefan-Boltzmann Constant): derived constant
- T (Temperature): The absolute temperature in Kelvin



Radiometric vs. Kinetic Temperature

Planck^{-1} | *Integrated across all wavelengths* | *Emissivity correction*

$$Radiance \rightarrow T_{Brightness} \rightarrow T_{Radiometric} \approx T_{Kinetic}$$

Temperature Type	Symbol	Definition	What it reflects
Kinetic Temperature	T_kin	True physical temperature of the surface (emissivity ε correction applied)	Actual molecular motion/ internal energy
Brightness Temperature	T_B	Temperature of a blackbody needed to emit the observed radiance at a given wavelength	Raw satellite measurement (assumes ε= 1)
Radiometric Temperature	T_rad	The "apparent" temperature across all wavelengths (via Stefan-Boltzmann)	Satellite-based LST products

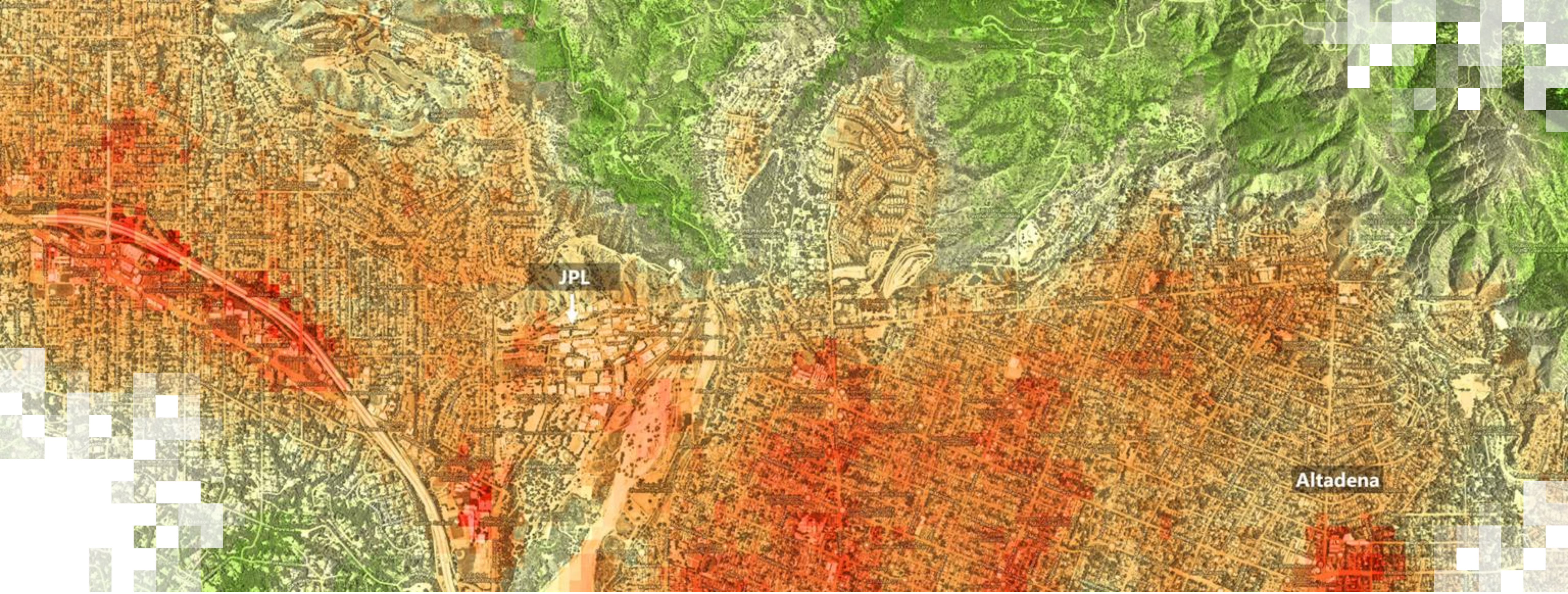
$$T_{rad} = \varepsilon^{1/4}\, T_{kin}$$

Since ε < 1 for all of Earth's surfaces, T_rad < T_kin.

Knowledge Check

To convert measured radiance to kinetic temperature, what additional information is needed?

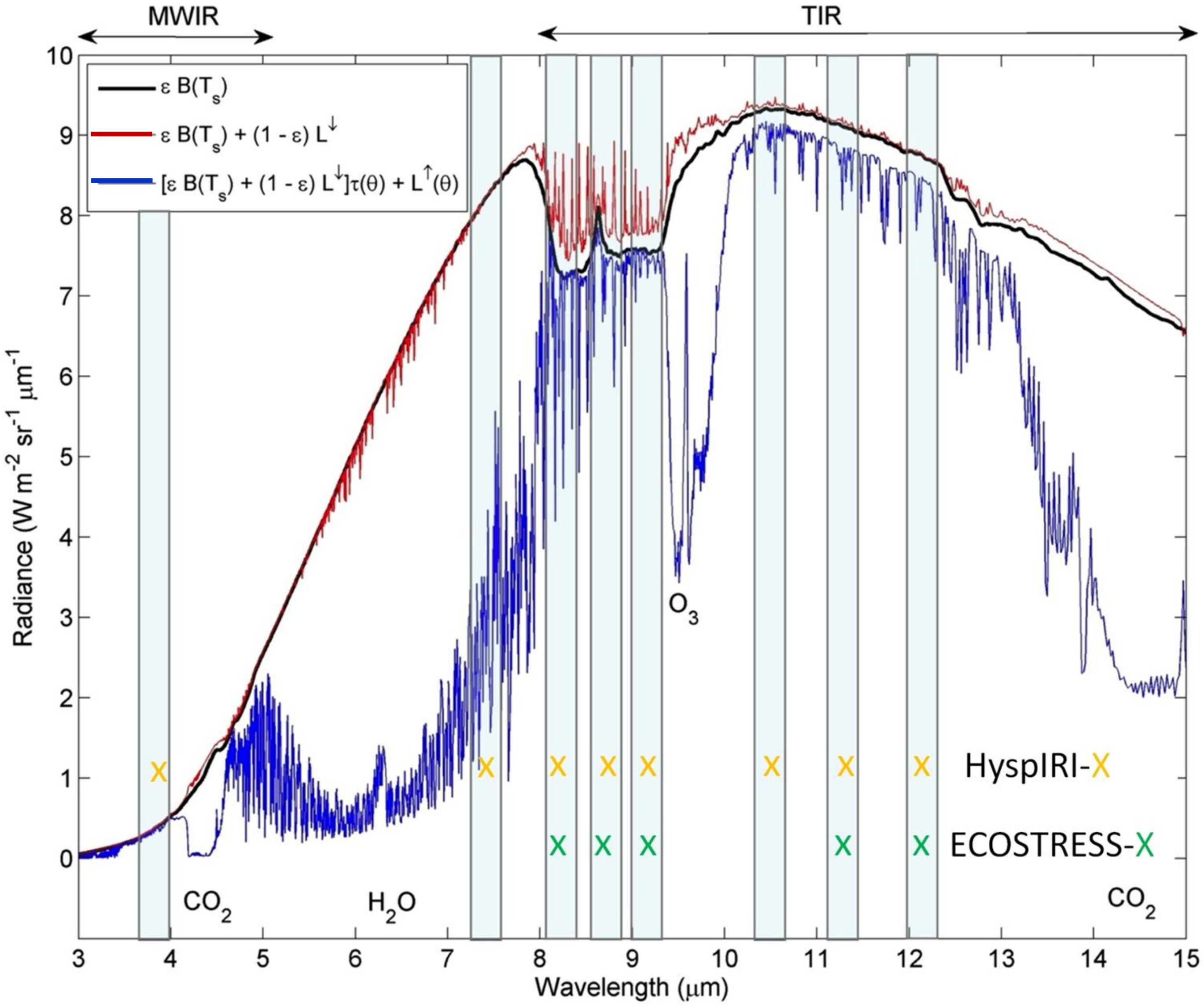
- A) Surface reflectance
- B) Surface emissivity
- C) Sun angle
- D) Viewing angle only



Part 1: Foundational Concepts in Thermal Remote Sensing

Section 2: Emissivity

Thermal Infrared Radiative Transfer



Credit: Hulley, Hook, Realmuto & Cawse-Nicholson (2020)

Surface Emissivity

Blackbody Radiance

$$L_\lambda = B_\lambda(T_s)$$

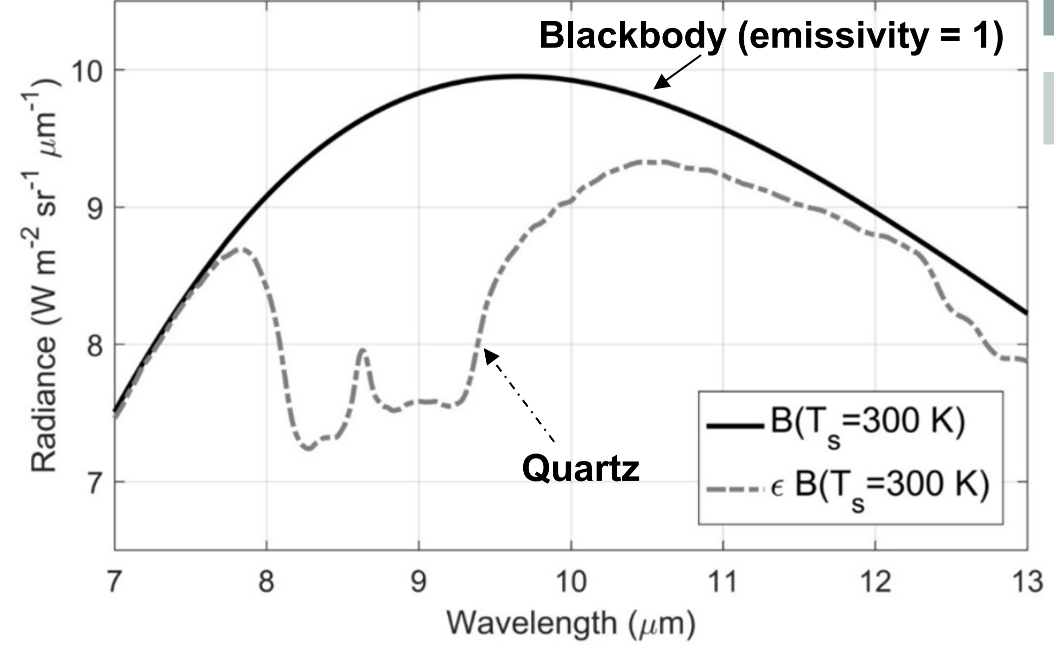
Planck

Spectral Emissivity

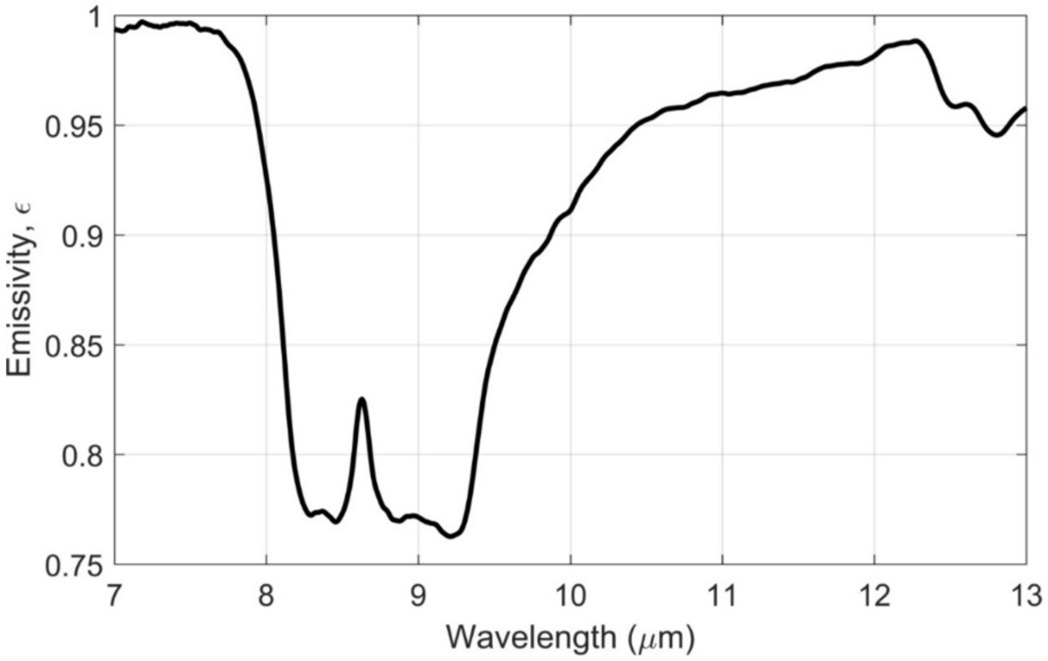
ratio of the spectral radiance of a material to that of a blackbody at the same temperature:

$$\varepsilon_\lambda = \frac{L_\lambda(\text{Material})}{L_\lambda(\text{Blackbody})}$$

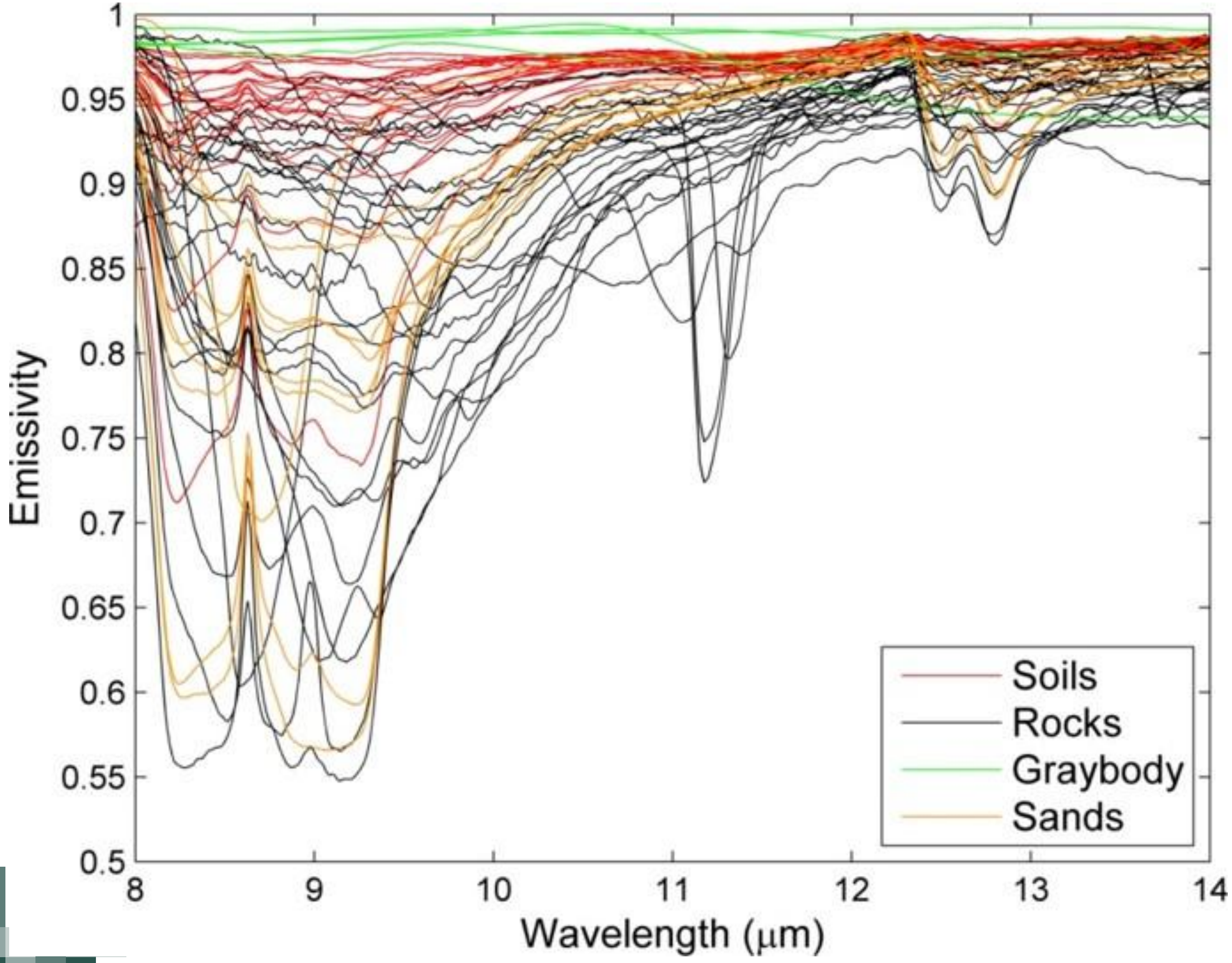
L_λ



ε_λ



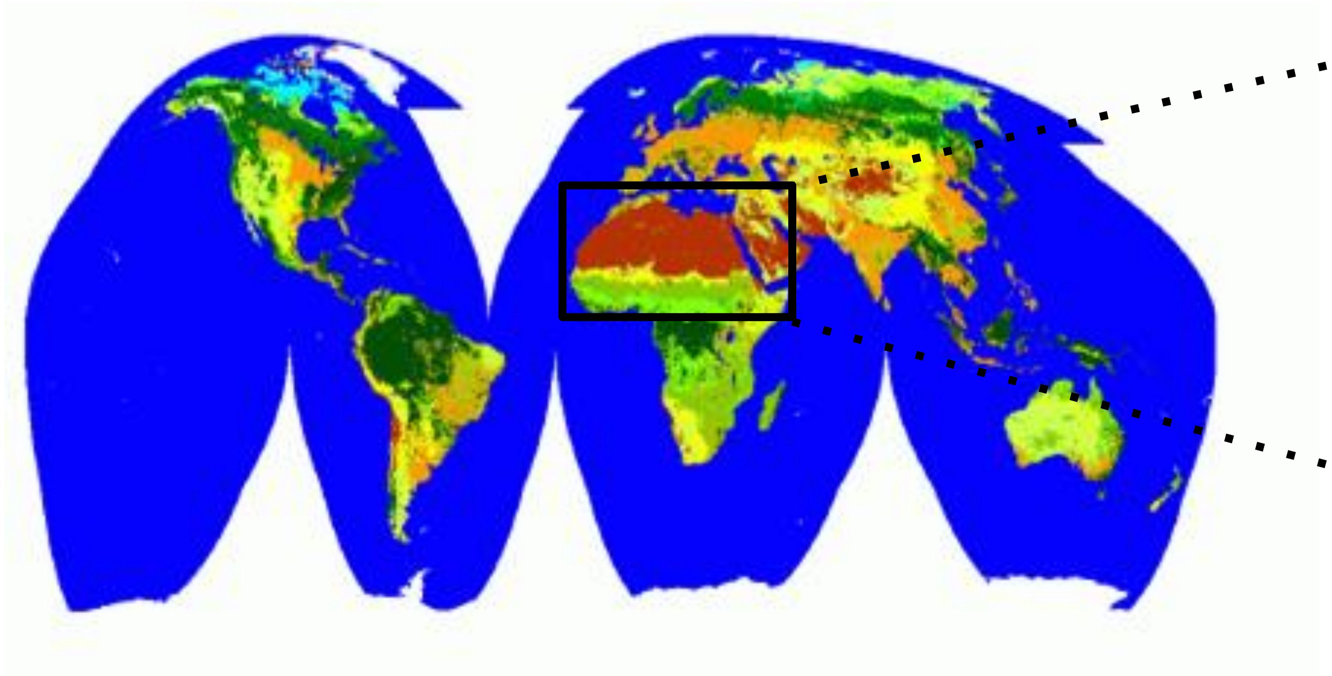
Emissivity for most natural surfaces varies from ~0.55-1



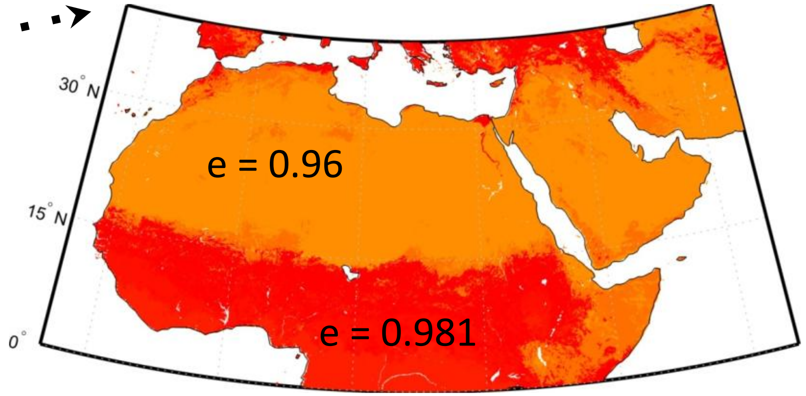
Sources:

- Meerdink, S. K., Hook, S. J., Roberts, D. A., & Abbott, E. A. (2019). The ECOSTRESS spectral library version 1.0. Remote Sensing of Environment, 230(111196), 1–8.
- Baldridge, A. M., S.J. Hook, C.I. Grove and G. Rivera, 2009.. The ASTER Spectral Library Version 2.0. Remote Sensing of Environment, vol 113, pp. 711-715.

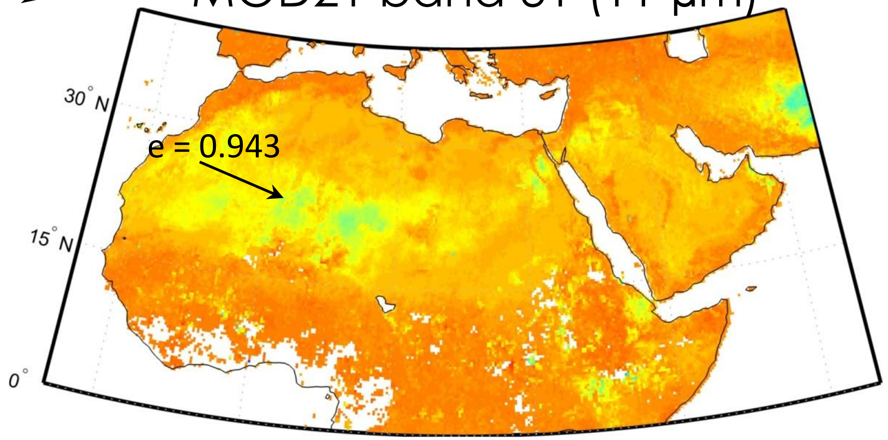
Emissivity: Split-Window versus TES retrieval



Split-window:
MOD11 band 31 (11 µm)



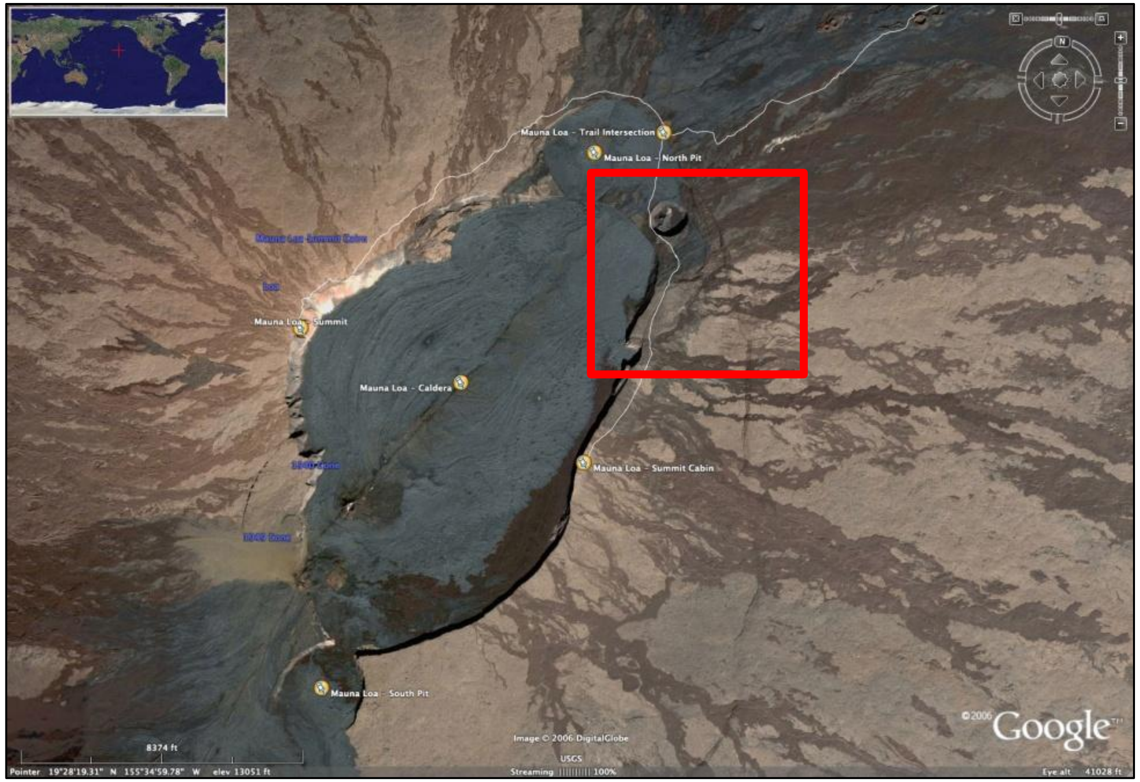
TES Retrieval:
MOD21 band 31 (11 µm)

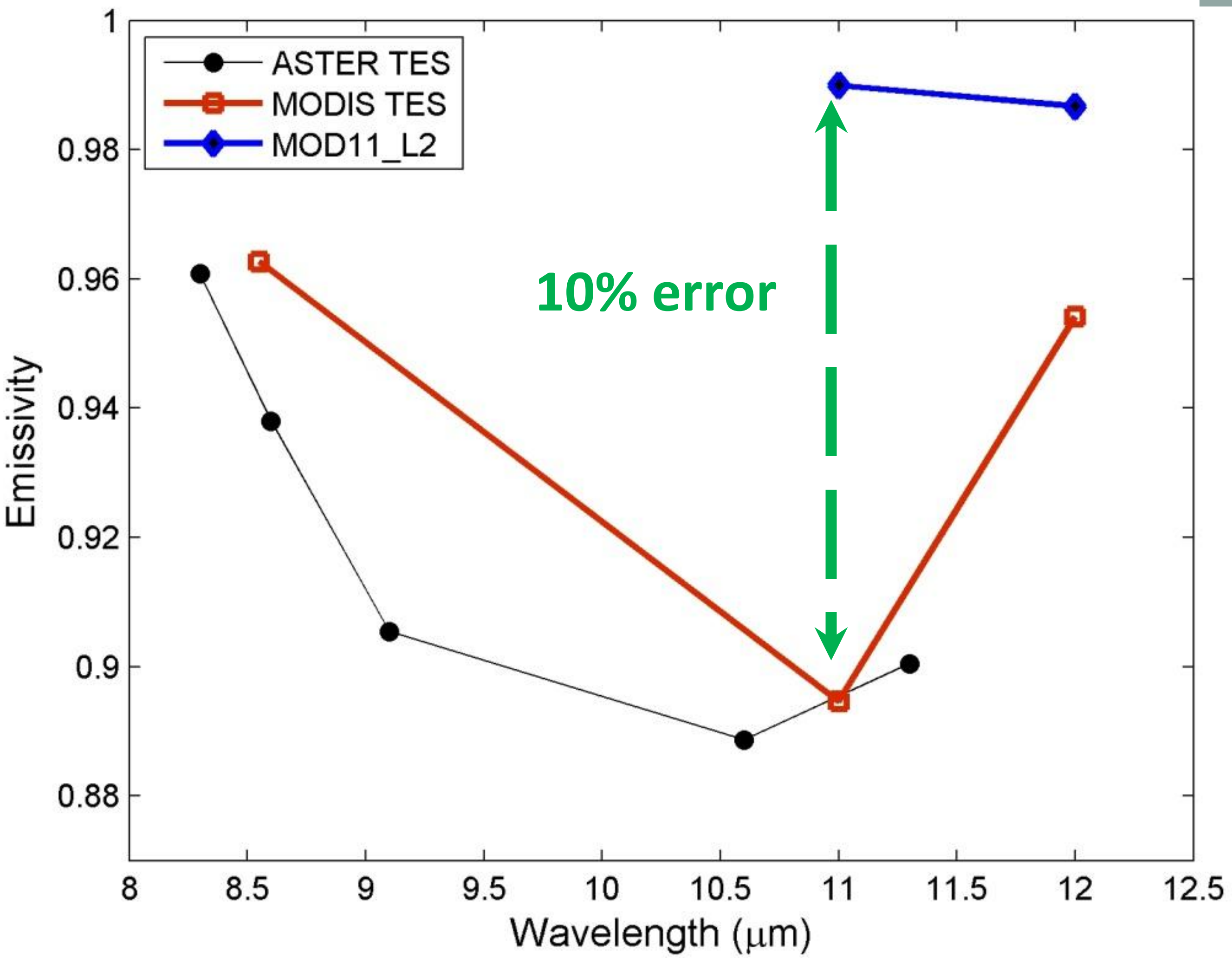


Credit: Hulley, Hook, Realmuto & Cawse-Nicholson (2020)

Temperature errors as a result of incorrect emissivity

Mauna Loa Caldera, Hawaii
Mafic lava flow (basalt)





Credit: Hulley, Hook, Realmuto & Cawse-Nicholson (2020)

Emissivity error propagation into Land Surface Temperature error

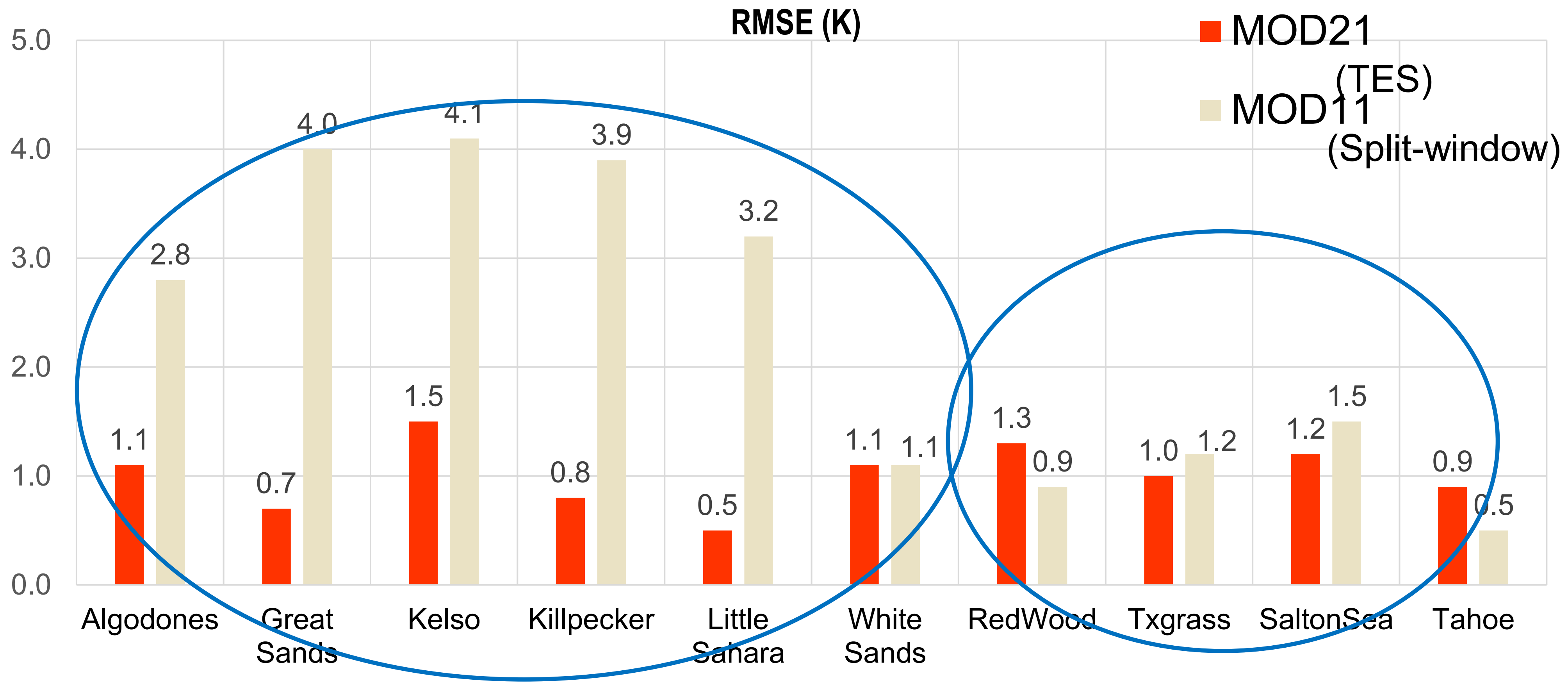
Edvard Munch (1893)

Retrieved temperatures over Mauna Loa Caldera

ASTER_TES:	322 ±1 K
MOD21_TES:	324 ±0.8 K
MOD11_Split:	310 ±0.5 K

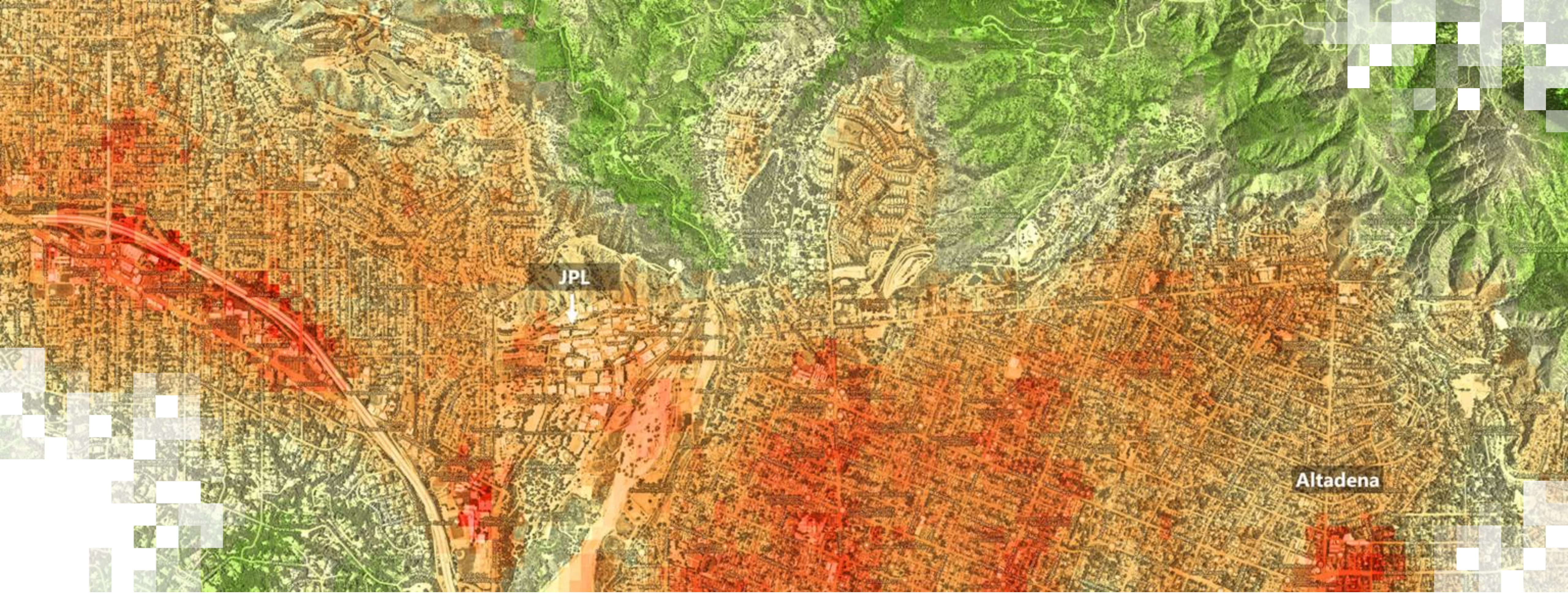
~1.5% emissivity error = ~1 K LST error

MODIS LST Validation Summary (2000-2018)



MOD11 Split-window cold bias over bare regions (3-5 K)

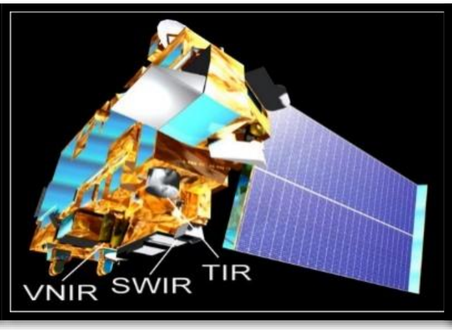
Similar accuracy over vegetation and water of ~1 K



Part 1: Foundational Concepts of Thermal Remote Sensing

Section 3: Current & Future Thermal Missions and Applications

Thermal Infrared Sensors


Platform	Terra/Aqua	Terra	Landsat 4&5, 7, 8 &9	ECOSTRESS	Twin Otter/ER2
Spatial resolution	1000 m	90 m	120m, 60 m, 100 m	38 x 69 m	1 - 30 m
TIR bands	3	5	1,1,2	5	256
Temporal resolution	Daily	16 days	16 days, 8 day offset between Landsat 8/9	3-5 days Diurnal cycle	Dedicated campaigns
Altitude	705 km	705 km	705 km	400 km	1-60 km

TIR Program of Record

High spatial resolution multispectral (3+ bands) TIR program of record

ASTER on Terra
5 TIR bands (8-12 µm)
90 m spatial resolution
16-day repeat cycle

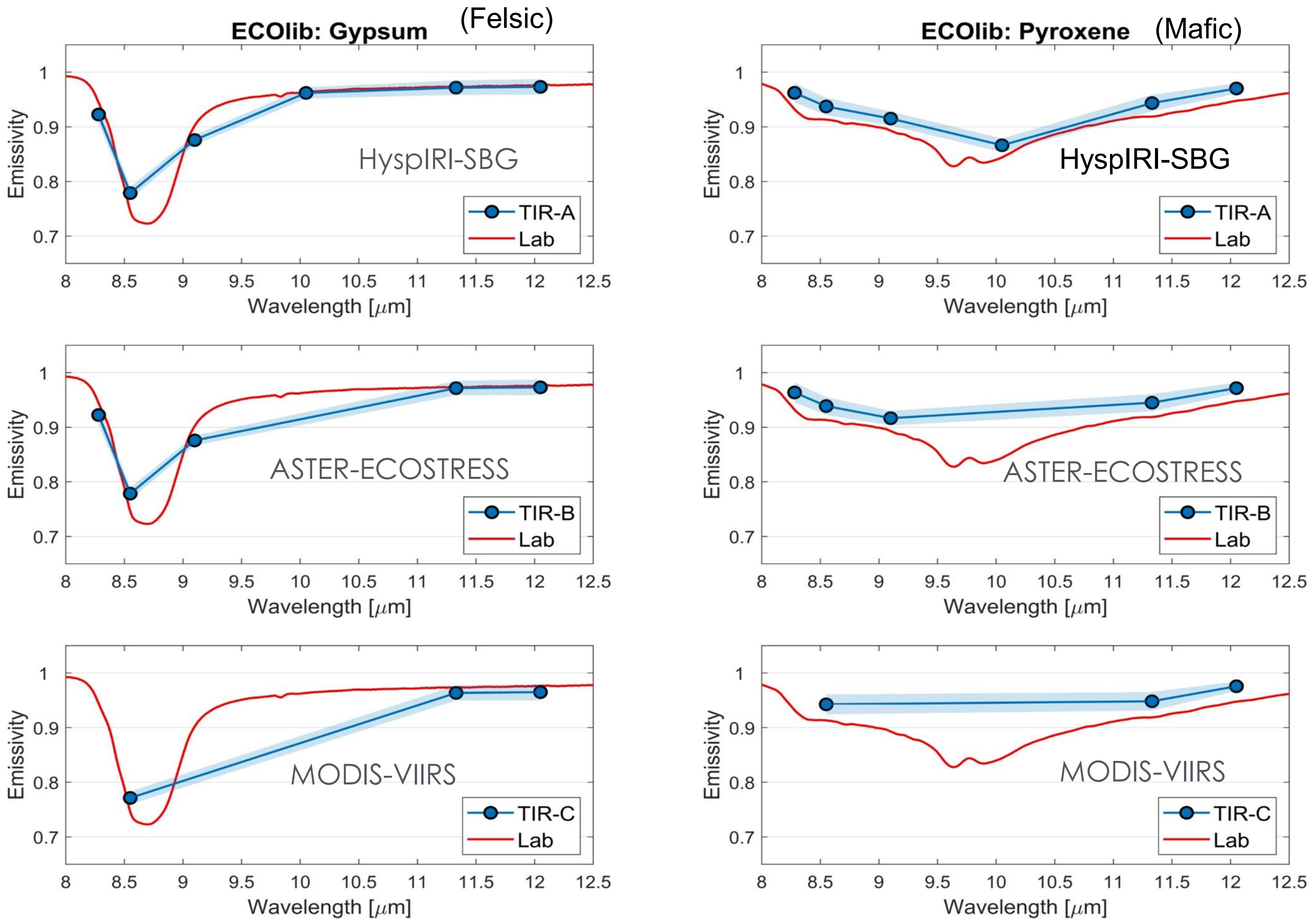
LSTM Copurnicus Expansion
5 TIR bands (8-12 µm) 50 m spatial resolution daily repeat cycle

ECOSTRESS on ISS
5 TIR bands (8-12 µm) 1 SWIR band (1.6 µm) 38x69 m spatial resolution 4-day diurnal repeat cycle

EAGLE-TIR (formerly SBG)
5-7 TIR bands (8-12 µm) 1 MWIR band (4µm) 60 m spatial resolution 3-day repeat cycle

TRISHNA (CNES/ISRO)
4 TIR bands (8-12 µm) 50-60 m spatial resolution 3-day repeat cycle

Emissivity as measured by different thermal sensors



Credit: Hulley, Hook, Realmuto & Cawse-Nicholson (2020)

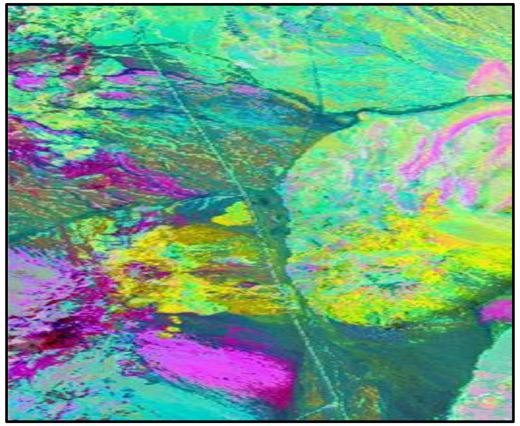
Thermal vs. Optical RS

	Optical RS	Thermal Infrared RS
Energy source	Reflected solar radiation	Emitted thermal radiation from the surface itself
Wavelength range	~0.4–2.5 µm (VIS, NIR, SWIR)	~3–14 µm (MWIR, TIR)
Day/Night capability	Daytime only (requires solar illumination)	Day and night (surface always emits)
Cloud penetration	No	No (clouds block TIR as well)
Primary surface property	Reflectance / albedo; biochemical properties (chlorophyll, moisture)	Land surface temperature (LST); emissivity (composition, mineralogy)
Atmospheric effects	Scattering (Rayleigh, Mie) dominates; aerosols critical	Absorption and emission by H_2O, CO_2, O_3; atmospheric correction essential
Spatial resolution (typical spaceborne)	10–30 m (Sentinel-2, Landsat)	30–1000 m (Landsat, ECOSTRESS, MODIS) — inherently coarser due to lower photon flux
Key applications	Vegetation mapping, land cover classification, surface reflectance products	LST, evapotranspiration, urban heat islands, drought monitoring, fire detection
Sensor noise limitation	Shot noise from solar photons	Thermal noise (NEdT) — signal-to-noise harder to achieve at fine resolution

Applications of Land Surface Temperature (LST) and Emissivity

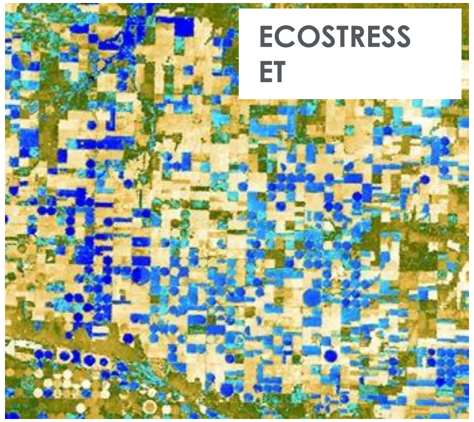
Mineral Mapping

Cawse-Nicholson et al. 2019
Kruse et al. 2015



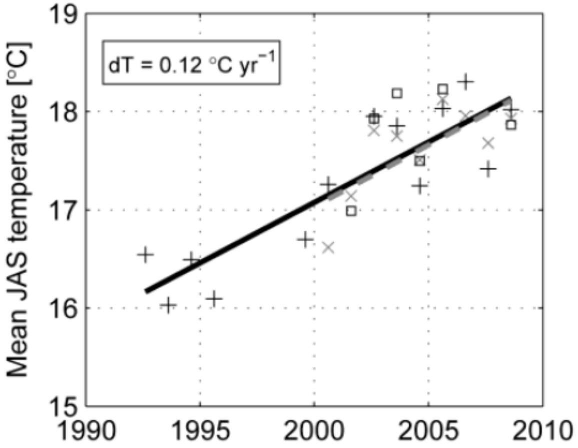
Hydrological modeling

Anderson et al. 2011, Fisher et al. 2019



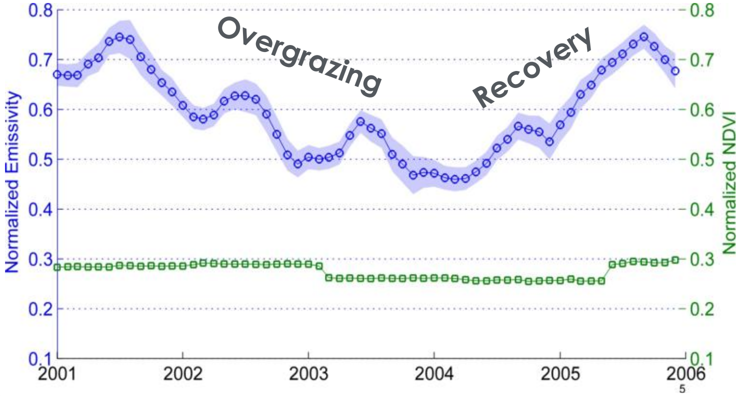
Climate change modeling

Schneider and Hook, 2010,
Hulley and Dousset, 2020



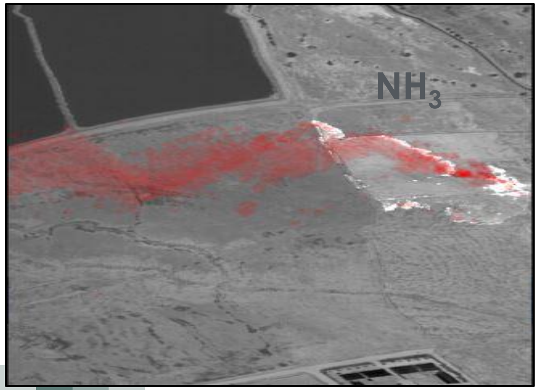
Land use & land cover change

Hulley et al. 2014



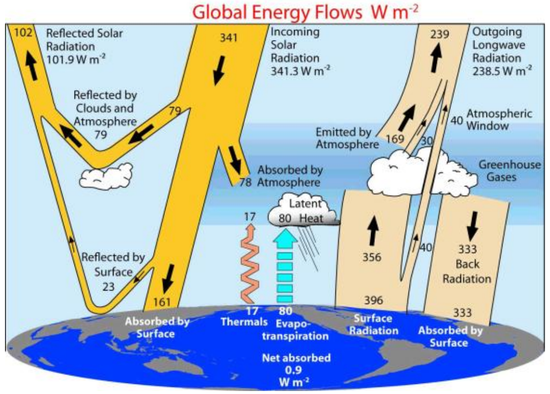
Fire emissions

Kuai et al. 2019



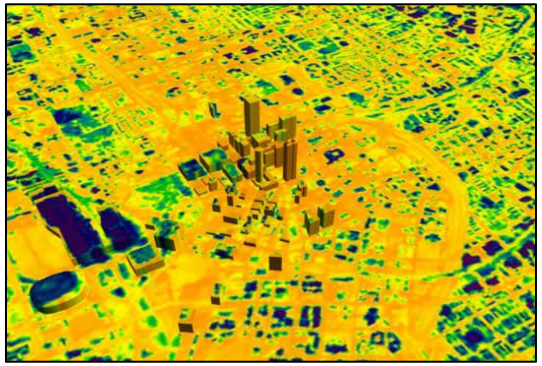
Surface energy balance

Zhou et al. 2003



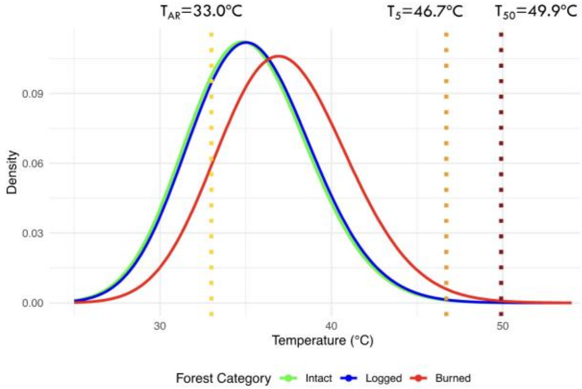
Urban heat island studies

Nichol et al. 2009

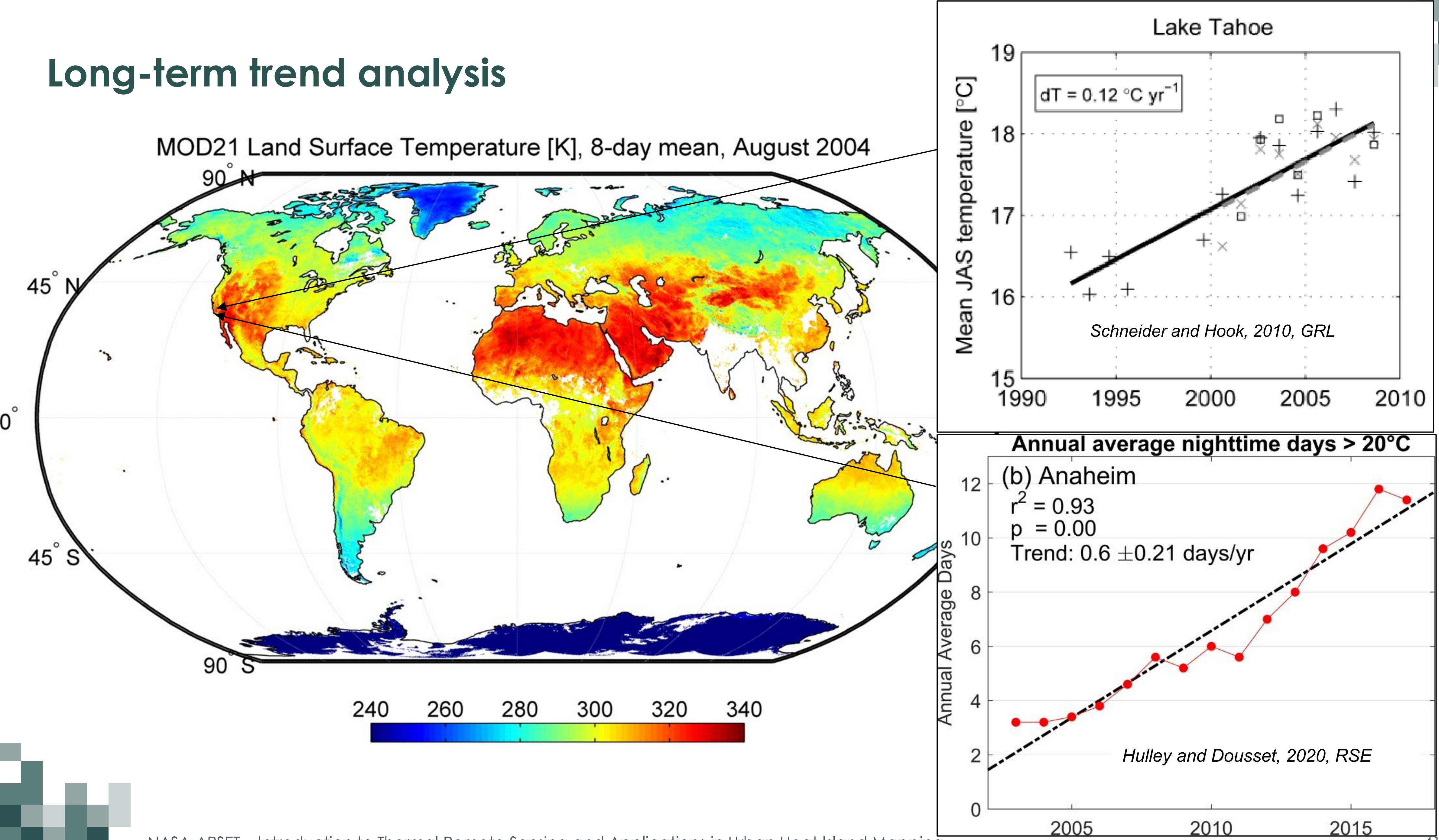


Ecosystem thermal stress

Daughty et al., 2020,
Cooley et al. 2025

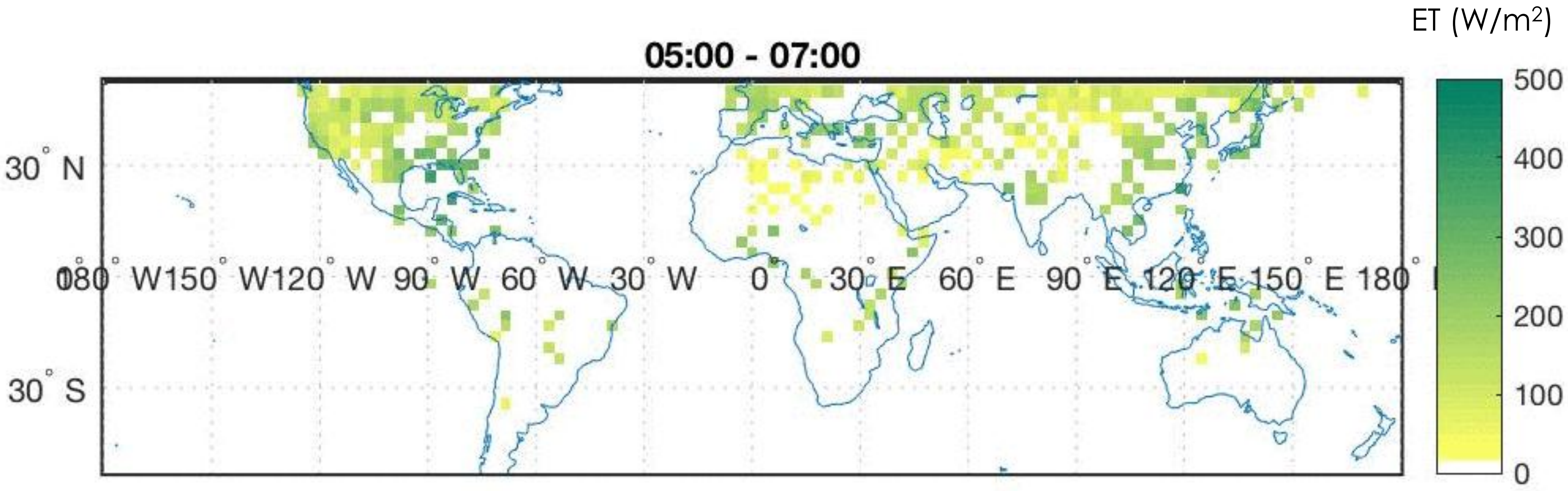


Long-term trend analysis



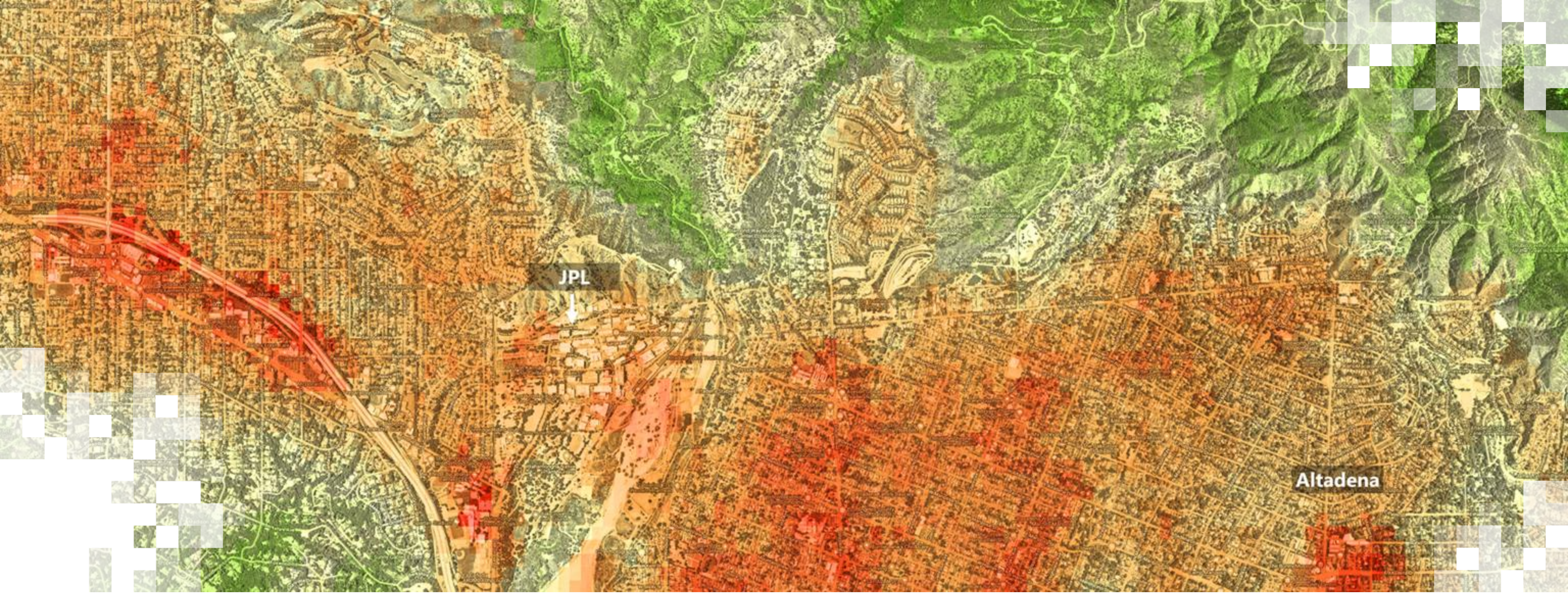
Deriving Evapotranspiration (ET) and other land surface properties

ECOSTRESS Diurnal Temperature for ET estimation



Average evapotranspiration at local time for June – August, 2019.

Hulley, Hook, Realmuto & Cawse-Nicholson (2020)



Part 1: Foundational Concepts of Thermal Remote Sensing

Summary

Summary

- The **thermal infrared window** (8–14 μm) is our primary working range for land surface temperature retrieval — it captures purely emitted energy with no solar contamination
- **Small temperature changes produce large radiance changes**, making TIR sensors highly sensitive
- **Emissivity** varies by material, wavelength, and roughness, and must be accounted for in LST retrieval
- Retrieval approaches
  - **Split-Window**: fast, assumes emissivity; cold bias over bare regions
  - **TES**: simultaneous T and ε retrieval; more accurate over heterogeneous surfaces
- **Land Surface Temperature (LST) critical applications**:
  - **urban heat island mapping**
  - ET estimation
  - ecosystem stress
  - drought monitoring
  - long-term climate trend analysis

Looking Ahead to Part 2

In Part 2, you will:

- Access and download ECOSTRESS LST data using AppEEARS
- Filter ECOSTRESS observations by quality flags in R
- Visualize LST spatial patterns across an urban study area
- Build a Random Forest downscaling model in Google Earth Engine to sharpen native 70 m ECOSTRESS LST to 10 m resolution using Sentinel-2 spectral predictors
- Analyze neighborhood-level urban heat island patterns and interpret differences in thermal exposure across socioeconomic and land cover gradients

Before Part 2, please:

- Ensure you have R and RStudio installed (download links on the training webpage)
- Sign up for a free Google Earth Engine account if you don't already have one
- Review the ECOSTRESS AppEEARS tutorial video linked on the training webpage

Homework and Certificates

- **Homework:**
  - One homework assignment
  - Opens on 02/06/2026
  - Access from the training webpage
  - Answers must be submitted via Google Forms
  - **Due by 16/06/2026**

- **Certificate of Completion:**
  - Attend all three live webinars (attendance is recorded automatically)
  - Complete the homework assignment by the deadline
  - You will receive a certificate via email approximately two months after completion of the course.

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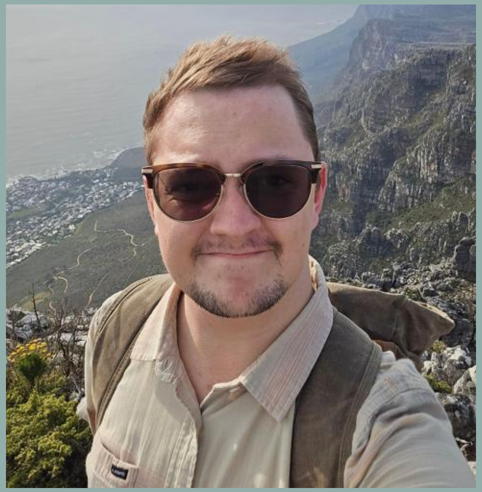

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For questions, comments, or to share how you have applied our trainings to your work or studies, email nasa.arset@gmail.com.

Join our quarterly newsletter to stay up-to-date on our latest trainings:

1. Send an email with no subject line to arset-join@lists.nasa.gov.
2. Follow the instructions sent in response.

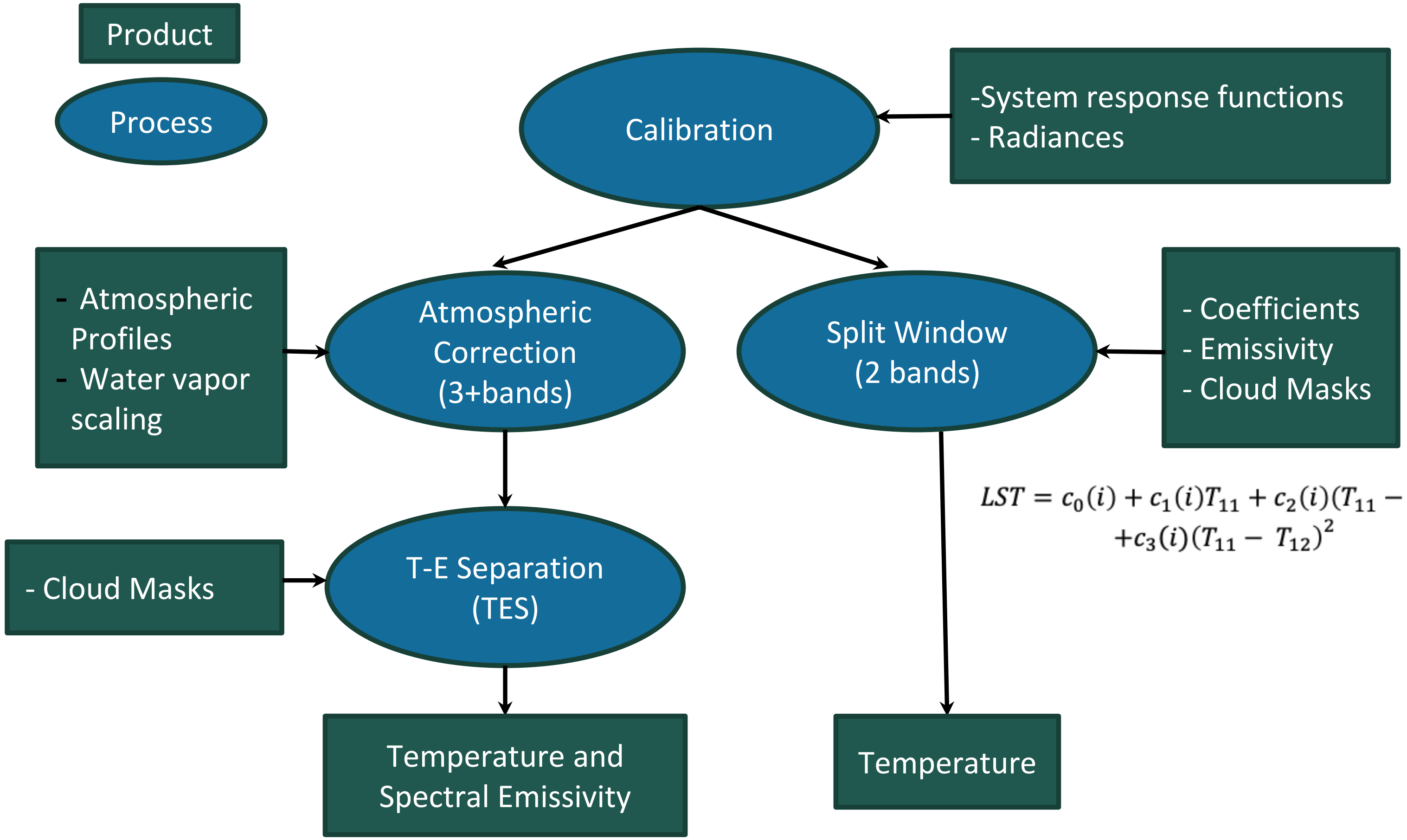
Resources

- Hulley & Ghent (2019) book: *Taking the Temperature of the Earth: Steps towards Integrated Understanding of Variability and Change*
- Hulley, et al., in review (HyTES validation study)
- Cooley, S. S., Hook, S., et al. in review.
- Donlon et al., 2014
- ECOSTRESS L1 and L2 ATBDs
- Hulley et al 2018
- Gillespie et al. 1998 (TES Algorithm)
- Hulley & Hook 2011
- Meerdink, S. K., Hook, S. J., Roberts, D. A., & Abbott, E. A. (2019). The ECOSTRESS spectral library version 1.0. Remote Sensing of Environment, 230(111196), 1–8.
- Baldridge, A. M., S.J. Hook, C.I. Grove and G. Rivera, 2009.. The ASTER Spectral Library Version 2.0. Remote Sensing of Environment, vol 113, pp. 711-715.

Thank You!

Extra slides

Emissivity retrieval algorithms (two common approaches)



$$LST = c_0(i) + c_1(i)T_{11} + c_2(i)(T_{11} - T_{12}) + c_3(i)(T_{11} - T_{12})^2$$

Temperature Emissivity Separation (TES) Algorithm ASTER (2000)

T-E separation is non-deterministic:

If N measurements, N+1 unknowns:

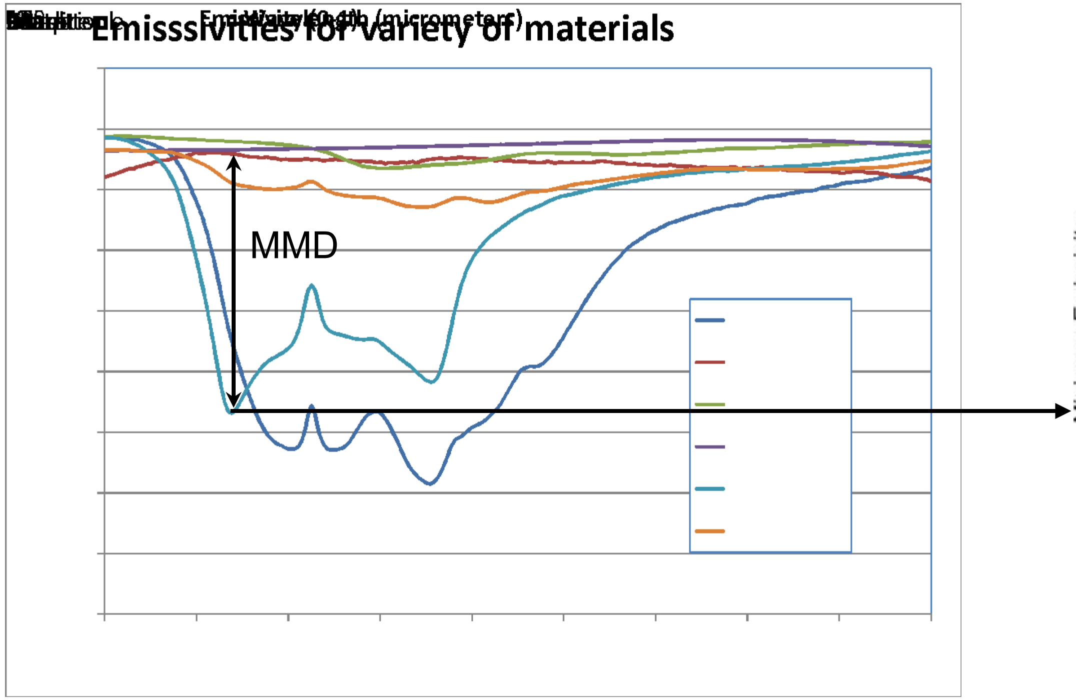
Radiance Band 1 = T + emissivity_1

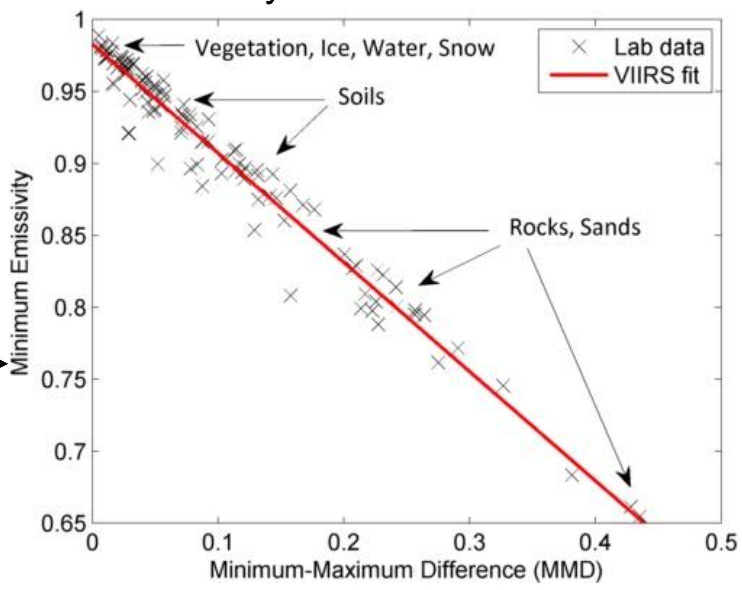
Radiance Band 2 = T + emissivity_2

Radiance Band 3 = T + emissivity_3

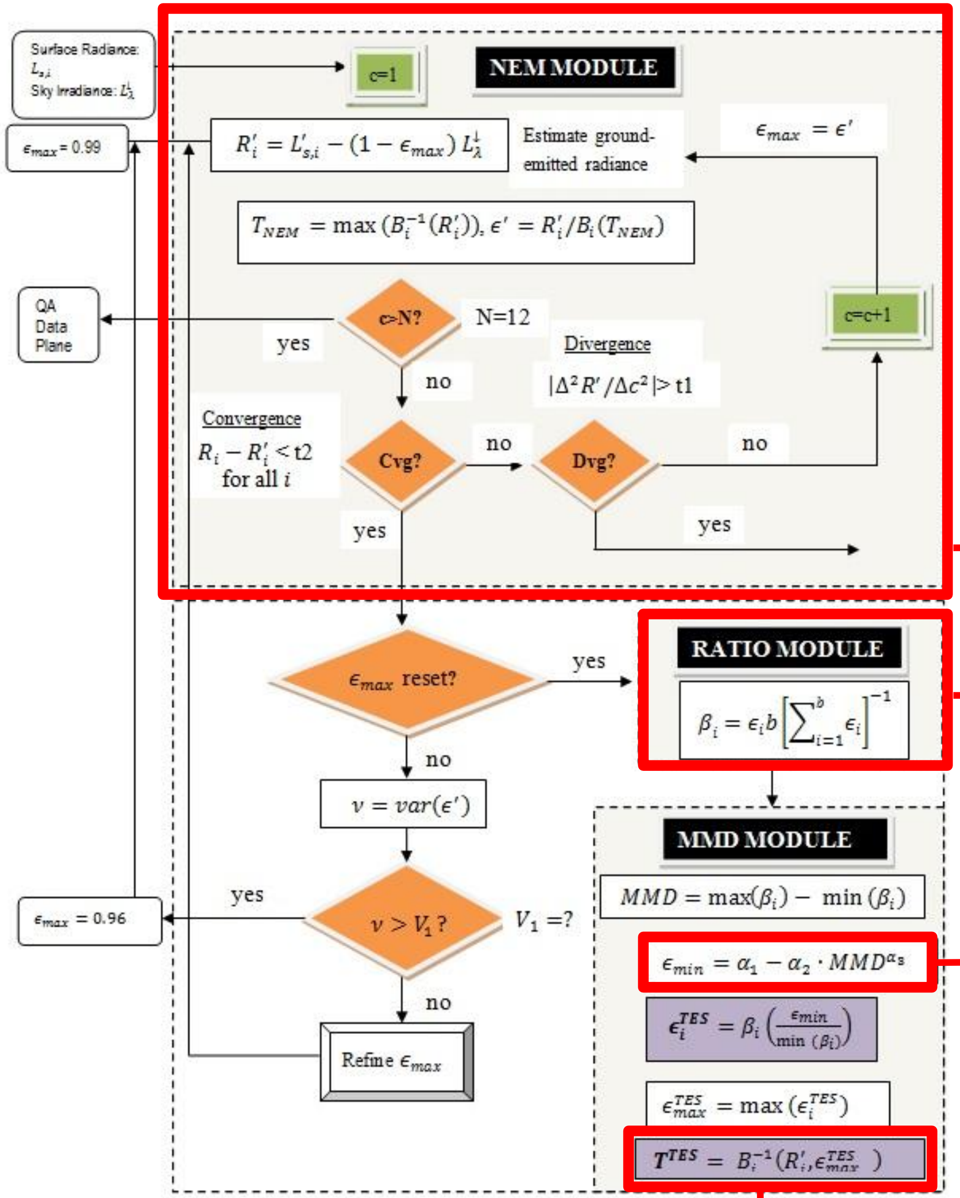
…………………………… ………………………

Need an additional 'constraint'





$$\varepsilon_{\min} = 0.994 - 0.687 \cdot MMD^{0.737}$$



TES Algorithm
(Gillepsie et al. 1998)

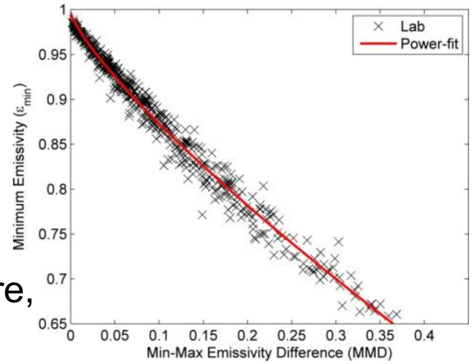
TES LST&E Products:
- **ASTER**
- **MODIS C6**
- **MASTER and HyTES (JPL)**
- **ECOSTRESS**
- **VIIRS C1**

1. Remove reflected downwelling component

2. Determine emissivity spectral shape by scaling

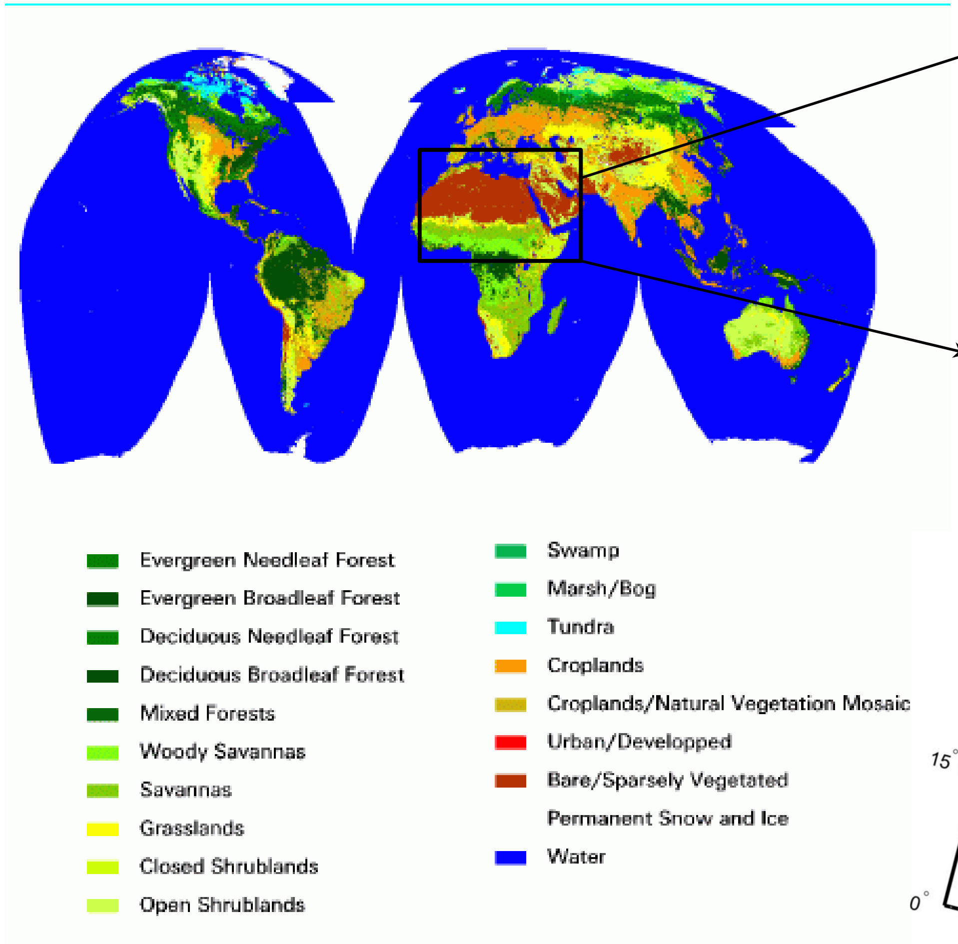
3. Calibrate emissivity into physical range

$$\varepsilon_{min} = 0.994 - 0.687 \cdot MMD^{0.737}$$

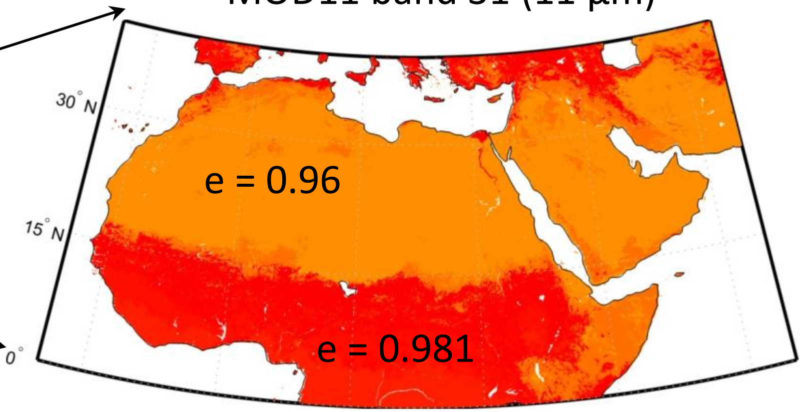


4. Invert Planck function to get temperature, given emissivity

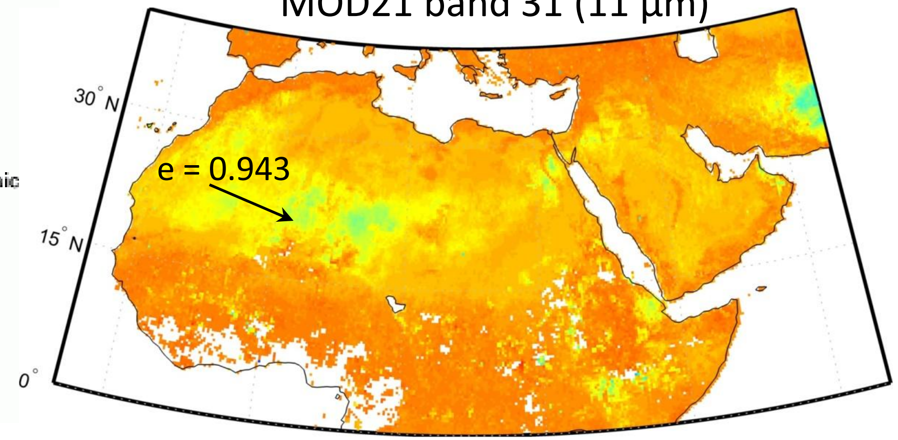
Emissivity: Split-Window versus TES retrieval



Split-window:
MOD11 band 31 (11 µm)

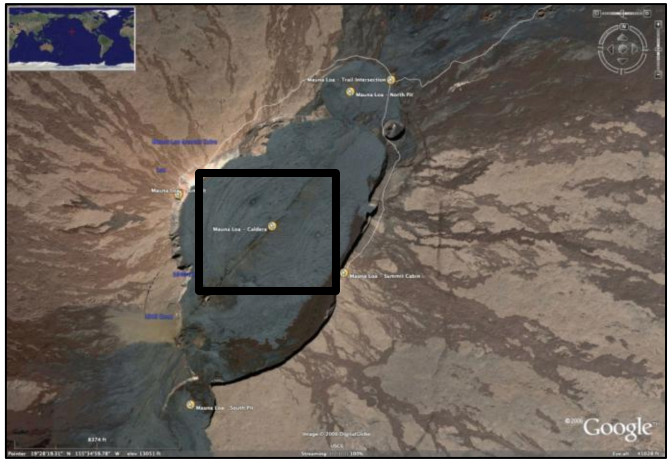


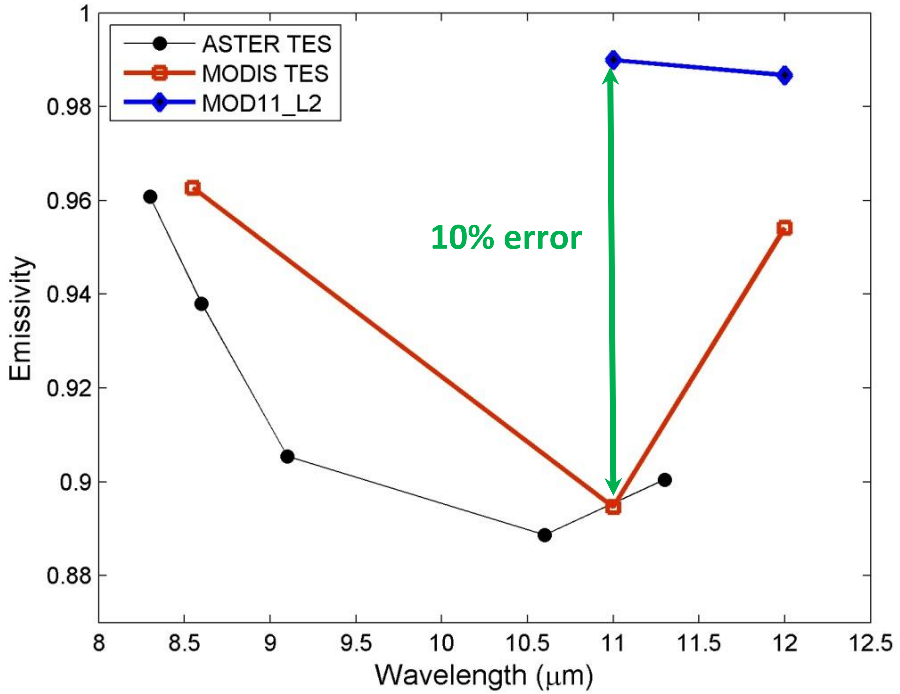
TES Retrieval:
MOD21 band 31 (11 µm)



Temperature errors as a result of incorrect emissivity

- Mauna Loa Caldera, Hawaii
- Mafic lava flow (basalt)





<u>Retrieved temperatures over Caldera</u>

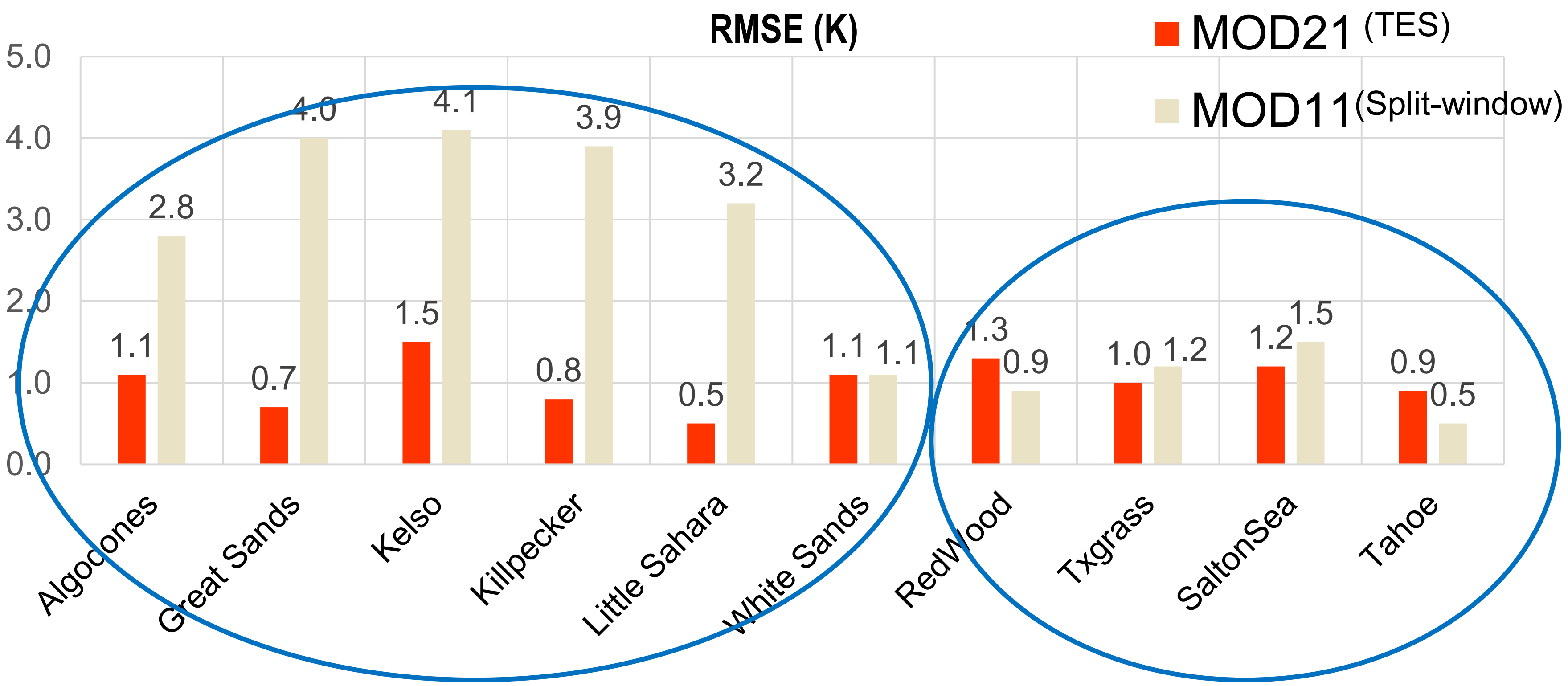
ASTER: 322 ±1 K

MOD21: 324 ±0.8 K

MOD11: 310 ±0.5 K

~1.5% emissivity error = ~1 K LST error

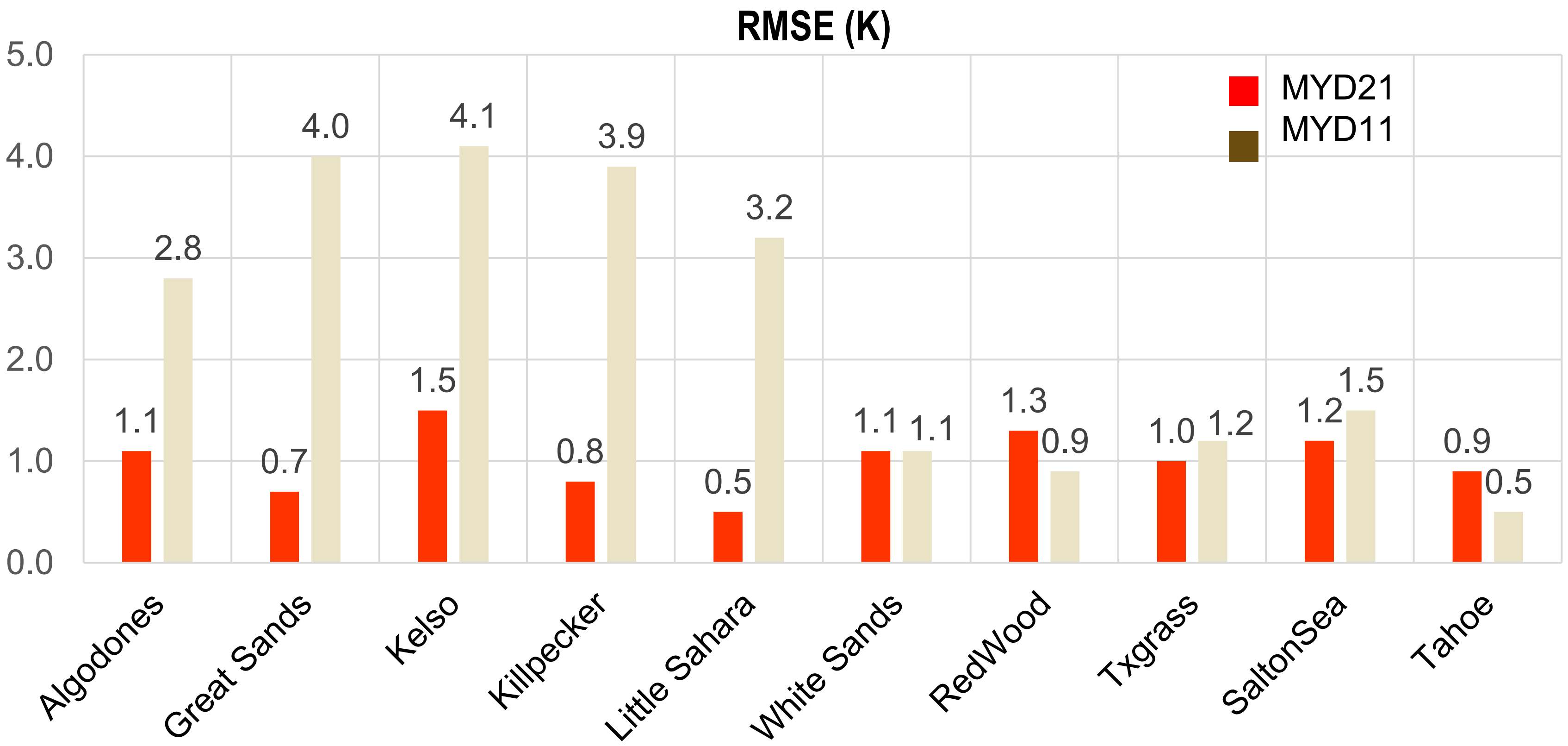
MODIS LST Validation Summary (2000-2018)



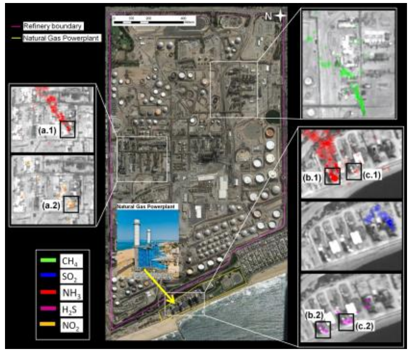
MOD11 Split-window cold bias over bare regions (3-5 K)

Similar Accuracy over vegetation and water of ~1 K

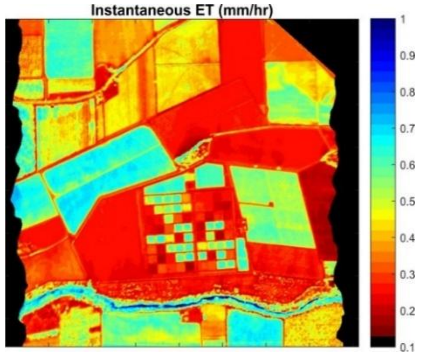
MODIS LST Validation Summary (2000-2018)



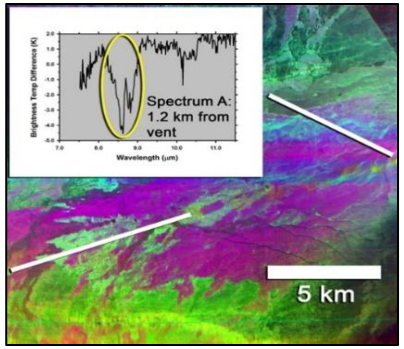
HyTES Science Highlights



Multi-species gas detection
Hulley et al. 2016



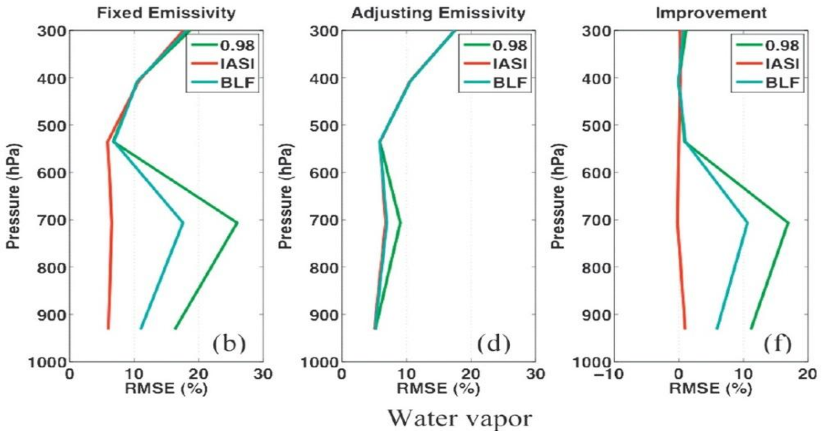
Surface energy balance
Hulley et al. 2019



Volcano monitoring and SO2 retrievals
Realmuto et al. 2017

Improving water vapor retrievals

Yao et al. 2011



Optimal set of TIR (8-12 micron) band characteristics

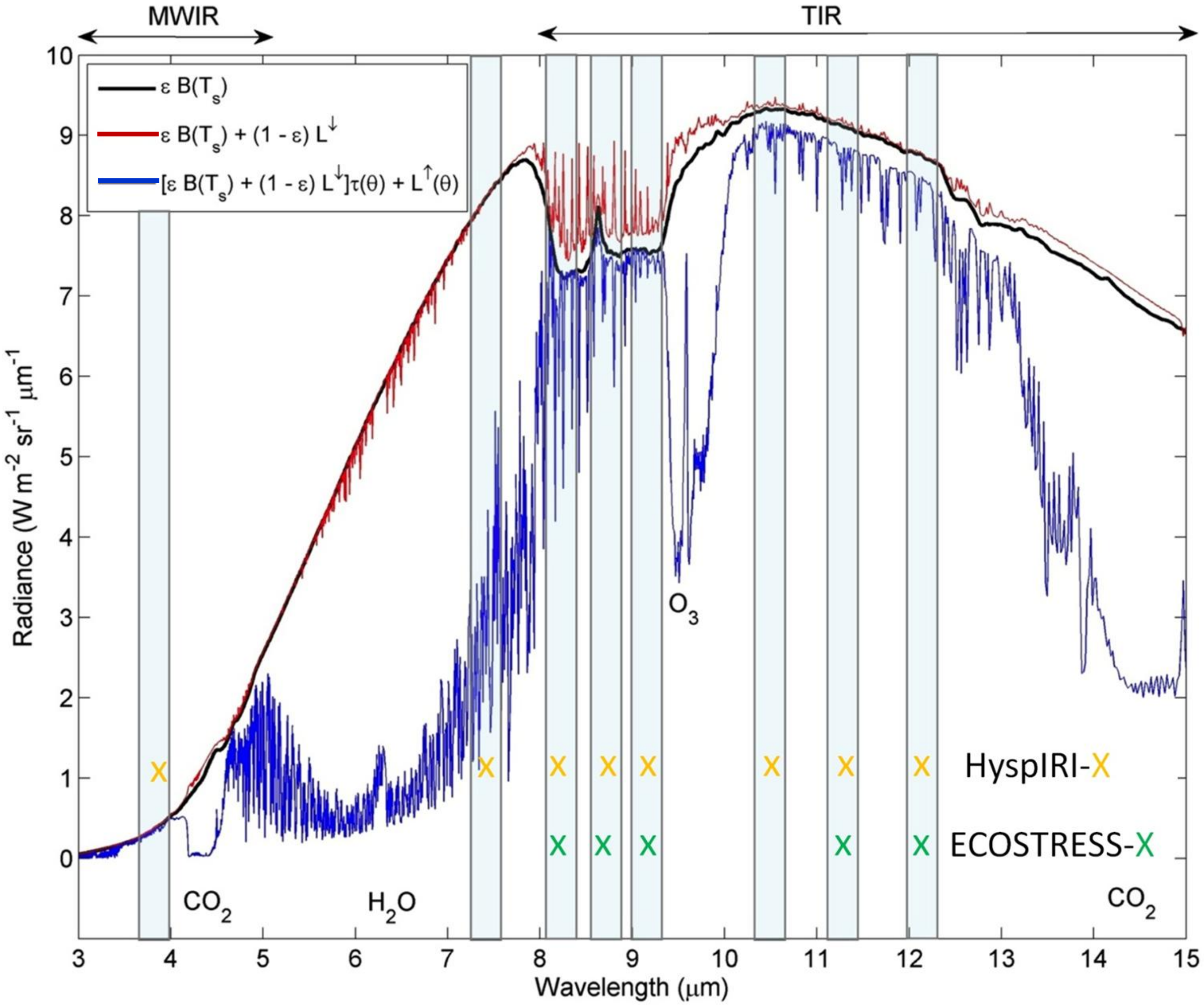
TIR bands	Center (nm)	Width (nm)	NEdT (K)	Usage (TE separation for all)
TIR1a	8300	200-250	<0.3	mineralogy
TIR1	8550	~350	<0.2	mineralogy, SO_2, cloud detection
TIR1b	9100	~350	<0.2	mineralogy
TIR2	10005	200-250	<0.3	silicate/clay/maffic discrimination, sulfate aerosol/ash discrimination in volcanic plumes
TIR3	11350	~550	<0.2	carbonates, cloud detection, ice/snow
TIR4	12000	~550	<0.2	cloud detection, ice/snow

Reference: http://www.pitt.edu/~mramsey/papers/Thompson_etal-2019.pdf *[Hulley et al. 2012, RSE, Hulley et al. 2009, GRL]*

TE separation = Temperature Emissivity separation

Thermal Infrared Radiative Transfer

$$L_{sat,\lambda} = \left[\varepsilon_\lambda B_\lambda(LST) + (1 - \varepsilon_\lambda) L^{\downarrow}_{sky,\lambda}\right] \tau_\lambda + L^{\uparrow}_{sky,\lambda}$$



Credit: Hulley, Hook, Realmuto & Cawse-Nicholson (2020)