Satellite Meteorology -4 (May 17)
Thermal Infrared Remote Sensing

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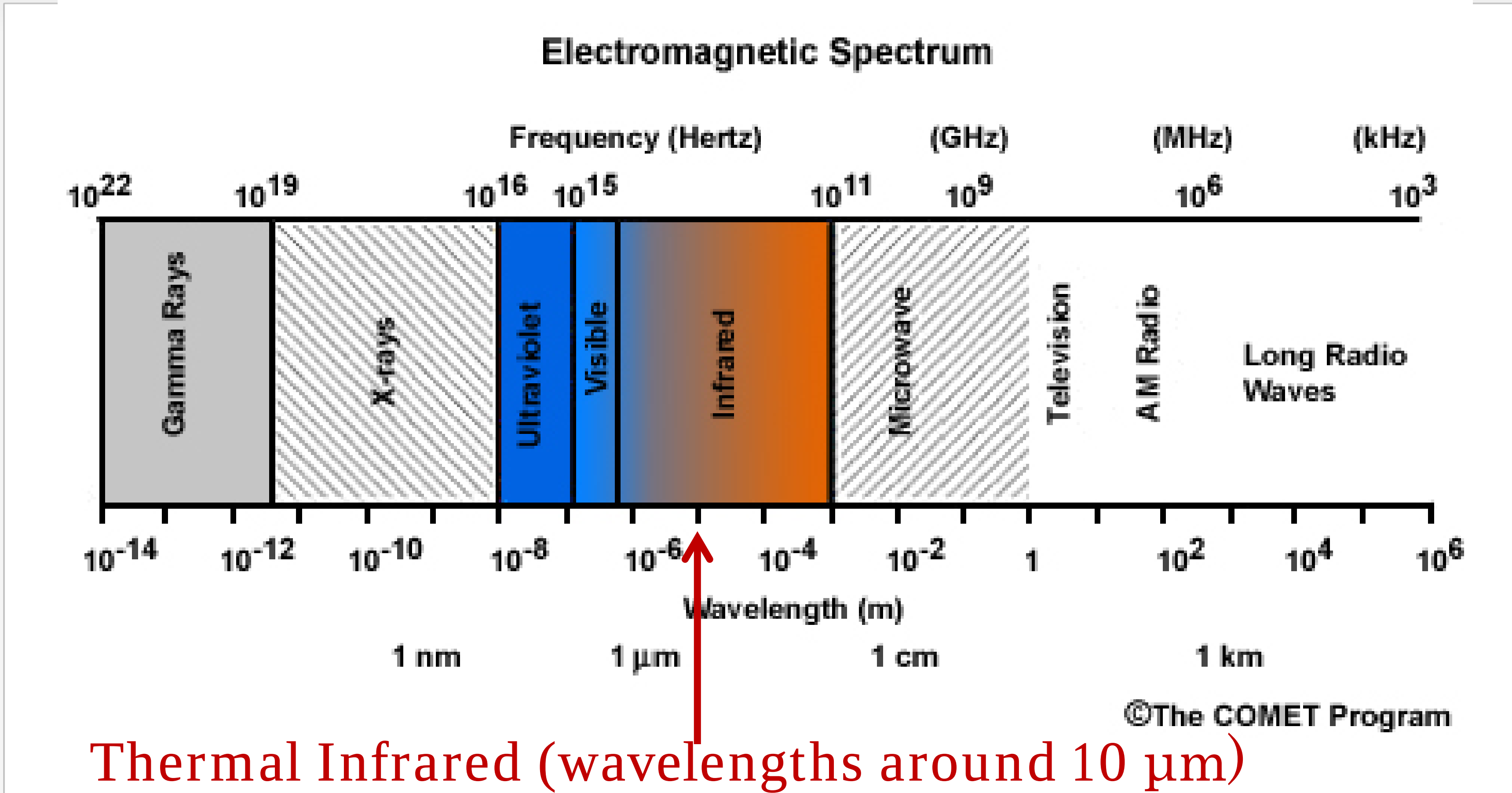
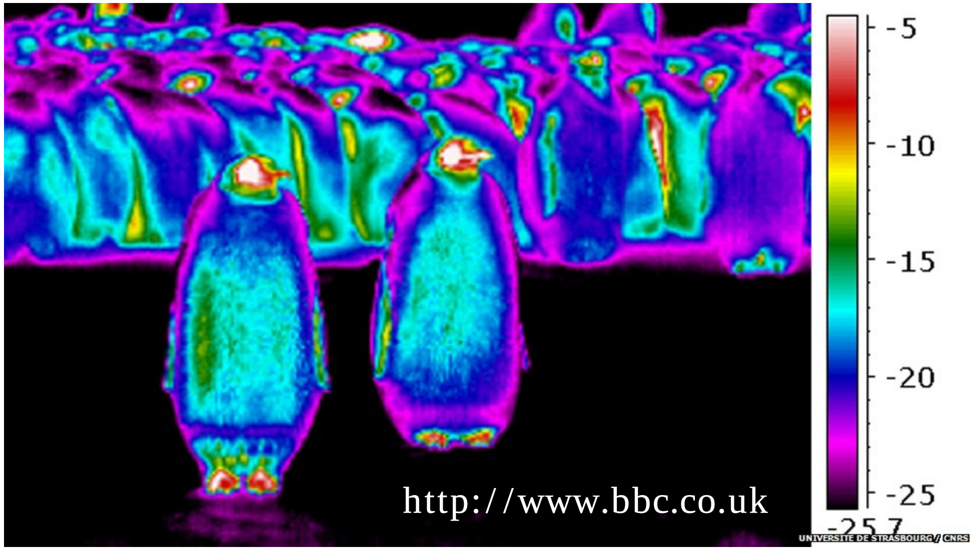
Electromagnetic spectrum

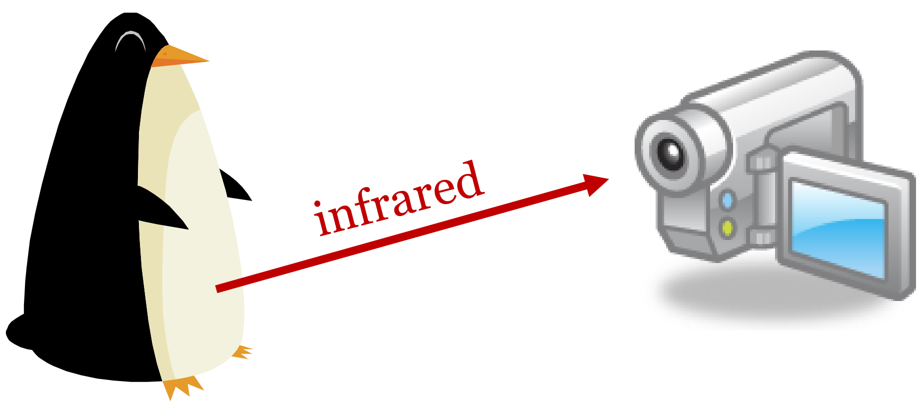


http://www.meted.ucar.edu/oceans/emeo/print.php

Infrared remote sensing: an example

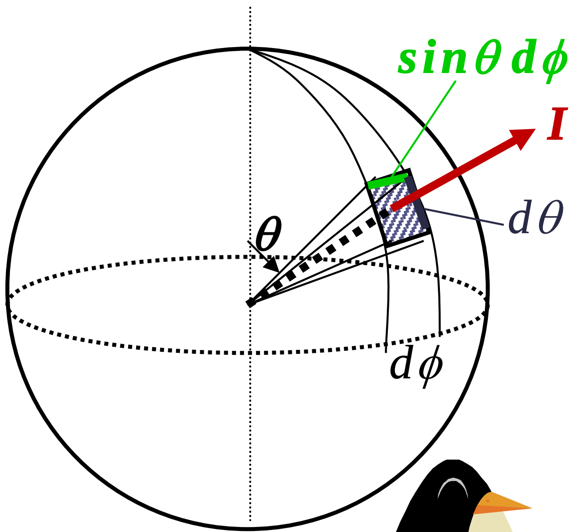
- Thermography
  - A device to measure the temperature of a target by infrared radiation





Basic parameters in radiative transfer

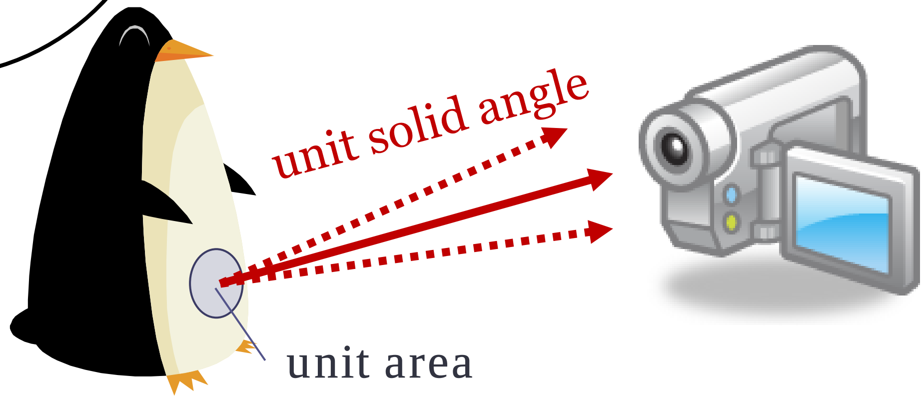
- Radiance and solid angle



Radiance I_λ [W/m²/str/μm] :
Radiative energy flow per unit time, unite area, and unit solid angle

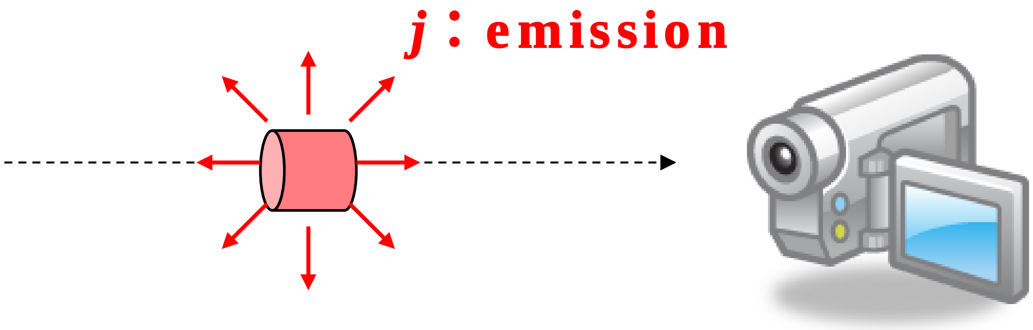
Solid angle (unit =steradian)

$$d\Omega = \sin\theta d\theta d\phi$$



Emission of radiation (射出) by a medium

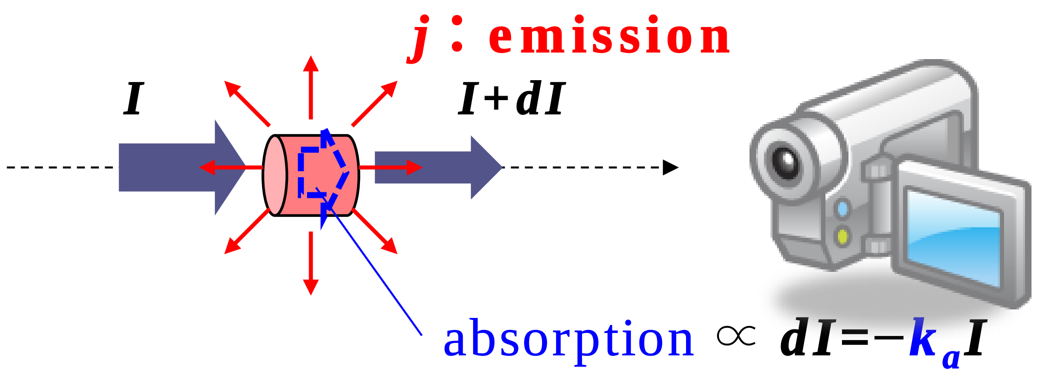
- Emission of radiation



Emissivity (射出率)　j_λ　[W/g/str/μm]：
The rate of energy emitted by a given medium per unit time, unite mass of the medium, unit solid angle and unit wavelength

Emission and absorption (吸収) of radiation

- Emission and absorption of radiation

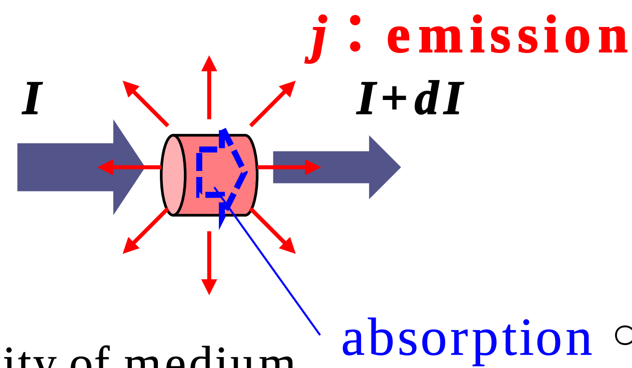


Emissivity (射出率) j_λ [W/g/str/μm]：
The rate of energy emitted by a given medium per unit time, unite mass of the medium, unit solid angle and unit wavelength

Absorptivity (吸収係数) $k_{a,\lambda}$ [m^2/g]：
Cross section of radiative absorption per unit mass of the medium

Radiative transfer for non-scattering media

- Radiative transfer for emitting/absorbing media



Mass density of medium

$$dI_\lambda = -k_{a,\lambda}\rho I_\lambda ds + j_\lambda \rho ds$$

吸収 (absorption) 射出 (emission)

$$\frac{dI_\lambda}{ds} = -k_{a,\lambda}\rho(I_\lambda - S_\lambda) \quad \text{where} \quad S_\lambda \equiv \frac{j_\lambda}{k_{a,\lambda}}$$

:Source function

Radiative transfer for non-scattering media

- Radiative transfer equation (non-scattering media)
  - Optical thickness (光学的厚さ) τ_a :$d\tau_{a,\lambda} \equiv k_{a,\lambda}\rho ds$
    - Radiative transfer (RT) equation is simplified with τ_a

$$\frac{dI_\lambda}{d\tau_{a,\lambda}} = -I_\lambda + S_\lambda$$

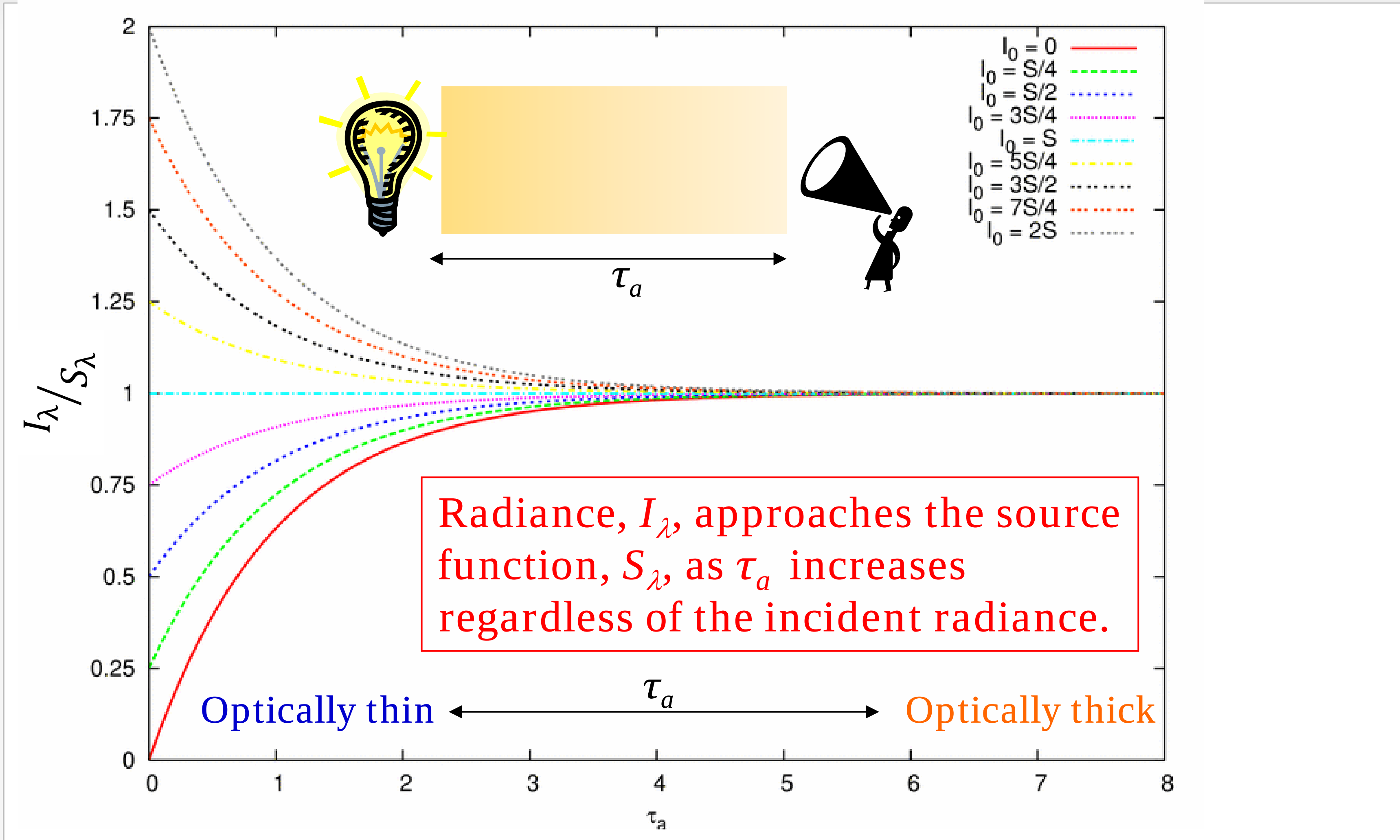
    - The solution in cases where S is independent of τ_a .

$$I_\lambda(\tau_{a,\lambda}) = \underline{I_{0,\lambda}} e^{-\tau_{a,\lambda}} + S_\lambda(1 - e^{-\tau_{a,\lambda}})$$

Boundary condition at $\tau_a=0$

  - Q. Confirm that this solution satisfies the RT equation.

Solutions of the non-scattering RT equation



Source Function and Kirchhoff's law

- Kirchhoff's law
  - For a medium in local thermodynamic equilibrium (局所熱平衡, or the state where energy levels obey the Boltzmann distribution, exp(-*E*/*kT*))

$$S_\lambda = \frac{j_\lambda}{k_\lambda} = B_\lambda(T)$$

The ratio of emissivity and absorptivity at each wavelength is determined solely by *T*.

  - Radiative transfer equation with the Kirchhoff's law

$$\frac{dI_\lambda}{d\tau_{a,\lambda}} = -I_\lambda + B_\lambda(T)$$

  - Solution: $I_\lambda(\tau_{a,\lambda}) = I_{0,\lambda} e^{-\tau_{a,\lambda}} + B_\lambda(T)(1 - e^{-\tau_{a,\lambda}})$

$B_\lambda(T)$: Planck function

- Black body（黒体）
  - An idealized medium that entirely absorbs/emits radiation at all wavelengths is called a "black body".
    - Radiation emitted by a black body of temperature T : $B_\lambda(T)$.
    - Often called the black body spectrum or the *Planck function*.

Planck function（per unit wavelength）

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{\exp\left(hc/\lambda kT\right)-1}$$

h **: Planck const.**
c **: speed of light**
λ **: wavelength**
k **: Boltzmann const.**
T **: temperature**

Properties of the Planck function

- Rayleigh-Jeans law
  - Asymptotic form for large λ

$$B_\lambda^{RJ}(T) = \frac{2c}{\lambda^4} kT \quad \text{for} \quad \frac{hc}{\lambda} << kT$$

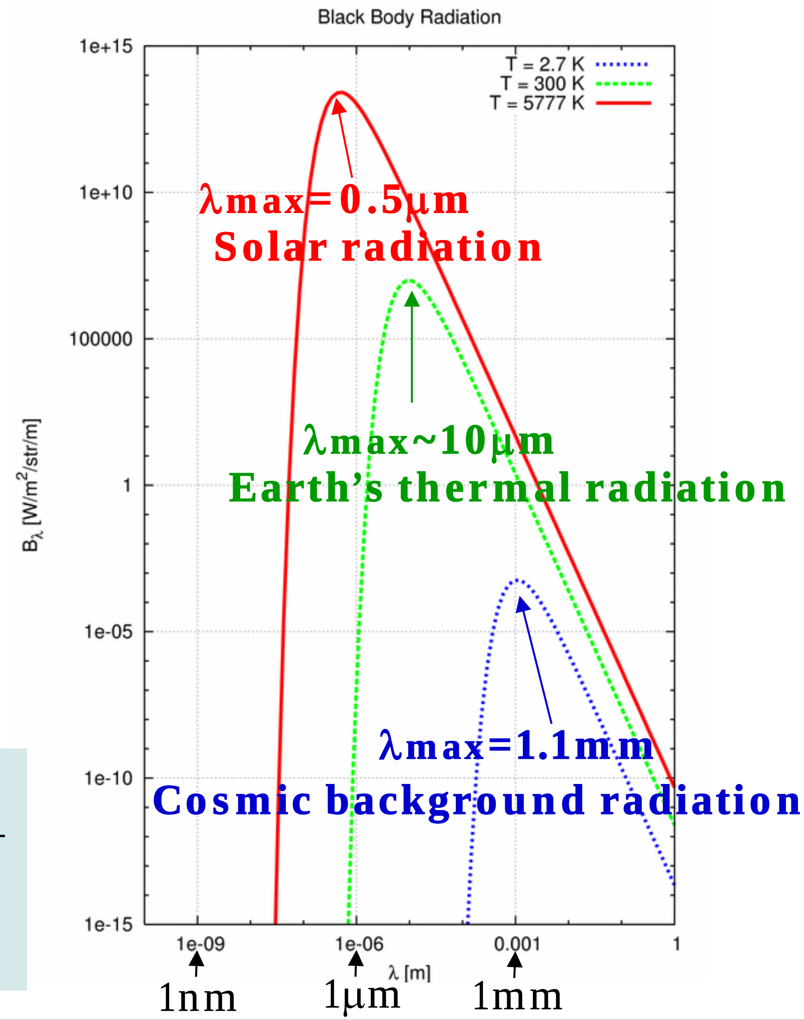
- Wien displacement law
  - λ that gives the maximum $B_\lambda(T)$

$$\lambda_{\max} T = 2.9 \text{mm} \cdot \text{K}$$

- Stefan-Boltzmann law
  - Integral over wavelengths

$$\int_0^\infty B_\lambda(T) d\lambda = \sigma T^4, \quad \text{where } \sigma \equiv \frac{2\pi^5 k^4}{15 c^2 h^3}$$

Stefan-Boltzmann constant

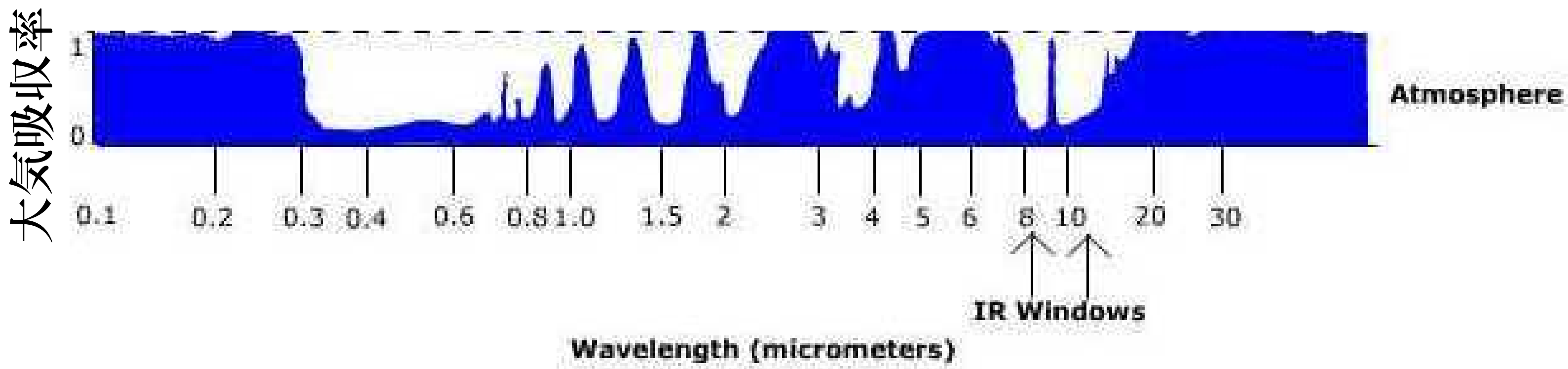


Utility of thermal infrared radiation

- Thermal infrared band : λ~ 10 μm
  - 1. Wavelengths at which the Earth is “brightest”.
    - Radiance is easy to detect when observed from space.

$$\lambda_{\max} T = 2.9\text{mm}\cdot\text{K} \quad \Rightarrow \quad \lambda_{\max} = \frac{2.9\text{mm}\cdot\text{K}}{\sim 290\,\text{K}} \approx 10\ \mu\text{m}$$

  - 2. Infrared “windows”: Atmosphere is nearly transparent.
    - Good for measuring temperature of Earth’s surface and clouds



Thermal infrared remote sensing

- Infrared observations of cloud-top temperature

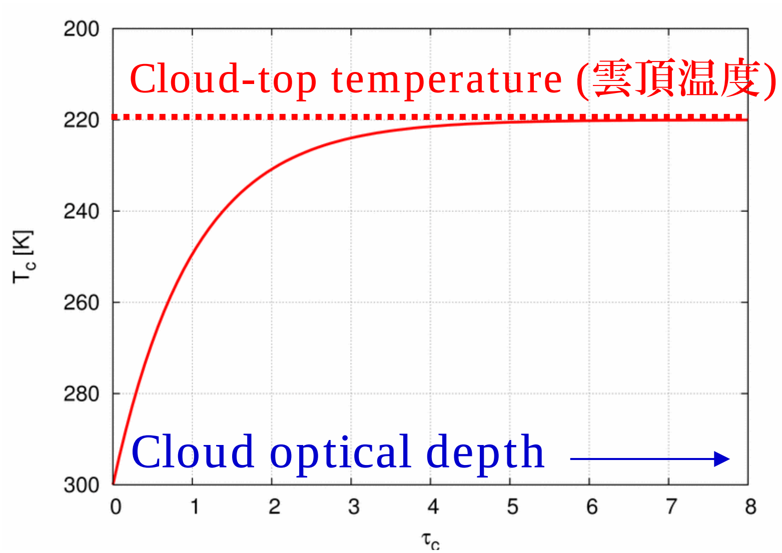
$$I_{\lambda 0} = B_\lambda(T_s), \quad S_\lambda = B_\lambda(T_c)$$

Cloud-top temperature

Surface temperature

$$I_\lambda(\tau_c) = B_\lambda(T_s)e^{-\tau_{c,\lambda}} + B_\lambda(T_c)(1-e^{-\tau_{c,\lambda}})$$

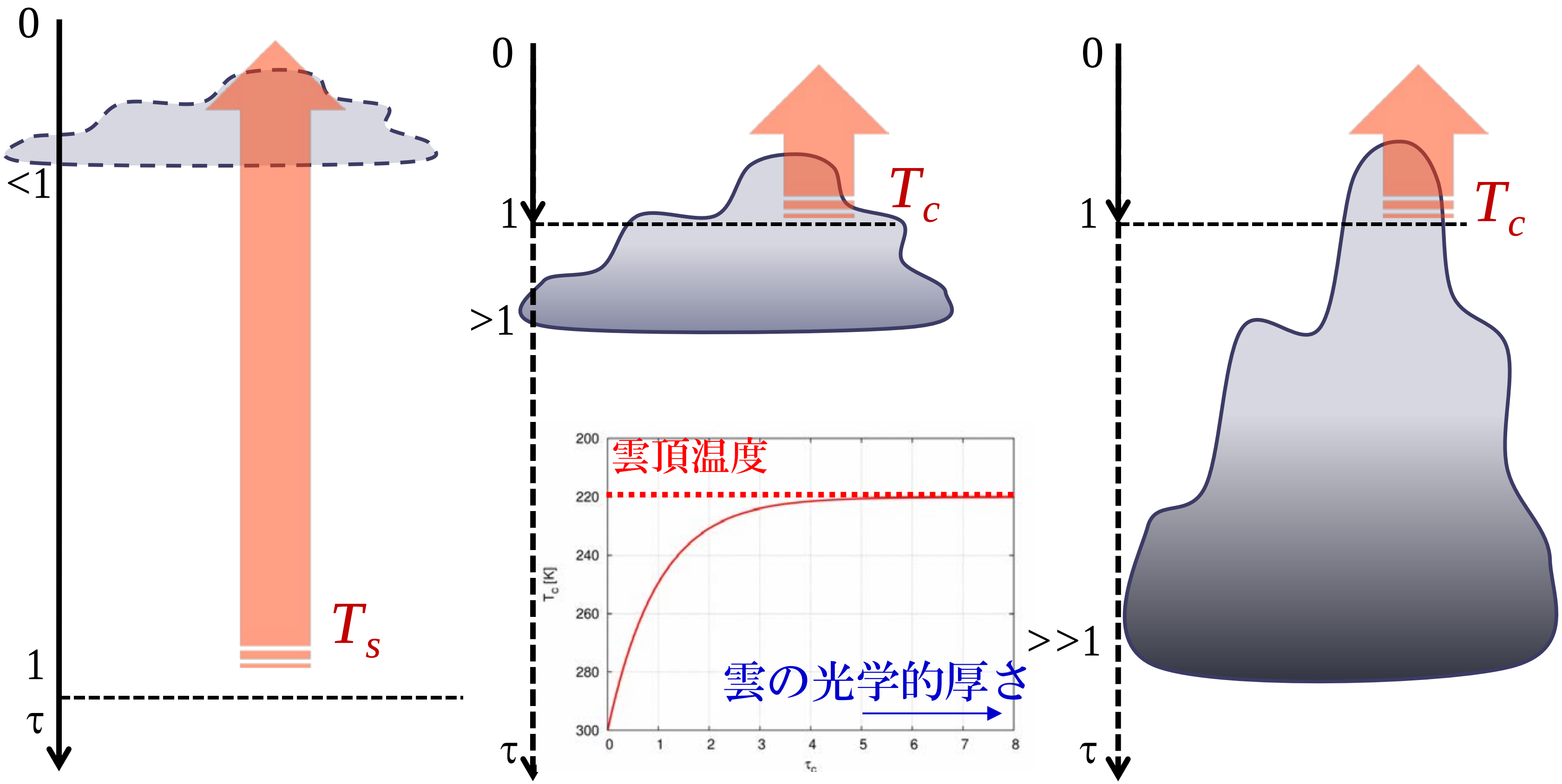
Cloud optical depth



* optical depth = optical thickness

Cloud temperature by infrared radiance

- Schematic



Brightness temperature (輝度温度)

- Brightness temperature (T_b)
  - Also called Equivalent Black Body Temperature (T_{BB})
  - The radiance converted to temperature unit [K] by solving inversely the Planck function.

$$I_\lambda(\tau_{c,\lambda}) = B_\lambda(T_s)e^{-\tau_{c,\lambda}} + B_\lambda(T_c)(1-e^{-\tau_{c,\lambda}})$$

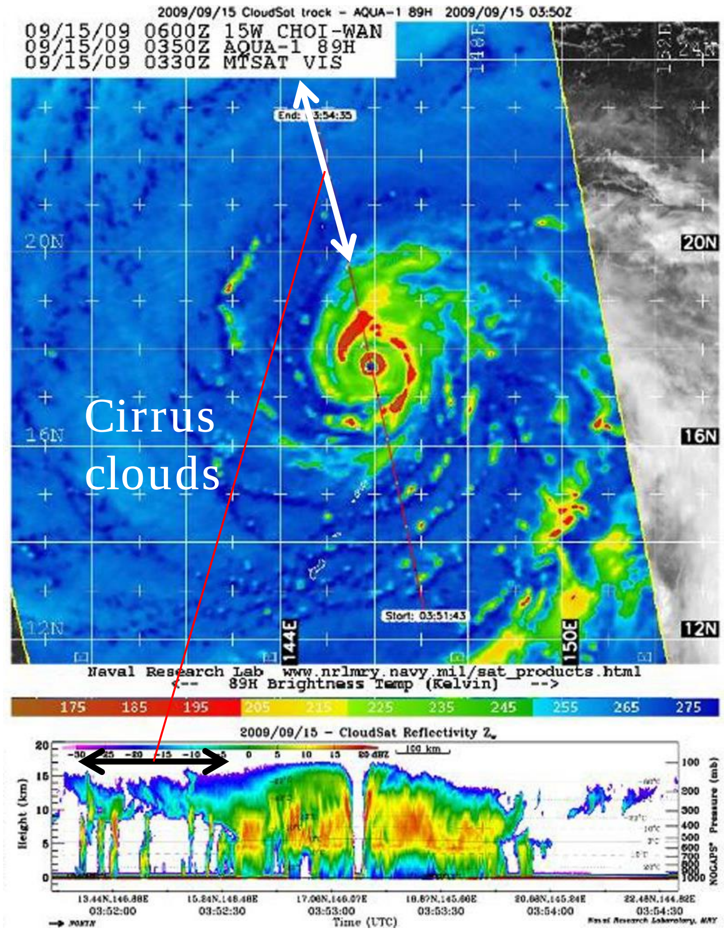
when $\tau_{c,\lambda} << 1$, surface temperature $T_s \approx B_\lambda^{-1}(I_\lambda)$

when $\tau_{c,\lambda} >> 1$, cloud-top temperature $T_c \approx B_\lambda^{-1}(I_\lambda)$

- When optical thickness has an intermediate value, T_b does not necessarily imply the physical temperature of the target.

IR brightness temperature: an example

- Aqua MODIS infrared and CloudSat radar



http://www.jpl.nasa.gov/spaceimages/

Summary

- Radiative transfer equation for non-scattering media
  - Radiance is a function of optical thickness (depth), τ_c.
    - Emission and absorption is each related to exp(- τ_c).
  - Radiation emitted from an optical thick medium
    - Depends only on the temperature (Planck function)

- Infrared remote sensing
  - Thermal infrared band : ~10 μm
    - Bright with terrestrial thermal radiation (Wien displ. law)
    - Atmosphere is relatively transparent at these wavelengths.
  - Useful for measuring surface and cloud temperatures
    - Care must be taken when the cloud is optically thin.