

Lectures 7 and 8: 13, 15 Oct 2009

Sea Surface Temperature

References:

Martin, S., 2004, An Introduction to Ocean Remote Sensing, Cambridge University Press, 454 pp. Chapter 7.

Robinson, I. S., 2004, Measuring the Oceans from Space: The principles and methods of satellite oceanography, Springer Praxis Books/Geophysical Sciences, 669 pp. Chapter 7.

Physical Oceanography (PO) Distributed Active Archive Center (DAAC) at the Jet Propulsion Laboratory http://podaac.jpl.nasa.gov/DATA_PRODUCT/SST/index.html

GHRSSST: The Global High Resolution Sea Surface Temperature project <http://www.ghrsst-pp.org/>

Satellite SST observations contribute to an understanding of ocean circulation and climate variability:

- The upper 10 m of the ocean has about the same mass as the overlying atmosphere
- The upper 3 m of the ocean has about the same heat capacity as the entire overlying atmosphere
- SST plays a fundamental role in setting the air-sea fluxes of heat and water vapor between the atmosphere and ocean – essential to weather and climate (sea breeze, El Nino, global change). [The wake of cold SST values can often be seen following the passage of hurricanes.]
- Fine scales in SST patterns visualize ocean currents: fronts, jets, eddies, upwelling, equatorial planetary waves, Rossby waves
- Satellite observed SST is used operationally for weather forecasting, ship routing, fish finding, and climate variability prediction.

Satellite SST data have been gathered using passive infrared instruments since the 1980s.

Lecture outline:

- IR physics
- Thermal behavior of the ocean
- Atmospheric effects and calibration
- Satellite instruments and systems

Passive infrared (IR) observations of SST commenced with the *Advanced Very High Resolution Radiometer* (AVHRR) on the NOAA-7 polar orbiter (1981)

Accuracy of the AVHRR instrument is about ± 0.4 K for any single datum. Greater accuracy is possible with spatial and temporal averaging and consistency error checking (calibration/validation to an in situ match-up database). The need for constant recalibration stems from the inability to completely adjust for atmospheric aerosols.

AVHRR instruments have been deployed on all NOAA satellites (now up to NOAA-19) and more accurate instruments (MODIS instrument) have been deployed on Terra (AM) and Aqua (PM) satellites and European Space Agency satellites ESA and Envisat (the ATSR and AATSR instruments).

AVHRR on NOAA POES satellite status reports: <http://www.oso.noaa.gov/poesstatus/>

METOP-A	AM Primary
NOAA 11	Decommissioned 16 June 2004.
NOAA 12	Decommissioned 10 Aug 2007
NOAA 14	Decommissioned 23 May 07
NOAA 15	AM Secondary
NOAA 16	PM Secondary
NOAA 17	AM Backup
NOAA 18	PM Secondary
NOAA 19	PM Primary

NOAA-19: Inclination angle 98.7° , altitude 870 km, precession rate -1.5 min/month, period 102.14 minutes

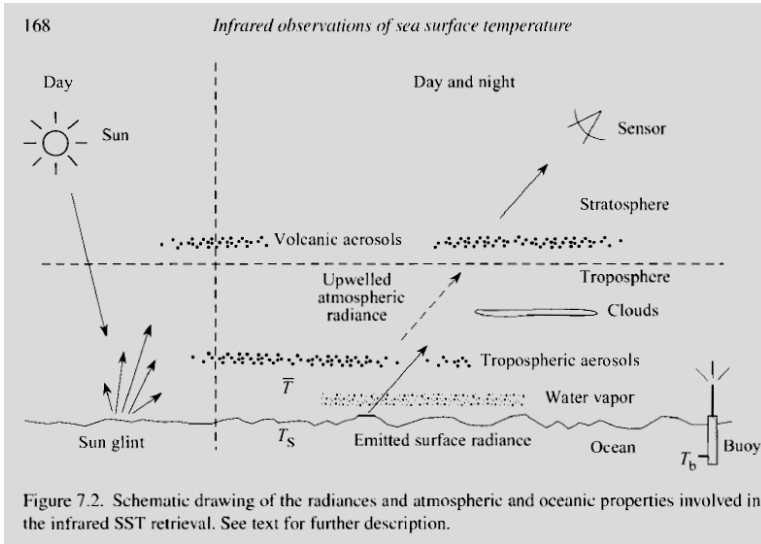
While atmospheric *sounding* instruments give information about the vertical profile of temperature within the atmosphere, satellites cannot observe the oceanic vertical profile of temperature.

What does an IR radiometer see?

Infrared wavelength EM radiation reaching the satellite at the top of the atmosphere, coming *from the direction* of the ocean

- affected by atmosphere transmittance
 - sources

- scattering
 - absorption
 - clouds obscure ocean surface
- emission by ocean depends on temperature and ocean physics



Planck’s radiation law gives the thermal emission as a function of wavelength for a body of a given temperature. Integrating over wavelength we get the total exitance, M:

$$M = \sigma T^4 \quad \text{where}$$

- σ is the Stefan-Boltzmann constant = $5.669 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
- T is the temperature in Kelvin

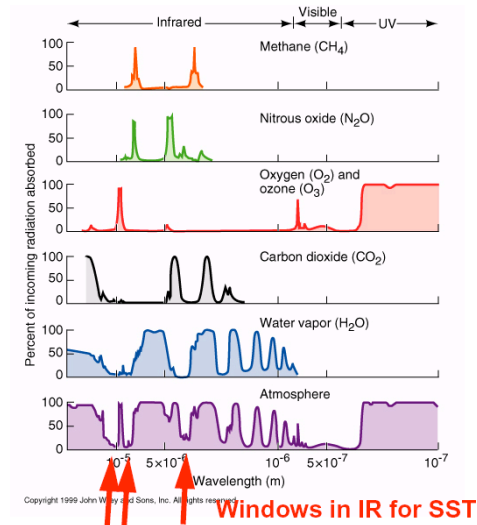
The emissivity of water is very close to 1, so M is very close to the exitance for ocean water of temperature T (in K).

The spectral peak of Planck’s law occurs at the wavelength given by *Wien’s Displacement Law*:

$$\lambda_{\text{max}} = b / T$$

where $b = 2.897 \times 10^{-3} \text{ m K}$ is Wien’s displacement constant

A consequence of this is that ocean surface



temperatures in the range 0°C to 40°C have an emission peak between 9 μm and 11 μm , with the radiation being spread over the range of about 4 μm to 20 μm .

An IR radiometer measures the *brightness temperature*, defined as the temperature of the blackbody that would emit the measured radiance, at a set of discrete wavelengths.

The actual temperature requires a correction for the true emissivity, and the intervening atmosphere.

Atmospheric absorption restricts IR radiometry of SST to spectral windows in the range of 3.5 to 4.1 μm and 10.0 to 12.5 μm .

During the day, reflection of light can influence the signal, and shallow heating of the ocean surface in a thin layer can mask the underlying mixed layer temperature of oceanographic interest.

Night-time IR SST data is generally a more reliable indicator of the ocean temperature than day-time data.

Received radiance is a combination of the surface-emitted radiance, and the atmospheric upwelled radiance (which depends on water vapor and aerosols, and atmosphere temperature).

Clouds can be opaque or thin, so cloud identification is an important step. Clouds are almost always significantly colder than the ocean surface.

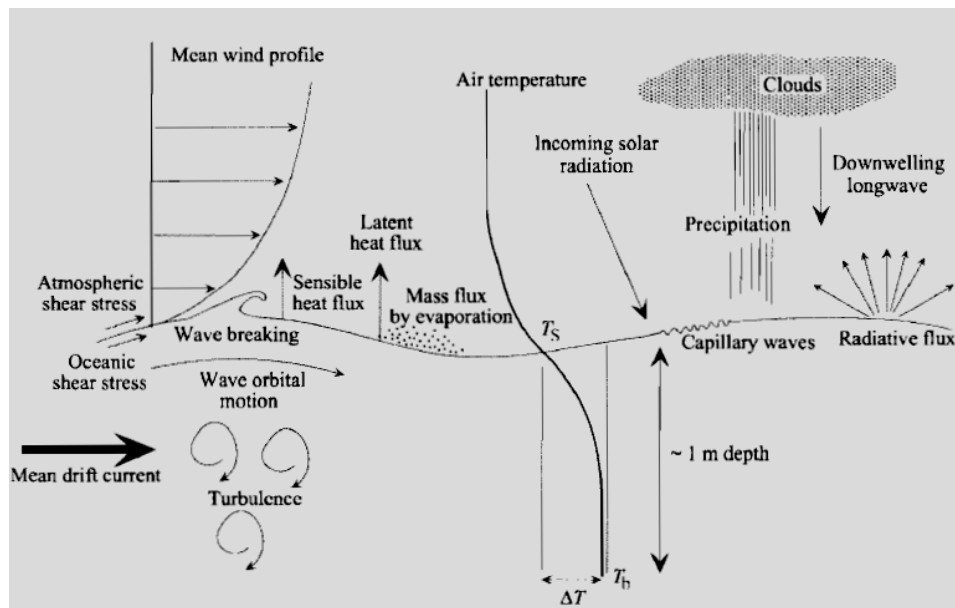


Figure 7.3. The factors that determine the surface temperature and the upper ocean interior temperatures, where ΔT is the temperature difference between the bulk and skin temperatures (Adapted from Figure 1 of Katsaros, 1980).

What is SST?

Factors that affect water temperature near the ocean surface include:

- upper ocean heats up during the day and cools at night from radiation
- day/night heating and radiative cooling affects the difference between T_s and T_b within the mixed layer. ΔT can be $\sim 1^\circ$
- air-sea heat exchange occurs through sensible (conduction) and latent (evaporation) fluxes
- wind speed and wave breaking affect these fluxes and the rate of mixing of heat through the ocean and atmosphere boundary layers
- net shortwave radiation heats the ocean, and net longwave radiation cools the ocean

But what temperature determines the upwelling radiance?

The absorption coefficient (an inverse length scale) for EM radiation varies with wavelength.

It is smallest for blue visible light, and increases rapidly to very high values $\sim 10^7 \text{ m}^{-1}$ for infrared.

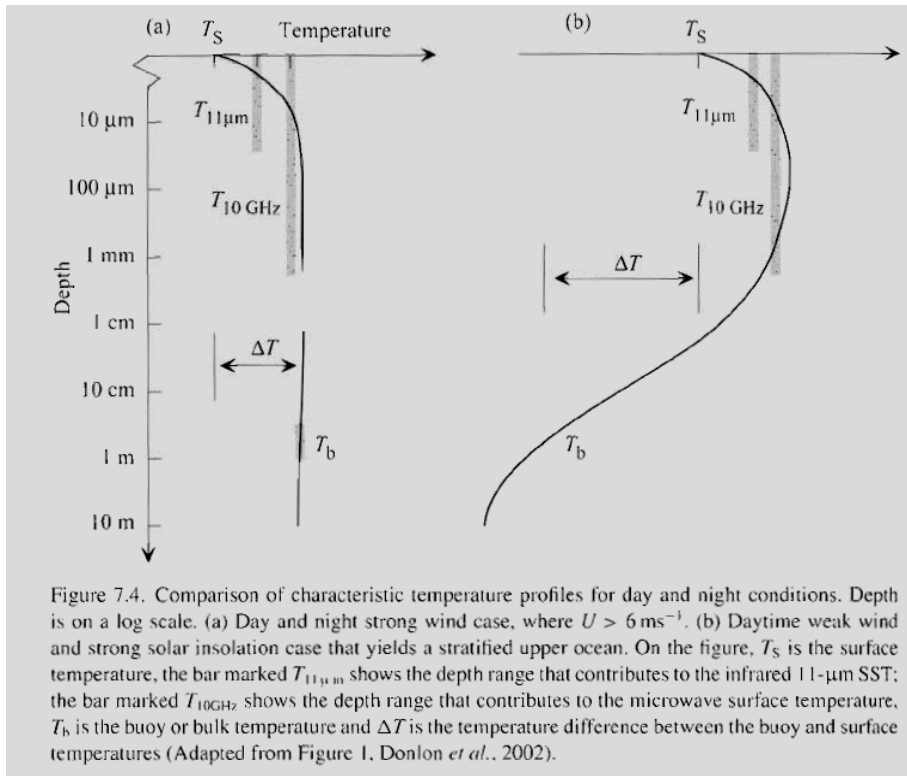
This means net infrared exitance at $11 \mu\text{m}$ wavelength comes only from the water within $30 \mu\text{m}$ of the sea surface.

The blackbody radiation emitted in water below this depth is absorbed by the neighboring water. Only at the sea surface can it escape.

The loss of heat by IR (longwave) radiation means there is a flux of heat from below toward the sea surface. This requires there be a vertical gradient in temperature getting warmer going down, i.e. there is a surface *cool bias* $\Delta T = \text{skin temperature} - \text{bulk temperature}$. Typically $\Delta T = -0.17 \pm 0.07 \text{ K}$

This is because the heating due to shortwave is occurring at a deeper depth of, on average, about 3 m.

It is bulk temperature (at say 1 m to 3 m depth) that an oceanographer wants to know, but skin temperature that an IR satellite observes.



If winds are weak, the absorption of solar shortwave radiation during daytime can warm just the top few centimeters producing a difference between near surface temperature (and hence skin temperature) and the bulk temperature below. This presents another problem for calibration.

(If winds are stronger, this near surface gradient is mixed away by ocean turbulence.)

At night, with weak winds, the absence of solar heating to maintain stratification means that the surface cooling will cause the water column to convect, removing the surface warm layer. (The skin temperature cool bias will remain).

AVHRR calibration is with respect to observations of bulk temperature, and uncertainty due to this temperature profile is a significant component of the AVHRR error.

Satellite IR sensors, calibrations, and corrections

AVHRR:

- A whisk-broom scanner

- Mirror rotating at 360 RPM = 6 scans per second
- Resolution on ground:

$$\text{sat. speed} = v = \sqrt{\frac{GM}{r}} = (3.986 \times 10^{14} / (833 \times 10^3 + 6373 \times 10^3))^{1/2}$$

$$= 7.4 \times 10^3 \text{ m s}^{-1}$$

$$\text{distance} = v \times 1/6 \text{ second} = 7.4 \times 10^3 / 6 = 1.2 \times 10^3 \text{ m} = 1.2 \text{ km}$$

- angular resolution of 1.4 milliradian
resolution: (Use $s=r\theta$) $833 \times 10^3 \times 1.4 \times 10^{-3} = 1.1 \times 10^3 \text{ m} = 1.1 \text{ km}$ at nadir
- swath half-width of 1350 km (orbit altitude is 833 km)
- quantum detector – counts photon flux
 - semi-conductor: must be cooled to significantly less than the ambient temperature of the satellite to reduce noise (< 100 K or -173°C)
 - thermal connection from base-plate of detector to radiative heat sink (high thermal emissivity) facing open space
 - internal surfaces facing the detector must be cooled to reduce spurious IR radiation
 - condensation can degrade sensor performance – periodic outgassing step
- sensor calibration is by pre-launch calibration, and operational viewing cold space (assumed to be 3K) and an internal blackbody source
 - bands 1, 2, and 3A are calibrated before launch but not on orbit
- sensors operate by observing 5 or 6 bands of different wavelength
 - 1 visible, 2 near IR, 3 in thermal IR
 - Band 2: $\sim 0.8 \mu\text{m}$ = near IR ... ocean emission is low so this
 - discriminates land/ocean boundary and cloud
 - Band 3A: $\sim 1.5 \mu\text{m}$ day time reflectance discrimination of
 - Snow, ice, clouds, forest fires

- Band 3B: $\sim 3.7 \mu\text{m}$ night time SST
 - Easily contaminated by sun glitter
- Bands 4 and 5: $\sim 10.8 \mu\text{m}$ and $\sim 12 \mu\text{m}$ day and night SST (split window algorithm)
- AVHRR transmits the 1 km resolution Local Area Coverage (LAC) data to HRPT receiving stations (High Resolution Picture Transmission) like the one on the roof of the IMCS building (over the loading dock).
- The satellite also stores Global Area Coverage (GAC) data and downloads this over a set of ground stations. GAC data are compiled from every 3rd scan, with 4 of 5 adjacent samples averaged. This reduces data volume by factor of 10 to a nominal resolution of 4 km.

