Lecture 15

Applications of passive remote sensing using emission: Remote sensing of sea surface temperature (SST)

Objectives:

1. SST retrievals from passive infrared remote sensing.
2. Microwave vs. IR SST retrievals.

Required reading:

G: 7.2;

Additional/advanced reading:

Electronic lecture on SST: http://see.gsfc.nasa.gov/edu/SEES/ocean/oc_class.htm

Barton, I.J., Satellite-derived sea surface temperatures: Current status. *Journal of Geophysical Research* 100: 8777–8790, 1995.

B. Emery et al., Estimating sea surface temperature from infrared satellite and in situ temperature data. *Bulletin of the American Meteorological Society*, 82, 2773-2785, 2001.

J.Vazquez-Cuervo and R. Sumagaysay, A comparison between sea surface temperature as derived from the European Remote Sensing Along-Track Scanning Radiometer and the NOAA/NASA AVHRR Oceans Pathfinder Dataset. *Bulletin of the American Meteorological Society*, 82, 925-945, 2001.

1. SST retrievals from passive infrared remote sensing

Principles:

measure IR radiances in the "atmospheric window" and correct for contribution from "clear" sky by using multiple channels (called "split-window" technique)

Using Eq.[14.7] , we can write IR radiance at TOA:

$$I_\lambda^\uparrow(0;\mu) = B_\lambda(\tau^*)\exp(-\frac{\tau^*}{\mu}) + \frac{1}{\mu}\int_0^{\tau^*}\exp(-\frac{\tau'}{\mu})\ B_\lambda(\tau')d\tau'$$

Let's re-write this equation using the transmission function

$T_\lambda(\tau^*/\mu) = \exp(-\frac{\tau_\lambda^*}{\mu})$ and that $B_\lambda(\tau^*) = B_\lambda(T_{sur})$

$$I_\lambda^\uparrow(0;\mu) = B_\lambda(T_{sur})T_\lambda(\tau^*/\mu) + B_\lambda(T_{atm})[1 - T_\lambda(\tau^*/\mu)]$$

[15.1]

where T_{atm} is an "effective" blackbody temperature which gives the atmospheric emission

$$B_\lambda(T_{atm}) = [1 - T_\lambda(\tau^*/\mu)]^{-1}\frac{1}{\mu}\int_0^{\tau^*}\exp(-\frac{\tau'}{\mu})\; B_\lambda(\tau')d\tau'$$

We want to eliminate the term with T_{atm} in Eq.[15.1]. Suppose we can measure IR radiances I_1 and I_2 at two at the adjacent wavelengths λ_1 and λ_1

$$I_1^\uparrow = B_1(T_{sur})T_1(\tau_1^*/\mu) + B_1(T_{atm})[1 - T_1(\tau_1^*/\mu)] \quad [15.2]$$

$$I_2^\uparrow = B_2(T_{sur})T_2(\tau_2^*/\mu) + B_2(T_{atm})[1 - T_2(\tau_2^*/\mu)] \quad [15.3]$$

NOTE: two wavelengths need to be close to neglect the variation in $B_\lambda(T_{atm})$

Let's apply the Taylor's expansion to $B_\lambda(T)$ at temperature $T = T_{atm}$

$$B_\lambda(T) \approx B_\lambda(T_{atm}) + \frac{\partial B_\lambda(T)}{\partial T}(T - T_{atm})$$

Using this expansion for both wavelengths, we have

$$B_1(T) \approx B_1(T_{atm}) + \frac{\partial B_1(T)}{\partial T}(T - T_{atm})$$

$$B_2(T) \approx B_2(T_{atm}) + \frac{\partial B_2(T)}{\partial T}(T - T_{atm})$$

and thus, eliminating $T - T_{atm}$, we have

$$B_2(T) \approx B_2(T_{atm}) + \frac{\partial B_2(T\ )/\partial T}{\partial B_1(T)/\partial T}[B_1(T) - B_1(T_{atm})] \qquad [15.4]$$

Let's introduce brightness temperatures for these two channels $T_{b,1}$ and $T_{b,2}$

$I_1 = B_1(T_{b,1})$ and $I_2 = B_2(T_{b,2})$

and use apply [15.4] to $B_2(T_{b,2})$ and to $B_2(T_{sur})$

$$B_2(T_{b,2}) \approx B_2(T_{atm}) + \frac{\partial B_2(T\ )/\partial T}{\partial B_1(T)/\partial T}[B_1(T_{b,2}) - B_1(T_{atm})]$$

and

$$B_2(T_{sur}) \approx B_2(T_{atm}) + \frac{\partial B_2(T\ )/\partial T}{\partial B_1(T)/\partial T}[B_1(T_{sur}) - B_1(T_{atm})]$$

Let's substitute the above expressions for $B_2(T_{b,2})$ and to $B_2(T_{sur})$ in Eq.[15.3]

$$B_2(T_{atm}) + \frac{\partial B_2(T\ )/\partial T}{\partial B_1(T)/\partial T}[B_1(T_{b,2}) - B_1(T_{atm})] =$$

$$T_2\ \{B_2(T_{atm}) + \frac{\partial B_2(T\ )/\partial T}{\partial B_1(T)/\partial T}[B_1(T_{sur}) - B_1(T_{atm})]\} + B_2(T_{atm})[1 - T_2]$$

it becomes

$$B_1(T_{b,2}) = B_1(T_{sur})T_2 + B_1(T_{atm})[1 - T_2]$$

Using Eq.[15.2] , we can eliminate $B_1(T_{atm})$

$$B_1(T_{sur}) = I_1 + \gamma[I_1 - B_1(T_{b,2)})] \qquad [15.4]$$

where $\gamma = \frac{1 - T_1}{T_1 - T_2}$

Performing liberalization of Eq.[15.4]

$$\boxed{T_{sur} \approx T_{b,1} + \gamma[T_{b,1} - T_{b,2}]} \qquad [15.5]$$

The principle of the SST retrieval algorithm:

SST is retrieved based on the linear differences in brightness temperatures at two IR channels

Bulk (1-5 m depth) SST measurements:

(1) Ships

(2) Buoys (since the mid-1970s): buoy SSTs are much lees nosy that ship SSTs

⇩

Data from buoys are included in the SST retrieval algorithm

Skin SST from infrared satellite sensors:

- SR (Scanning Radiometer) and VHRR (Very High Resolution Radiometer) both flown on NOAA polar orbiting satellites: since mid-1970
- AVHRR (Advanced Very High Resolution Radiometer):
  since 1978 (4 channels, started on NOAA-6)
  since 1988 (5 channels, started on NOAA-11)

Table 15 .1
AVHRR CHANNELS

AVHRR Channel	Wavelength (μm)
1	0.58 - 0.68
2	0.72 - 1.10
3	3.55 - 3.93
4	10.3 - 11.3
5	11.5 - 12.5

AVHRR MCSST (Multi-Channel SST) algorithm:

$$SST = \boldsymbol{a}\, \boldsymbol{T_{b,4}} + \gamma(\boldsymbol{T_{b,4}} - \boldsymbol{T_{b,5}}) + \boldsymbol{c}$$

where ***a*** and ***c*** are constants.

$\gamma = \dfrac{1 - T_4}{T_4 - T_5}$, T_4 and T_5 are transmission function at AVHRR channels 4 and 5

AVHRR NLSST (Non-Linear SST) operational algorithm (Version 4.0):

$$SST = \boldsymbol{a} + \boldsymbol{b}\, \boldsymbol{T_{b,4}} + c(\boldsymbol{T_{b,4}} - \boldsymbol{T_{b,5}})\, SST_{guess} + \boldsymbol{d}(\boldsymbol{T_{b,4}} - \boldsymbol{T_{b,5}})[\sec(\theta_{sat}) - 1]$$

where

SST_{guess} if a first-guess SST;

$\boldsymbol{T_{b,4}}$ and $\boldsymbol{T_{b,5}}$ are brightness temperature measured by AVHRR channels 4 and 5;

a, b, and ***c*** are coefficients that calculated for two different regimes of ($\boldsymbol{T_{b,4}} - \boldsymbol{T_{b,5}}$): one set for ($\boldsymbol{T_{b,4}} - \boldsymbol{T_{b,5}}$) < or = 0.7 and another set for ($\boldsymbol{T_{b,4}} - \boldsymbol{T_{b,5}}$) > 0.7

The coefficients ***a, b***, and ***c*** are estimated from regression analyses using co-located in situ buoy and satellite measurements (called "matchups").

Alternative approach

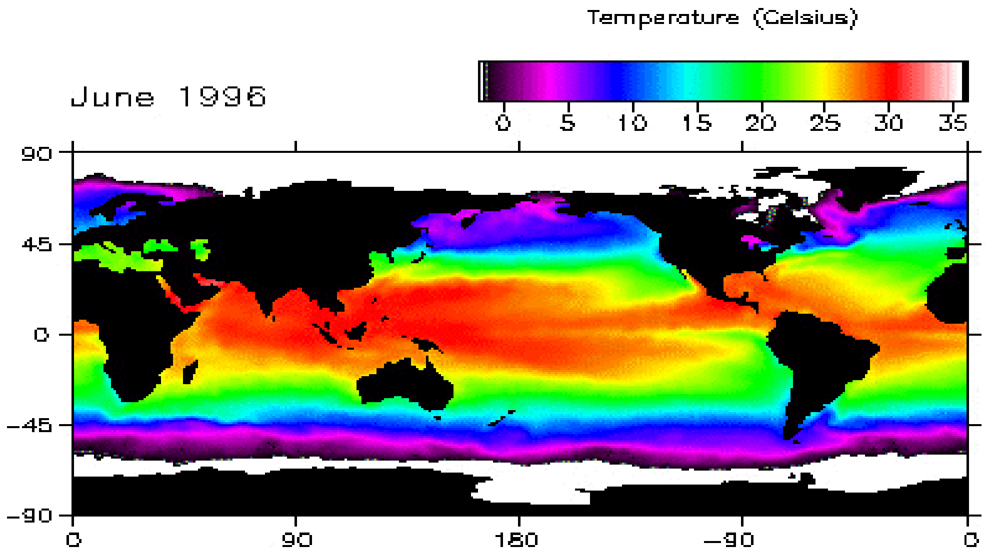
(used in the SST retrieval algorithm in ATSR (Along-Track Scanning Radiometer) on ERS; ATSR has 4 channels 1.6, 3.7, 10.8 and 12 μm)

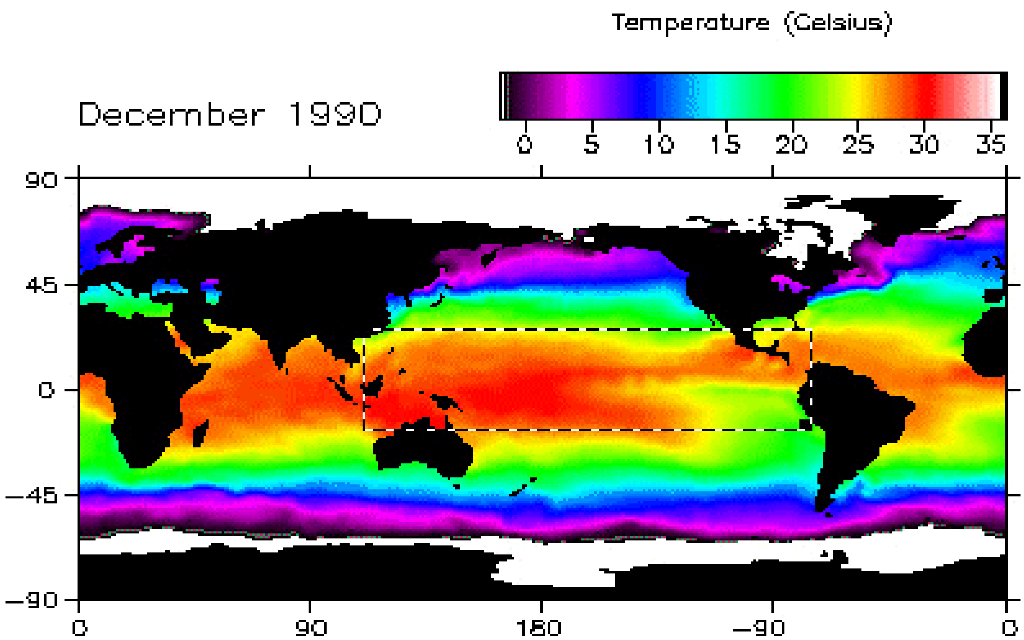
$$SST = a_0 + \sum a_i T_{b,i}$$

Coefficients $\boldsymbol{a_i}$ are calculated from a fit to a radiative transfer model instead of in situ observations as in the AVHRR algorithm.

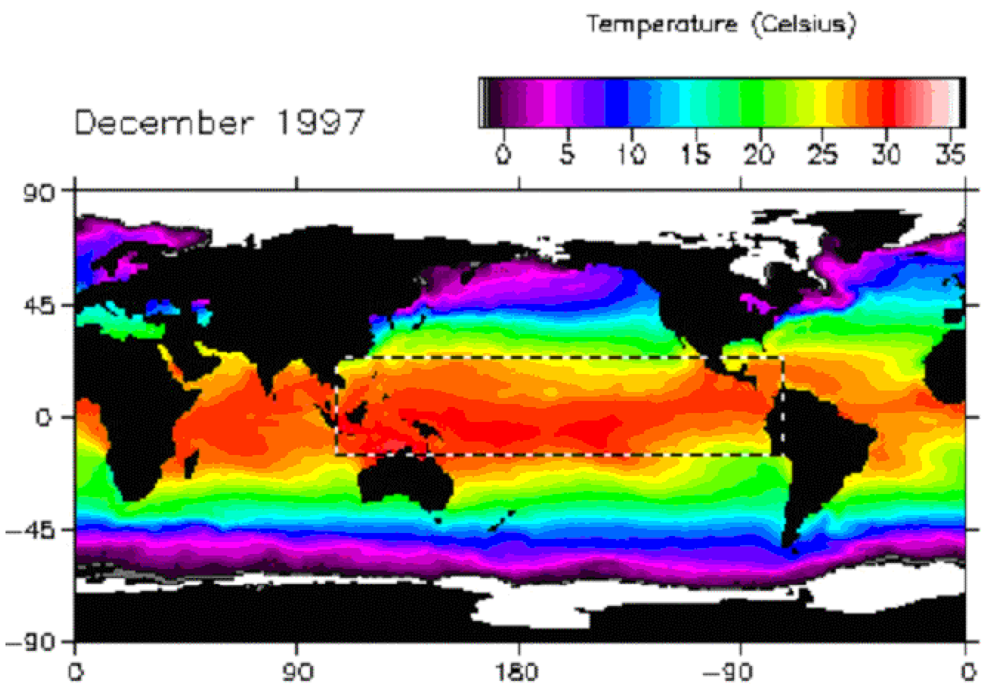
NOTE: both algorithms work for cloud-free pixels => cloud mask is required

- **SST Applications.**




Temperature (Celsius)
December 1990
0 5 10 15 20 25 30 35
90
45
0
−45
−90
0
90
180
−90
0

El Nino


Temperature (Celsius)
December 1997
0 5 10 15 20 25 30 35
90
45
0
−45
−90
0
90
180
−90
0

2. Microwave vs. IR SST retrievals

Factor affecting radiometry	**Infrared radiometry**	**Microwave radiometry**
Magnitude of emitted radiation from the sea surface	[+] large B(λ, T)	[-] small B(λ, T)
Sensitivity of brightness to SST	[+] large $\frac{1}{B}\frac{\partial B}{\partial T}$	[-] small $\frac{1}{B}\frac{\partial B}{\partial T}$ (B is proportional to T)
Emissivity	[+] ε = about 1	[-] ε = about 0.5
Clouds	[-] Not transparent	[+] Clouds largely transparent (improvement at longer wavelengths)
Sea state (e.g.,, roughness)	[+] Independent	[-] ε varies with sea state
Atmospheric interference	[-] Requires complex correction	[+] Easily corrected with multichannel radiometer
Spatial resolution	[+] A narrow beam can be focused. Diffraction is not a problem in achieving high spatial resolution with a small instrument	[+] Diffraction controls the beam at large wavelengths. Large antenna required for high spatial resolution
Viewing direction on surface	[+] Surface radiance largely independent of viewing direction	[-] ε varies with viewing direction
Absolute calibration	[+] Readily achieved using heated on-board target	[-] Absolute calibration target not readily achieved
Presently achievable sensitivity	0.1 degree K	1.5 degree K
Presently achievable absolute accuracy	0.6 degree K	2 degree K