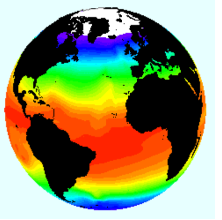
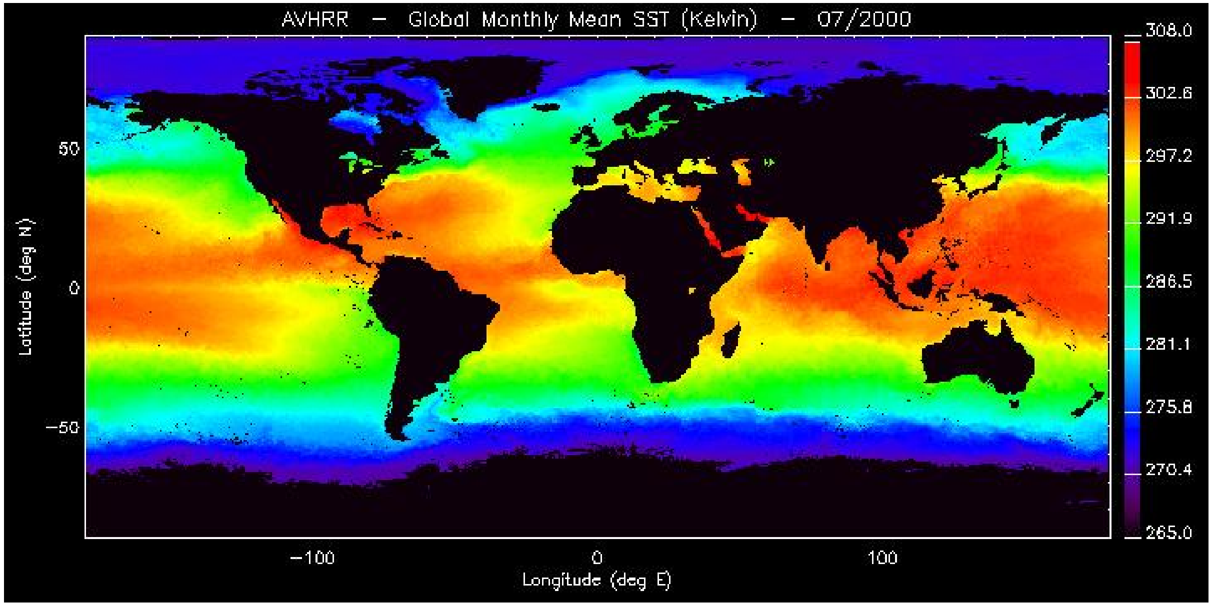


SECOND YEAR: 2604
REMOTE SENSING

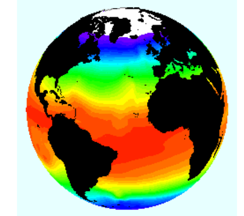
PASSIVE SOUNDING OF THE SEA SURFACE

Prof. HARTMUT BOESCH

Earth Observation Science, Dept. of Physics and Astronomy, University of Leicester



PURPOSE OF THIS LECTURE



To introduce passive sensing of Planetary surfaces via the Planck function

- Schwarzchild’s equation (IR)
- Window regions (IR)
- Single gas layer model

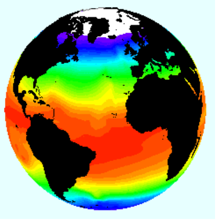
To describe applications of IR and microwave passive sensing of the Earth’s sea surface

- Sea surface temperature (SST): IR and microwave
- ATSR and dual viewing
- Sea surface salinity

To introduce passive sensing of the sea surface via reflected visible radiation

- Ocean colour

PASSIVE REMOTE SENSING FOR THE OCEAN



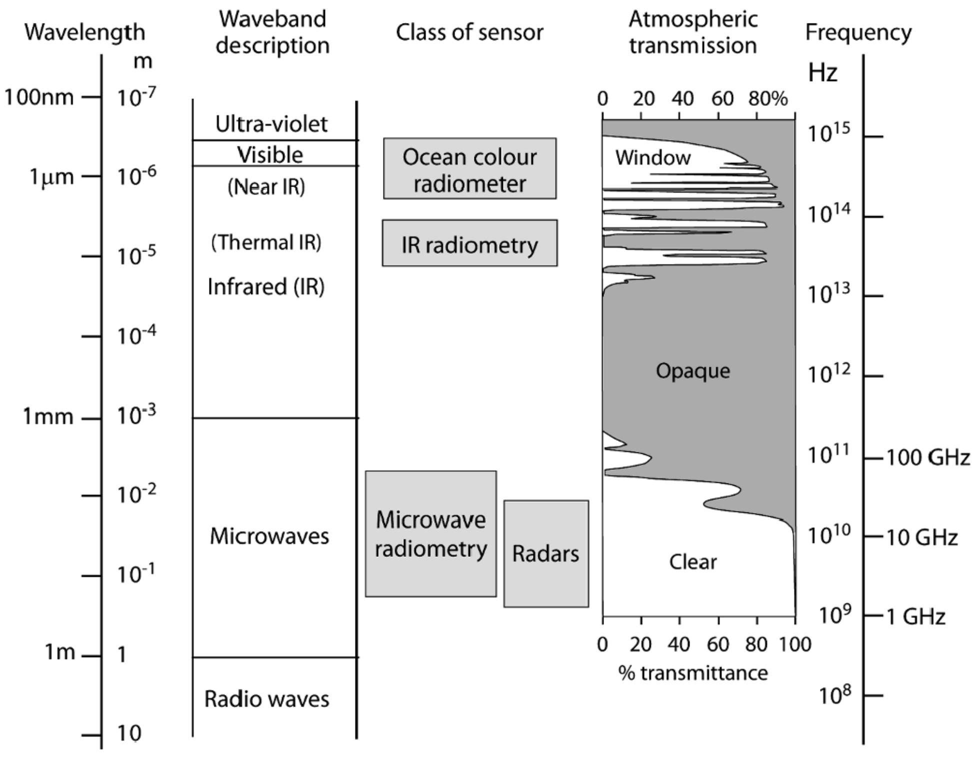


Figure 2.10. The electromagnetic spectrum, showing the regions exploited by typical remote-sensing instruments.

Visible:

- **Reflection from surface or scattering from particles in water**
- **Very good for ice**
- **Difficult for water but does work.**

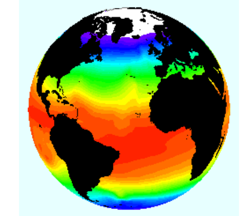
IR and Microwave

- **Emission from surface: $I = \varepsilon_s B(T_s)$**

Things we have to worry about

- **Which part (depth) of the surface?**
- **The atmosphere between the surface and the sensor**

RECAP: SCHWARZSCHILD'S EQUATION (NADIR)



Infra-red top of the atmosphere signal: surface emission of radiation (Planck fn.) modified by complex series of absorption and emission processes in the atmosphere.

Schwarzchild's eqn (IR nadir):

$$I(\lambda) = \varepsilon_S B(\lambda, T_s)\, \mathcal{T}(\lambda, \infty)$$
$$+ \int B(\lambda, T_z)\, d\mathcal{T}(\lambda, \rho, T_z)/dz\; dz$$
$$+ R_S\, I_{Down}(\mathrm{atm})\, \mathcal{T}(\lambda, \infty)$$

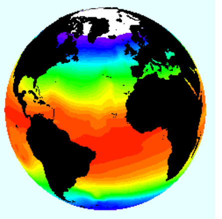
$I(\lambda)$: *intensity* or *radiance* at the top of the atmosphere (signal observed by a perfect satellite instrument).

T_z is the *temperature* of the atmosphere at altitude z.

$R_S\, I_{Down}(\mathrm{atm})\, \mathcal{T}(\lambda, \infty)$ is the radiation emitted by the atmosphere towards the surface and reflected back towards space.

This is the full expression for radiative transfer generally integrated numerically (i.e. by computer).

ATMOSPHERIC CORRECTION



Schwarzchild's equation in parts:

1st term: Surface emission, $\varepsilon_s B(\lambda,T_s)$, modified by the transmission of atmosphere between ground and space, $\mathcal{T}(\lambda,\infty)$.

2nd term: Emission from the Planck fn. at each height in the atmosphere, $B(\lambda,T_z)$, modified by $d\mathcal{T}(\lambda,\rho,T)/dz$.

3rd term: Reflection, R_s, of radiation emitted from the atmosphere back towards the ground.

In this course, can neglect R_s providing that this is stated as an assumption.

Hence can measure T_s of surface from $B(\lambda,T_s)$ and properties of surface from $\varepsilon_s(\lambda)$

However, *the atmosphere matters* because of :

- **$\mathcal{T}(\lambda,\infty)$ in the 1st term**
- **the 2nd term (purely atmosphere).**
- **the atmospheric emission in the 3rd term.**

***"Atmospheric correction"* is therefore important.**

Minimise atmosphere influence by choosing a window region.

Brightness Temperature

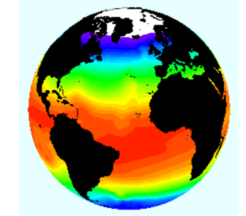
Radiance or signal, $I(\lambda)$, are often expressed as *brightness temperature (BT)*.

BT is the temperature for which the Planck function would have the *same* value as the measured intensity (an equivalent blackbody temperature).

Usually, we find $BT < T_s$ because

- **mean atmospheric temperature of gas layer is *lower* than that of the sea surface i.e. the bulk of the absorption is in the troposphere!**
- **surface emissivity $\varepsilon_s < 1$ (In IR $\varepsilon_s \approx 1$ over ocean)**

RECAP: SINGLE LAYER GAS MODEL



Assume R_s term can be neglected, total signal:

$$I(\lambda) = \mathcal{T}(\lambda)\, I_o(\lambda) + (1 - \mathcal{T}(\lambda)) \times B(\lambda, T)$$

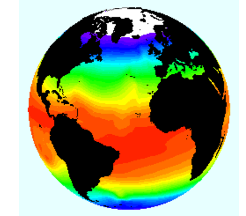
Surface of emissivity, $\varepsilon_s(\lambda)$, and temperature, T_s:

$$I(\lambda) = \varepsilon_s(\lambda) \times B(\lambda, T_s) \times \mathcal{T}(\lambda) + (1 - \mathcal{T}(\lambda)) \times B(\lambda, T_g)$$

To sense Surface Temperature T_S we require:

- **Thermal emission measurements in the infra-red or microwave so we can use $B(\lambda,T_S)$ to get T_S.**
- **A knowledge of the emissivity of sea water, ε_S.**

EXAMPLE 1



A satellite radiometer measures the radiance from the Earth's sea surface in the nadir direction at 12 μm and observes a brightness temperature of 290 K.

Assuming the temperature of the atmosphere is the same as that of the ocean, calculate the sea surface temperature of the scene if the transmission of the atmosphere at this wavelength is $\mathcal{T} = 0.9$

$$I(\lambda) = \varepsilon_s(\lambda) \times B(\lambda, T_s) \times \mathcal{T}(\lambda) + (1 - \mathcal{T}(\lambda)) \times B(\lambda, T_a)$$

$$B(290\ K) = \varepsilon_s(\lambda) \times B(\lambda, T_s) \times 0.9 + (1 - 0.9)\, B(\lambda, T_a)$$

$$= \varepsilon_s(\lambda) \times B(\lambda, T_s) \times 0.9 + 0.1 \times B(\lambda, T_a)$$

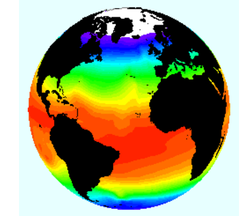
Assume $T_s = T_a$ where T_a = temperature of the atmosphere

$$B(\lambda, Ts) = B(290K) / (0.9\, \varepsilon_s + 0.1)$$

If $\varepsilon_s = 1$ then $T_s = 290$ K.

If $\varepsilon_s = 0.9$ then $B(T_s) = B(290\ K)/0.91$

EXAMPLE 2



An instrument measures the Top of the Atmosphere radiance (TOA) in the 11μm window. What is the decrease in equivalent Planck function (i.e. signal) due to the atmosphere given that the transmission of the atmosphere at 11μm is $\mathcal{T}$ = 0.903 and the surface-emitted radiance is $B(T_0)$. [Assume that $B(T_a) \times (1-\mathcal{T}) = 0.083\, B(T_0)$].

Decrease in signal due to atmosphere $\Delta B = B(\lambda,T_0) - I(\lambda)$

$$\Delta B = B(T_0) - [\, B(T_0)\mathcal{T} + B(T_a) \times (1-\mathcal{T})\,]$$

$$\Delta B = B(\lambda,T_0)\,(\, 1-\mathcal{T}\,) + B(T_a) \times (\, 1-\mathcal{T}\,)\,]$$

$$= (1-0.903)\, B(T_0) - 0.083\, B(T_0) = 0.014\, B(T_0) \quad \textbf{(1.4\% reduction)}$$

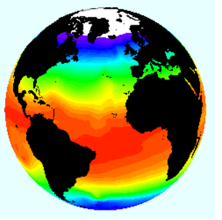
What would be the error in inferring the SST from these radiance measurements if the atmosphere signal was not taken into account

Wien Approx. $$B \cong \frac{2hc^2}{\lambda^5}\frac{1}{exp(hc/\lambda kT)}$$ **and** $$\frac{dB}{dT} = B\frac{hc}{\lambda kT^2}$$

$$\Delta T = \frac{dT}{dB}\Delta B = \frac{\lambda kT^2}{hc}\frac{\Delta B}{B} = = \frac{\lambda kT^2}{hc} \times 0.014 = 0.95\mathrm{K}\ (\mathrm{for}\ \mathrm{T_0} = 290\mathrm{K})$$

Is this a reasonable error?

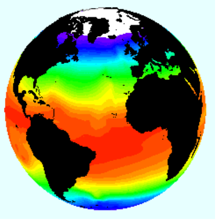
WHY MEASURE SEA SURFACE TEMPERATURE (SST) FROM SPACE?

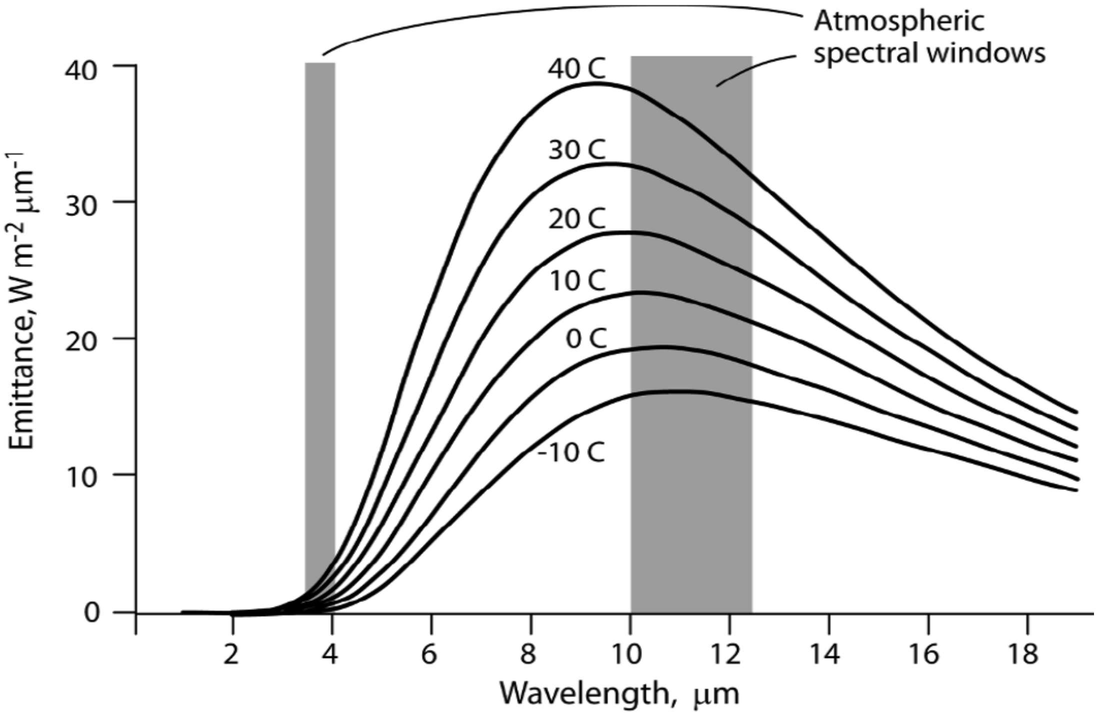


1. SST is an indicator of climate change (temperature trends)
2. SST controls the heat and moisture fluxes passing from the ocean to the atmosphere. Heat fluxes include:
   - latent heat (evaporation and condensation)
   - sensible heat (conduction)
   - radiative heating i.e. the Planck function.

   Heat fluxes result in surface winds through the creation of atmospheric pressure gradients.
3. Evaporation (related to SST) results in changes in the density of sea water and for example, sinking motion (linked to salinity)
4. SST can act as a tracer or probe of the underlying large scale ocean circulation and of travelling waves. Such motions transfer heat and momentum from region to region e.g the Gulf Stream.
5. Changes in SST at the poles will influence the formation of sea ice, and hence sea levels.
6. Operational oceanography requires SST

IR Remote Sensing of Sea Surface Temperature

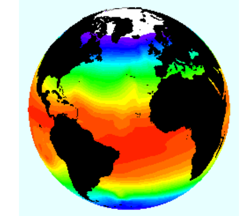




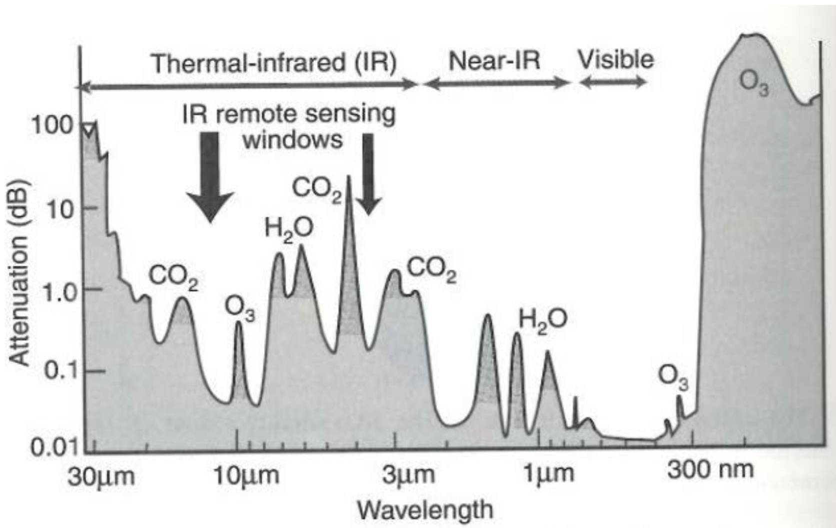
- **Very good sensitivity to SST as we measure near the peak of Planck Function**
- **Ability to use atmospheric windows: 3.5-4 µm and 10-12 µm**

  -> ‘small' atmospheric corrections

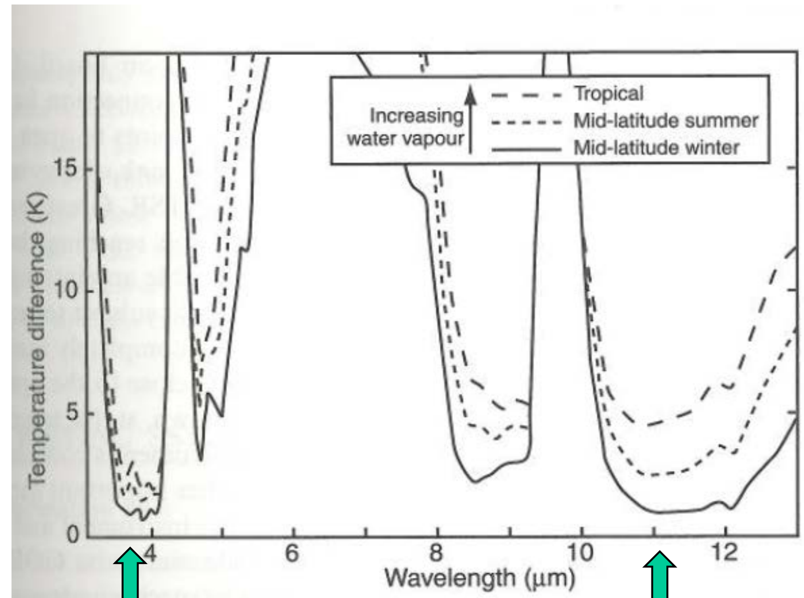
IR Remote Sensing of Sea Surface Temperature



Atmospheric 'windows' used for IR retrievals



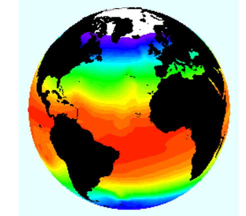
Atmospheric effect on brightness temperature



IR Windows

Atmospheric correction- equivalent to 1K at high latitudes and up to 20 K in the tropics

EMISSIVITY



The surface term in the radiance equations depends on the surface temperature but also most critically on the *surface emissivity.*

Surface emissivity needs to be known when measuring surface temperature

The emissivity, ε_{sea}, of water depends on:

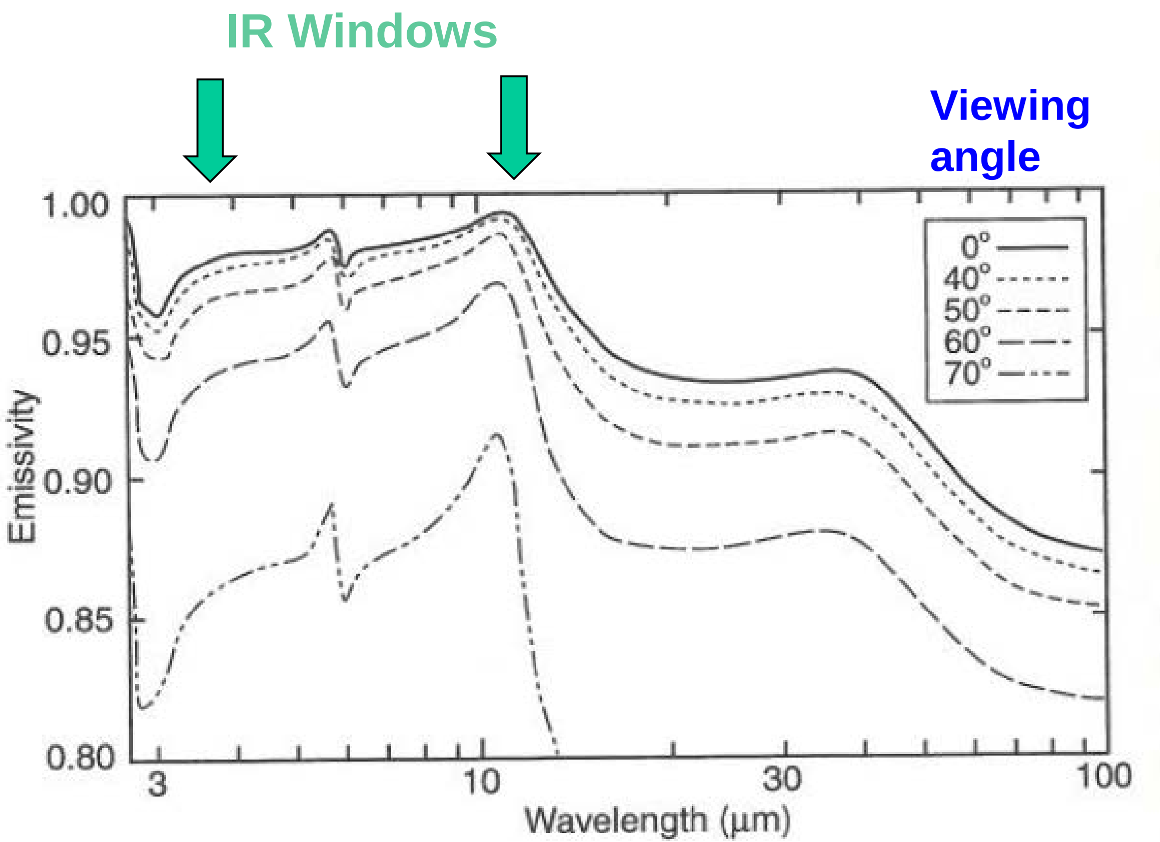
1. Frequency or wavelength, λ.

   Infra-red: ε_{sea} = 0.98 - 0.99 (at 0° incidence)

   Microwave: ε_{sea} = 0.4 at 10 GHz (at 0° incidence)

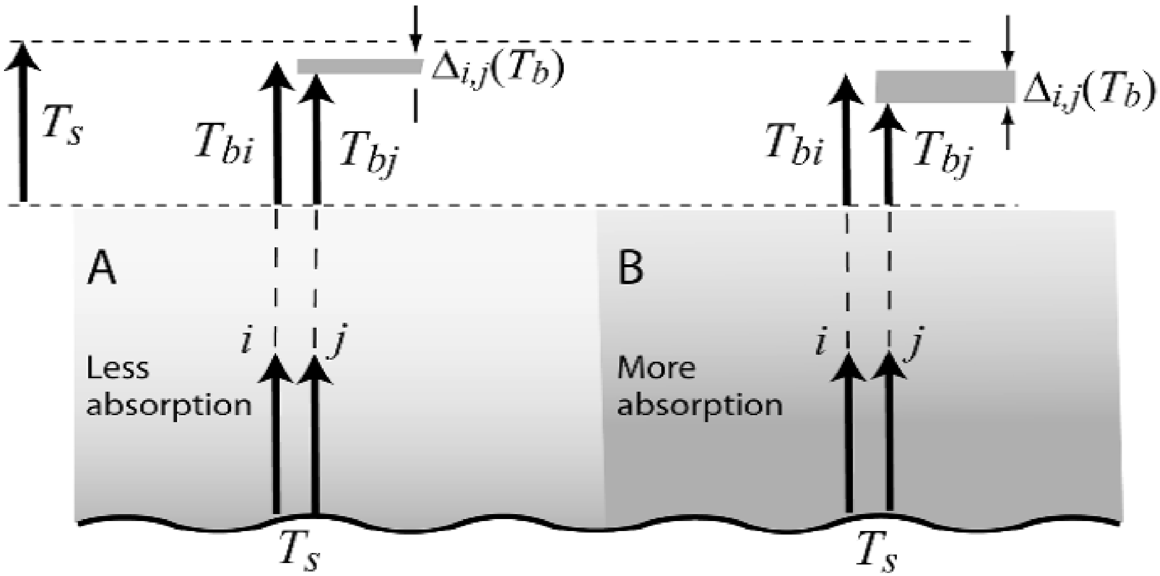
2. Incidence angle for radiation (usually angle from the vertical)
3. Wind speed and wave motion because of the dependence on angle.
4. Ionic composition (weakly) – principally sea salt influence below 5 GHz.
5. Temperature, particularly in the microwave.

IR EMISSIVITY VARIATIONS WITH WAVELENGTH AND ANGLE



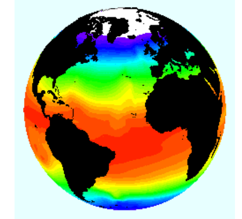
- Emissivity close to 1 (0.98-0.99 for nadir view)
- Reflectivity of surface is small but non-zero
- Weak (but noticeable) dependence on viewing angle
- Drop in emissivity towards larger wavelength

Atmospheric Correction



- **Use 2 wavebands *i* and *j* which respond differently to atmospheric absorption (water vapour)**
  - **difference in brightness temperatures T_{bi} and T_{bj}: $\Delta_{i,j}(T_b)$**
- **Difference will be smaller in case A (less absorption) than in case B (more absorption)**
- **Spectral difference $\Delta_{i,j}(T_b)$ is related to the number of absorbing gases in the atmospheric path**
  - **$\Delta_{i,j}(T_b)$ provides a measure of the degree of atmospheric attenuation that enables atmospheric correction**
- **The same applies when using 2 different views for the same waveband**

INFRA-RED AND MICROWAVE INSTRUMENTS FOR SST



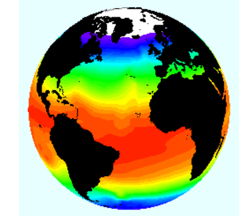
INFRA-RED (IR) INSTRUMENTS:

- **Measure near the peak of the Planck fn. (≈ 10μm) so much greater T sensitivity!**
- **Larger, more uniform emissivity of sea water (close to 1).**
- **Very small field-of-view (FOV) of instrument (typically 1 km diameter pixel for SST measurements).**
- **Better end-to-end calibration of instrument.**

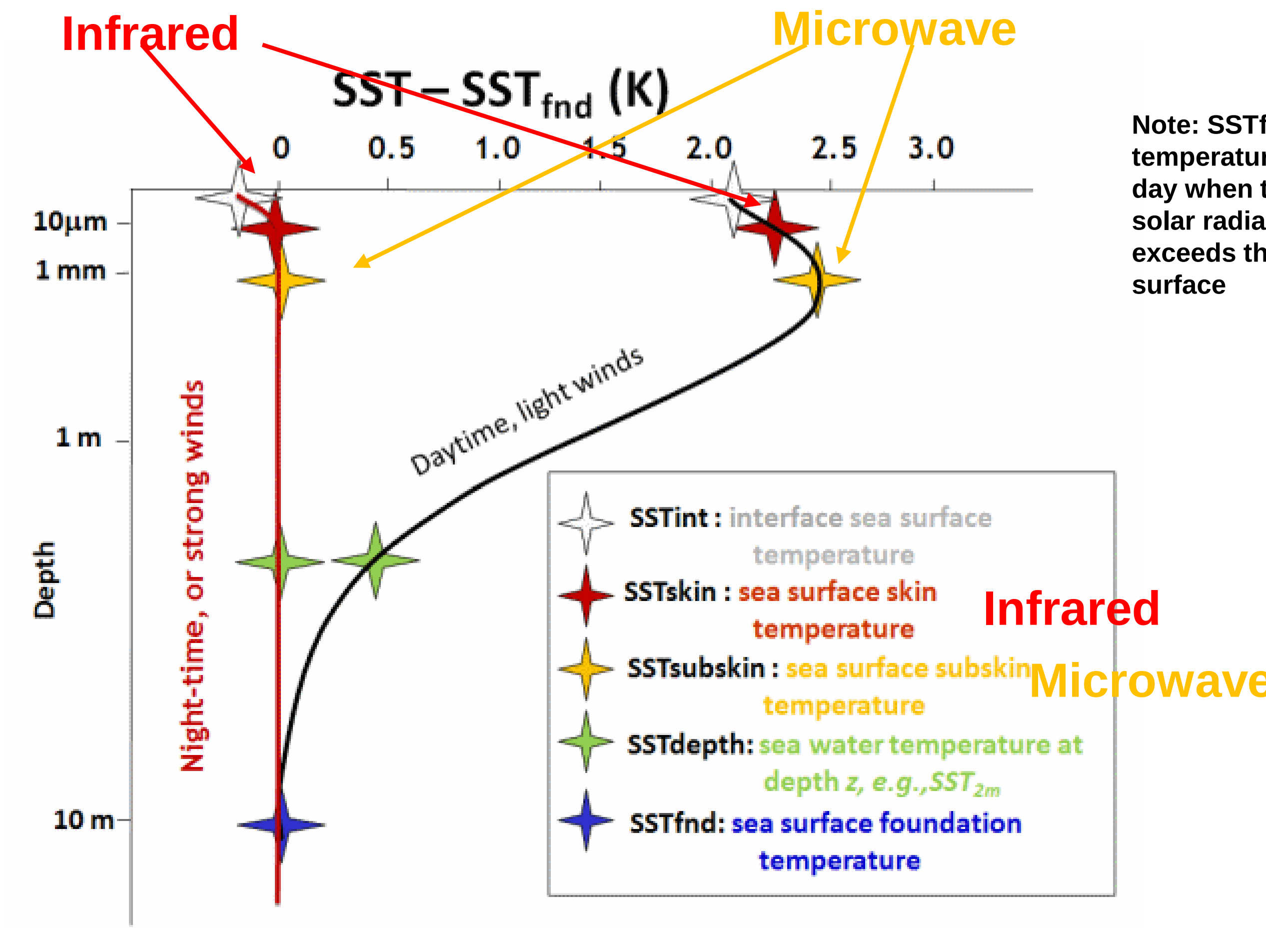
MICROWAVE (MW) INSTRUMENTS

- **Very low noise instruments**
- **Can see through many clouds unlike the infra-red.**
- **Simpler atmospheric correction problem (high atmospheric transmission)**
- **Microwave instruments: FOV ≈ 10 – 100 km "pixel" diameter, also side-lobes introduce far-away signals.**

Emission Depth for IR and MW



Oceanic Temperature Profile



Note: SSTfnd is defined as the temperature at the first time of the day when the heat gain from the solar radiation absorption exceeds the heat loss at the sea surface

ΔSST(MW-IR) ~0.25K during daytime

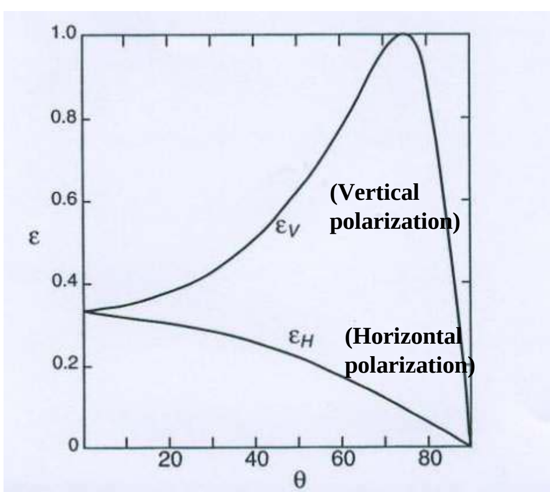
But ΔSST(MW-IR) ~0K during night time

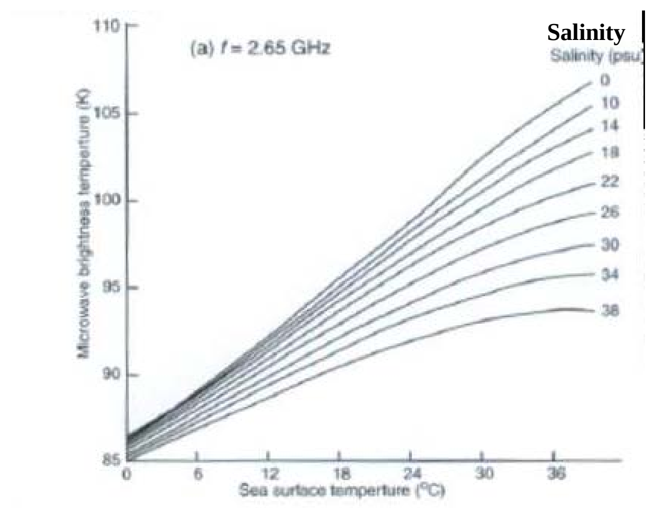
Microwave emissivity

- **In MW, Planck function can be described by Rayleigh Jeans Law (approximation for large λ)**

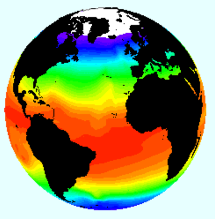
$$I_S = \frac{2kT_S\varepsilon_S}{\lambda^2}$$

- **But MW observations of surface are difficult because**
  - **MW emissivity of water typically much less than 1 (BT << T_s)**
  - **Emissivity varies strongly with viewing angle and polarization direction**
  - **Emissivity depends on temperature (and salinity), thus dependence of microwave BT on SST is not linear.**





IR Instruments for SST



- Nadir Infra-red measurements in atmospheric windows give the best sensitivity to SST.
- Accuracies of 1.0 K or better are possible at horizontal resolutions of 1 to 4 km.
- Typical instruments:

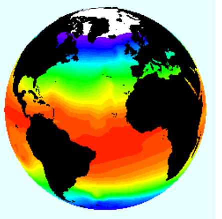
AVHRR (Advanced Very High Resolution Radiometer)

- Nadir view only
- SST tied to buoy network
- Time series since 1978

ATSR series (Along Track Scanning Radiometer)

- Dual view
- SST derived independently
- Time series since 1991

THE ALONG TRACK SCANNING RADIOMETER (ATSR)



The Along Track Scanning Radiometer (ATSR) is probably the most accurate SST space instrument

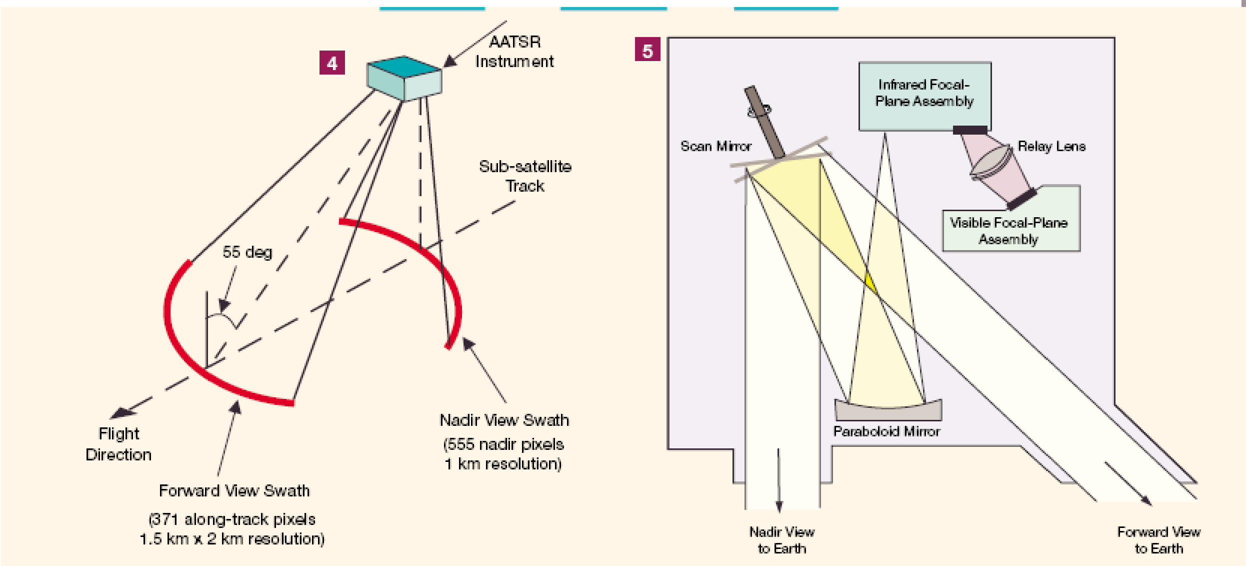
Advantage: can correct intrinsically for the majority of the atmosphere contribution *through a dual angle view*.

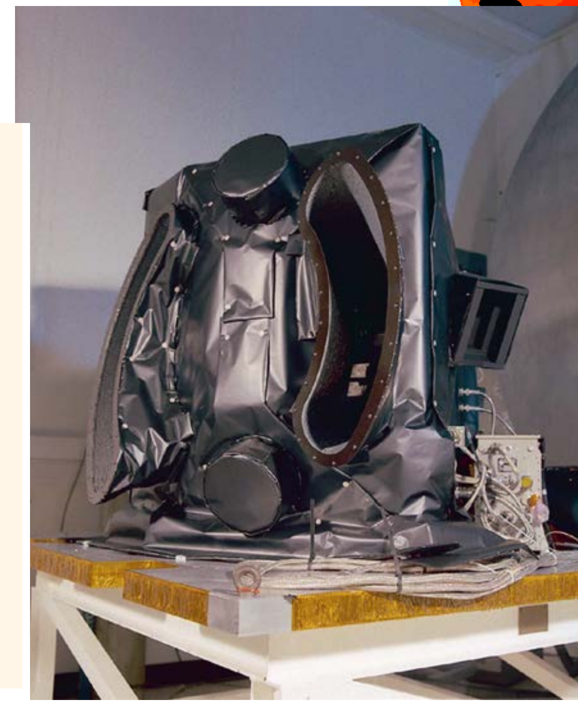
The ATSR series of instruments (3 so far):

- **ATSR-1/ERS-1 [July 1991]**
- **ATSR-2/ERS-2 [April 1995]**
- **AATSR (Advanced!)/ENVISAT [March 2002].**
- **SLSTR (Sea and Land Surface Temperature Radiometer, launched on 16 Feb. 2016 on Sentinel 3)**

[All are on LEO, sun synchronous satellites]

THE ATSR SERIES OF INSTRUMENTS





- Implementation via a conical scan mirror rotating at 6.6 revs per second; the satellite is moving with a ground speed of ≈ 7 km/s. Views are therefore spaced along the orbit by 1 km (i.e. one pixel).
- Calibration occurs in the non-scene viewing parts of the scan (blackbodies at 265 K,305 K).
- Low-noise infra-red detectors cooled to less than 95 K with a mechanical Stirling cycle cooler

ATSR INFRA-RED CHANNELS

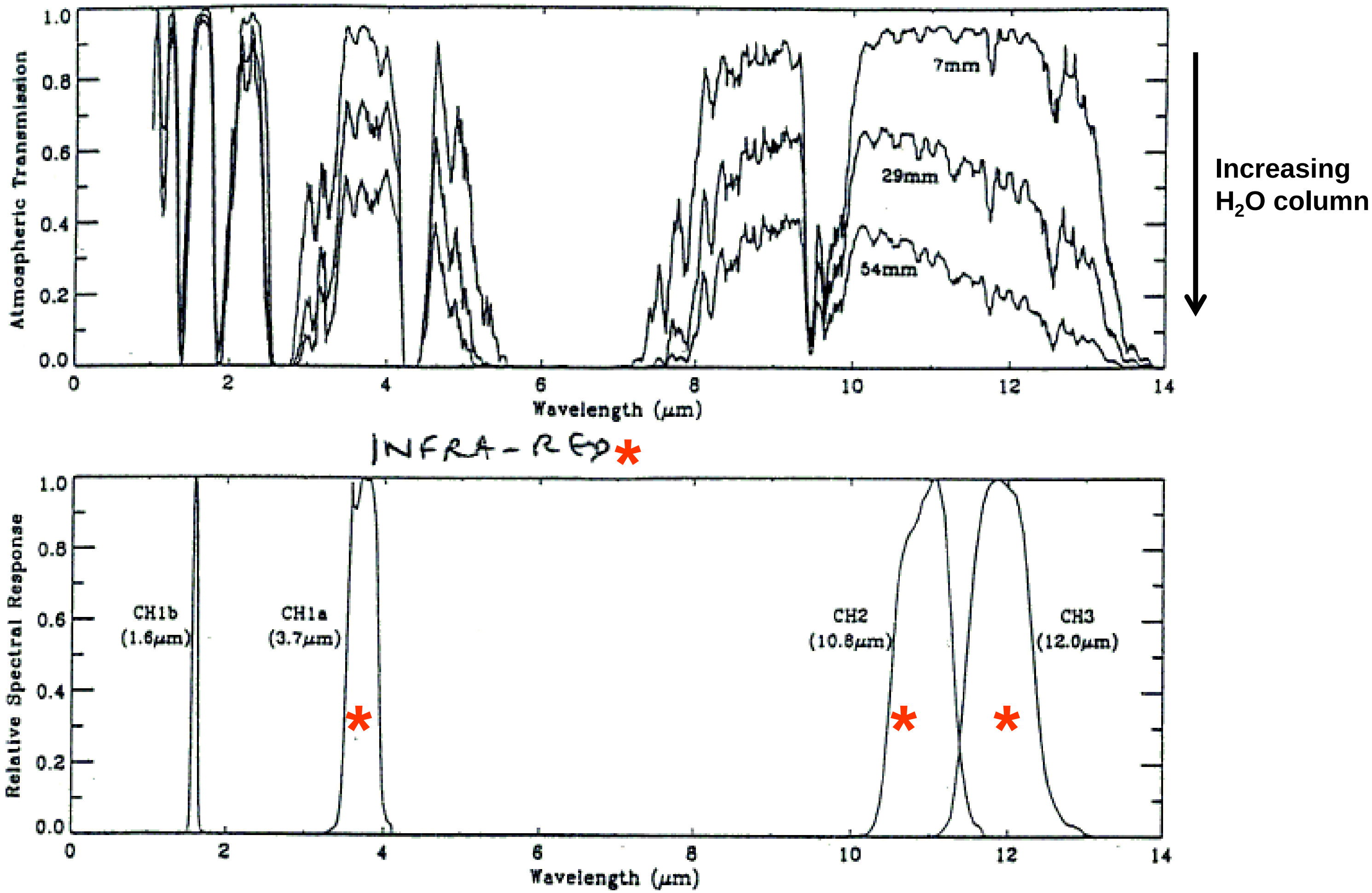
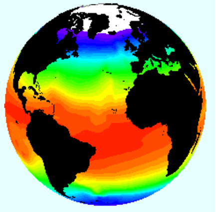


Figure 2.1: Atmospheric transmission for three different amounts of precipitable water (7mm — polar; 29mm — temperate; 54 mm — tropical), and the ATSR spectral channels matched to atmospheric 'window' regions.

ATSR CHANNELS



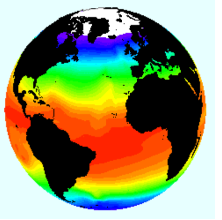
Target	Wavelength	Bandwidth	ATSR1	ATSR2/ AATSR	DETECTOR TYPE[2]
Chlorophyll	0.55μm	20nm	N	Y	Si
Vegetation[1]	0.67μm	20nm	N	Y	Si
Vegetation[1]	0.87μm	20nm	N	Y	Si
Clouds	1.6μm	0.3μm	Y	Y	PV InSb
SST	3.7μm	0.3μm	Y	Y	PV InSb
SST	10.8μm	1.0μm	Y	Y	PC MCT
SST	12.0μm	1.0μm	Y	Y	PC MCT

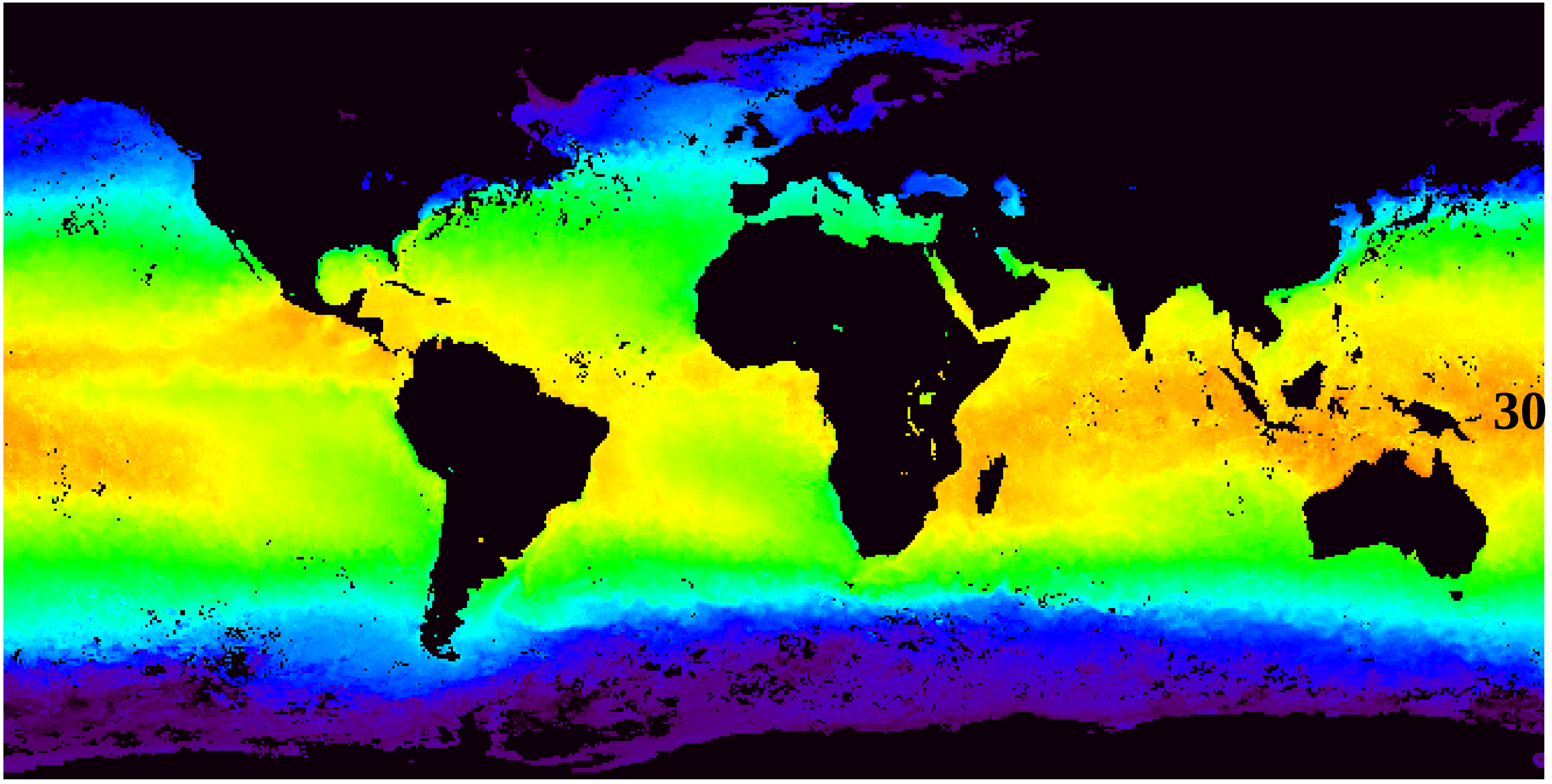
1 For computation of vegetation index.

2 PV= Photovoltaic; PC Photoconductive; MCT=HgCdTe(mercury Cadmium Telluride).

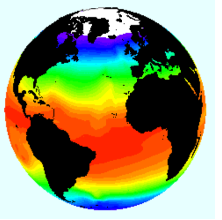
A combination of IR channel is needed for cloud screening

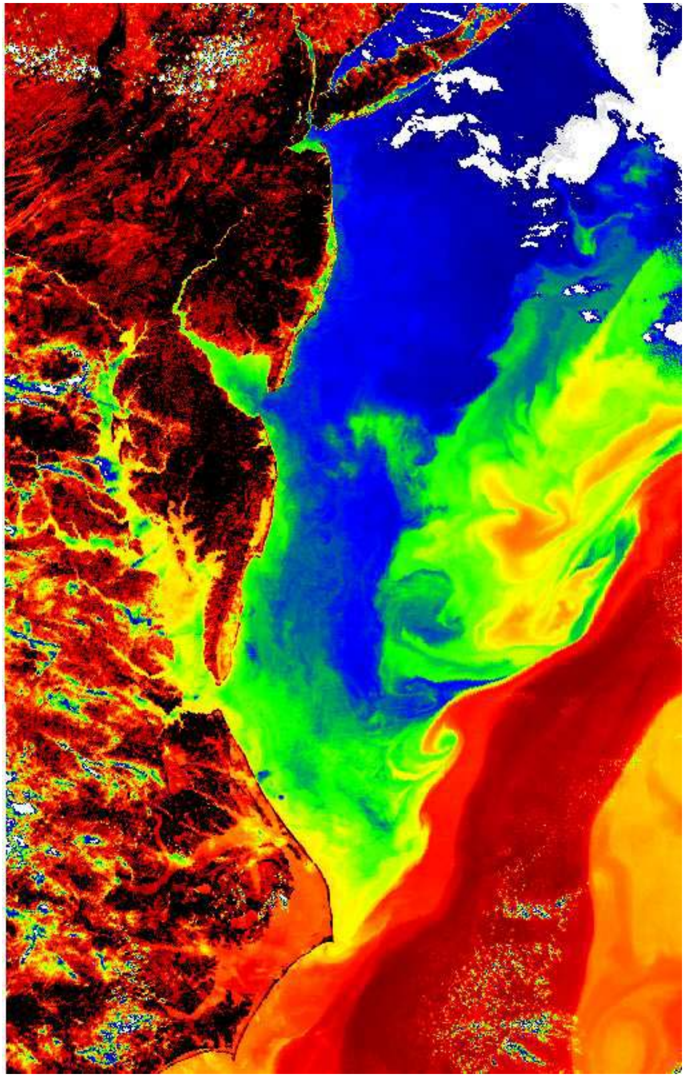
SEA SURFACE TEMPERATURE FROM INFRA-RED MEASUREMENTS by AATSR (MONTHLY AVERAGE)



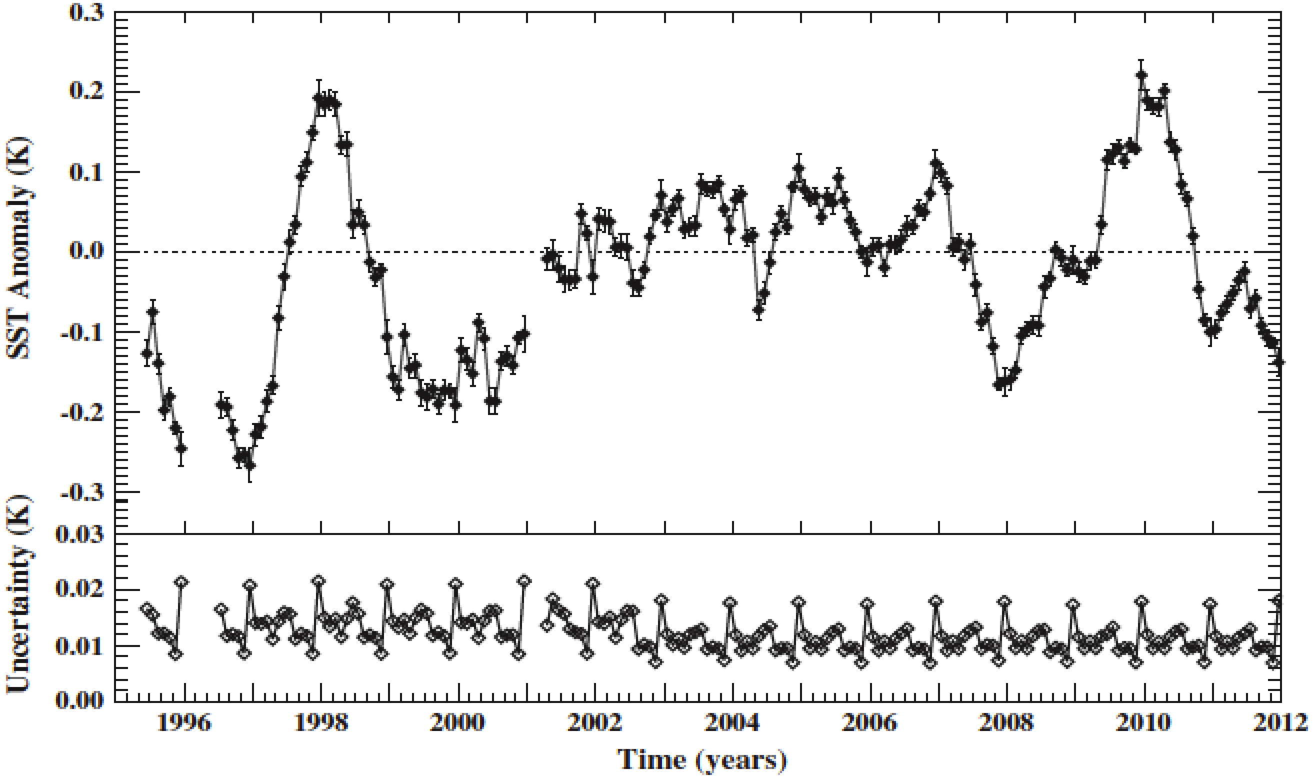


ATSR-2 SST SHOWING WARM GULF STREAM WATER OFF EASTERN COAST OF U.S.A



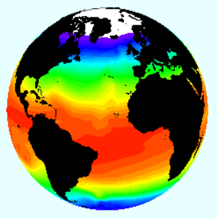


Climate based SST records



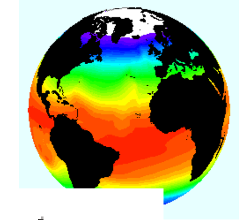
Night-time dual-view 3-channel monthly mean global SST anomaly (to climatology for the base period January 1997 to December 2011). Error bars indicate the estimated 1 sigma uncertainty (Veal et al., RSE, 2013)

OCEAN SALINITY



- **The emissivity of sea water below 10 GHz depends on the concentration of dissolved sea salt (NaCl) – this is known as the salinity.**
- **Salinity is important because it affects the density of water e.g. as the Gulf Stream moves North from the Equator, the water cools and becomes very dense until it sinks. The sinking (deep water formation) is followed by transport in the deep ocean back to the Equator.**
- **Salinity is observed by the Soil Moisture and Ocean Salinity (SMOS) experiment. The SMOS is an Earth Explorer Opportunity Mission launched in 2009.**
- **The SMOS employs a 1.4 GHz (L band), dual polarisation passive interferometer composed of 72 radiometers on a Y structured antenna.**

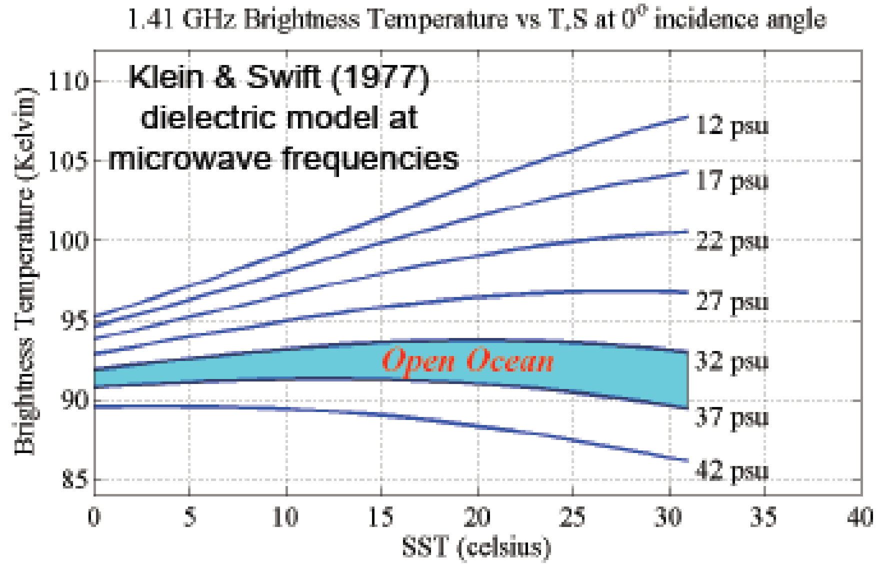
1.4 GHz radiometry: relation to salinity

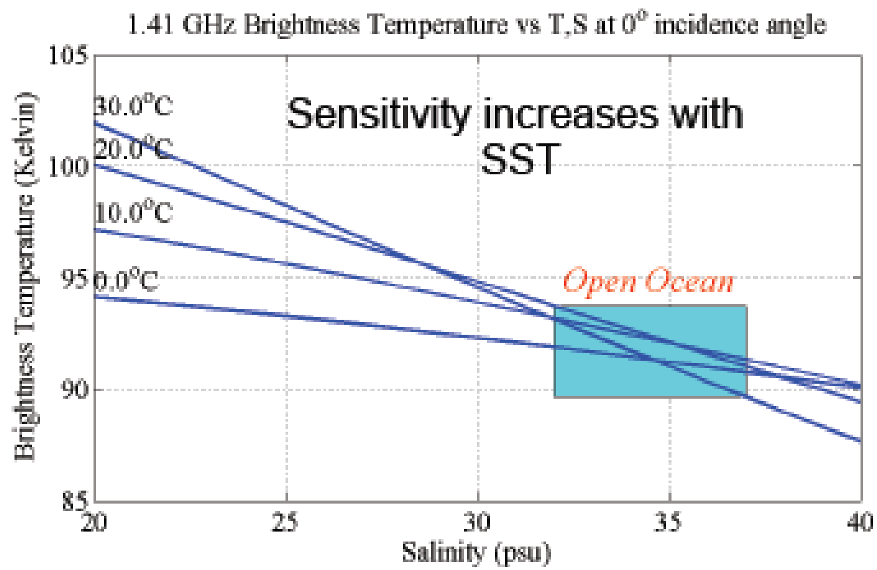


ε_S in MW depends on SST and salinity SSS

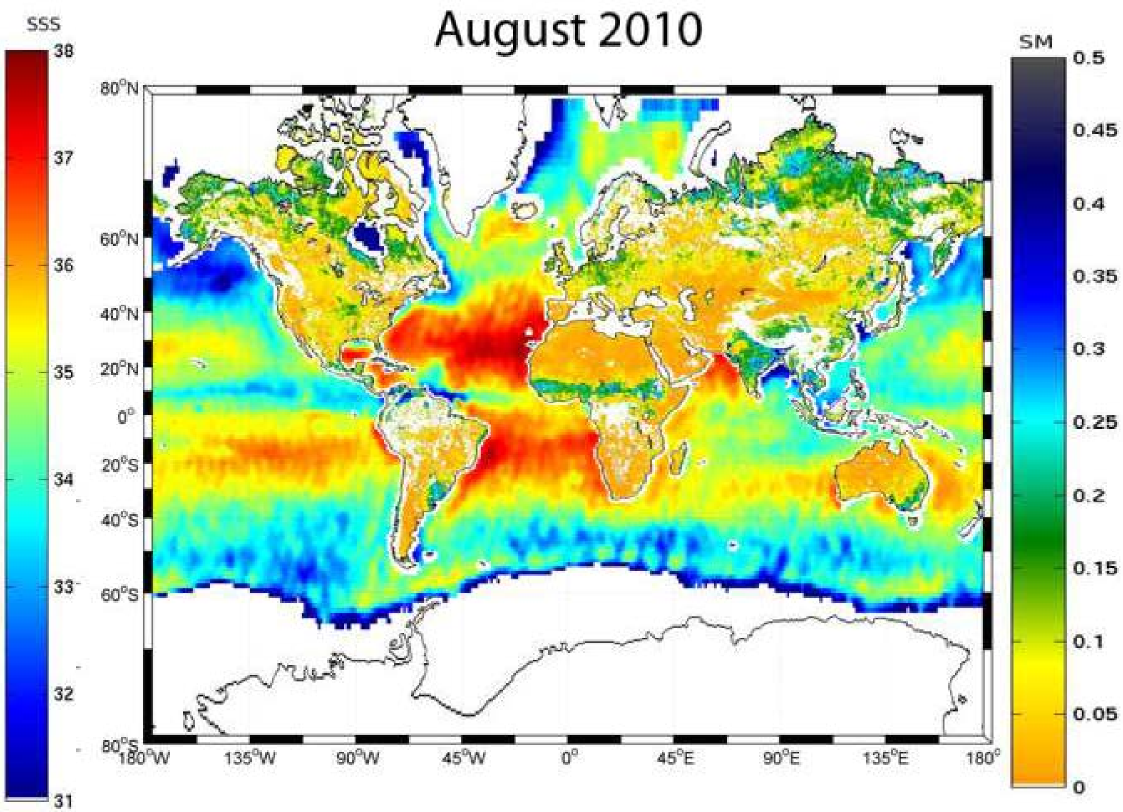
If SST is known (from other sources) then SSS can be derived from ε_S

This is the key idea supporting the SMOS mission





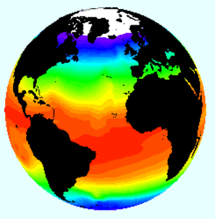
SEA SURFACE SALINITY OR SSS



SMOS sea-surface salinity and soil moisture have been combined on one map (August 2010). The SSS data have a spatial resolution of 1×1° and a quasi-global accuracy of 0.4 psu

(http://www.esa.int/SPECIALS/smos/SEMM1K4PVFG_0.html)

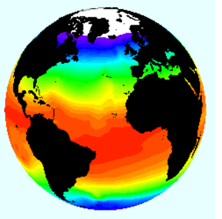
REFLECTION OF VISIBLE LIGHT: OCEAN COLOUR

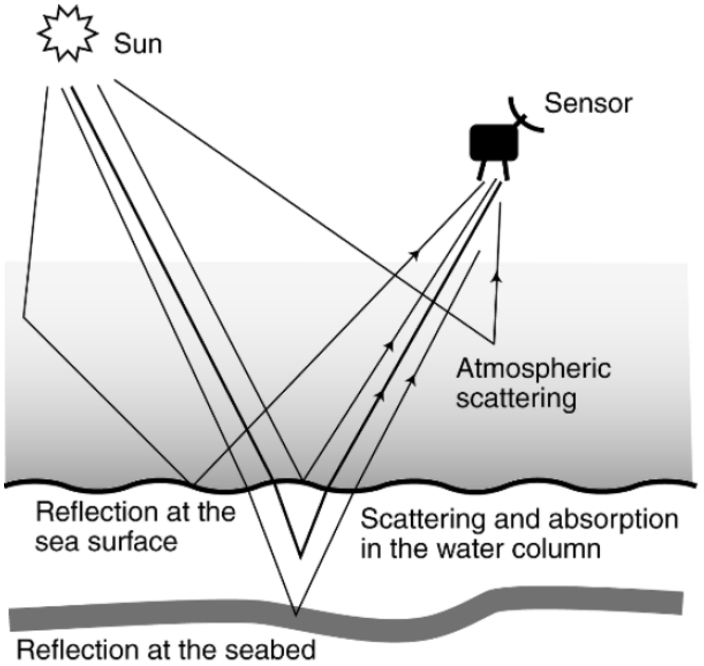


- **Ocean colour is a measure of the magnitude and spectral composition of visible light leaving the ocean**
- **The radiation is not only reflected by the surface but also selectively absorbed, scattered, and reflected in the upper layers of the ocean (tens of metres). The intensity is determined by the *interactions* of incident light with substances or particles present in the water.**
- **The most significant constituents are free-floating photosynthetic organisms: phytoplankton!!**

  The phytoplankton contain chlorophyll, which absorbs light at blue and red wavelengths and transmits in the green.
- **Particulate matter can also reflect and absorb light: a) reduces the clarity (light transmission) of the water; b) effects its colour.**

OCEAN COLOUR REMOTE SENSING

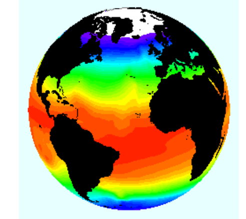




Factors which affect the light reaching an ocean color sensor.

Scattering plays an important role in visible, eg remember λ^{-4} dependence of Rayleigh scattering (but also Mie scattering)

- **In the visible, signal at TOA is result of many effects**
- **Ocean colour observation (water leaving radiance) is challenging**
- **Careful separation of atmospheric scattering and surface reflection from true water-leaving radiance**



OCEAN COLOUR REMOTE SENSING

Observed signal by satellite:

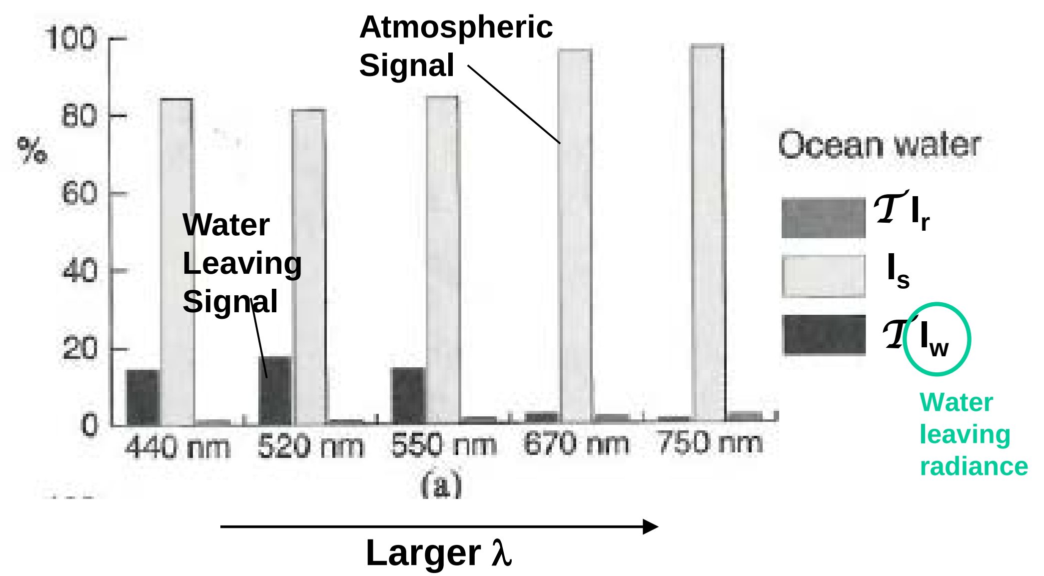
$I_{TOA} = I_s + \mathcal{T} I_r + \mathcal{T} I_w$

I_s: scattered radiance

I_r: reflected radiance

I_w: water leaving radiance

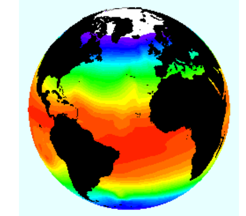
Contribution to the observed signal

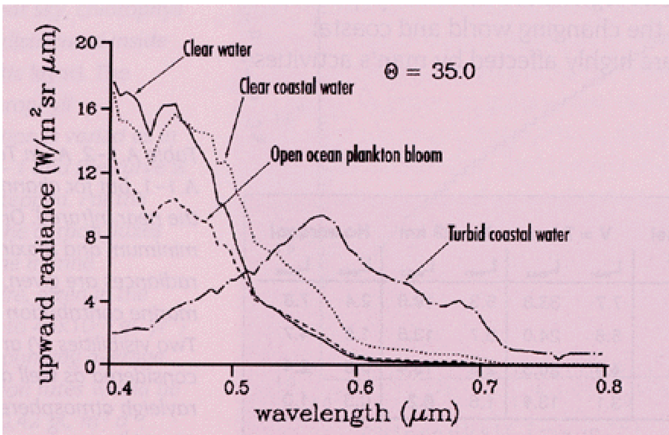


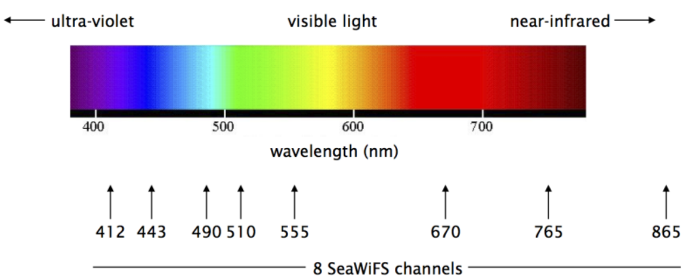
- **Atmospheric scattering can contribute up to 90% of total measured radiance**
- **Water-leaving radiance will also be attenuated in atmosphere**

-> Significant atmospheric correction required

Ocean Colour and Atmospheric Correction







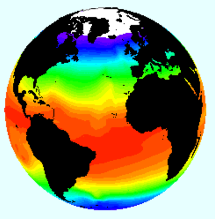
Ocean Colour (Chlorophyll) channels

NIR channels

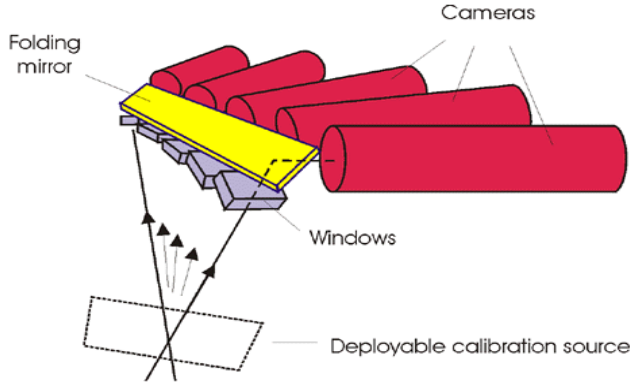
Approach: use spectral bands from the near infrared (NIR) spectrum.

- **Ocean absorbs almost all solar NIR incident (no ocean colour) upon it**
- **Light in NIR measured at TOA must have been scattered by atmosphere or reflected at surface**
- **NIR gives estimate how much scattering has occurred in visible channels & the correction needed**

Ocean Colour Instruments

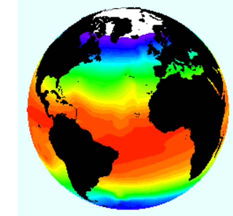


- Coastal Zone Colour Scanner (CZCS)
  - Channels at 443, 520, 550, 670 and 750 nm
- Sea-Viewing Wide Field-of-View Sensor (SEAWIFS)
  - 402-885 nm in discrete bands; quasi-continuous
- MODIS [December 1999]
  - 36 spectral filter regions between 0.405 mm and 14.385 mm.
- MERIS/ENVISAT [March 2002] has:
  - 15 programmable spectral bands between 390 nm and 1040 nm.
  - A swath width of 1150 km (68° field-of-view) through 5 cameras
  - 300 m/ 1200 m spatial resolution
  - CCD imaging (across-track; along-track motion of satellite completes scan)

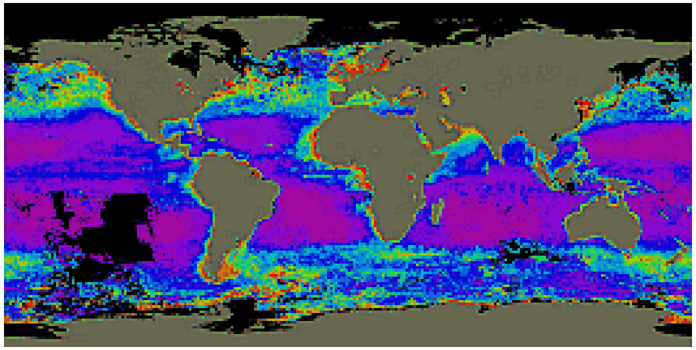


MERIS: cameras are arranged in a fan shape configuration in which the fields of view overlap slightly

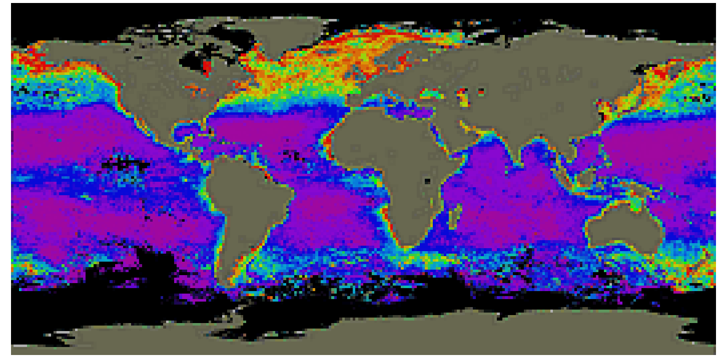
PHYTOPLANKTON: SEASONAL



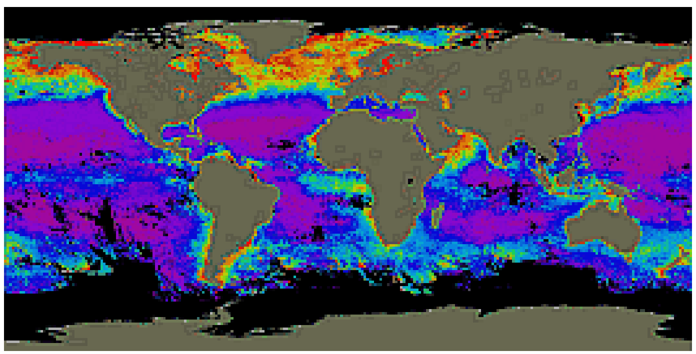
JAN-MAR



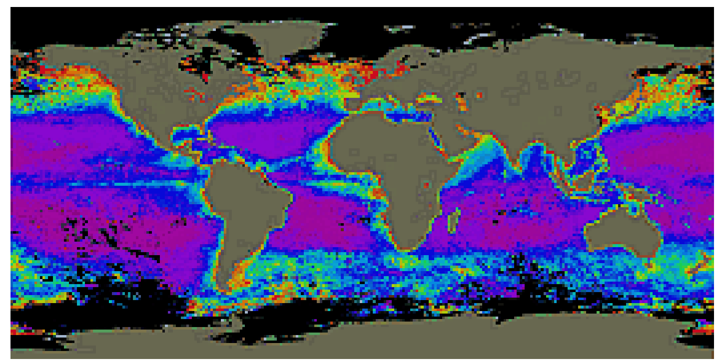
APR-JUN



JUL-SEP



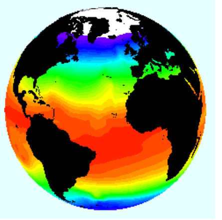
OCT-DEC

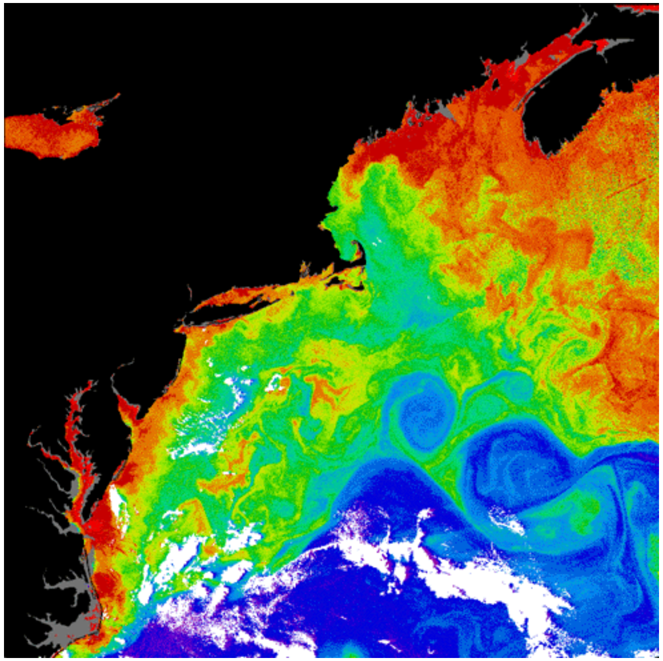


Global phytoplankton concentrations change seasonally, as revealed by these three-month "climatological" composites for all months between November 1978-June 1986 during which the CZCS collected data:

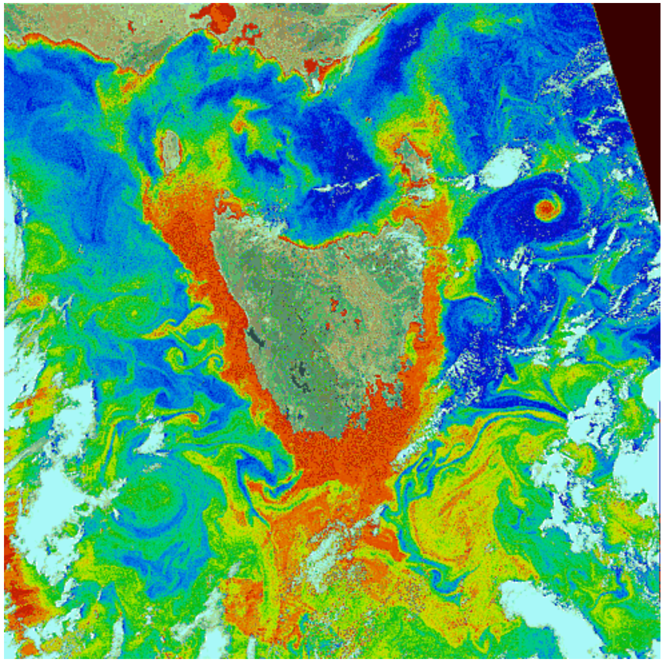
Note the "blooming" of phytoplankton over the entire North Atlantic with advent of northern hemisphere spring, and seasonal increases in equatorial phytoplankton concentrations in both Atlantic and Pacific Oceans, and off the western coasts of Africa and Peru

PHYTOPLANKTON: IMAGES





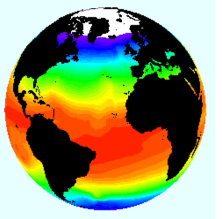
FALSE COLOUR IMAGE OF GULF STREAM: PHYTOPLANKTON (CZCS)



FALSE COLOUR IMAGE OF TASMANIA:

PHYTOPLANKTON(CZCS)

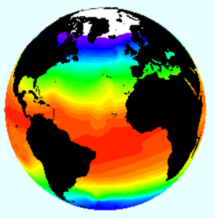
Other Applications



Active range can provide a range of other observations of ocean surface parameter

- **Sea-surface height (SSH) measurements**
- **Wave height and sea-surface roughness**
- **Wind speed**
- **Ice-sheet altimetry**
- **…**

What do you need to know



- Schwarzchild eqn. and Single gas layer model and applications to ocean surface emote sensing
- Importance of SST
- Measurement of SST using IR and microwave
- ATSR series of instruments in detail
- Sea surface salinity
- Concept of ocean colour measurements in the visible
- Chlorophyll and spectral bands
- Ocean colour instruments