Satellite Oceanography: Sea-Surface Temperature and Climate Data Records

Peter J Minnett
Rosenstiel School of Marine and Atmospheric Science,
University of Miami, USA
Satellite Oceanography

Passive remote sensing – measuring emitted or reflected electromagnetic radiation.

(Active remote sensing – using artificial illumination radars & lidars)

Three lectures:

– Infrared
– Visible
– Microwave
Outline

• Historical perspective.
• Review Planck function, atmospheric transmission....
• Radiometric calibration.
• Instrument descriptions:
  – Line scanners: AVHRR, MODIS, VIIRS.
  – Dual-view conical scanners: (A)ATSR, SLSTR.
• Cloud screening.
• Atmospheric corrections.
• What are oceanographic signals detectable from space.
• What is Sea-Surface Temperature?
• How can we generate an SST Climate Data Record?
Early knowledge of SST variability

In 1770, Benjamin Franklin and Timothy Folger published a chart of North Atlantic Currents, which included a depiction of the Gulf Stream. In addition to the surface flow it was realized there were temperature gradients associated with the Gulf Stream.
SST Variability in IR images

The Gulf Stream is seen as darker water extending to northeast from Cape Hatteras. Very High Resolution Radiometer (VHRR) on the NOAA-3 Satellite, April 28, 1974.

(http://www.photolib.noaa.gov/htmls/spac0301.htm)
Tropical Instability Waves revealed in satellite IR images

That was then, this is now


Courtesy Bob Evans et al.
Global 4km VIIRS SST (3.7, 11, 12 µm; night-time) for February 4-6, 2012. Processed at the native 0.75km resolution and a 4km output pixel generated as the average of the 'best' quality retrievals within the 4km cell. SSTs computed using the pre-launch coefficients derived at NGST.

Courtesy Bob Evans et al.
In searching for a theoretical derivation of blackbody radiation, Planck made the revolutionary assumption that an oscillating atom in the wall of a cavity can exchange energy with the radiation field inside a cavity only in discrete bundles called *quanta* given by $\Delta E = h\nu$, where $h$ is known as Planck's constant.

With this assumption, he showed that the radiance being emitted by a blackbody is given by

$$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{\exp \left( \frac{hc}{\lambda kT} \right) - 1}$$  \hspace{1cm} (3)

where $k$ is Boltzmann's constant, and $T$ is the absolute temperature.

This is the *Planck function*; it earned him the Nobel Prize in 1918. The Planck function is more conveniently written as

$$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\exp \left( \frac{c_2}{\lambda T} \right) - 1}$$  \hspace{1cm} (3.8)

where $c_1$ and $c_2$ are the first and second radiation constants. Since the radiance from a blackbody is independent of direction, the radiant exitance from a blackbody is simply $\pi B_\lambda$. 

---

**Planck Function**

- In searching for a theoretical derivation of blackbody radiation, Planck made the revolutionary assumption that an oscillating atom in the wall of a cavity can exchange energy with the radiation field inside a cavity only in discrete bundles called *quanta* given by $\Delta E = h\nu$, where $h$ is known as Planck's constant.
- With this assumption, he showed that the radiance being emitted by a blackbody is given by
  $$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{\exp \left( \frac{hc}{\lambda kT} \right) - 1}$$ \hspace{1cm} (3)
- where $k$ is Boltzmann's constant, and $T$ is the absolute temperature.
- This is the *Planck function*; it earned him the Nobel Prize in 1918. The Planck function is more conveniently written as
  $$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\exp \left( \frac{c_2}{\lambda T} \right) - 1}$$ \hspace{1cm} (3.8)
- where $c_1$ and $c_2$ are the first and second radiation constants. Since the radiance from a blackbody is independent of direction, the radiant exitance from a blackbody is simply $\pi B_\lambda$. 

---

**Charts and Diagrams**

- Chart (a) shows the radiance, $B$, in W m$^{-2}$ sr$^{-1} \mu$m$^{-1}$ as a function of wavelength $\mu$m for temperatures $0^\circ$C, $10^\circ$C, $20^\circ$C, and $30^\circ$C.
- Chart (b) illustrates the radiance, $B$, in W m$^{-2}$ sr$^{-1}$ at $10^\circ$C as a function of wavelength $\mu$m. The radiance peaks at a specific wavelength.
What can happen to a beam of radiation as it passes through the atmosphere?

There are four processes that can alter the radiation as it passes through an elemental slab of the atmosphere:

- Radiation from the beam can be absorbed by the atmosphere
- Radiation can be scattered out of the beam into other directions
- Radiation can be emitted by the atmosphere
- Radiation can scattered into the beam from other directions

Leads to the Radiative Transfer Equation
Applications of infrared radiometry

• Infrared radiometry is used to measure temperature
  – in oceanography this is of the sea surface (SST)
  – in meteorology temperature profiles through the atmosphere can be derived (also humidity profiles, and trace gas concentrations)
  – for land studies land surface temperature (LST) and some information about land cover

• Measurements have to be well-calibrated, using on-board black-body targets.
Infrared radiometers

- Channels are selected where atmosphere is relatively transparent, for surface temperatures, and where there are spectral gradients in transmissivity for sounding.
- Reflected and scattered solar radiation is not important in thermal infrared window (10 - 12μm) but leads to contamination in the mid-ir window (3.5 - 4μm). Thermal measurements available night and day, mid-ir only during the night or when there is confidence in lack of sun-glitter or scattering contamination.
- Scattering may be of importance
  - Rayleigh is not significant
  - Aerosols may be a problem
- Clouds (scattering and emission) ➔ discard data
- Even in atmospheric windows, atmospheric effects (absorption and emission) are very important for quantitative remote sensing. Water vapor is the main concern - very variable in time and space
- In-flight calibration is tractable, using one or two on-board black-body calibration targets.
Atmospheric transmissivity in the infrared

Spectral dependence of the atmospheric transmission for wavelengths of electro-magnetic radiation from about 1 to 14 µm, for three characteristic atmospheres (above), and (below) the black-body emission for temperatures of 0, 10, 20 and 30°C, and the relative spectral response functions of the bands MODIS (Flight Model 1) on *Aqua* used to derive SST.
Satellite infrared radiometers for SST

AVHRR  |  Broad swath (>3000km), ~1km² resolution, operational, 1 blackbody + space view for in-flight calibration, 10-bit digitization, 3 ir SST channels.

MODIS  |  Broad swath (~2330km), ~1km² resolution, 1 bb + space view for in-flight calibration, 12-bit digitization, 5 ir SST channels

VIIRS  |  Broad swath (>3000km), ~0.75kmxkm resolution, pixel aggregation to try to compensate for pixel growth away from nadir, operational, 1bb + space view for in-flight calibration, 12-bit digitization, 4 ir SST channels

(A)ATSR | Narrow swath (~500km), ~1km² resolution, “experimental”, 2bb for in-flight calibration, 12-bit digitization, 3 ir SST channels, with two views.

SLSTR  |  Narrow swath (1675 km (near-nadir view), 750km (backward view)), ~1km² resolution, 2bb for in-flight calibration, 12-bit digitization, 3 ir SST channels, with two views.
Calibration of infrared radiometers

- In-flight measurements every mirror scan of:
  - A black body at a known temperature & view of cold space
  - Or of two on-board black bodies
- These give a two point calibration for converting the digital outputs of the detectors to calibrated channel radiances.
- Integrals of radiance across each channel’s relative spectral response functions to convert calibrated channel radiances to brightness temperatures.
NOAA-nn Polar Orbiters

AVHRR

Advanced Very High Resolution Radiometer
NOAA-N* (broken)
AVHRR-
Advanced Very High Resolution Radiometer
Path length effects and scan patterns

AVHRR gaseous absorption spectra
### Table 5. Calculated AVHRR top of atmosphere brightness temperature deficits (deg K) due to various atmospheric gases for the three infrared channels viewing a black body surface at 287.2K through a U.S. standard atmosphere for a nadir view.

<table>
<thead>
<tr>
<th>Species</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>0.79</td>
<td>0.83</td>
<td>1.51</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.02</td>
<td>0.25</td>
<td>0.07</td>
</tr>
<tr>
<td>O$_3$</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0.45</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HNO$_3$</td>
<td>-</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>N$_2$</td>
<td>0.13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>F11</td>
<td>-</td>
<td>-</td>
<td>0.15</td>
</tr>
<tr>
<td>F12</td>
<td>-</td>
<td>0.18</td>
<td>0.03</td>
</tr>
</tbody>
</table>
MODIS: MODeRate-Resolution Imaging Spectroradiometer

**MODIS Technical Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit:</td>
<td>705 km, 10:30 a.m. descending node (AM-1) or 1:30 p.m. ascending node (PM-1), sun-synchronous, near-polar, circular</td>
</tr>
<tr>
<td>Scan Rate:</td>
<td>20.3 rpm, cross track</td>
</tr>
<tr>
<td>Swath Dimensions:</td>
<td>2330 km (cross track) by 10 km (along track at nadir)</td>
</tr>
<tr>
<td>Telescope:</td>
<td>17.78 cm diam. off-axis, afocal (collimated), with intermediate field stop</td>
</tr>
<tr>
<td>Size:</td>
<td>1.0 x 1.6 x 1.0 m</td>
</tr>
<tr>
<td>Weight:</td>
<td>250 kg</td>
</tr>
<tr>
<td>Power:</td>
<td>162.5 W (single orbit average)</td>
</tr>
<tr>
<td>Data Rate:</td>
<td>10.8 Mbps (peak daytime); 6.2 Mbps (orbital average)</td>
</tr>
<tr>
<td>Quantization:</td>
<td>12 bits</td>
</tr>
<tr>
<td>Spatial Resolution:</td>
<td>250 m (bands 1-2)</td>
</tr>
<tr>
<td></td>
<td>500 m (bands 3-7)</td>
</tr>
<tr>
<td></td>
<td>1000 m (bands 8-36)</td>
</tr>
<tr>
<td>Design Life:</td>
<td>6 years</td>
</tr>
</tbody>
</table>
# MODIS Bands - I

<table>
<thead>
<tr>
<th>Primary Use</th>
<th>Band</th>
<th>Bandwidth 1</th>
<th>Spectral Radiance 2</th>
<th>Required SNR 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land/Cloud Boundaries</td>
<td>1</td>
<td>620 - 670</td>
<td>21.8</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>841 - 876</td>
<td>24.7</td>
<td>201</td>
</tr>
<tr>
<td>Land/Cloud Properties</td>
<td>3</td>
<td>459 - 479</td>
<td>35.3</td>
<td>243</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>545 - 565</td>
<td>29.0</td>
<td>228</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1230 - 1250</td>
<td>5.4</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1628 - 1652</td>
<td>7.3</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2105 - 2155</td>
<td>1.0</td>
<td>110</td>
</tr>
<tr>
<td>Ocean Color/Phytoplankton/Biogeochemistry</td>
<td>8</td>
<td>405 - 420</td>
<td>44.9</td>
<td>880</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>438 - 448</td>
<td>41.9</td>
<td>838</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>483 - 493</td>
<td>32.1</td>
<td>802</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>526 - 536</td>
<td>27.9</td>
<td>754</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>546 - 556</td>
<td>21.0</td>
<td>750</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>662 - 672</td>
<td>9.5</td>
<td>910</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>673 - 683</td>
<td>8.7</td>
<td>1087</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>743 - 753</td>
<td>10.2</td>
<td>586</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>862 - 877</td>
<td>6.2</td>
<td>516</td>
</tr>
<tr>
<td>Atmospheric Water Vapor</td>
<td>17</td>
<td>890 - 920</td>
<td>10.0</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>931 - 941</td>
<td>3.6</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>915 - 965</td>
<td>15.0</td>
<td>250</td>
</tr>
</tbody>
</table>
## MODIS Bands - II

<table>
<thead>
<tr>
<th>Primary Use</th>
<th>Band</th>
<th>Bandwidth&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Spectral Radiance&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Required NE[delta]T(K)&lt;sup&gt;4&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface/Cloud Temperature</td>
<td>20</td>
<td>3.660 - 3.840</td>
<td>0.45(300K)</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>3.929 - 3.989</td>
<td>2.38(335K)</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>3.929 - 3.989</td>
<td>0.67(300K)</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>4.020 - 4.080</td>
<td>0.79(300K)</td>
<td>0.07</td>
</tr>
<tr>
<td>Atmospheric Temperature</td>
<td>24</td>
<td>4.433 - 4.498</td>
<td>0.17(250K)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>4.482 - 4.549</td>
<td>0.59(275K)</td>
<td>0.25</td>
</tr>
<tr>
<td>Cirrus Clouds Water Vapor</td>
<td>26</td>
<td>1.360 - 1.390</td>
<td>6.00</td>
<td>150(SNR)</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>6.535 - 6.895</td>
<td>1.16(240K)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>7.175 - 7.475</td>
<td>2.18(250K)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>8.400 - 8.700</td>
<td>9.58(300K)</td>
<td>0.05</td>
</tr>
<tr>
<td>Ozone</td>
<td>30</td>
<td>9.580 - 9.890</td>
<td>3.69(250K)</td>
<td>0.25</td>
</tr>
<tr>
<td>Surface/Cloud Temperature</td>
<td>31</td>
<td>10.780 - 11.280</td>
<td>9.55(300K)</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>11.770 - 12.270</td>
<td>8.94(300K)</td>
<td>0.05</td>
</tr>
<tr>
<td>Cloud Top Altitude</td>
<td>33</td>
<td>13.185 - 13.485</td>
<td>4.52(260K)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>13.485 - 13.785</td>
<td>3.76(250K)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>13.785 - 14.085</td>
<td>3.11(240K)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>14.085 - 14.385</td>
<td>2.08(220K)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

<sup>1</sup> Bands 1 to 19 are in nm; Bands 20 to 36 are in μm

<sup>2</sup> Spectral Radiance values are (W/m²-μm-sr)

<sup>3</sup> SNR = Signal-to-noise ratio

<sup>4</sup> NE[delta]T = Noise-equivalent temperature difference
Characteristics of MODIS IR Focal Planes SST Product Input Bands

<table>
<thead>
<tr>
<th>Band number</th>
<th>Center Wavelength µm</th>
<th>Bandwidth µm</th>
<th>NEΔT at T=300K</th>
<th>SNR at T=300K</th>
<th>Saturation Temperature K</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Midwave IR</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>3.7882</td>
<td>0.1826</td>
<td>0.026</td>
<td>9000</td>
<td>333</td>
</tr>
<tr>
<td>22</td>
<td>3.9719</td>
<td>0.0882</td>
<td>0.030</td>
<td>837.5</td>
<td>328</td>
</tr>
<tr>
<td>23</td>
<td>4.0567</td>
<td>0.0878</td>
<td>0.026</td>
<td>987.5</td>
<td>329</td>
</tr>
<tr>
<td><strong>Longwave Thermal IR</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>11.0144</td>
<td>0.5103</td>
<td>0.024</td>
<td>28088</td>
<td>399</td>
</tr>
<tr>
<td>32</td>
<td>12.0282</td>
<td>0.4935</td>
<td>0.040</td>
<td>18245</td>
<td>391</td>
</tr>
</tbody>
</table>

* Averaged over ten detectors in each band

MODIS has 4 focal planes, each band with 10 - 1km detectors:
2 for visible
2 for IR
Principal Scan Angles Mapped to Scan Mirror Angles of Incidence

Angle of Incidence changes pixel by pixel with paddle-wheel scan mirror

MODIS Scan Mirror

Principal Scan Angles
(Earth View: -55 to 55)

Angles of Incidence
(Earth View: 10.5 to 65.5)
VIIRS Components

- MODIS-heritage Solar Diffuser
  Stability Monitor refined to improve performance
- 4-mirror anastigmat All-reflective Aft optics imager
- Electronics module (EM) & cables refined to minimize EMI
- MODIS-heritage Solar Diffuser screen redesigned to minimize solar modulation
- MODIS-heritage blackbody relocated to minimize Earth shine
- 3-Mirror Anastigmat Rotating telescope refined to eliminate modulated instrument background (MIB)
- Constant-speed rotating telescope
- Simple all-reflective diamond point turned bolt-together optics
- Proven emissive/reflective calibration
- Passive Cryoradiator
- Cold FPA Dewar Assembly
VIIRS SST RSRs
VIIRS pixel aggregation

GSD: Ground Sampling Distance
HSI: Horizontal Sampling Interval

HSI Returns to Nadir size at the two transition points (31.71° and 47.87°)
(A) ATSR

- ATSR – Along-Track Scanning Radiometer
  - ASTR on ERS-1
  - ATSR-2 on ERS-2
  - AATSR (Advanced ATSR) on Envisat
  - SLSTR (Sea Land Surface Temperature Radiometer) on Sentinel-3a to be launched in 2014.

- Only spacecraft radiometers optimized for SST measurements
Advanced Along Track Scanning Radiometer

- Imaging radiometer
- Designed to measure global SST at the levels of precision and accuracy required for climate research (better than 0.3 K; 1σ)
- Contributes to 20 year unbroken record of accurate SST measurements on a global scale
AATSR Principles of Operation

• 7 spectral channels
  – 3 IR (3.7 µm, 11 µm, 12 µm)
  – 4 Vis/NIR (0.55 µm, 0.67 µm, 0.87 µm, 1.6 µm)
• 500 km swath
• 1 km IFOV at nadir
• Dual view (nadir and 55° to nadir)
• On board calibration
  – 2 on-board black bodies for IR calibration
  – VISCAL unit for visible channel calibration
• Stirling Cycle Coolers, cooling low noise detectors to 80K, for optimum signal-to-noise ratios
AATSR - SCAN GEOMETRY

Blackbodies viewed every scan.
Sea and Land Surface Temperature Radiometer - SLSTR

• SLSTR has been designed to measure SST and Land Surface Temperature with an equivalent baseline performance to ENVISAT AATSR.

• Designed to extend and improve the (A)ATSR series but maintains fundamental concepts and elements of the original.

• SLSTR is an IR self-calibrating instrument using on-board calibration blackbody cavities.
SLSTR scan geometry

- Uses two scan mechanisms and a flip mirror to enable wider swath.
- Nadir swath is offset to cover OLCI swath.
- One VIS channel (865nm) is used for co-registration with OLCI swath.
- Oblique view 55° inclination maintains a longer atmospheric path length compared to nadir for better atmospheric correction.
S3 SLSTR: Spectral Bands
Cloud Screening for SST

• Spectral and textural information are powerful means for cloud screening (classification problem – cloud-free and cloud-contaminated).
• Several layers of tests needed to identify all pixels contaminated by clouds e.g. temperature thresholds, reflected sunlight (during the day), “spatial coherence”, channel differences (fog and cirrus).
• Problems remain with marine stratus, fog, cirrus, and partially cloud-filled pixels.
• Undetected aerosols remain a problem.
• Better to have false positives than false negatives.
AVHRR Pathfinder SST cloud screening (1)

AVHRR Pathfinder SST cloud screening (2)

Thresholds tuned to NOAA-14 AVHRR

Predicted MODIS brightness temperatures at satellite height

Temperature deficit

Surface temperature range, -10 to 40°C

Change in BT with surface T relatively small for bands 22, 23 - significantly larger for bands 20, 31, 32

N=13950
The SST atmospheric correction algorithms

The form of the daytime and night-time algorithm for measurements in the long wave atmospheric window is:

\[ SST = c_1 + c_2 \times T_{11} + c_3 \times (T_{11} - T_{12}) \times T_{sfc} + c_4 \times (\sec(\theta) - 1) \times (T_{11} - T_{12}) \]

where \( T_n \) are brightness temperatures measured in the channels at \( n \ \mu m \) wavelength, \( T_{sfc} \) is a ‘climatological’ estimate of the SST in the area, and \( \theta \) is the satellite zenith angle. This is based on the Non-Linear SST algorithm.


The MODIS night-time algorithm, using two bands in the 4\( \mu \)m atmospheric window is:

\[ SST4 = c_1 + c_2 \times T_{3.9} + c_3 \times (T_{3.9} - T_{4.0}) + c_4 \times (\sec(\theta) - 1) \]

Note, the coefficients in each expression are different. They can be derived in three ways:

- empirically by regression against SST values derived from another validated satellite instrument
- empirically by regression against SST values derived surface measurements from ships and buoys
- theoretically by numerical simulations of the infrared radiative transfer through the atmosphere.
MODIS SST

MAY 2001
V 3.3.1

-2 5 10 15 °C 20 25 30 35

MODIS/CEAN GROUP
GSFC, RSMAS

UNIVERSITY OF MIAMI
ROSENSTIEL
SCHOOL of MARINE & ATMOSPHERIC SCIENCE

ESA EARTH OBSERVATION SUMMER SCHOOL
ON EARTH SYSTEM MONITORING & MODELLING
30 July - 10 August 2012
Typical oceanographic thermal signals

• The El Niño SST signal is an example of a large SST signal and is typically ~3-4K; temperature differences across large ocean fronts are similar. If satellite data are to be used to study such features, the accuracy of the retrieved SSTs should be at one order of magnitude smaller than the signal ~0.3K.

• For climate studies:
  – Accuracy 0.1K.
  – Stability 0.04K/decade.

What is SST?

• SST is a variable function of time and space, determined by integrated fluxes (including insolation), turbulent mixing, and advection (including upwelling).
• “SST” depends on how and where measured:
  – Heat flux between ocean and atmosphere leads to a skin layer at the ocean surface
  – Absorption of insolation can lead to surface gradients, especially in low winds.
SST & the thermal skin layer

• The skin layer exists as a consequence of heat exchange from ocean to atmosphere.
• The skin layer is a ‘bottleneck’ in the heat flow from ocean to atmosphere, and it is this flow of heat that drives evaporation and sensible heat flow.
• The skin-bulk temperature difference, can be a significant fraction of the conventional air-sea temperature difference.
• SST could be an indicator of climate change, and satellite radiometers a global thermometer.
What is SST? –skin vs. bulk

The optical depth of sea water at infrared wavelengths is < 1mm. The source of the infrared signal used in remote sensing is the skin layer of the ocean, which is generally cooler than the subsurface layer because of heat flow from the ocean to the atmosphere.

The conventional meaning of SST is the temperature measured at a depth of a meter or more by a contact thermometer; the so-called bulk temperature.

At the levels of accuracy at which SST needs to be, and can be, measured from space, skin and subsurface temperatures are not the same.
Schematic Temperature Profiles

(a) Night time situation, light wind

(b) Day time situation, strong solar radiation and light winds

Wind speed dependence of diurnal & skin effects

As wind speed increases, magnitude of diurnal heating decreases and peak moves to later in the afternoon

Wind speed dependence of diurnal & skin effects

As wind speed increases, magnitude of diurnal heating decreases and peak moves to later in the afternoon

Terra and Aqua overpass times.
Wind speed dependence of the skin effect

Note collapse of envelope at moderate to high wind speeds > 7ms$^{-1}$, asymptotic value $\sim -0.15$K.
Measurements of Diurnal Warming

- Skin SST measured by M-AERI
- Bulk SST by a thermostalinograph at a depth of ~3m
- Winds and insolation measured on the ships

Examples of large amplitude diurnal heating

Large amplitude diurnal heating is identified in independent satellite data.

SEVIRI (Spinning Enhanced Visible and Infrared Imager) is on the Meteosat 8 & 9 – geostationary satellites. Images generated every hour. Symbols are where diurnal heating $>6K$. Background color is number of days in the year where wind $<1\text{ms}^{-1}$ at 14:00 LST.

Good estimates of error, or uncertainties, are needed for data assimilation, and to assess significance of trends.

Each processing step is prone to additional error sources.

L2 is where the uncertainties in the SST retrievals by comparison with independent measurements.

L4 fields are used to initialize climate models, and in other climate studies.
Climate Data Records

• What does “Climate Data Record” mean?
• What is the path to a CDR of SST?
• Can we generate a CDR of SST?
Reference to SI units

The First Recommendation of the 20th Conférence Générale des Poids et Mesures:

“that those responsible for studies of Earth resources, the environment, human well-being and related issues ensure that measurements made within their programs are in terms of well-characterized SI units so that they are reliable in the long term, are comparable world-wide and are linked to other areas of science and technology through the world’s measurement system established and maintained under the Convention du Mètre”

Laying the foundations

• Provides a basis for consistent long-term records from a variety of sources
• Provides consistency between different groups making related measurements
• For satellite-derived sea-surface temperature, it provides a mechanism for consistent time series to be generated over multiple missions.
Essential Climate Variables

**GCOS Essential Climate Variables**

The Essential Climate Variables (ECVs) are required to support the work of the UNFCCC and the IPCC. All ECVs are technically and economically feasible for systematic observation. It is these variables for which international exchange is required for both current and historical observations. Additional variables required for research purposes are not included in this table. It is emphasized that the ordering within the table is simply for convenience and is not an indicator of relative priority. Currently, there are 44 ECVs plus soil moisture recognized as an emerging ECV.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Essential Climate Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmospheric</strong></td>
<td>Surface: Air temperature, Precipitation, Air pressure, Surface radiation budget, Wind speed and direction, Water vapour.</td>
</tr>
<tr>
<td></td>
<td>Upper-air: Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction, Water vapour, Cloud properties.</td>
</tr>
<tr>
<td></td>
<td>Composition: Carbon dioxide, Methane, Ozone. Other long-lived greenhouse gases[1], Aerosol properties.</td>
</tr>
<tr>
<td></td>
<td><strong>Oceanic</strong></td>
</tr>
<tr>
<td></td>
<td>Surface: Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure.</td>
</tr>
<tr>
<td></td>
<td>Sub-surface: Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.</td>
</tr>
<tr>
<td></td>
<td><strong>Terrestrial</strong></td>
</tr>
<tr>
<td></td>
<td>River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, Permafrost and seasonally-frozen ground, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (APAR), Leaf area index (LAI), Biomass, Fire disturbance, Soil moisture[2].</td>
</tr>
</tbody>
</table>

[1] http://www.esa.int/esaMP/SEZ7T1H1P0K.html
[2] http://www.esa.int/esaMP/SEZ7T1H1P0K.html
The Essential Climate Variables (ECVs) are required to support the work of the UNFCCC and the IPCC. All ECVs are technically and economically feasible for systematic observation. It is these variables for which international exchange is required for both current and historical observations. Additional variables required for research purposes are not included in this table.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Essential Climate Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanic</td>
<td>Surface: Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure.</td>
</tr>
<tr>
<td></td>
<td>Sub-surface: Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.</td>
</tr>
<tr>
<td>Terrestrial[2]</td>
<td>River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, Permafrost and seasonally-frozen ground, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index (LAI), Biomass, Fire disturbance, Soil moisture[3].</td>
</tr>
</tbody>
</table>

Sea-surface temperature.
Climate Data Records

• National Academy of Sciences Report (NRC, 2000): “a data set designed to enable study and assessment of long-term climate change, with ‘long-term’ meaning year-to-year and decade-to-decade change. Climate research often involves the detection of small changes against a background of intense, short-term variations.”

• “Calibration and validation should be considered as a process that encompasses the entire system, from the sensor performance to the derivation of the data products. The process can be considered to consist of five steps:
  – instrument characterization,
  – sensor calibration,
  – calibration verification,
  – data quality assessment, and
  – data product validation.”
How can we generate SST CDRs?

• Satellite radiometers may be well-calibrated and well-characterized prior to launch, but is this sustained through launch and on orbit?

• Satellite instruments are not recovered for post-deployment re-calibration...

• Accurate brightness temperatures measured in space do not necessarily mean accurate SSTs, as effects of imperfect atmospheric corrections dominate.

• SST CDRs require SI traceability: can only be achieved through validation programs.
Temperature measurements from drifting buoys

- Deployed from ships and aircraft.
- Telemeter data via satellite links.
- Measure SST and $P_0$.
- Satellites determine position.
- Changes in positions from day-to-day give surface currents; often with a drogue.
Drifting buoys

Before & After
M-AERI cruises for MODIS, AATSR & AVHRR validation

Explorer of the Seas: near continuous operation
ISAR cruises for MODIS, AATSR & AVHRR validation
International radiometer workshops

• There have been three international workshop on infrared radiometry held at RSMAS, University of Miami.
  – The first was held prior to the launch of Terra
  – The second in 2001, before the launch of Aqua
  – The third took place in May 2009, under the auspices of the GEO/CEOS (Group on Earth Observations / Committee on Earth Observation Satellites)

• The data from the third workshop were analyzed at the National Physical Laboratory (NPL), Teddington, UK, and the results have been published in reports of the NPL

• Through the participation of NIST these workshops provide traceability to national radiometric and thermodynamic temperature standards through the characterization of the laboratory radiometers used to assess the validity of the internal calibration of the radiometers used at sea. This traceability to SI standards is achieved by using the NIST Transfer Radiometer (TXR)
The NIST EOS TXR

Unique EOS Standard
Cryogenic detectors (liquid N$_2$)
$\lambda = 5 \& 10\mu m$

NIST water-bath black-body calibration target

Traceability to SI references is achieved.
Significant differences between SI & non-SI uncertainties? 

- **Y**: Matchup analysis of SI collocated measurements 
  - **Laboratory calibration** 
  - **SI-standard blackbody calibrator** 
  - **Radiometric characterization e.g. NIST TXR** 
  - **SI-traceable thermometers** 
  - **SI-traceable blackbody calibrator** 
- **N**: Satellite-derived SSTs and uncertainties 
  - **Laboratory water-bath blackbody calibrator** 
  - **Non-SI traceable in situ measurements** 
  - **Matchup analysis of non-SI collocated measurements** 
  - **Non-SI Traceable uncertainty budget** 
  - **Matchup analysis of non-SI collocated measurements** 
  - **Derivation of SST from satellite measurements** 
  - **Multi-year satellite radiometer measurements** 

**CDR of SST** 

- **SI Traceable uncertainty budget** 
- **Ship radiometer measurements**
Significant differences between SI & non-SI uncertainties?

- Non-SI Traceable uncertainty budget
- SI Traceable uncertainty budget

CDR of SST
CDR Summary

- Generation of SST CDRs requires validation with NIST-traceable radiometers.
- NIST TXR is the transfer reference standard for infrared radiometry
- The Miami Infrared Workshops have provided a mechanism for traceability to NIST standards of satellite-derived SSTs.
- SST CDRs are a reality.
Questions ?