Prospects for Improved Sea Surface Temperatures from MODIS - Superior Accuracy and Refined Applications.

MODIS Science Team Meeting
Columbia, MD, January 2001

Overview

- SST from MODIS
- Validation of MODIS SSTs
- Applications: air-sea fluxes

Why measure SST ?

• The ocean is a thermometer for detecting climate change – time series of absolutely calibrated SST is a critical indicator of a changing climate.

• The exchange of heat, moisture and gases between ocean and atmosphere controls the habitability of the planet – these ocean-atmosphere fluxes are determined, to a large part, by SST.

• The global oceanic thermohaline circulation (*i.e.* driven by small, large-scale variations in the sea-water density distribution) is driven by geographical variations in the surface heat budget of the ocean and the difference between precipitation and evaporation (P-E). SST is a controlling factor in evaporation, and an indicator of the surface heat budget. The thermohaline circulation is responsible for most of the poleward movement of heat (*e.g*. Gulf Stream and N.Atlantic Drift – warming western Europe). The “engine” of the circulation is “deep-water formation” is at high latitudes – driven by air-sea fluxes of heat and moisture.

Why measure SST ? (cont.)

• Evaporation is the source of atmospheric moisture – water vapor is a potent greenhouse gas. It is factor in convective cloud formation over the ocean – Clouds influence the surface radiation budget, and the heating rates within the atmosphere. Distributions of SST in *e.g.* the tropical Western Pacific are related to local convective activity – in turn this drives the global (Hadley) circulation.

• Solubility of gases, *e.g.* CO_2, is temperature dependent. Air-sea flux of CO_2 depends on SST; uncertainties of ~0.3K in SST can cause uncertainties of >10% in estimates of global CO_2 fluxes.

• El Niño forecasting and early detection depends on accurate SST fields in the Pacific Ocean.

• Distributions of the SST reveal oceanic circulation patterns on scales of a few km to ocean basins.

• Improved input for weather forecast models.

• Improved input and validation of coupled ocean-atmosphere models used in climate change research.

Why measure SST from space?

Satellite radiometry offers the only way of obtaining consistent, basin scale SSTs with good spatial resolution, good repeat times and good absolute accuracy.

Improved accuracy -> Better and new applications.

SST measurements from MODIS

MODIS channel selection permits SST to be derived, on a pixel-by-pixel basis, in two independent parts of the infrared spectrum measured at satellite height:

Bands 31 & 32 – conventional 'split-window' SST, at 10 μm to 12 μm.

Bands 20, 22 & 23 – mid-infrared range, at μm 3.5 to 4.2 μm.

Merits of the two SST retrievals

Bands 31 & 32

Advantages	Disadvantages
• Heritage – AVHRR/2 since 1981 • Long time series of SST for climate research. • Demonstrated (AVHRR) accuracy ~0.3K	• Accuracy influenced by variability in atmospheric water vapor • Demonstrated (AVHRR) accuracy ~0.3K

Bands 20, 22 & 23

Advantages	Disadvantages
• Largely insensitive to variability in atmospheric water vapor. • Good theoretical accuracy, <0.2K rms.	•Lack of heritage. •No time series for climate change detection. •Unproven accuracy.

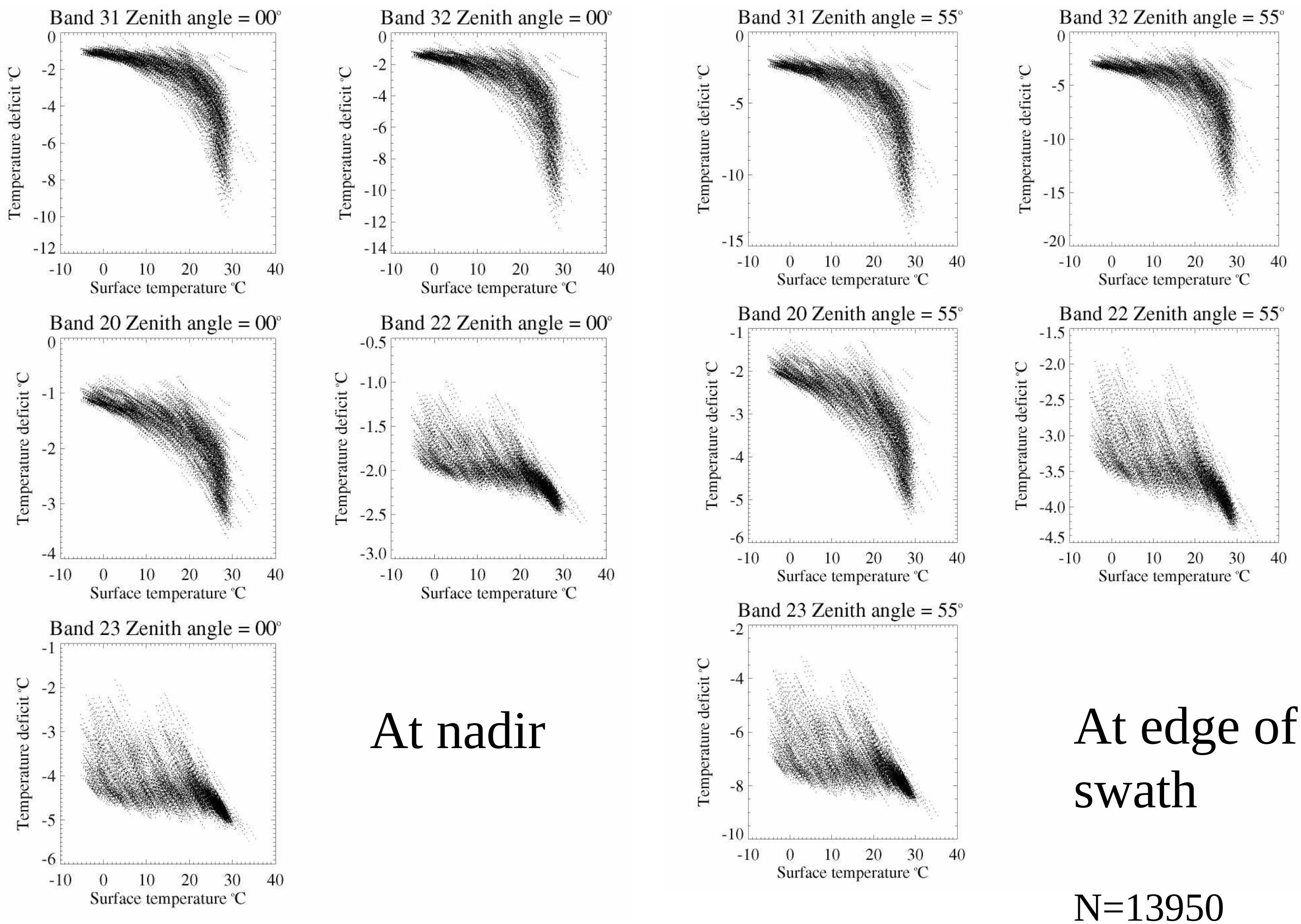
SST algorithms from numerical simulations

Algorithms derived from numerical simulations of MODIS measurements:

- State-of-the-art, line-by-line radiative transfer code (based on that used for ATSR, with more recent line strength data and water vapor continuum model).
- ECMWF atmospheric descriptions – uniform distribution over the ocean.
- MODIS NEdTs.
- Atmospheric correction algorithm for Bands 31 & 32 based on successful Miami AVHRR Pathfinder formulation.
- Simple expressions for atmospheric correction algorithms for Bands 20, 22 & 23.

Predicted brightness temperatures

Temperature deficit



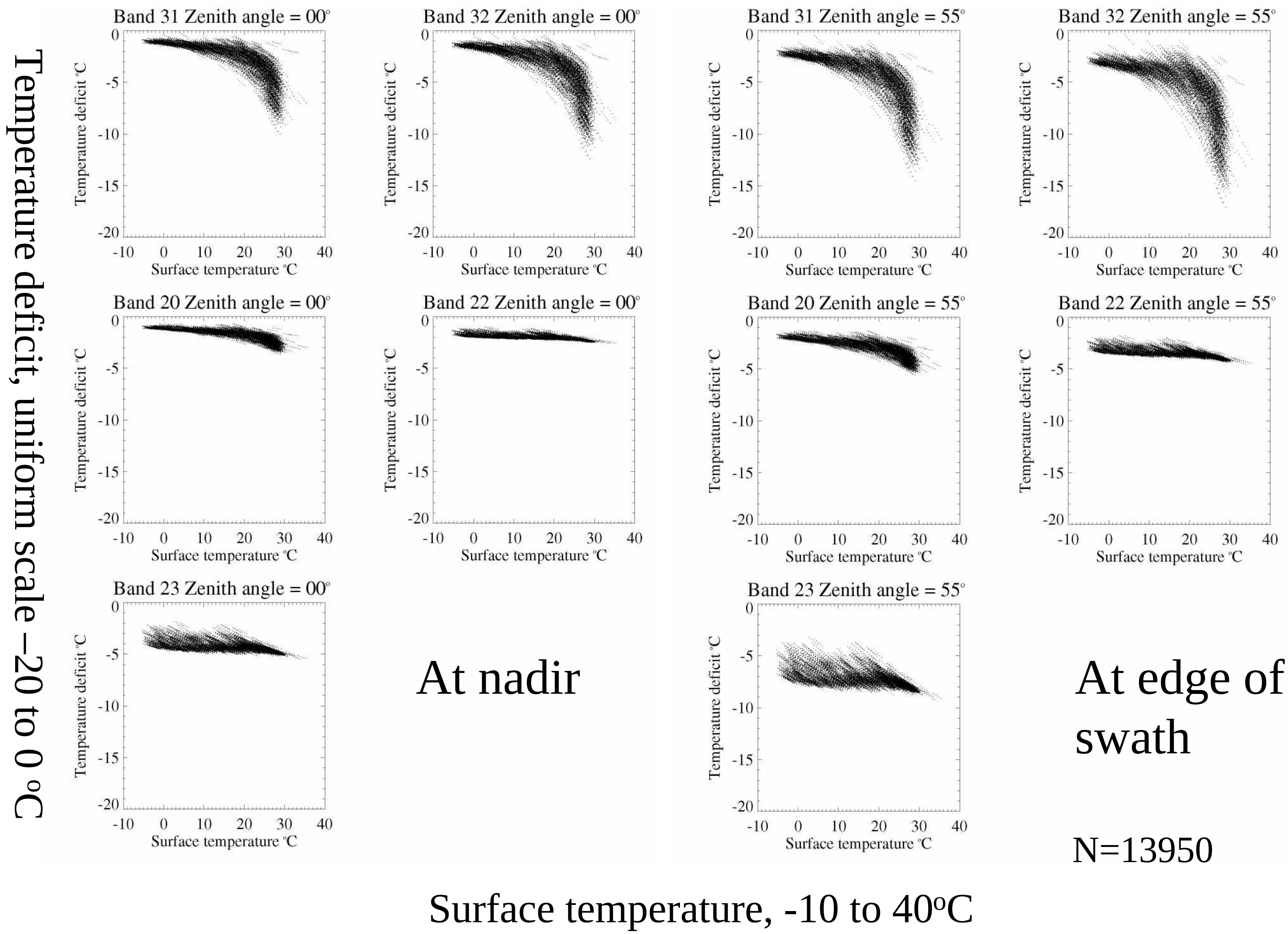
At nadir

At edge of swath

N=13950

Surface temperature, -10 to 40°C

Predicted brightness temperatures



SSTs from Bands 20, 22 and 23

Simulations predict absolute accuracies of SSTs measured in the 3.5 to 4.2 μm spectral interval, with multi-band algorithms, of <0.2K.

Single band SST (band 22) uncertainties <0.3K.

Requires excellent MODIS characterization, calibration and behavior.

Cannot be used in areas of sun glint during the day.

The need for SST validation

The SST fields are validated to confirm the procedures used to generate them from the radiometer data are performing as believed.

If the validation is done well, the error characteristics, referred to a temperature standard, are also determined. Ideally, the measured top-of-atmosphere radiances are well calibrated and free of significant instrumental artifacts, and the uncertainties in SST are caused by imperfections in the atmospheric correction algorithm.

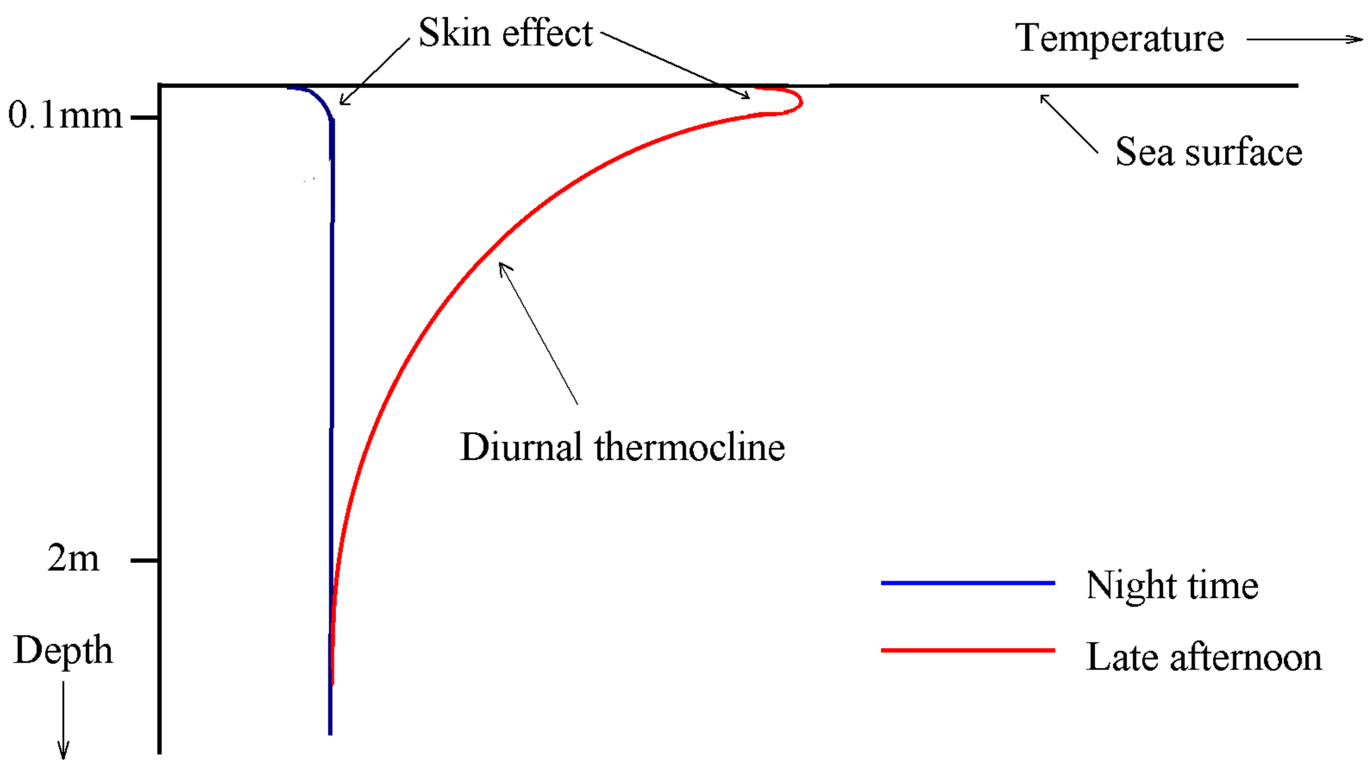
What is SST? – the skin vs. ***bulk debate***

The optical depth of sea water at infrared wavelengths is < 1mm. The source of the MODIS SST signal 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 can be measured by MODIS, and that required for many applications, skin/bulk T are not the same.

Near surface temperature gradients – ideal, conceptual situation



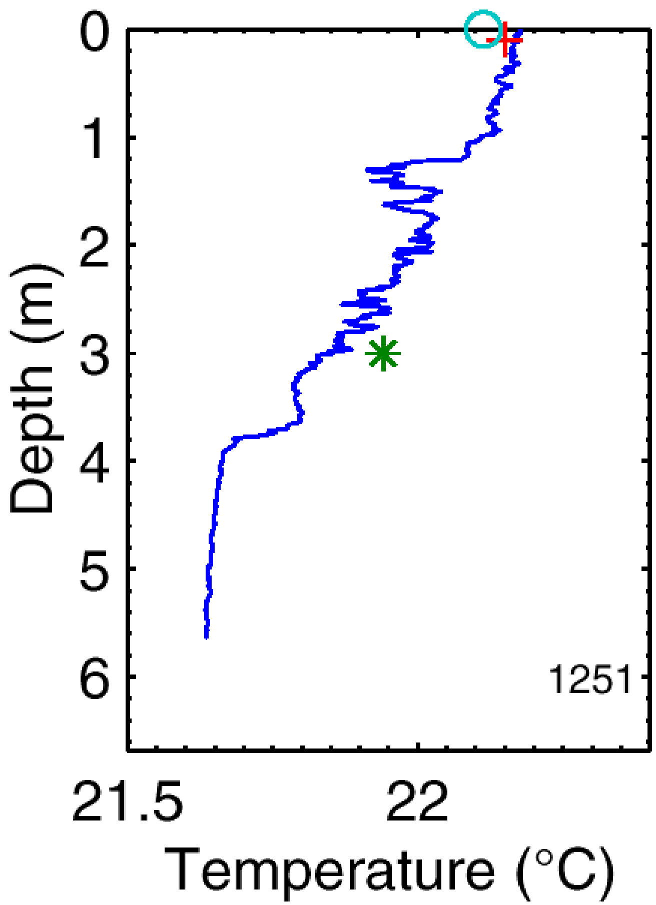
Combined effect of skin and diurnal thermocline effects

- Skin effect responds quickly to changing surface fluxes on time scales of seconds; vertical scale <1mm.

- Diurnal thermocline integrates fluxes, and responds to changing surface fluxes on time scales of minutes to hours; vertical scale of several m.

- Signs of effects are usually opposite.

Near surface temperature gradients – reality



Profile measured at 12:51 local time on 4 October 1999. Off Baja California, R/V *Melville* MOCE-5 cruise.

Blue line = SkinDeEP* profile

Blue circle = M-AERI skin temp.

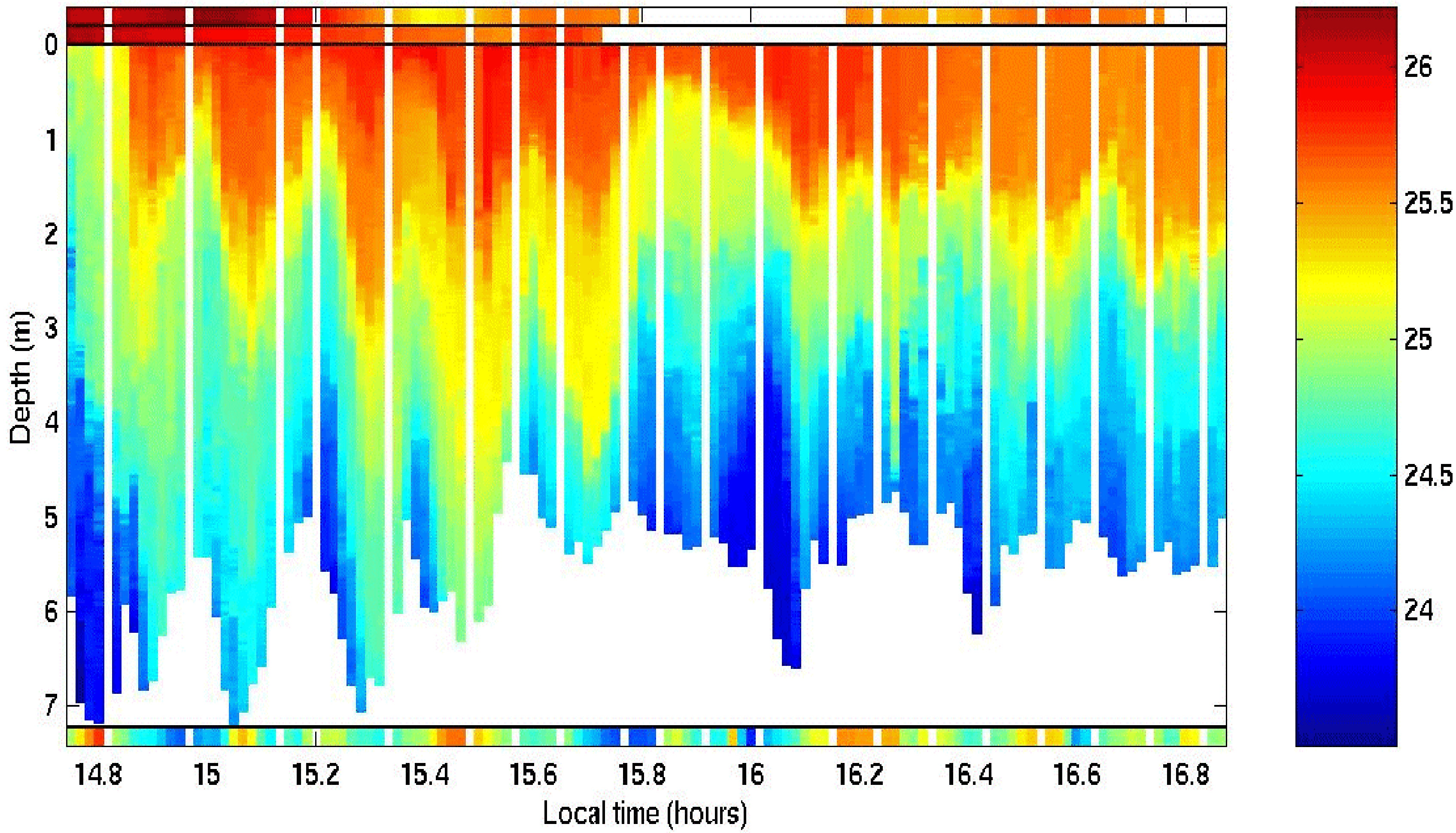
Red cross = Float bulk SST at ~0.05m

Green star = Ship thermosalinograph at ~3m

***SkinDeEP is an autonomous upper-ocean profiler.**

From Ward, B. and P. J. Minnett, 2001. An autonomous profiler for near surface temperature measurements. Gas Transfer at Water Surfaces. American Geophysical Union Monograph. In the press.

Time evolution of near surface gradients



SkinDeEP profiles on 12 October 1999. Off Baja California, R/V *Melville*.

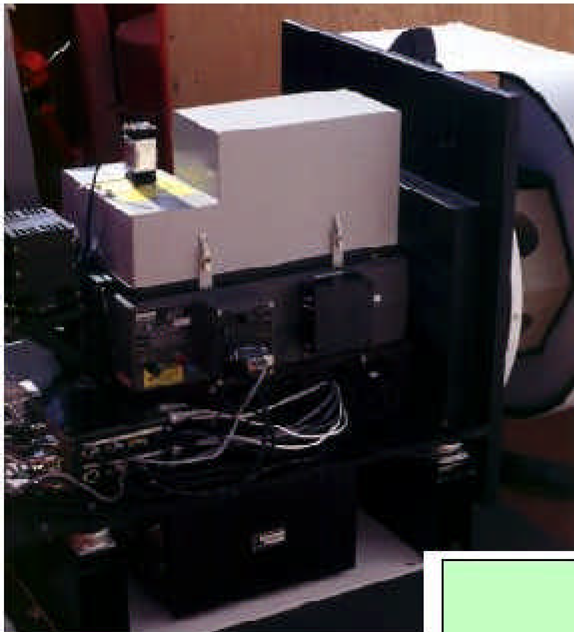
From Ward, B. and P. J. Minnett, 2001. An autonomous profiler for near surface temperature measurements. Gas Transfer at Water Surfaces. American Geophysical Union Monograph. In the press.

Measurements of skin temperature

Because of the effects of diurnal thermoclines and the skin layer, primary validation of MODIS SSTs should be by reference to surface-level measurements of skin temperature. This can be measured by filter radiometers or spectro-radiometers on ships, aircraft or fixed platforms.

The instruments must be well calibrated to reach the level of <0.1K absolute uncertainties. There are few such instruments available. One of which is the M-AERI……

Marine-Atmosphere Emitted Radiance Interferometer



Specifications

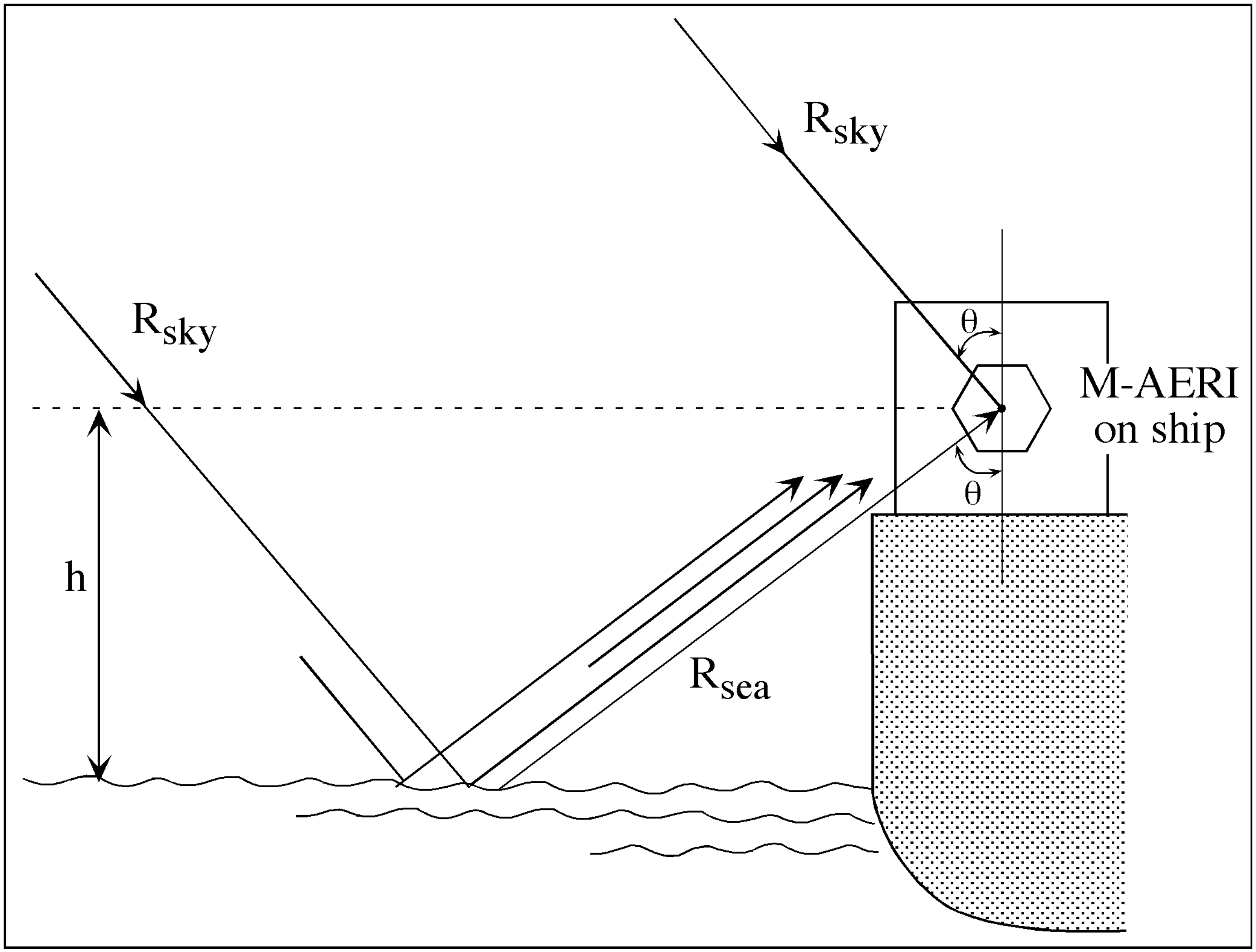
Spectral interval	~3 to ~18µm
Spectral resolution	0.5 cm^{-1}
Interferogram rate	1Hz
Aperture	2.5 cm
Detectors	InSb, HgCdTe
Detector temperature	78°K
Calibration	Two black-body cavities
SST retrieval uncertainty	<< 0.1K (absolute)

Laboratory tests of M-AERI accuracy

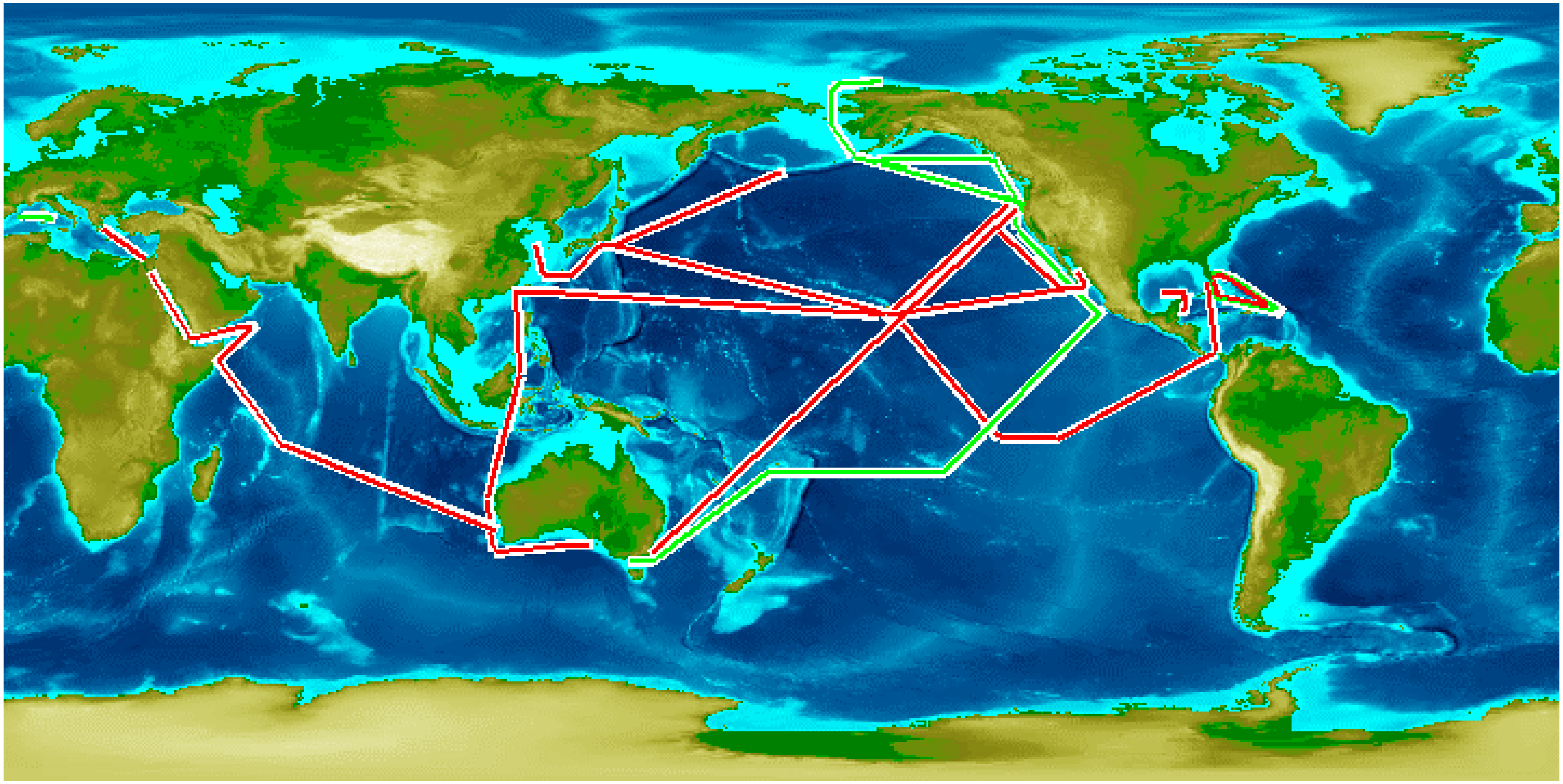
Target Temp.	LW (980-985 cm^{-1})	SW (2510-2515 cm^{-1})
20°C	+0.013 K	+0.010 K
30°C	-0.024 K	-0.030 K
60°C	-0.122 K	-0.086 K

The mean discrepancies in the M-AERI 02 measurements of the NIST water bath blackbody calibration target in two spectral intervals where the atmosphere absorption and emission are low. Discrepancies are M-AERI minus NIST temperatures.

Shipboard measurement of skin SST by M-AERI



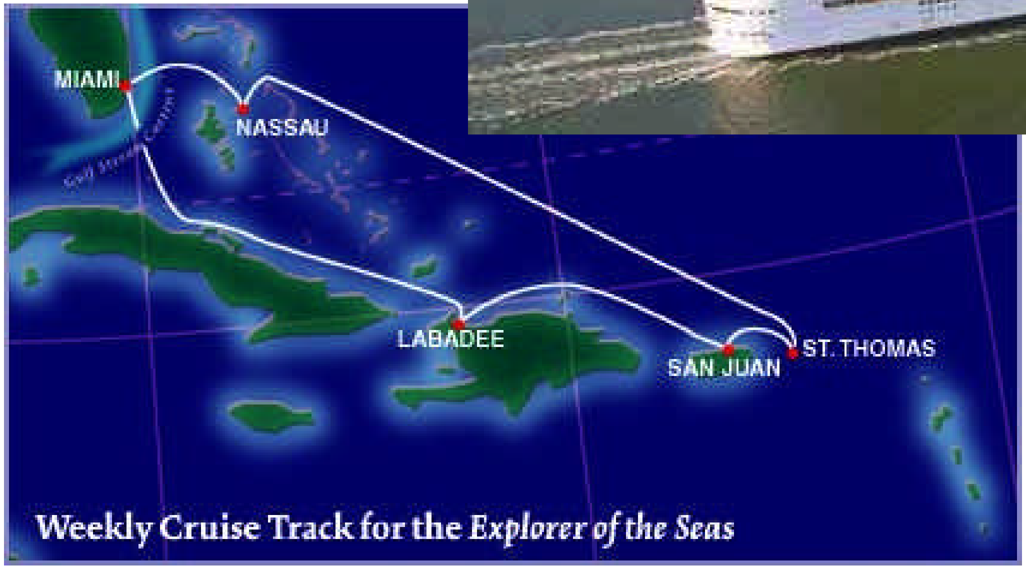
M-AERI Cruises since launch of Terra ***MODIS***



In 2000 In 2001

Time-series of M-AERI measurements on Explorer of the Seas

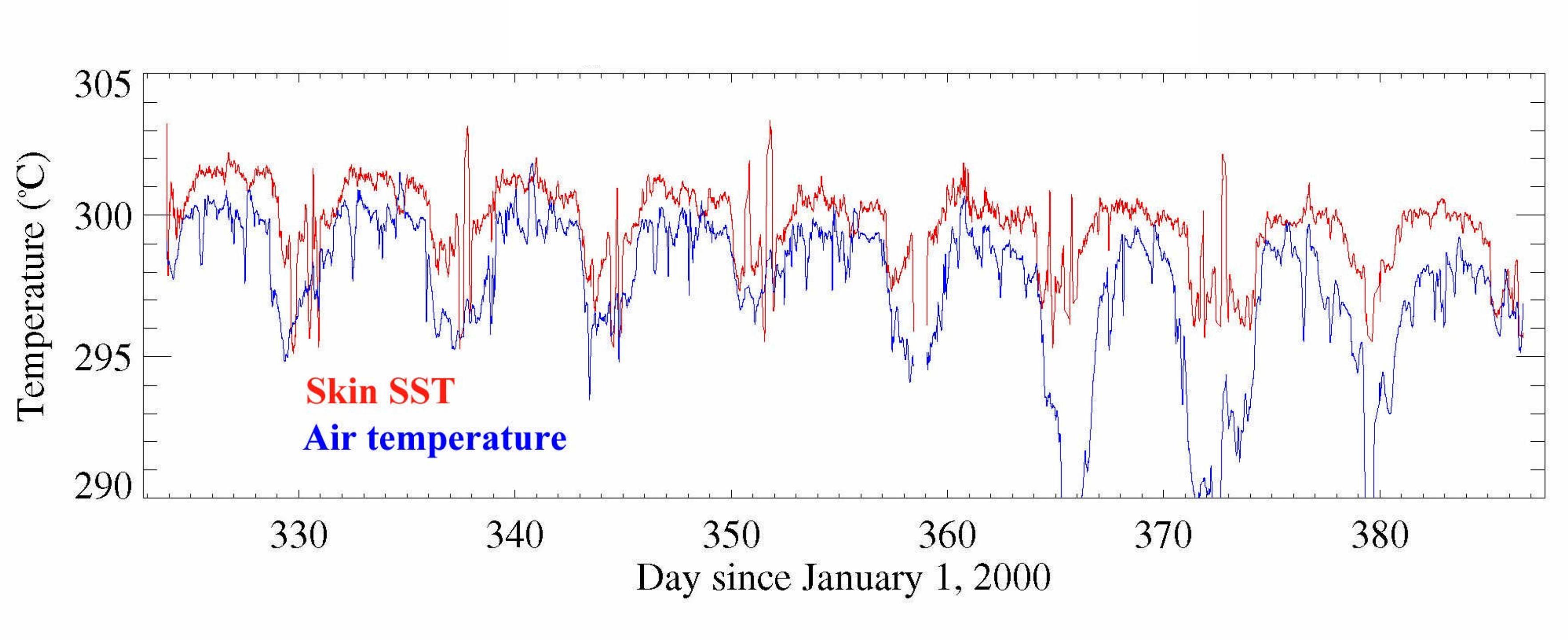
Year-round deployment for SST validation on a weekly schedule.



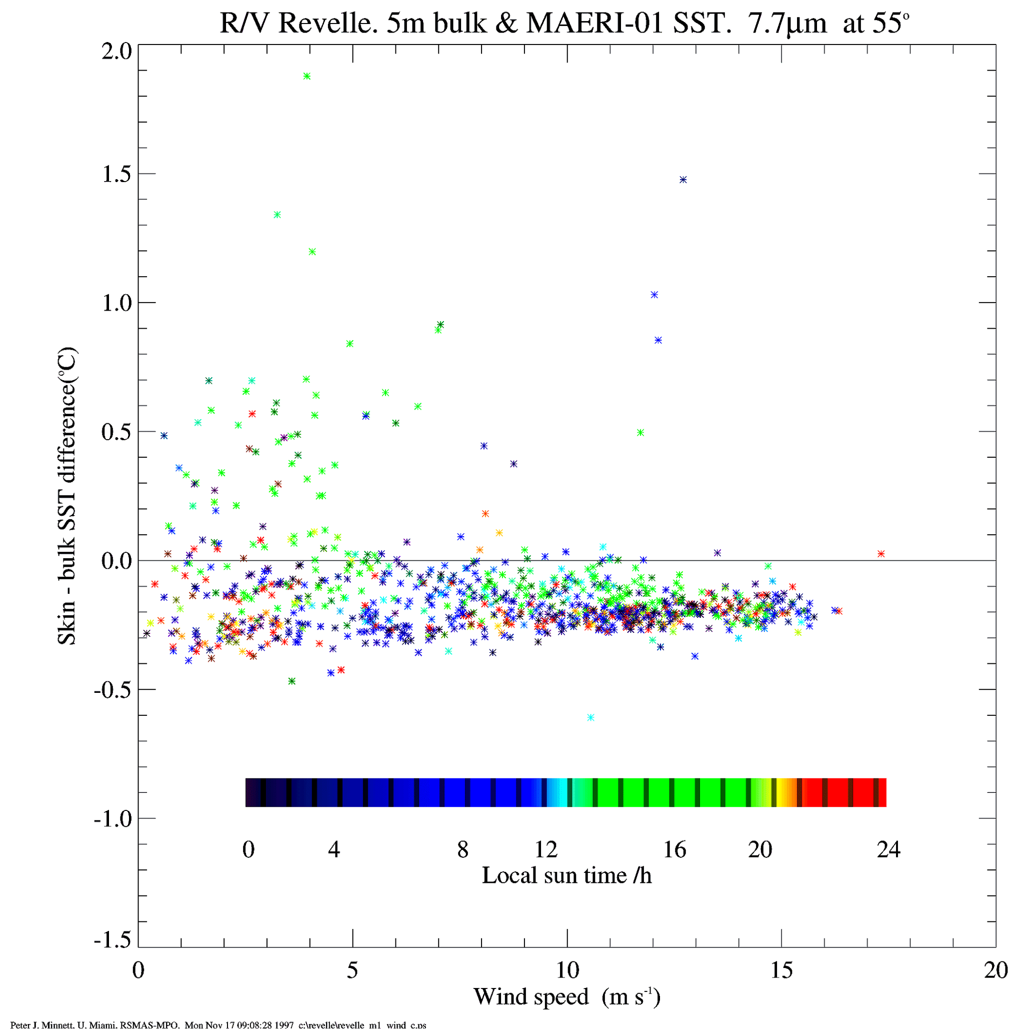
A cruise ship is equipped as an oceanographic and atmospheric research vessel. See www.rsmas.miami.edu/rccl

Photo – Kvaerner Masa Yards

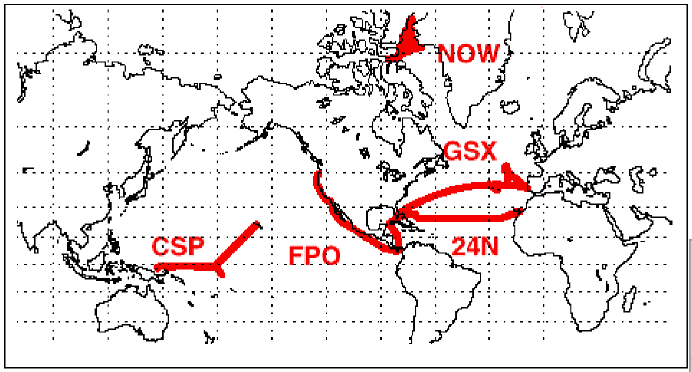
M-AERI data from
Explorer of the Seas



Wind speed dependence of the skin effect



AVHRR-MAERI SST validation experience



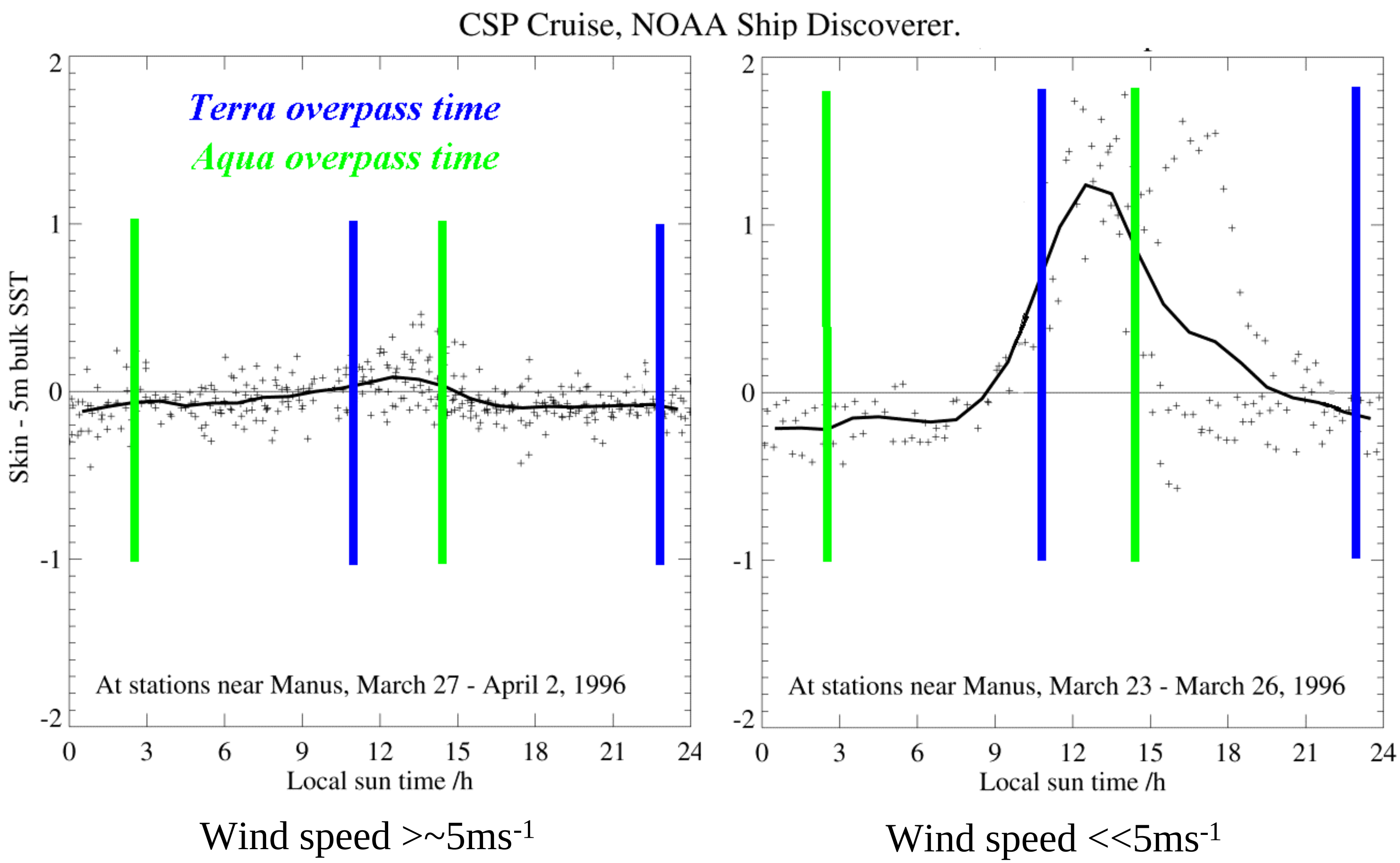
M-AERI validation of Pathfinder SSTs

Cruise Name	N	Mean K	St. Dev. K
CSP 1996	23	0.16	0.20
24N 1998	16	0.03	0.18
GASEX 1998	168	-0.01	0.25
FPO 1998	47	0.27	0.40
NOW 1998 (Arctic)	176	0.24	0.44
Total, all data	430	0.13	0.37
Total, excluding NOW data	254	0.06	0.29

Using skin temperatures reduces the uncertainties by about a factor of two.

See Kearns *et al*, 2000, ***Bull. Am. Met. Soc***., **81**, 1525-1536

How skin and diurnal thermocline effects may partially compensate



Air sea fluxes

Four methods of measuring turbulent air-sea fluxes:

- Direct correlative measurement of turbulence in the atmospheric boundary layer.
- Measurements of spectral slopes of turbulent parameters (dissipation) in the atmospheric boundary layer.
- Measurements of gradients in the atmospheric boundary layer.
- Application of “Bulk Aerodynamic” formulae

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Only 4 is tractable using satellite data

Turbulent air-sea fluxes of heat

Bulk Aerodynamic Formulae:

Sensible heat flux

$$H = \_ \; c \; C_H \; U \; (SST - T_a)$$

Latent heat flux

$$E = \_ \; L \; C_L \; U \; (Q_o - Q_a)$$

Measured by MODIS:

- SST

Measured by other EOS instruments:

- U – wind speed

Dependent on SST:

- Q_o – surface specific humidity
- C_H – Exchange coefficient for sensible heat
- C_L - Exchange coefficient for latent heat

Dependent of other satellite-measurement:

- Q_a – near-surface specific humidity

Constant or slowly varying:

- _ – surface air density
- c – specific heat of air
- L – Latent heat of evaporation of water

Not measurable from space:

- T_a – surface air temperature

Turbulent air-sea fluxes of heat

Bulk Aerodynamic Formulae:

Sensible heat flux

Not measurable from space

$$H = \_\ c\ C_H\ U\ (SST - T_a)$$

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Constant or slowly varying:

_ – surface air density

c – specific heat of air

L – Latent heat of evaporation of water

Not measurable from space:

T_a – surface air temperature

Air sea fluxes of CO_2

$$F_{CO2} = k * \Delta C = k\, s\, \Delta pCO_2$$

where ΔpCO_2 is the air-sea pCO_2 difference, s is the the solubility in sea water.

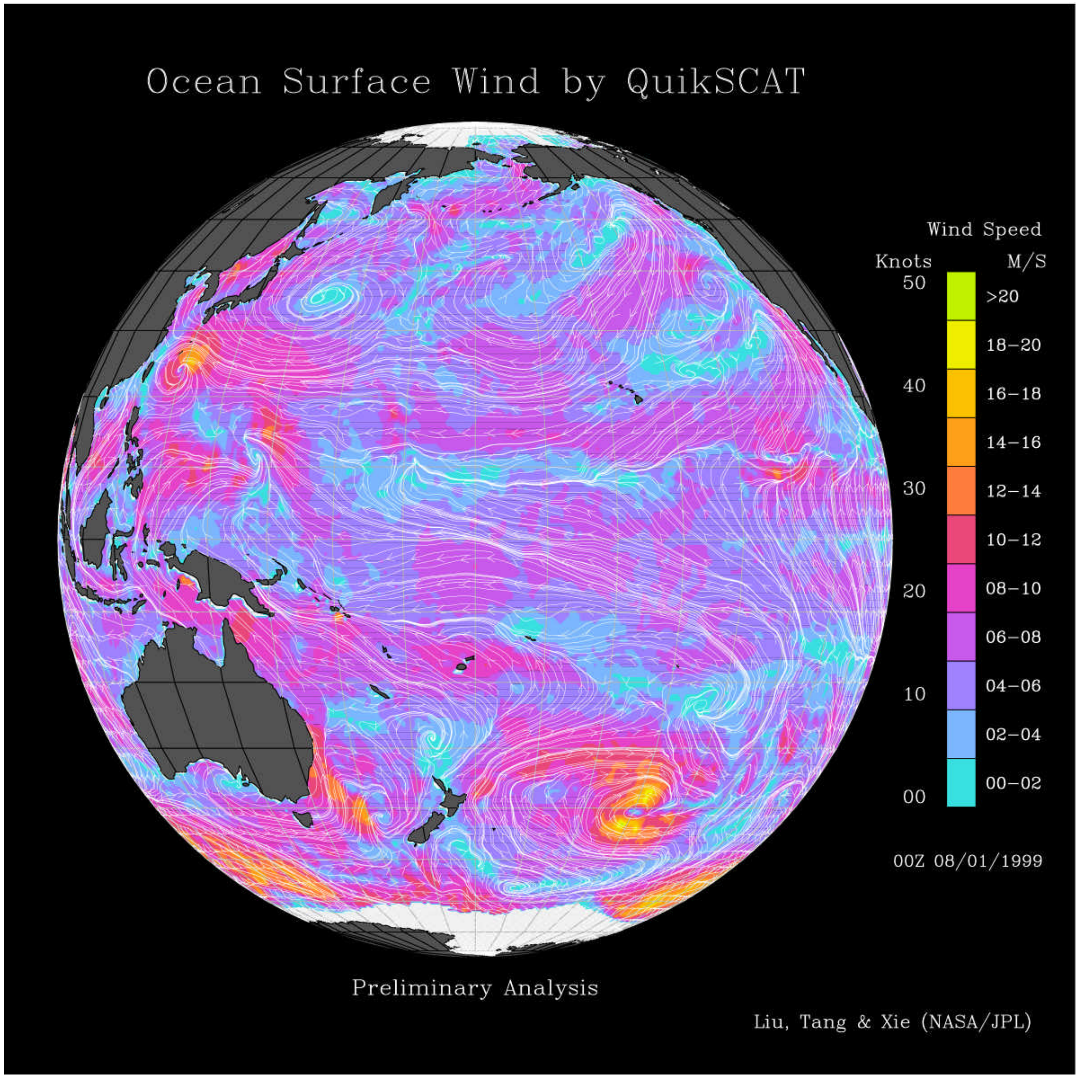
$k = 0.0283\, u^3\, (Sc/660)^{-1/2}$ for short-term winds

$k = (1.09\, u_{av} + 0.353\, u_{av}^2 + 0.078\, u_{av}^3)(Sc/660)^{-1/2}$ for long-term winds

(Wanninkhof, R., and W.M. McGillis, A cubic relationship between gas transfer and wind speed, *Geophys. Res. Let.*, *26*, 1889-1893, 1999)

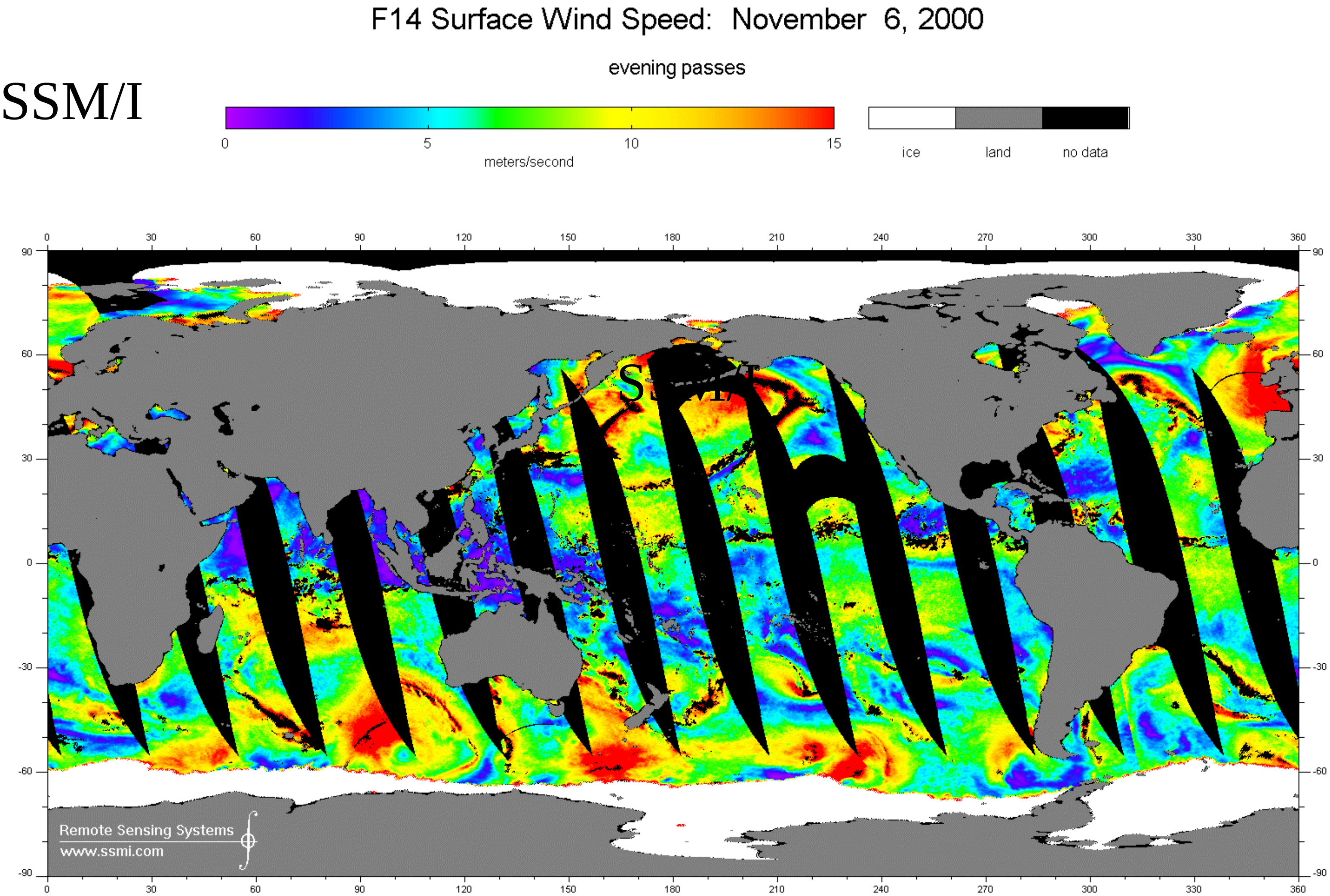
$$[\partial(\ln(pCO_2))/\partial(SST)] = 0.0423\ ^oC^{-1}$$

Surface winds-scatterometer



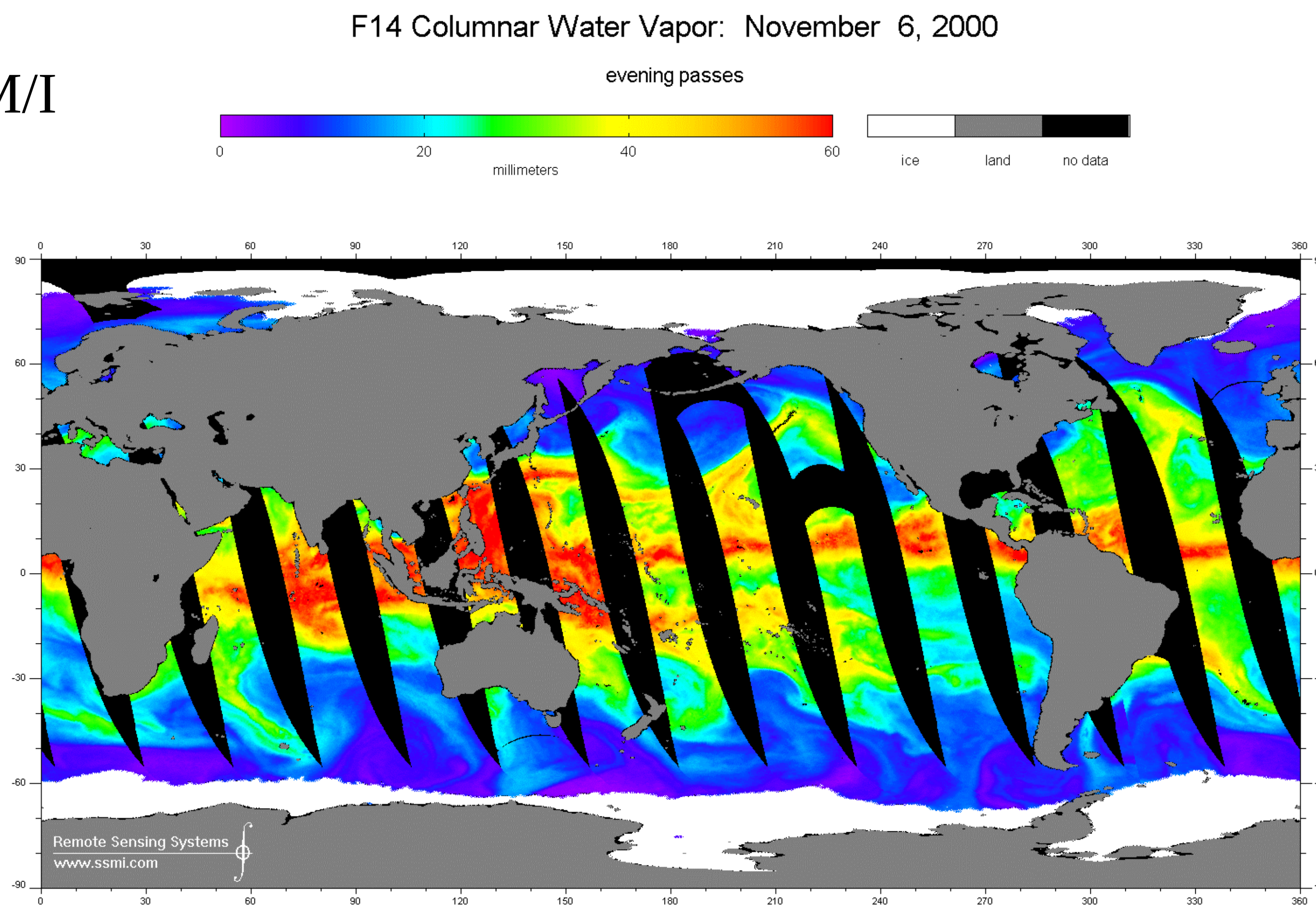
Surface winds – microwave radiometer

SSM/I



Precipitable water – microwave radiometer

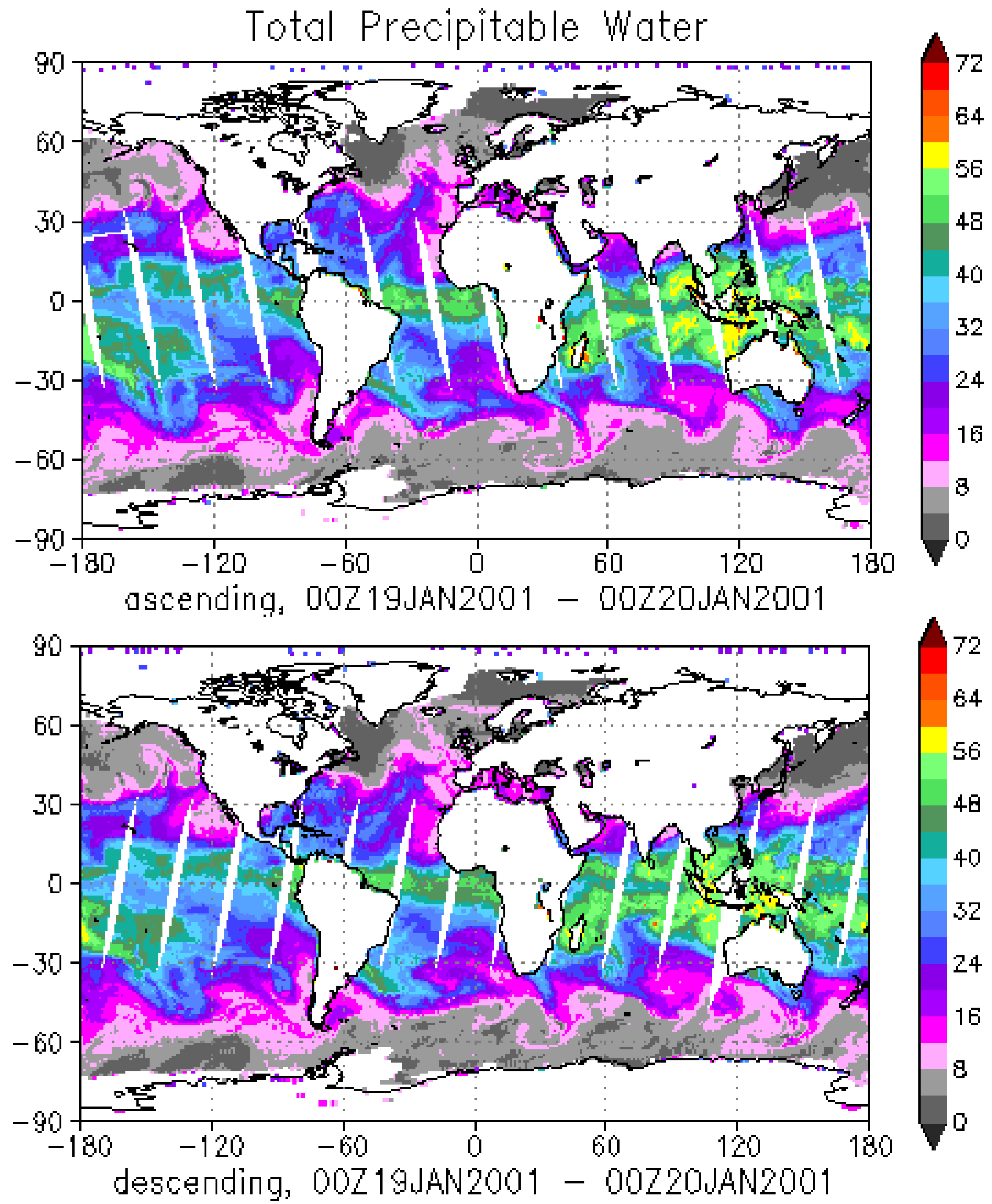
SSM/I



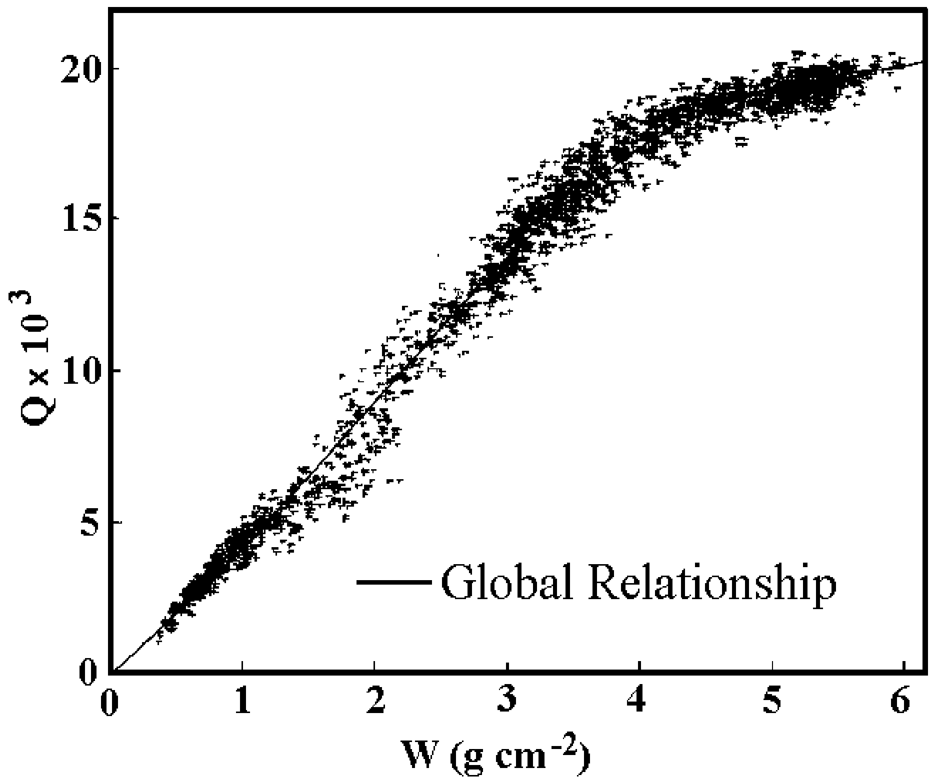
Total Precipitable water – microwave radiometer

NOAA-15 AMSU

(Advanced Microwave Sounding Unit)



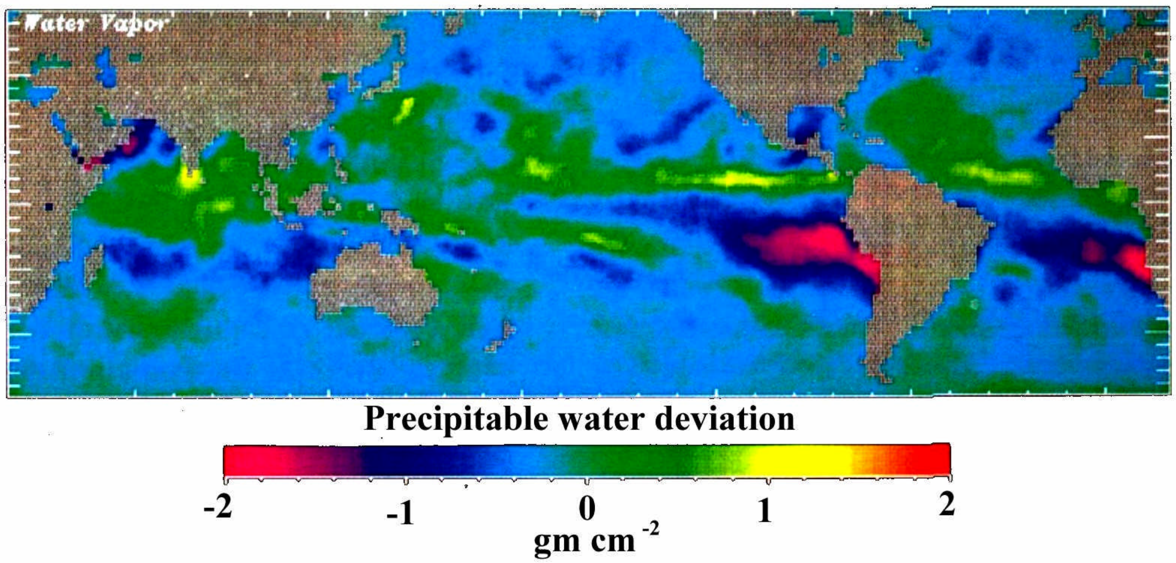
Surface humidity

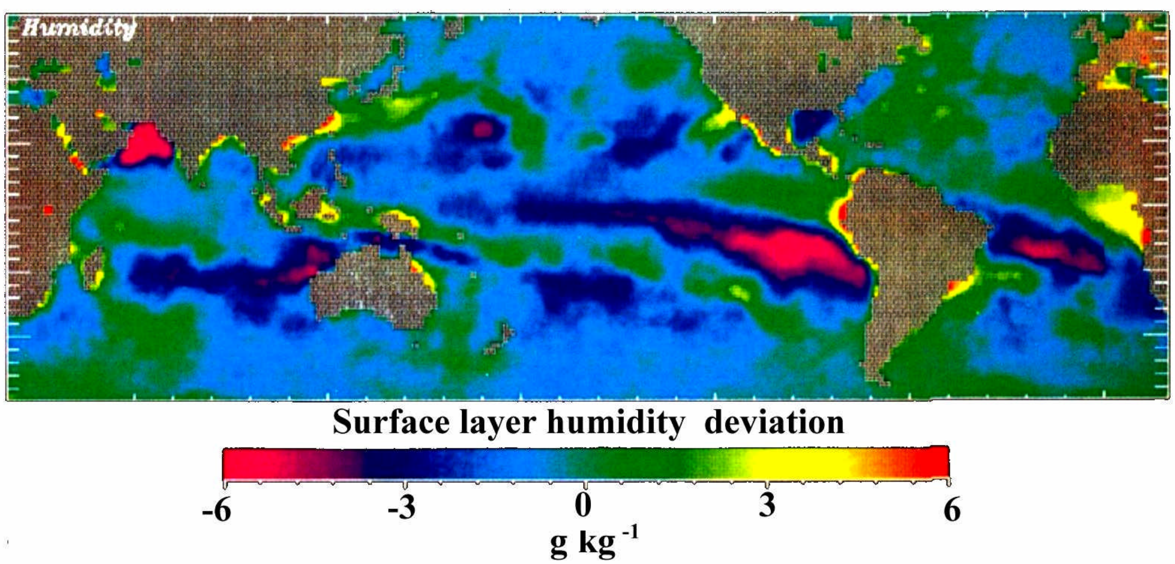


Global relationship between monthly averaged surface specific humidity (Q_a) and precipitable water (W), derived from radiosonde profiles. Points are for island and coastal stations of the North Pacific Ocean.

From Liu, W.T., Statistical relationship between monthly mean precipitable water and surface level humidity over global oceans, *Mon. Wea. Rev.*, *114*, 1591-1602, 1986.

Surface humidity from precipitable water

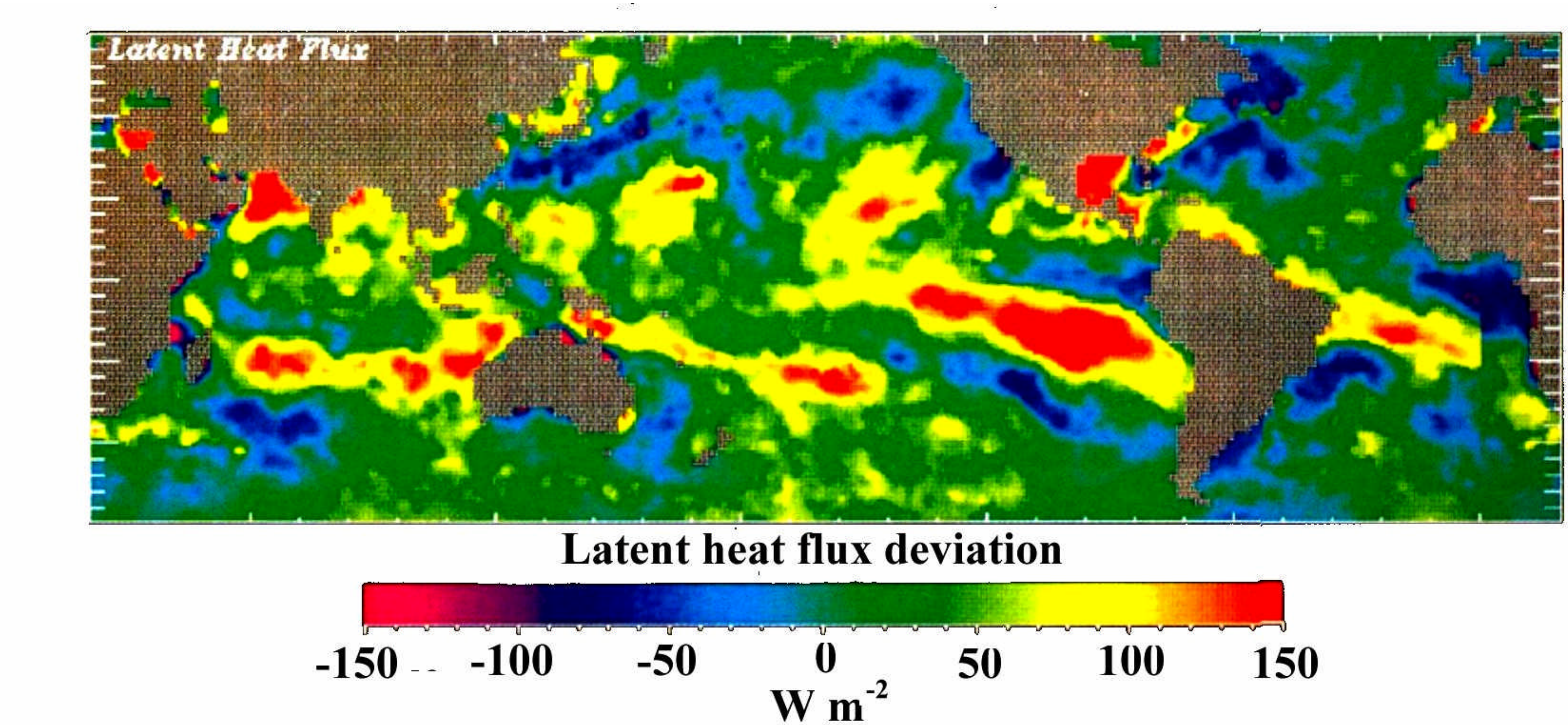




Shown as deviations from ECMWF estimates, October 1987.

(From Liu, W.T., Evaporation from the ocean, in ***Atlas of satellite observations related to global change,*** edited by R.J. Gurney, J.L. Foster, and C.L. Parkinson, pp. 265-278, 1993.)

Latent heat flux from satellite

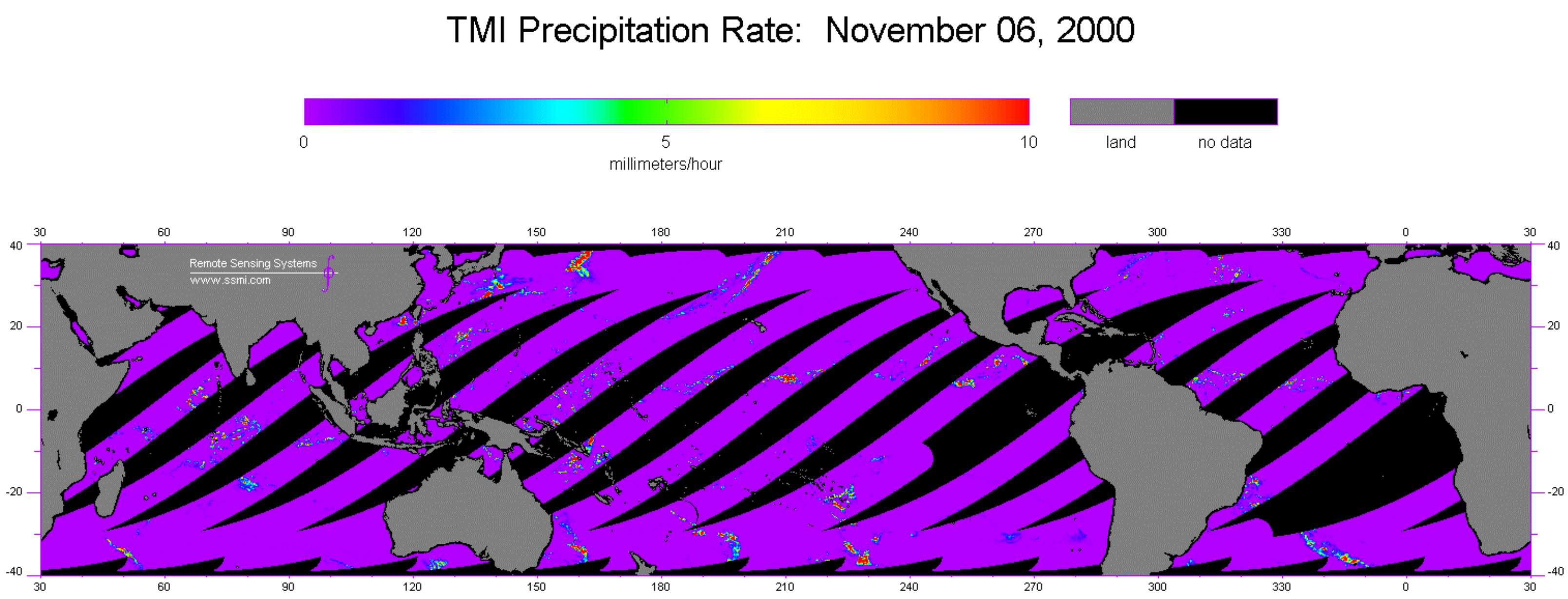


Shown as deviation from ECMWF estimates, October 1987.

These uncertainties need to be reduced by an order of magnitude – is this possible in the EOS era?

(From Liu, W.T., Evaporation from the ocean, in ***Atlas of satellite observations related to global change,*** edited by R.J. Gurney, J.L. Foster, and C.L. Parkinson, pp. 265-278, 1993.)

Precipitation from microwave radiometry



From the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager.

Aqua ***AMSR-E***

Oceanic Parameter	Accuracy	Spatial Resolution
Brightness Temperature	0.2 - 0.7 K	6 - 76 km
Ocean Wind Speed	1.5 m/s	12 km
Water Vapor Over Ocean	0.2 g/cm^2	23 km
Rainfall Over Ocean	1 mm/hr or 20% (whichever is greater)	10 km
Sea Surface Temperature	0.5 K	76 km
Cloud Liquid Water Over Ocean	3 mg/cm^2	23 km
Global Rain Type (Convection fraction)	N/A	10 km

Synergisms with Aqua

High accuracy SST from *Aqua* MODIS and Several variables derived from AMSR-E offer exciting new prospects to determine global air-sea exchanges.

Using two sensors on the same satellite removes uncertainties of combining data taken at different times.

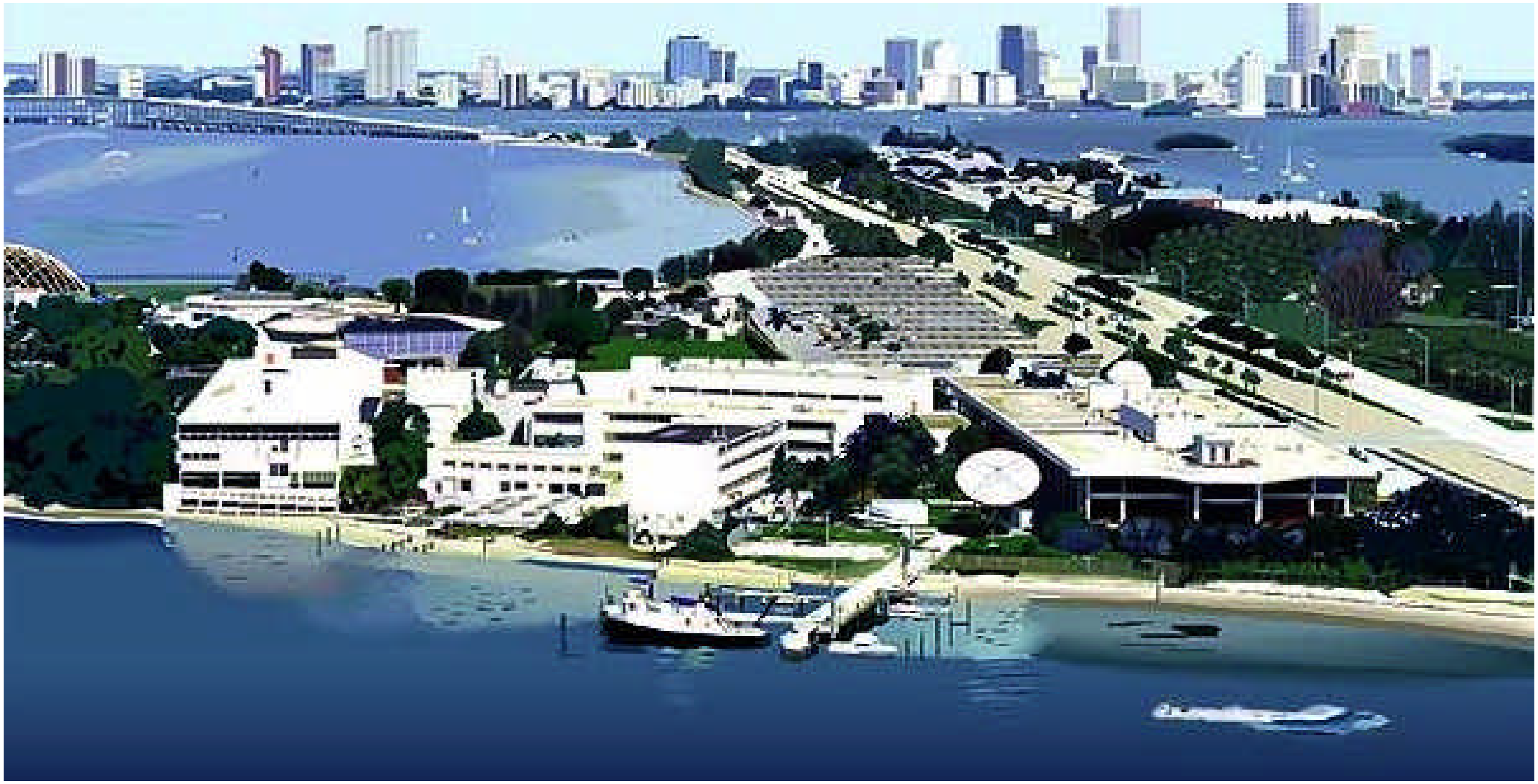
Use of data from other satellites (Terra MODIS, Quickscat, TRMM, GPM…) provides mechanism for examining diurnal effects.

Conclusions

- MODIS Bands 20, 22, 23 SSTs offer new levels of accuracy
- Instruments exist for the validation of SSTs at this accuracy
- New levels of accuracy facilitate new applications including air sea fluxes, *e.g*. heat and gases
- Fluxes require synergistic melding of data from several EOS sensors, especially MODIS and AMSR-E
- Several outstanding issues :-
    - accuracies,
    - matching different footprint sizes,
    - robustness of correlations between measurable and non-measurable variables.

Acknowledgements

- Captains, officers, crews and fellow scientists of the ships that have hosted the M-AERI
- Remote Sensing Group at RSMAS, University of Miami
- AERI group at the Space Science and Engineering Center, University of Wisconsin–Madison.
- Research funding from
  - NASA
  - DOE ARM
  - NOAA



Results from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS): Global and Arabian Sea Regional Ocean Color and Thermal Observations

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January 2001

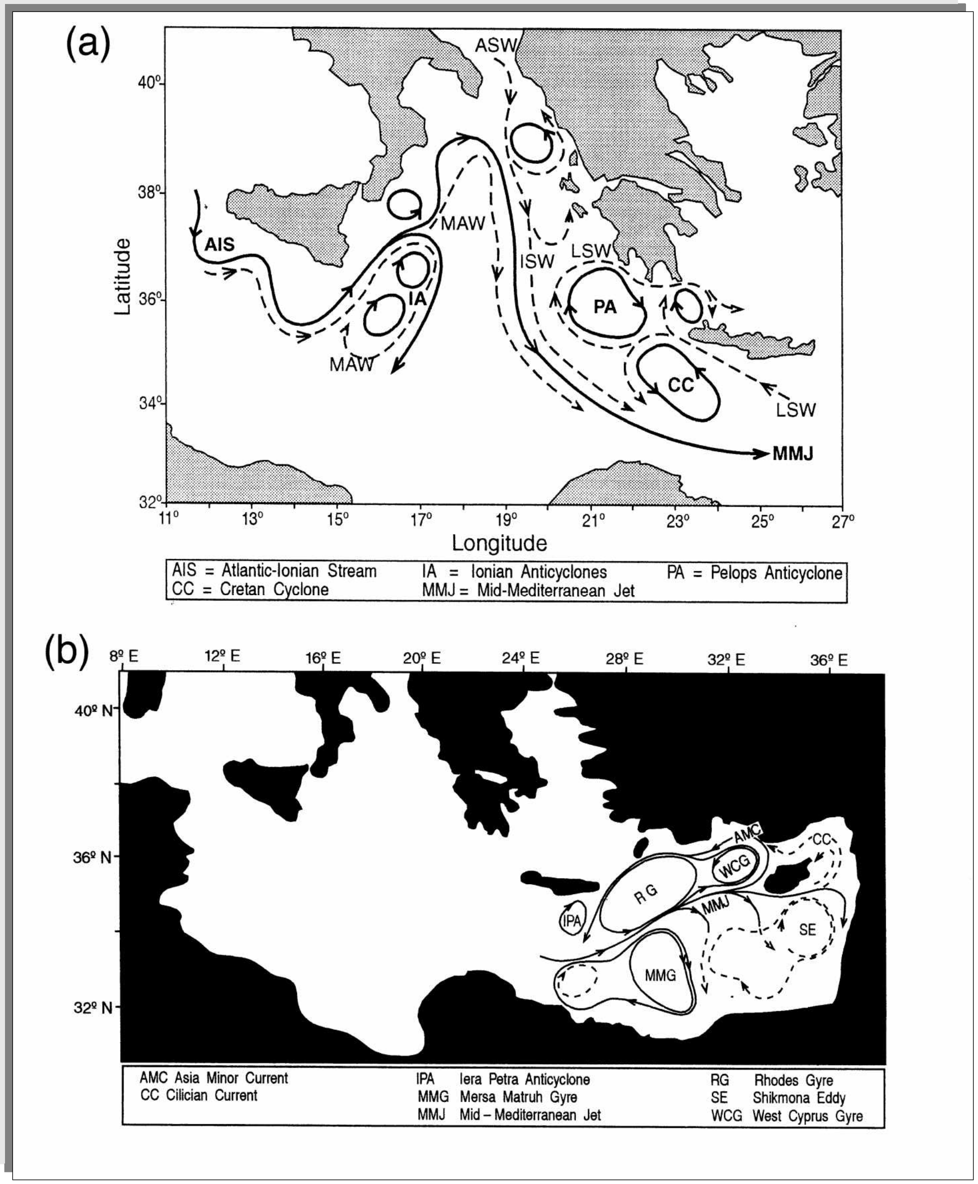
Overview

- **Topics Presented:**
  - **Comparison of thermal features in the eastern Mediterranean observable from MODIS and AVHRR**
  - **Absorbing aerosol coverage limitation in Arabian Sea, SeaWiFS and MODIS**
  - **Results from future candidate atmospheric correction and water leaving radiance retrieval approachthat includes both absorbing and scattering aerosols**
  - **Concurrent observation of absorbing aerosol effects in ocean visible and infrared bands (Med)**
  - **MODIS observation of a 'fish kill' upwelling event in Gulf of Oman, the geophysical alternative to an assertion of illegal ship discharge**

Overview

- **Sensor characterization has provided initial corrections for :**
  - **Detector-to-detector discrepancies within wavebands**
  - **Variations in the mirror response as a function of angle of incidence**
  - **Differences in characteristics between mirror sides**
  - **Effects of spatial and spectral cross-talk**
  - **Problems associated with polarization and sun glint.**
- **Spectral calibration for ocean color bands 8-16 (412-865nm) developed through comparison of MOBY/MOCE in situ observations with MODIS Lw water leaving radiance.**

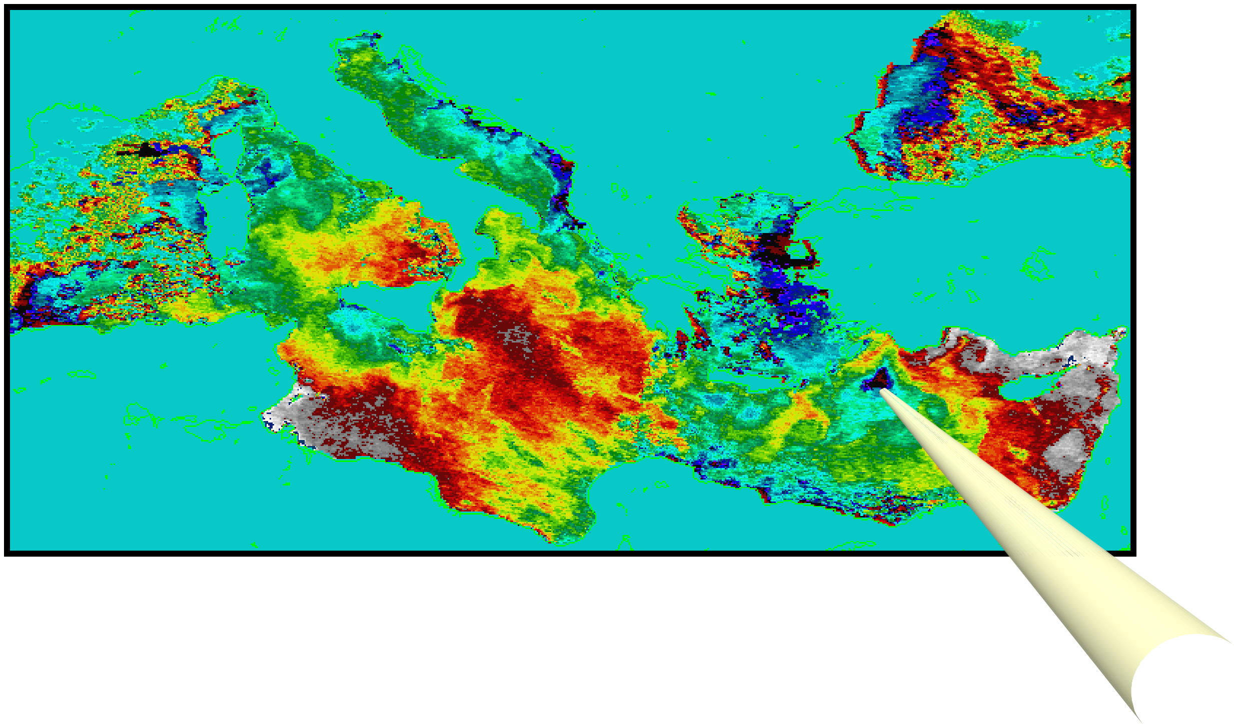
Eastern Mediterranean Circulation



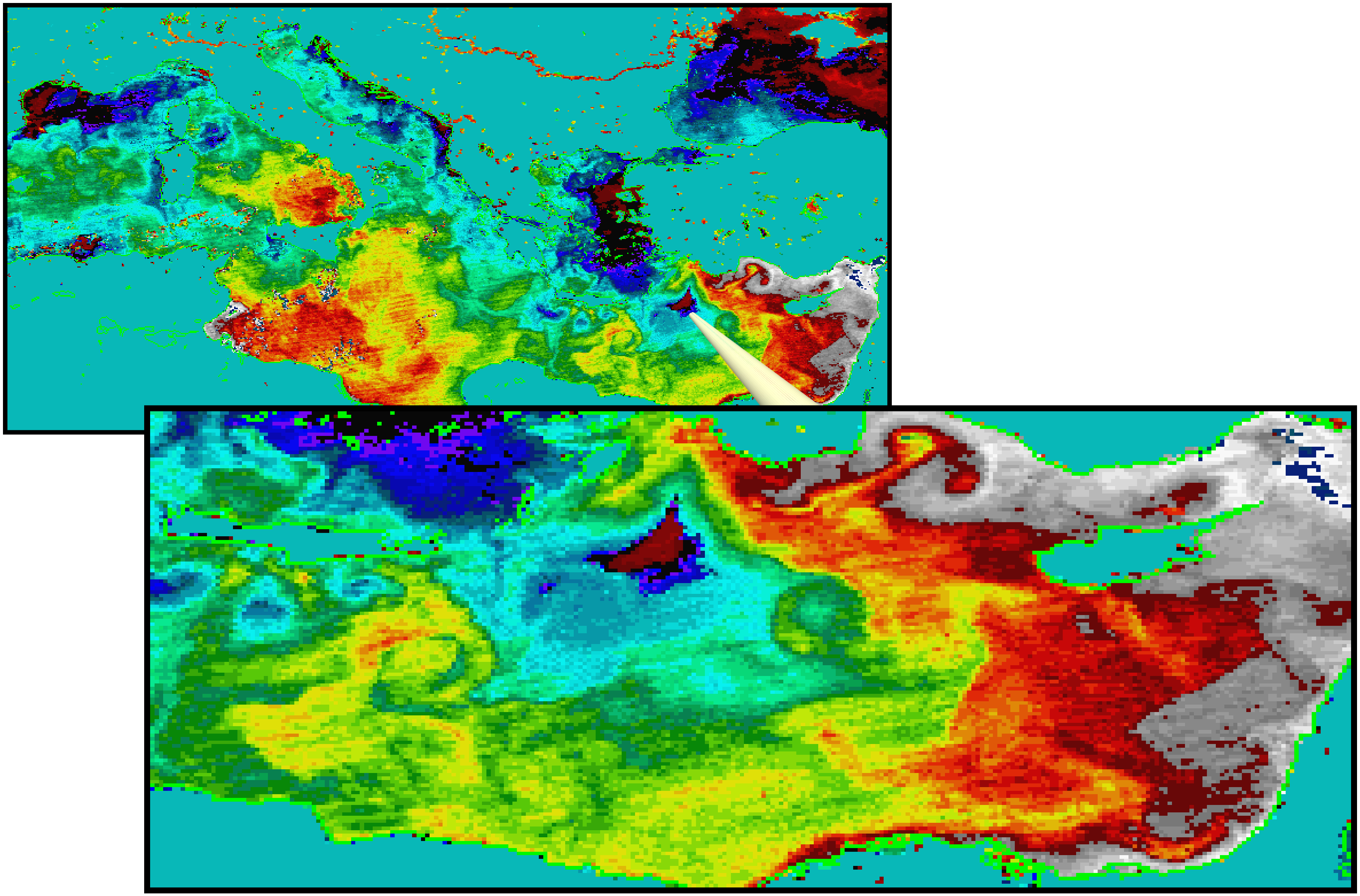
Malanotte-Rizzoli *et al*.,1999

Robinson and Golnaraghi, 1994

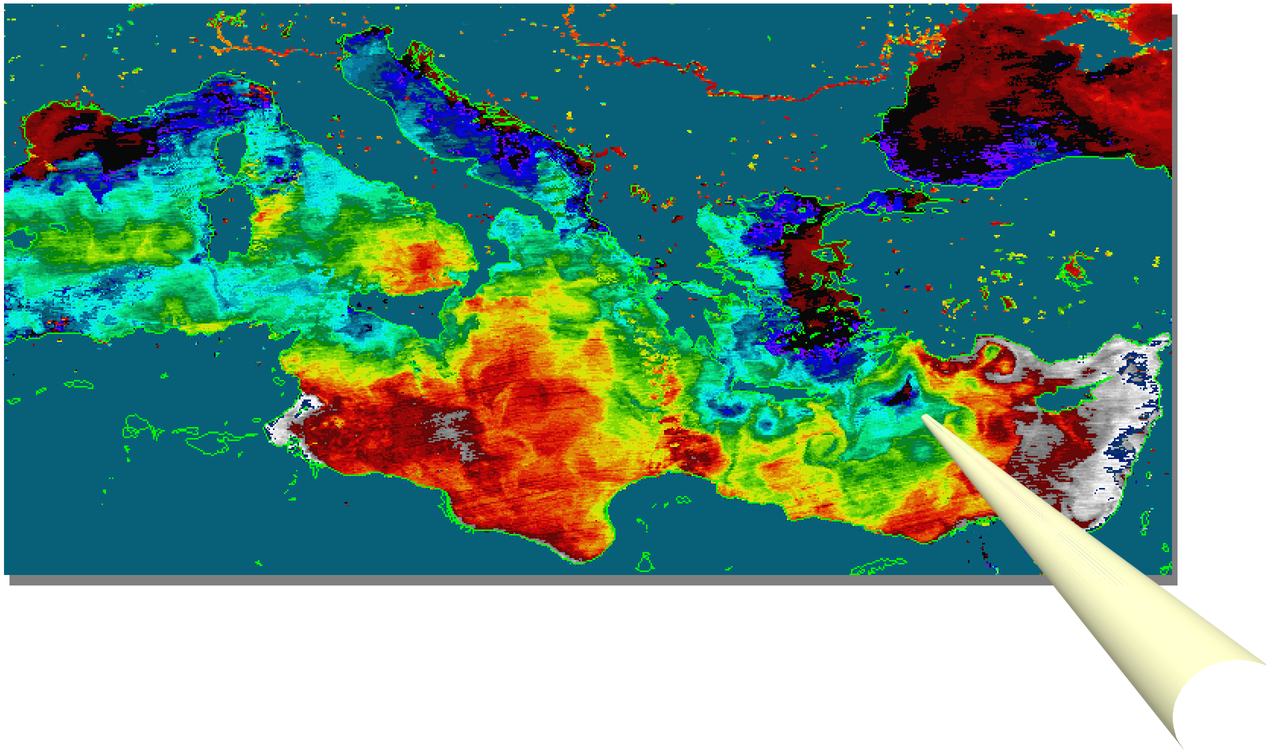
August 30, 2000, 4km, 0.15C Steps
AVHRR Pathfinder Thermal-IR SST



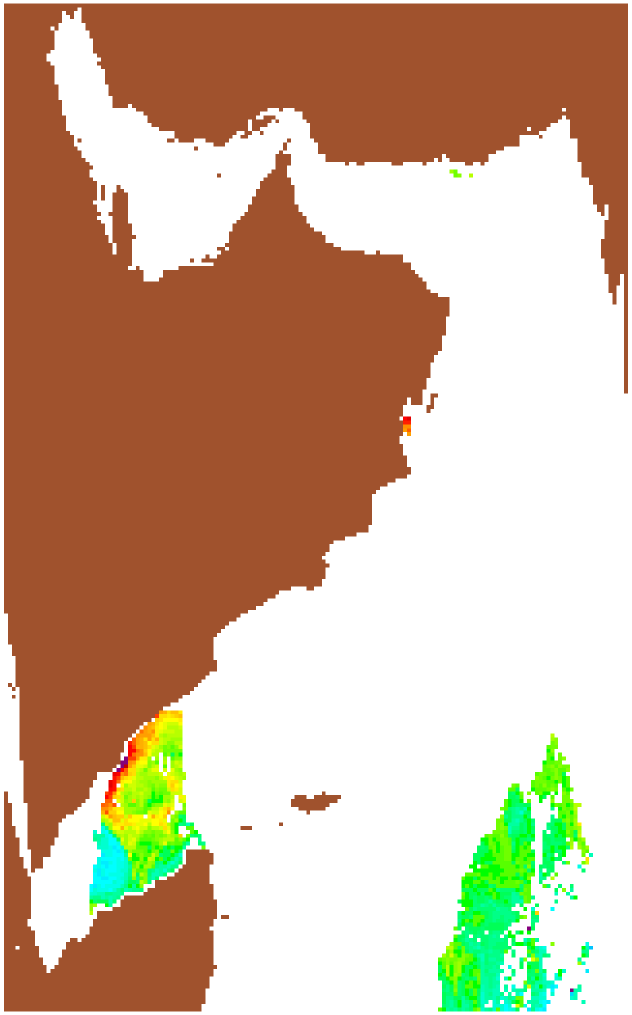
August 30, 2000, 4km, 0.15C Steps
MODIS Thermal-IR SST



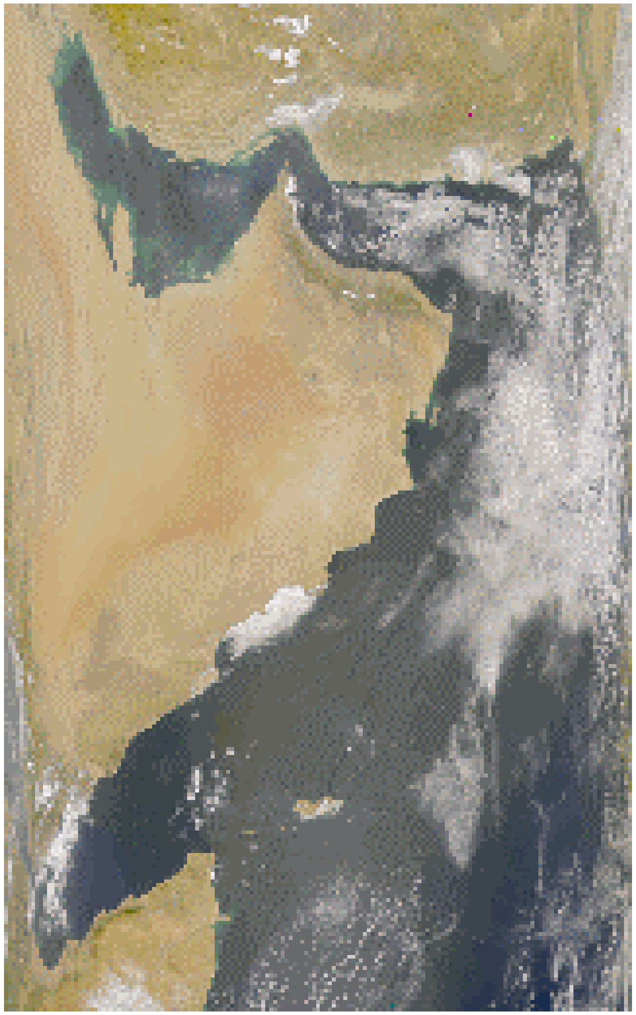
August 30, 2000, 4km, 0.15C Steps
MODIS Mid-IR SST



SeaWiFS August 28, 2000



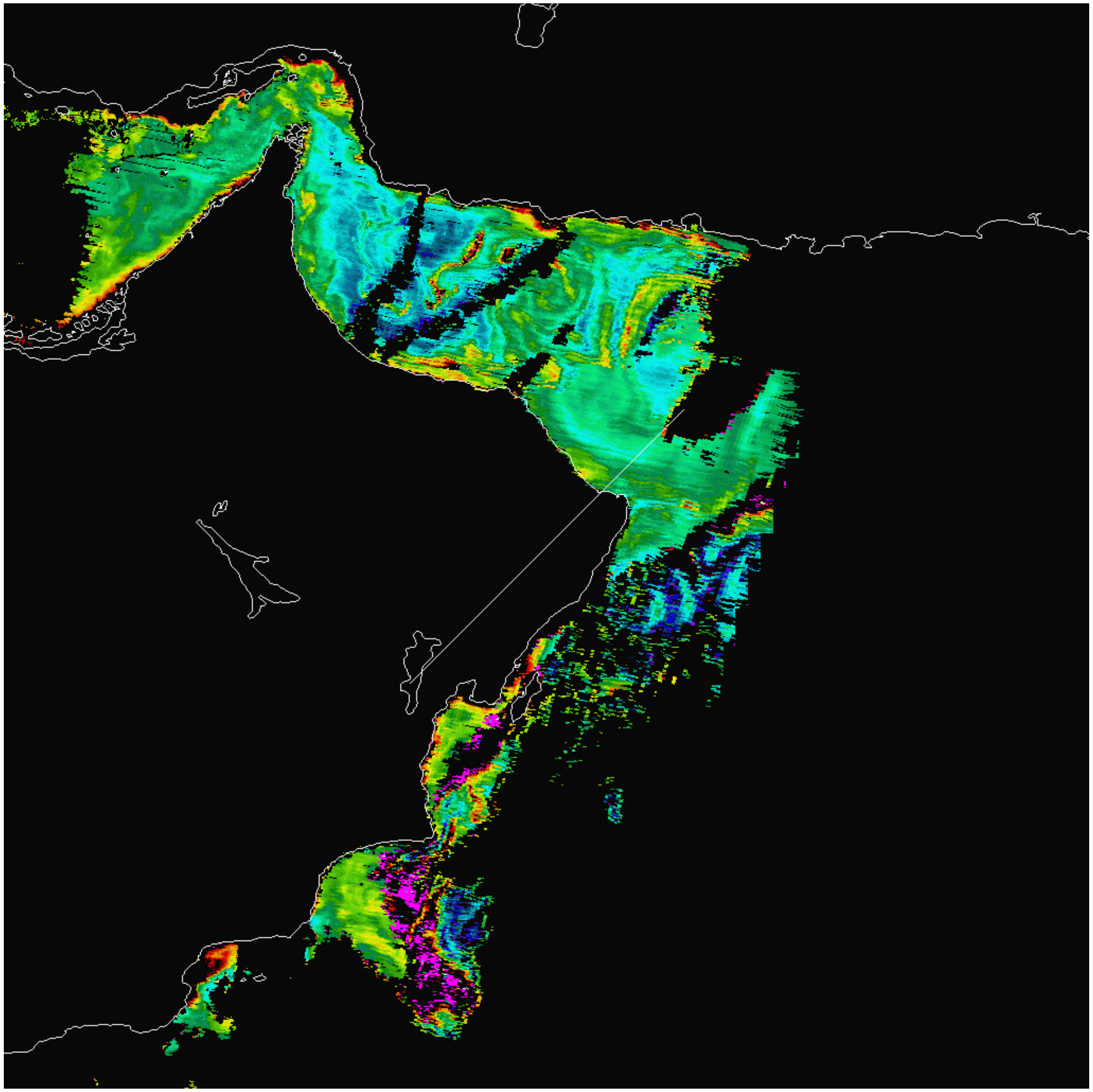
Chlorophyll



True Color

MODIS Chlorophyll - August 28, 2000

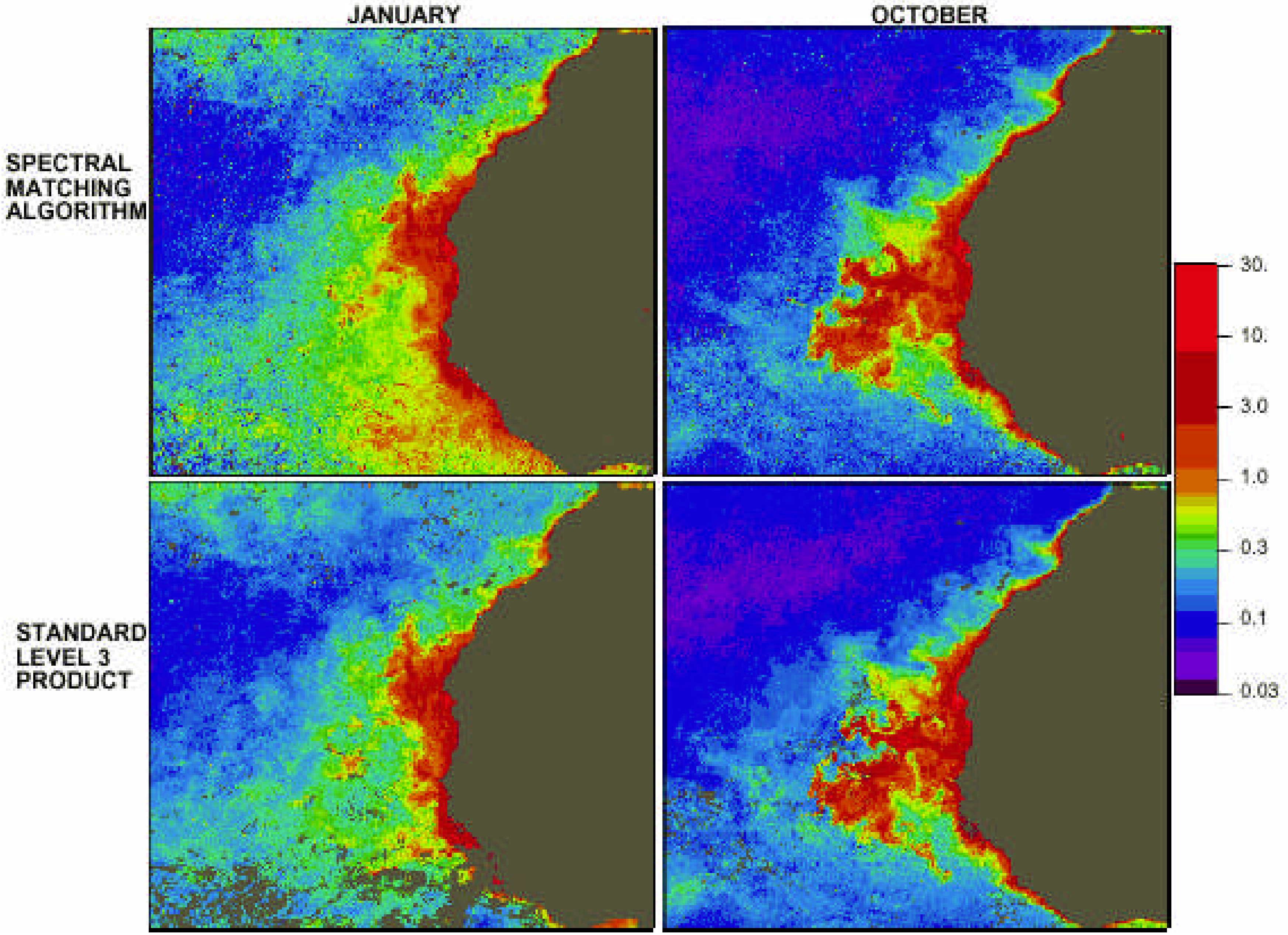
Processed using Absorbing Aerosol Model



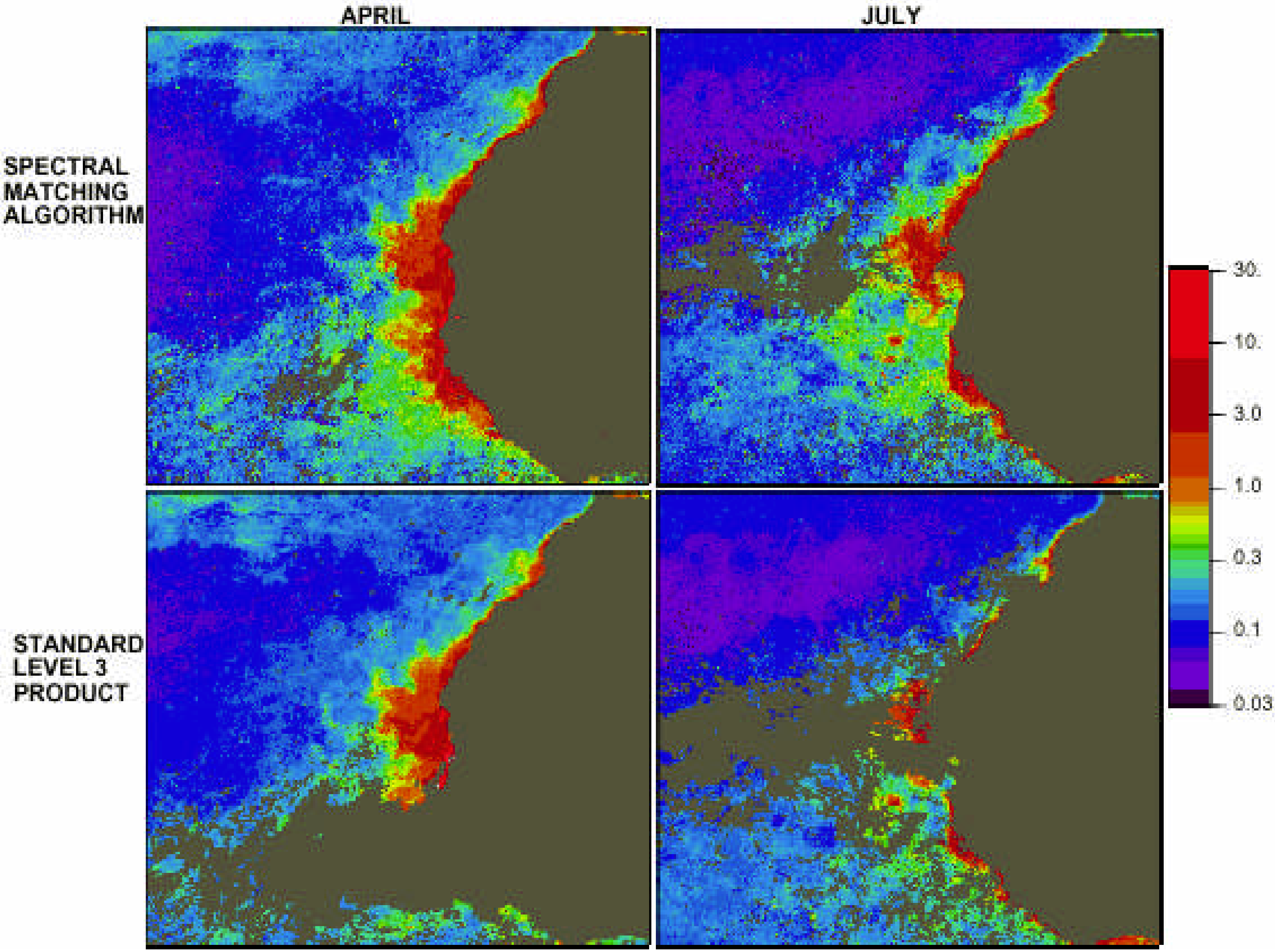
Spectral Matching Algorithm-SeaWiFS Comparison

- SMA is a candidate SeaWiFS/MODIS ocean color atmospheric correction algorithm that includes scattering and absorbing aerosols
- SMA uses atmospheric and ocean optics models to simultaneously solve for atmospheric and ocean radiance
- For this comparison, SMA is used to provide only atmospheric correction, the model-derived pigments are ignored.
  - After removing the SMA-estimated atmospheric contribution, the resulting water-leaving radiances are then used with the OC4v4 SeaWIFS (operational) bio-optical algorithm to derive the Chlorophyll a concentration.
- Note the excellent agreement with increased coverage (SMA) compared to the standard product during the April and July time frames in the Saharan dust zone.

Spectral Match-SeaWiFS Comparison

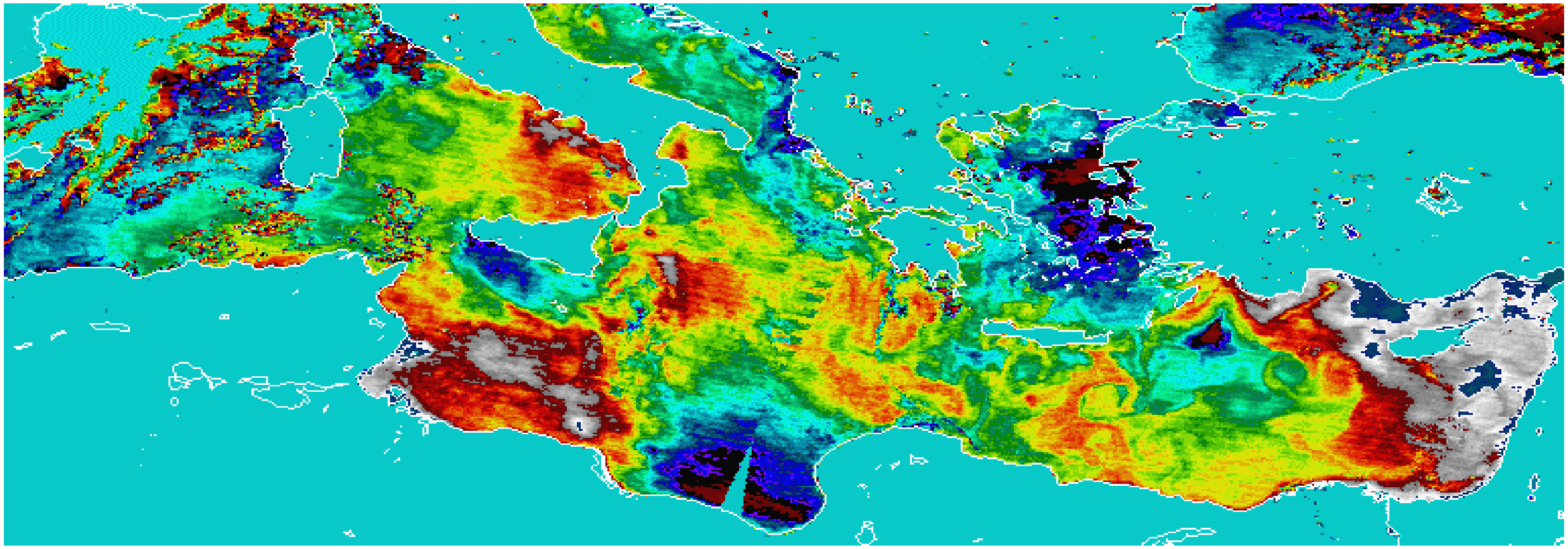


Spectral Match-SeaWiFS Comparison

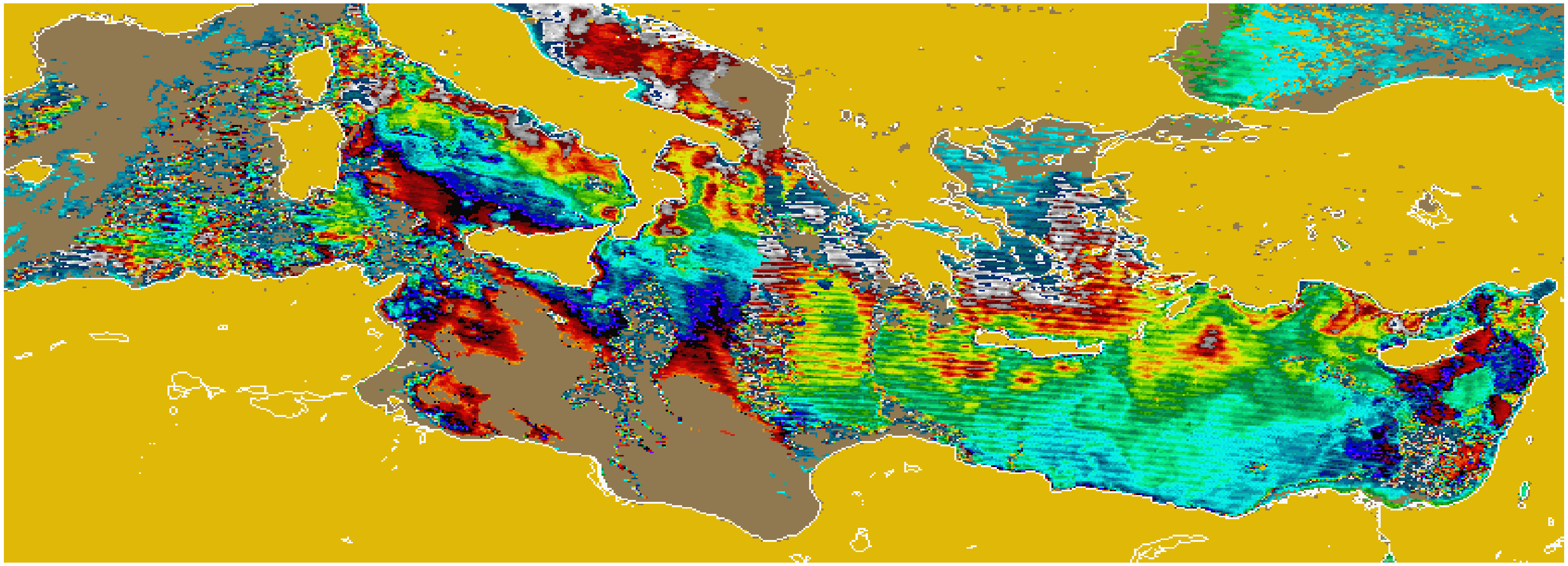


Day 243 MODIS SST and Chlorophyll

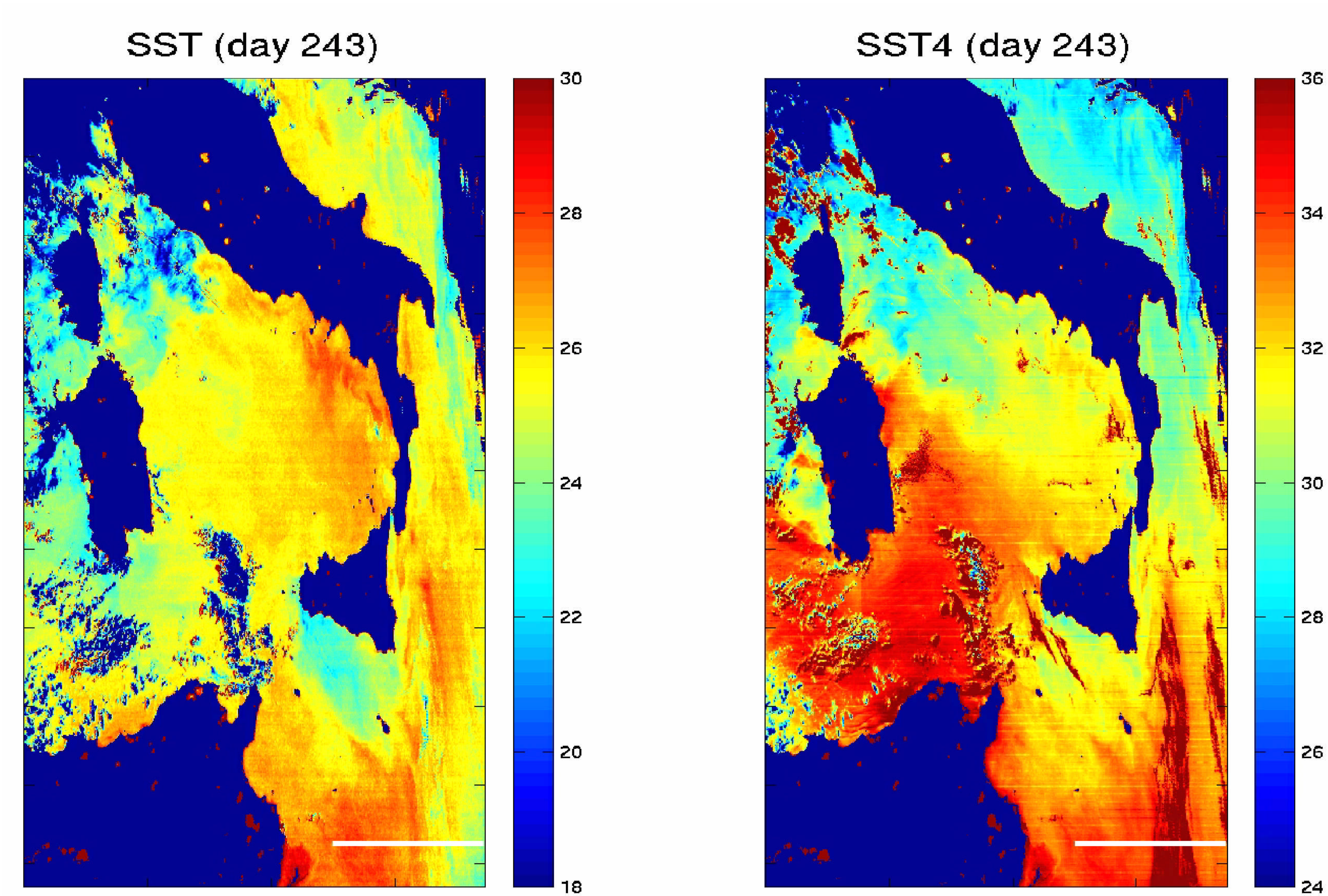
Thermal SST



Chlorophyll

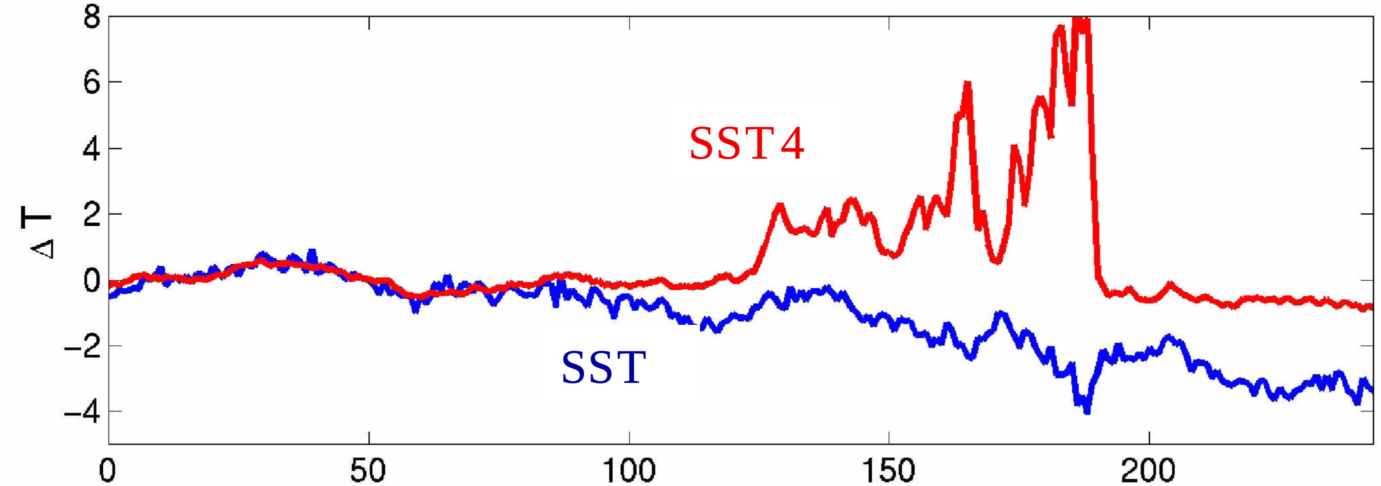


Thermal Midwave SST – Day 243

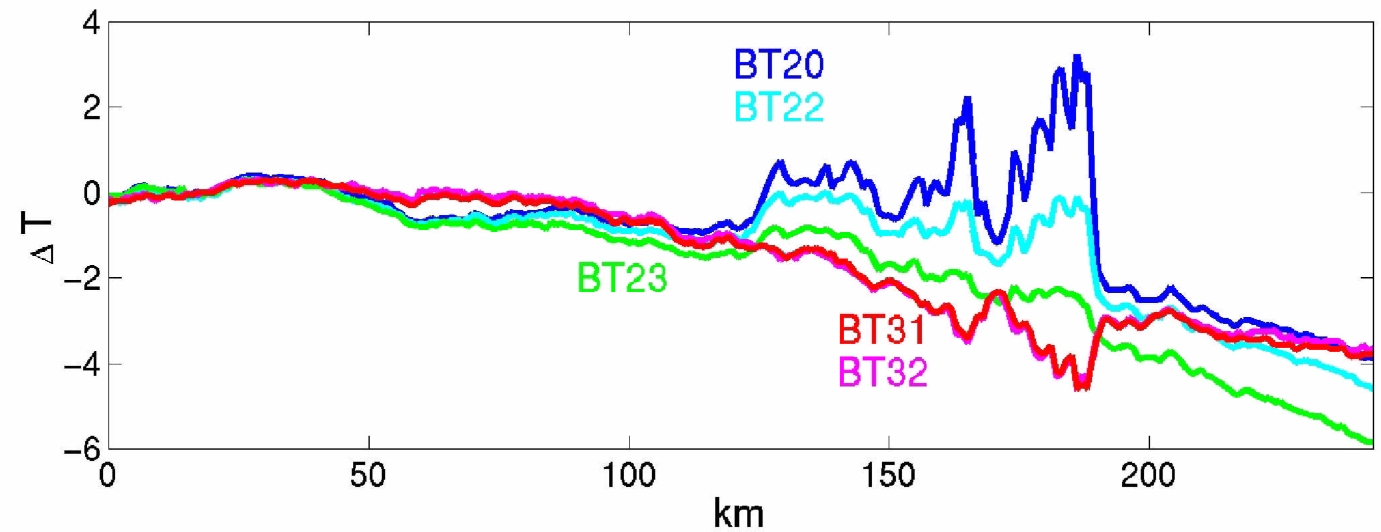


Dust Affected Temperature Section Day 243

Thermal and Midwave SST

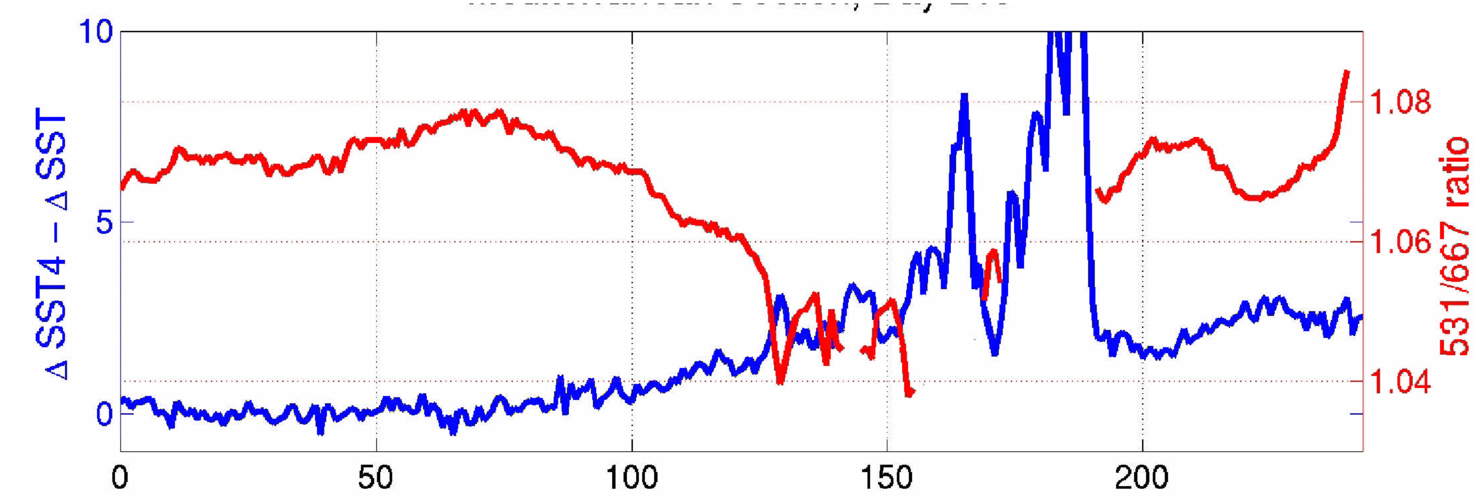


Brightness Temperature

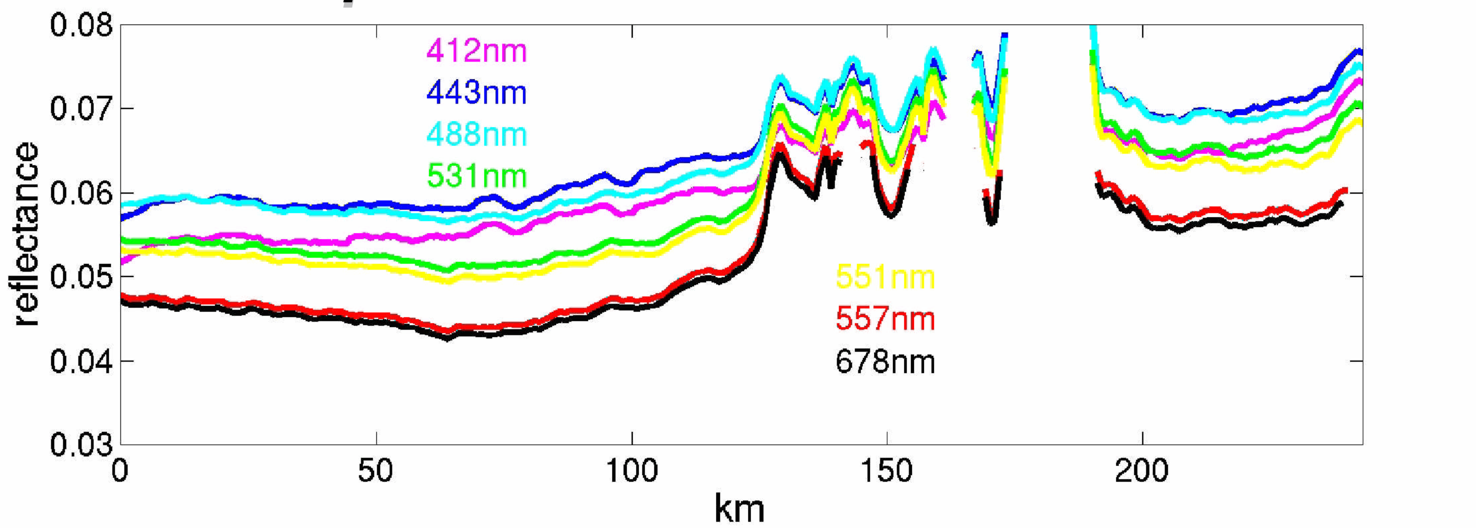


Dust Affected Temperature Section Day 243

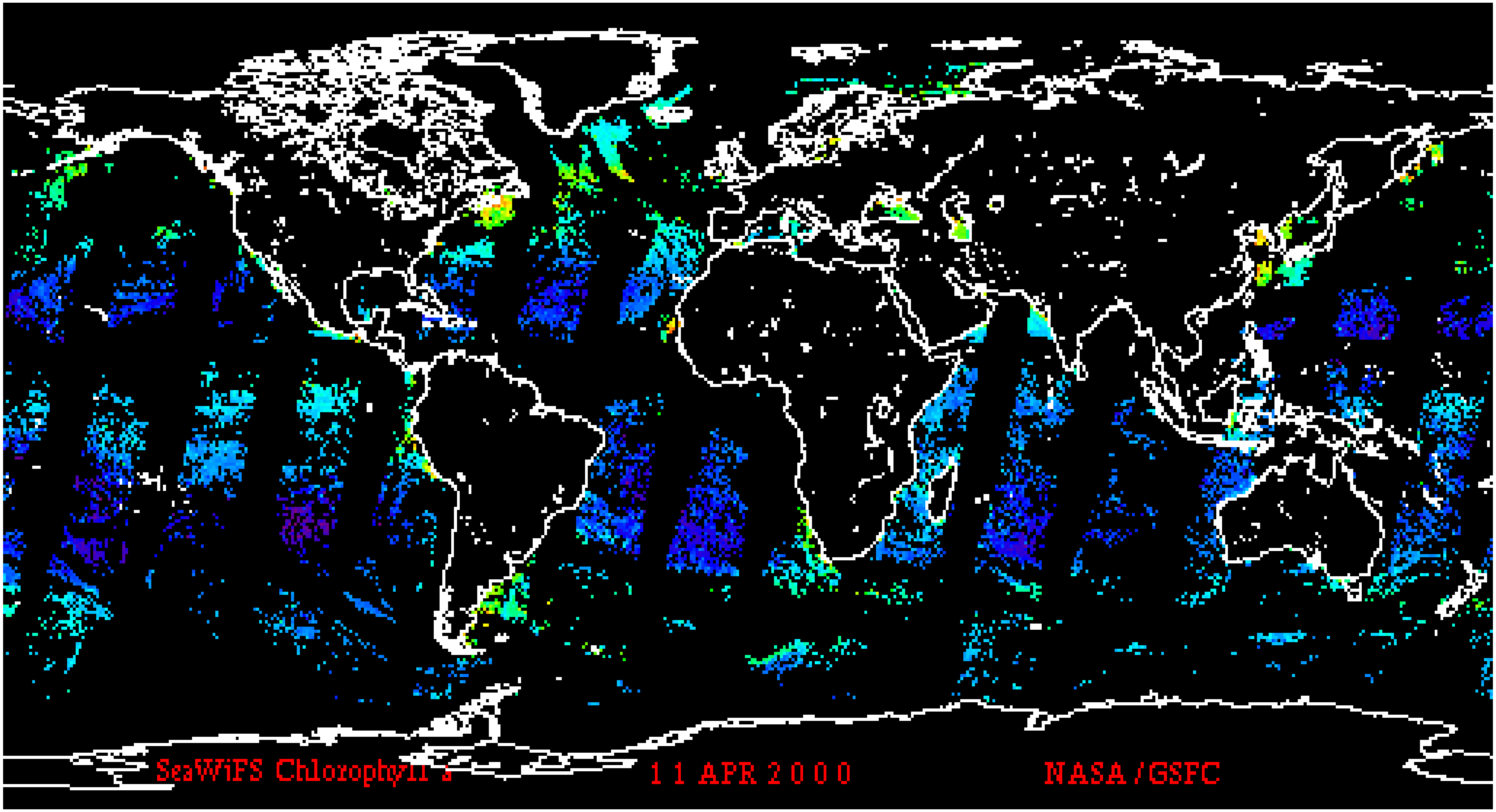
SST Difference



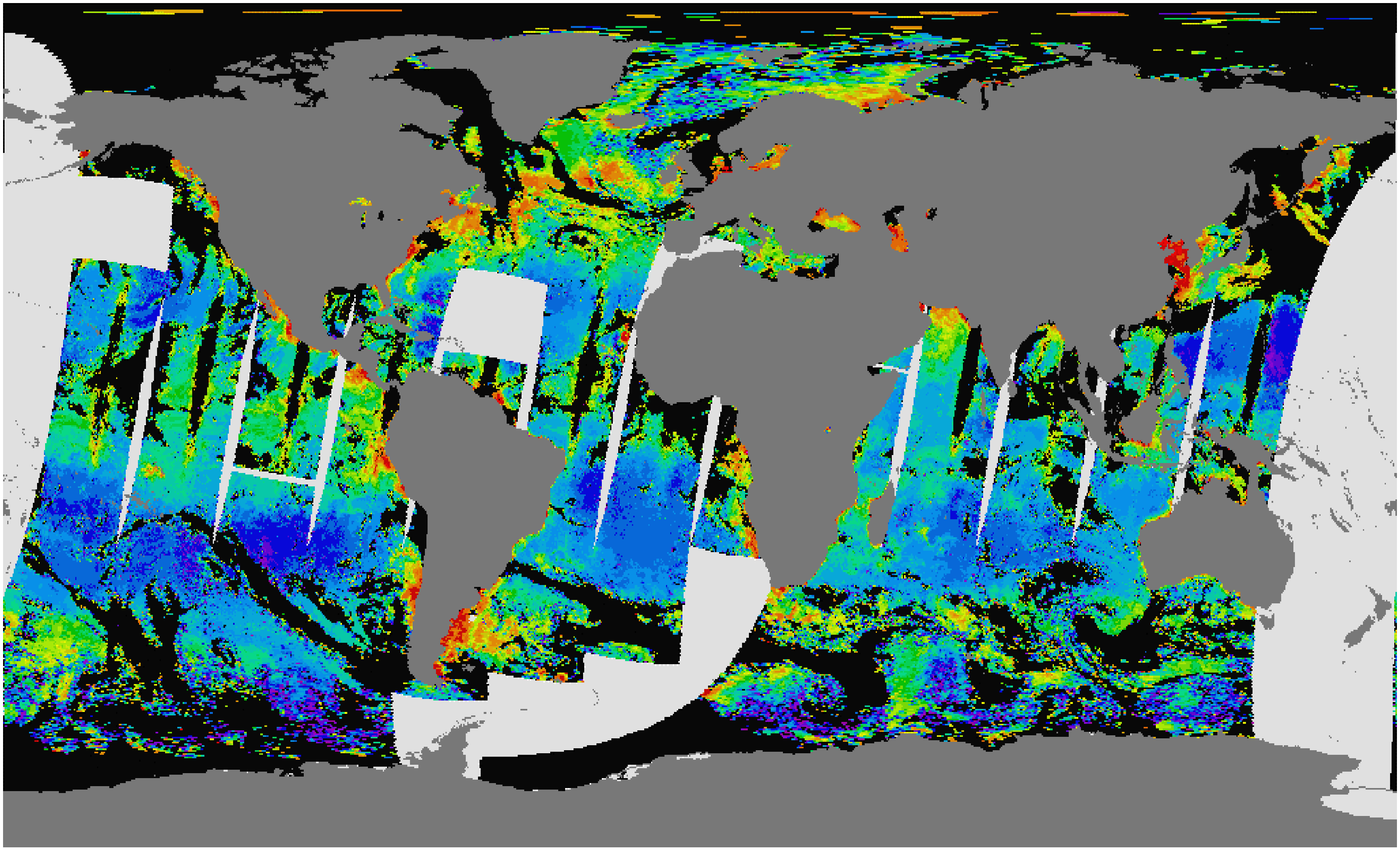
Spectral Aerosol Reflectance



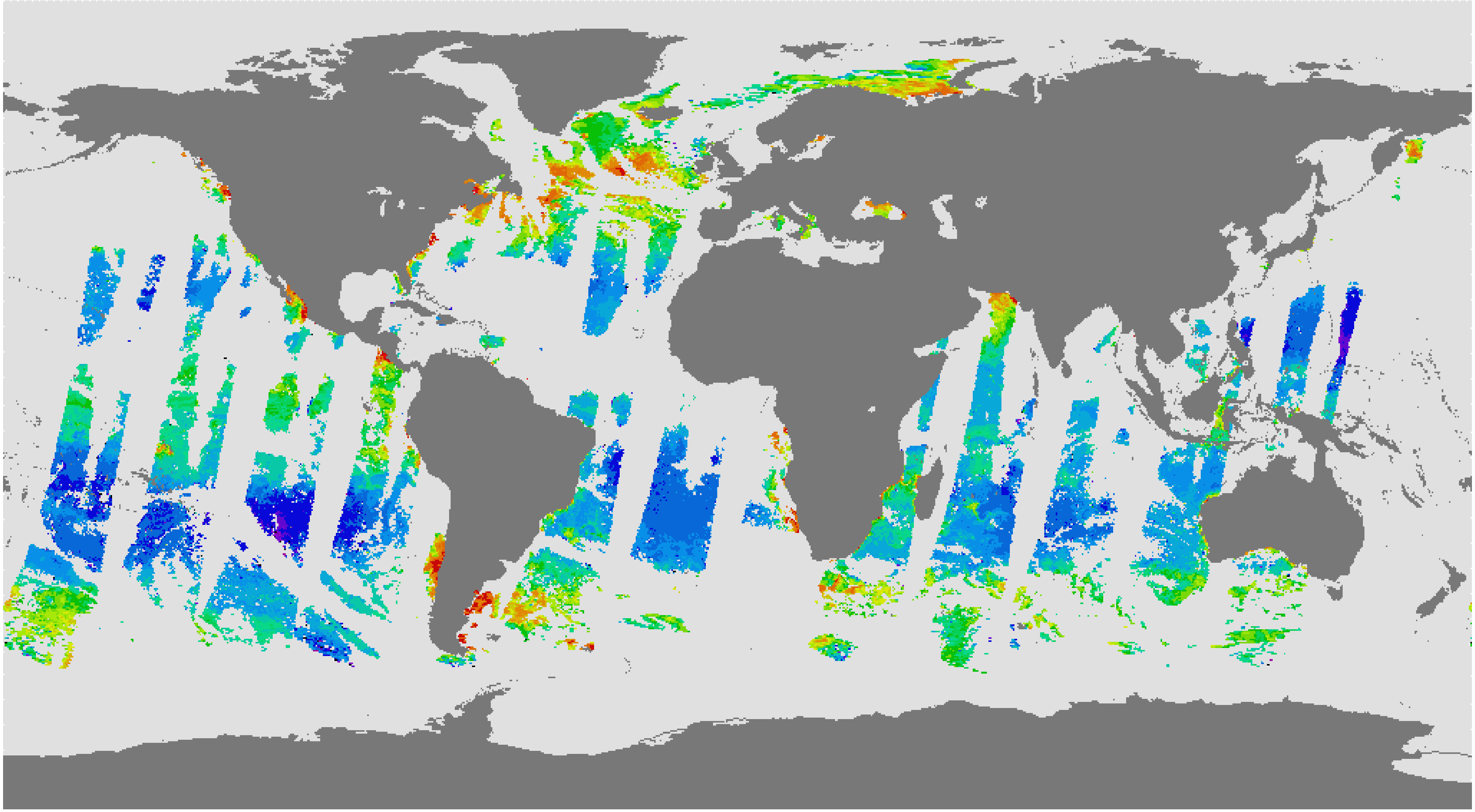
SeaWiFS Chl, 4/11/00, Best pixels



Modis Chl-Clark, 4/11/00, All pixels

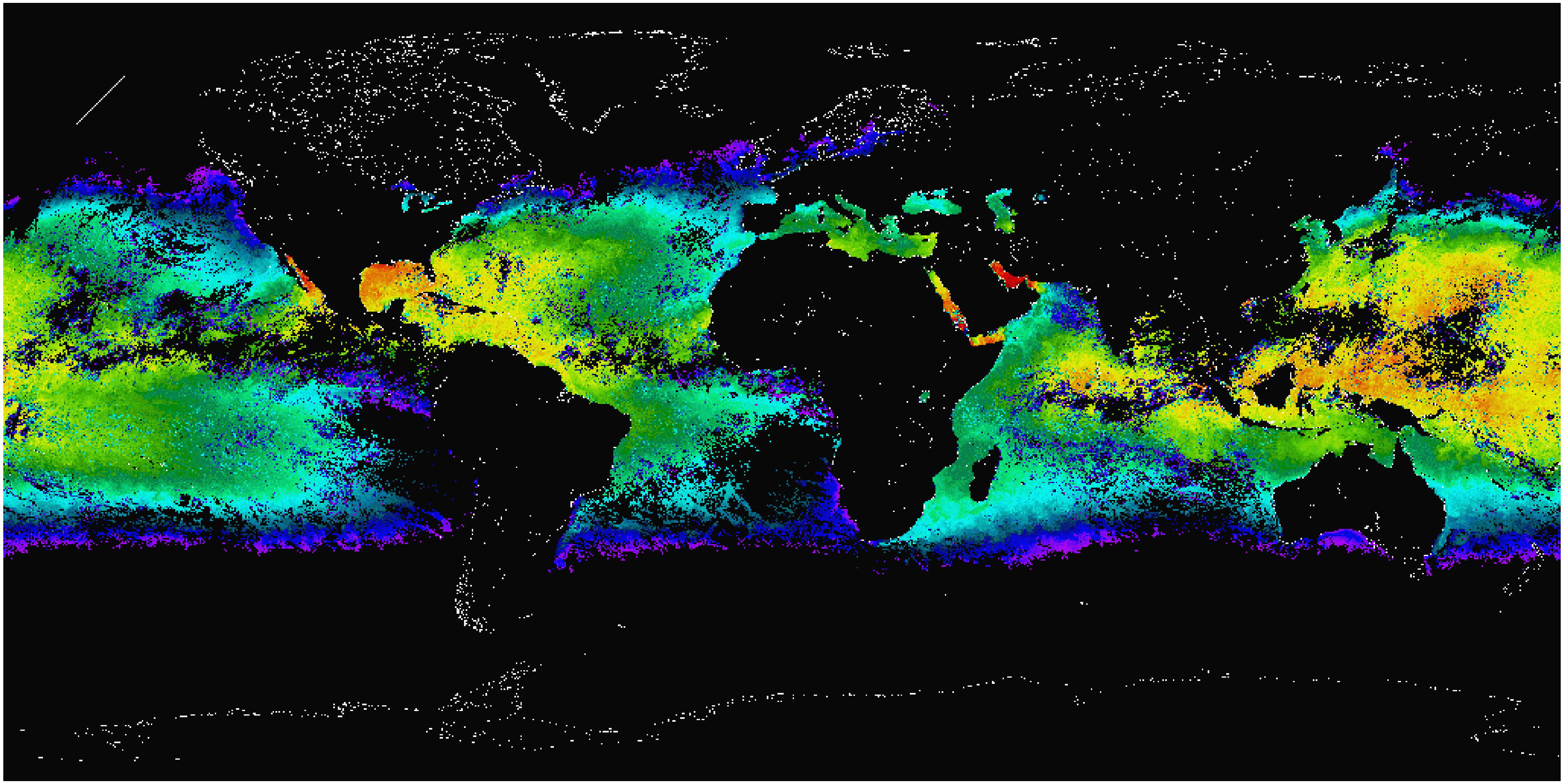


Modis Chl-Clark, 4/11/00, Best pixels



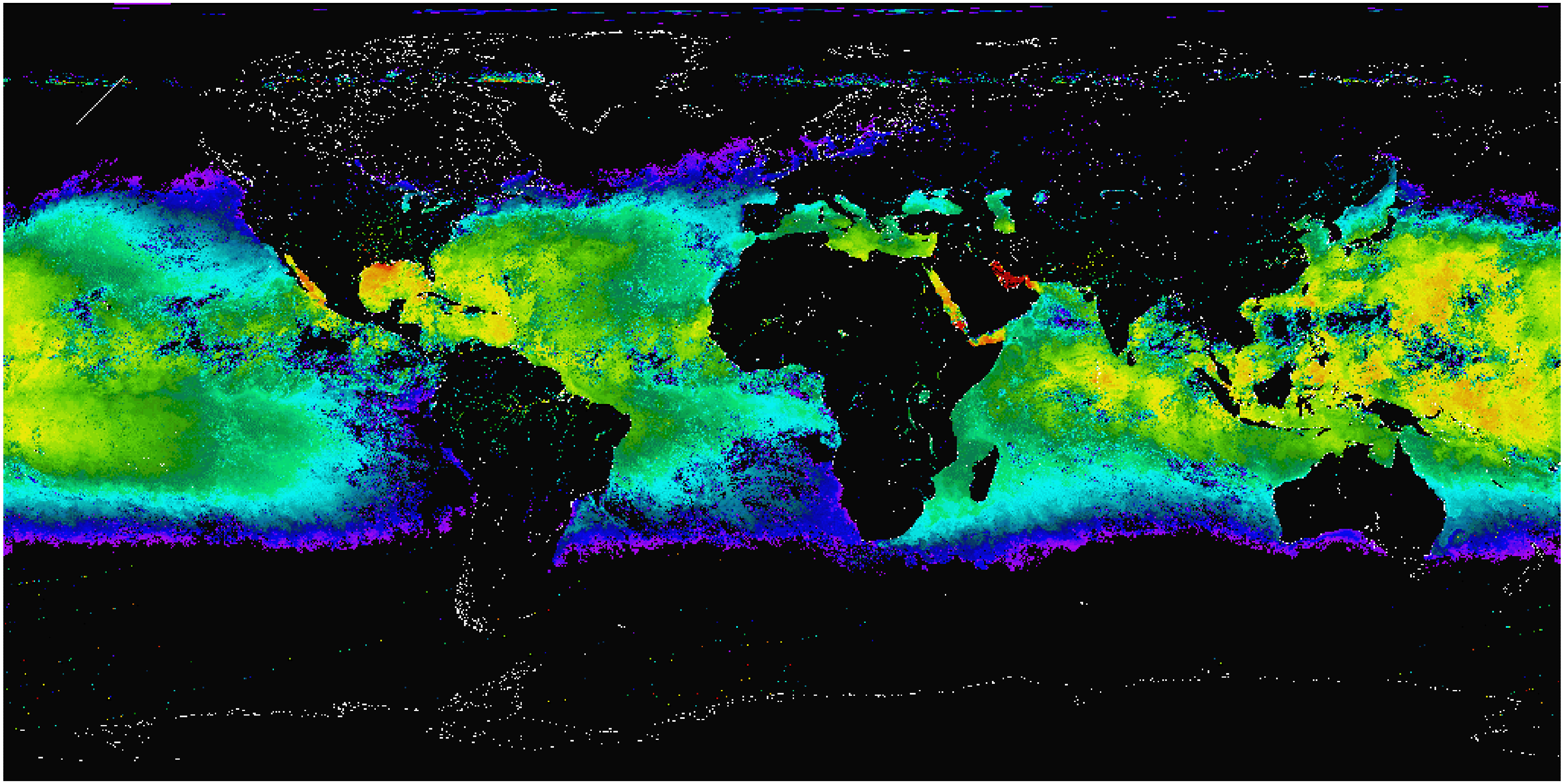
Pathfinder SST-Thermal

Sept 1-6, 2000 Weekly Night, 4km resolution

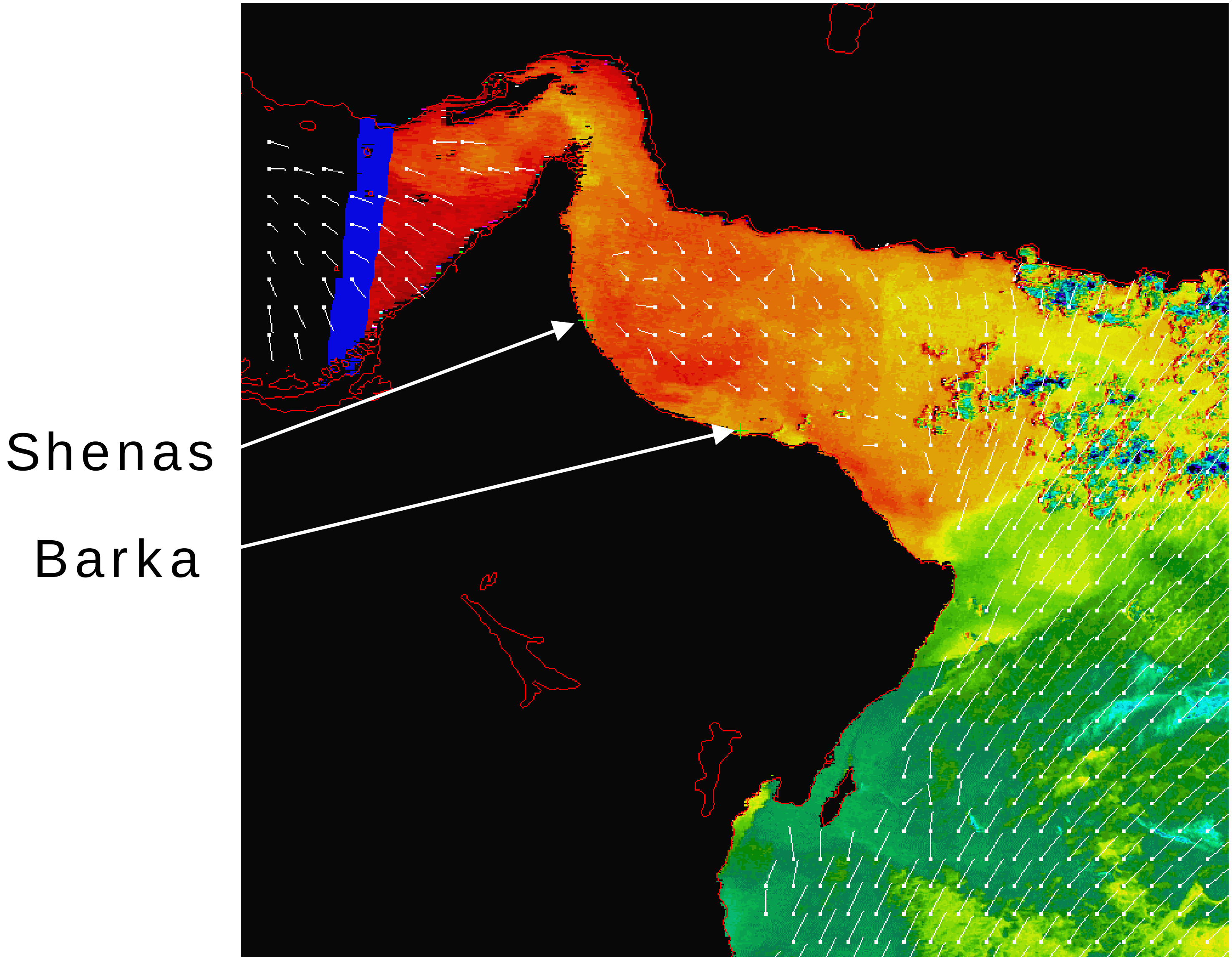


MODIS SST-Midwave

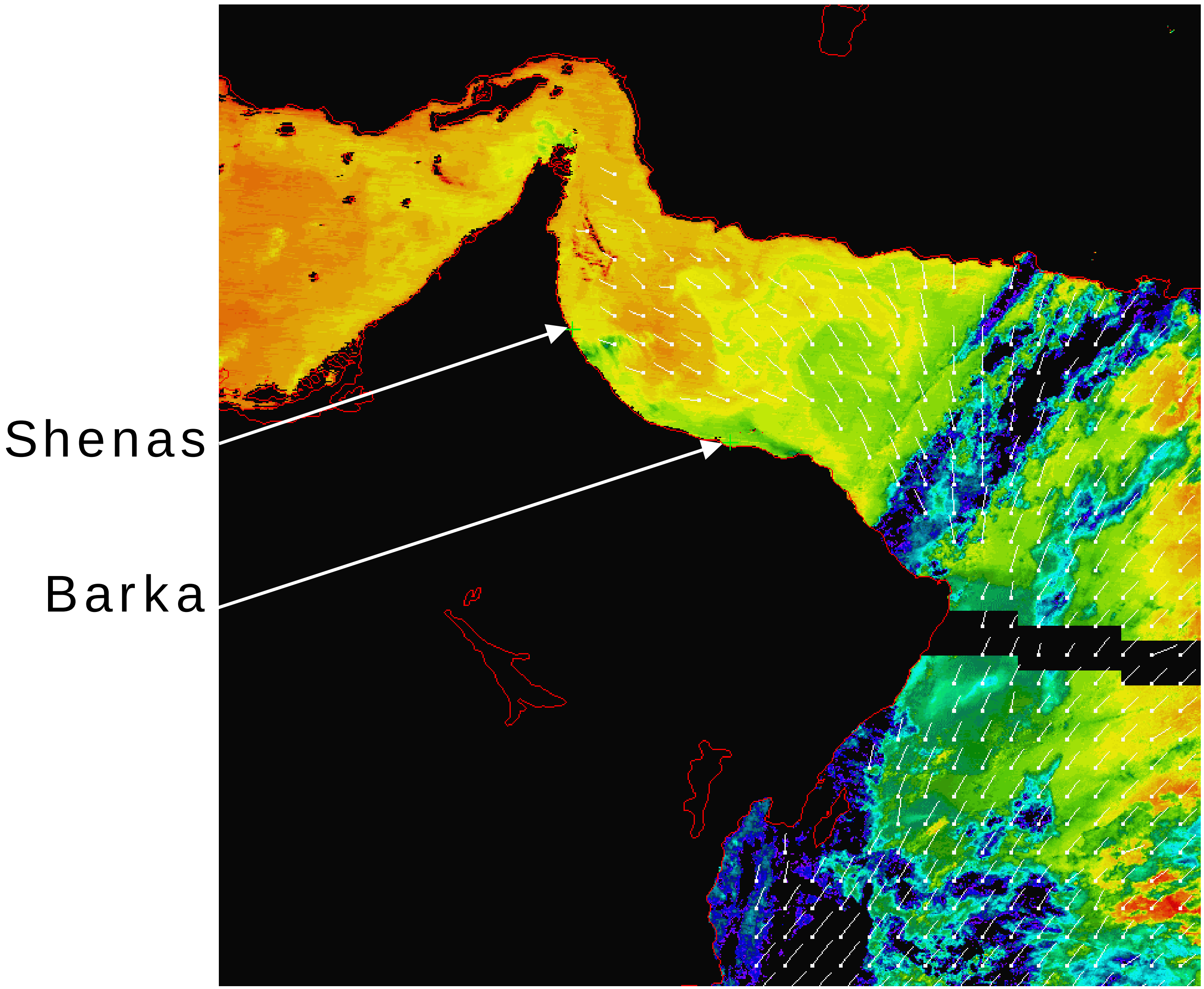
Sept 1-6, 2000 Weekly Night, 4km resolution



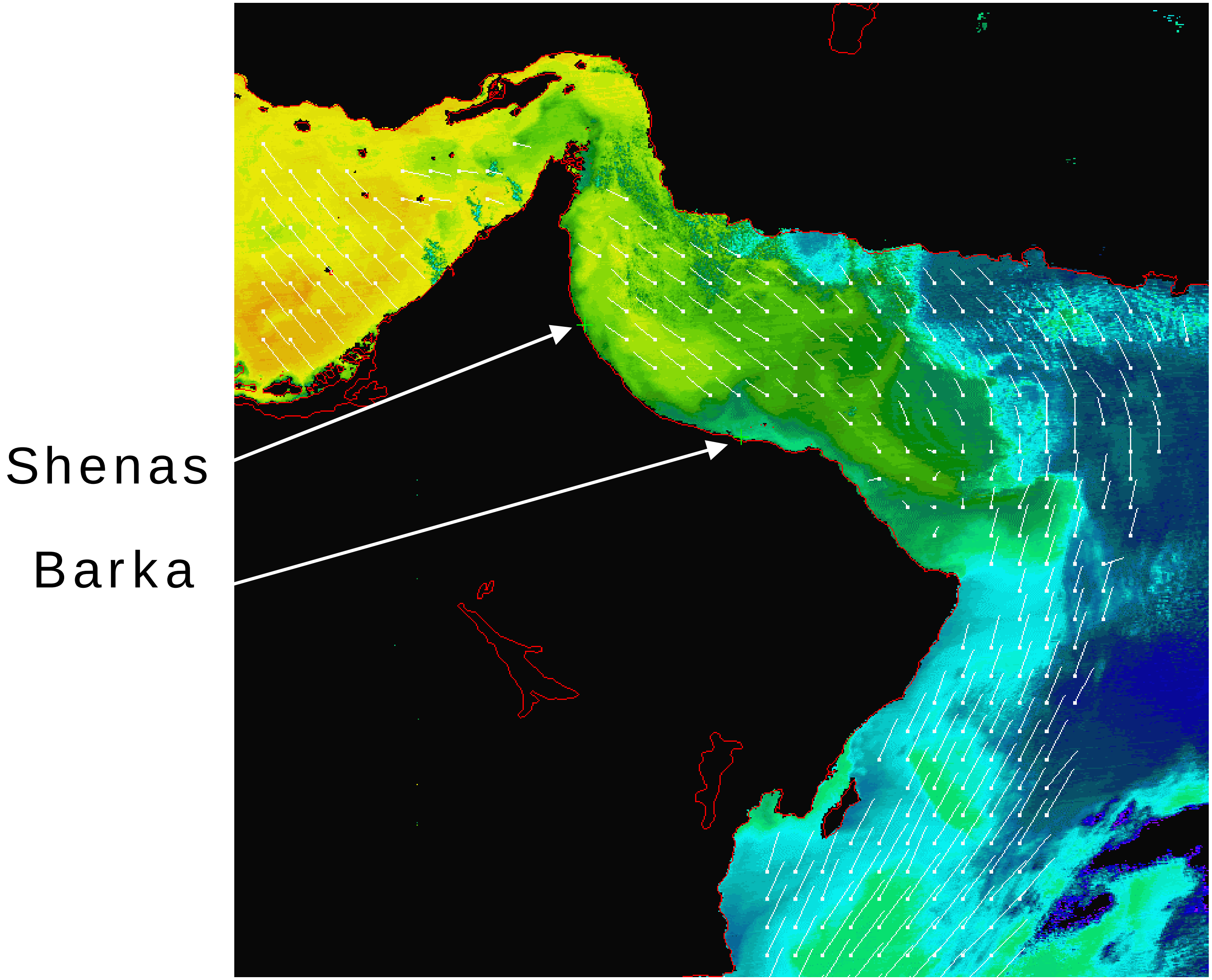
September 7 – Normal Fish Catch



27 August – Start of Fish Kill



September 2 – Height of Fish Kill



Summary

- SST, Chlorophyll gradients stable at levels close to sensor digitizer precision
- To realize these capabilities, the sensor must be 'calibrated/flat fielded' at this level of precision, better than 0.1%
- Preliminary observations show co-located affects of absorbing aerosol in both visible and infrared bands.
- Small scale features, width order 1-3km, seen throughout world's oceans
- Eddy population more extensive than seen with previous sensors
- Combination of '10:30' orbit when cloud fraction is smaller and 12 bit, low noise detectors significantly improves ability to view ocean surface features