Shipboard radiometric measurements of some surface meteorological parameters

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RSMAS

ROSENSTIEL SCHOOL OF MARINE AND ATMOSPHERIC SCIENCE • UNIVERSITY OF MIAMI •

High Resolution Marine Meteorology Workshop, COAPS-FSU

3-5 March 2003

Overview

Ship board measurements:

- M-AERI
- *Explorer of the Seas*
- CEOS Radiometer Workshop
- Radiometric measurements of air-sea temperature differences
- SST radiometers for VOS fleet (NOPP)
- Satellite SST validation

Fourier Transform Interferometers

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THIRD SERIES.

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WITH PLATES II TO IX.

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THE

AMERICAN JOURNAL OF SCIENCE.

[THIRD SERIES.]

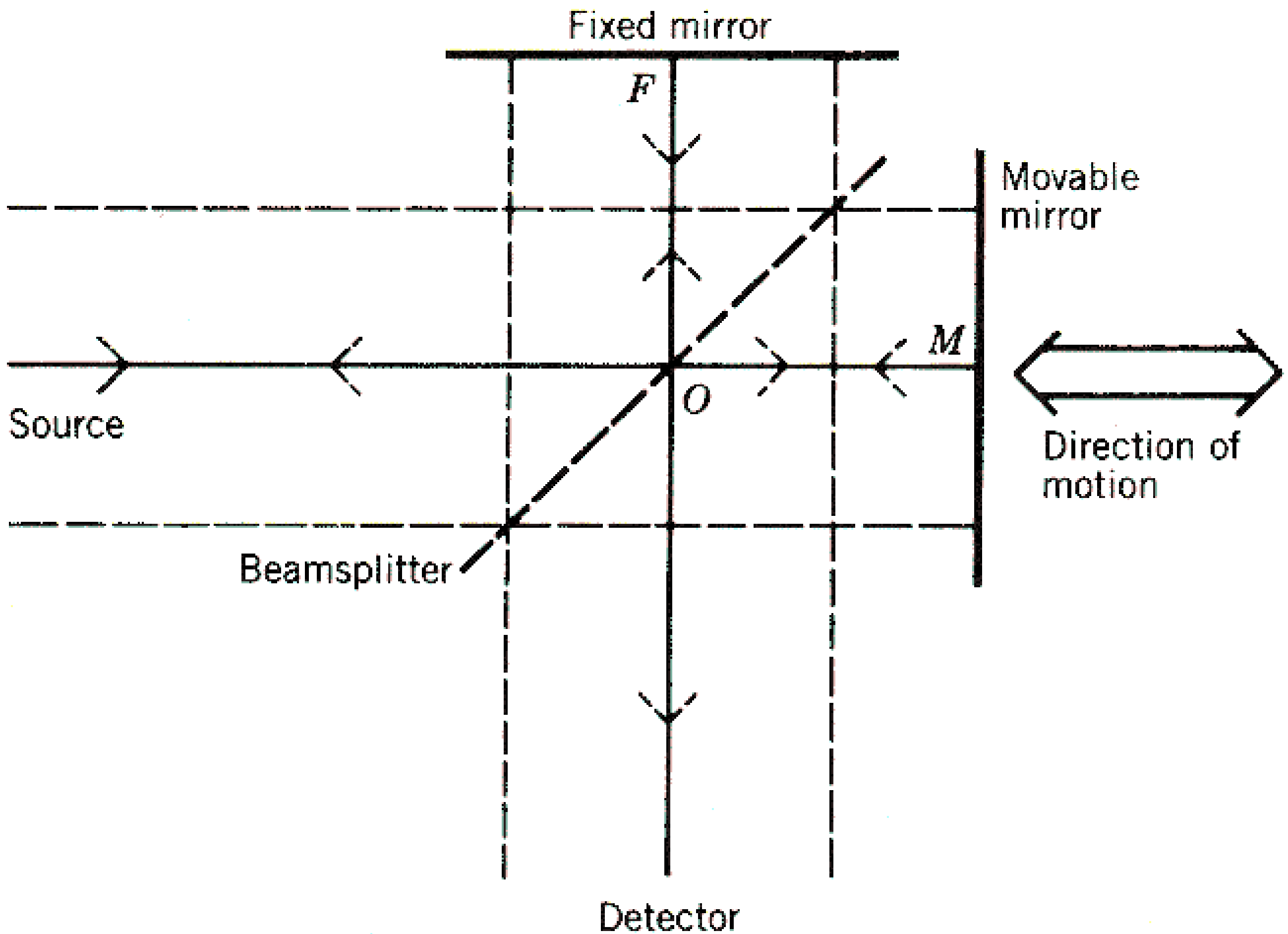
ART. XXXVI.—*On the Relative Motion of the Earth and the Luminiferous Ether*; by ALBERT A. MICHELSON and EDWARD W. MORLEY.*

THE discovery of the aberration of light was soon followed by an explanation according to the emission theory. The effect was attributed to a simple composition of the velocity of light with the velocity of the earth in its orbit. The difficulties in this apparently sufficient explanation were overlooked until after an explanation on the undulatory theory of light was proposed. This new explanation was at first almost as simple as the former. But it failed to account for the fact proved by experiment that the aberration was unchanged when observations were made with a telescope filled with water. For if the tangent of the angle of aberration is the ratio of the velocity of the earth to the velocity of light, then, since the latter velocity in water is three-fourths its velocity in a vacuum, the aberration observed with a water telescope should be four-thirds of its true value.†

* This research was carried out with the aid of the Bache Fund.

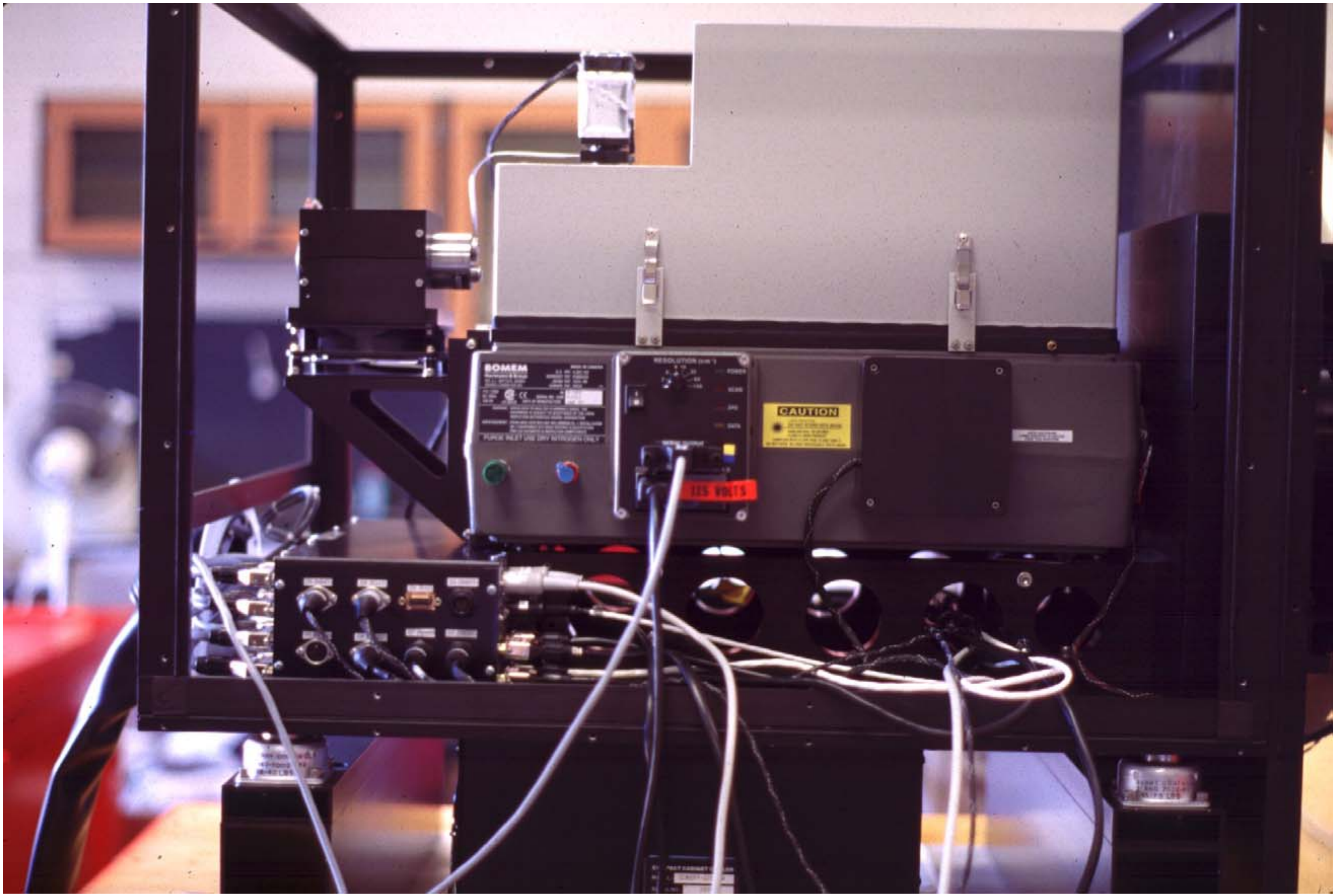
† It may be noticed that most writers admit the sufficiency of the explanation according to the emission theory of light; while in fact the difficulty is even greater than according to the undulatory theory. For on the emission theory the velocity of light must be greater in the water telescope, and therefore the angle of aberration should be less; hence, in order to reduce it to its true value, we must make the absurd hypothesis that the motion of the water in the telescope carries the ray of light in the opposite direction!

Michelson interferometer

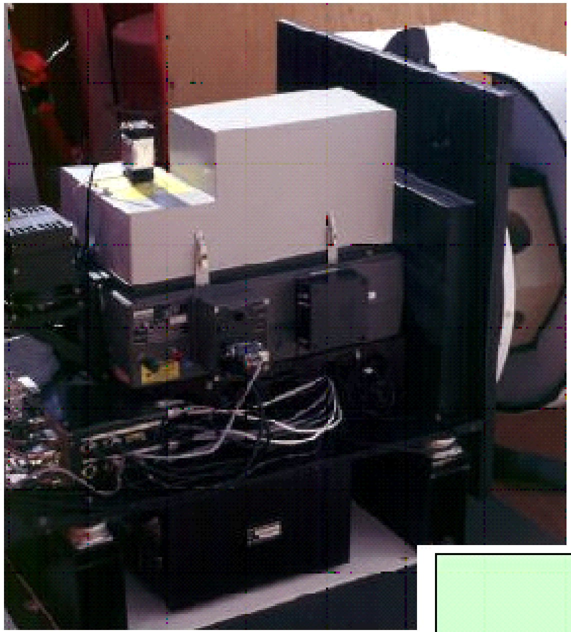


Schematic representation of a Michelson interferometer. The median ray is shown by the solid line, and the extremes of the collimated beam are shown by the broken lines.

The M-AERI



Marine-Atmospheric Emitted Radiance Interferometer (M-AERI)



Specifications

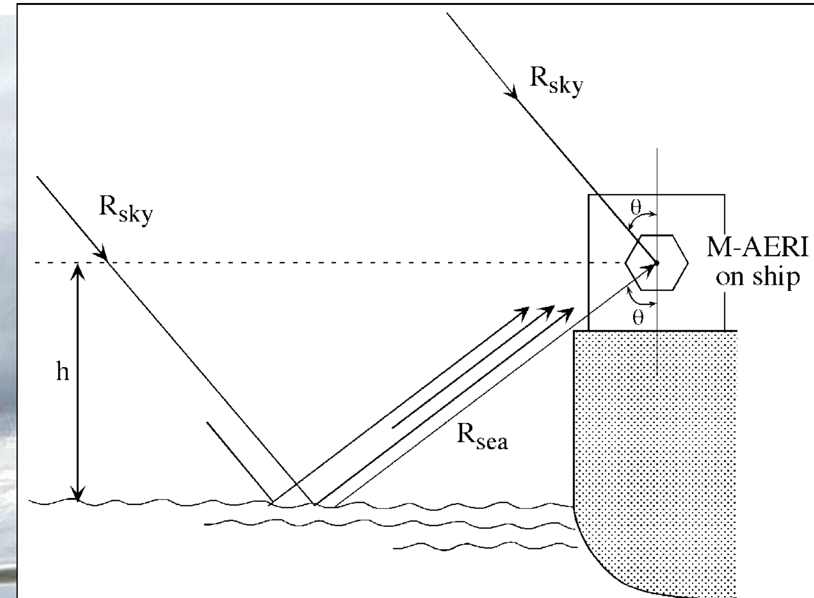
Spectral interval	~3 to ~18μm
Spectral resolution	0.5 cm^{-1}
Interferogram rate	1Hz
Aperture	2.5 cm
Detectors	InSb, HgCdTe
Detector temperature	78^oK
Calibration	Two black-body cavities
SST retrieval uncertainty	<< 0.1K (absolute)

Laboratory tests of M-AERI accuracy

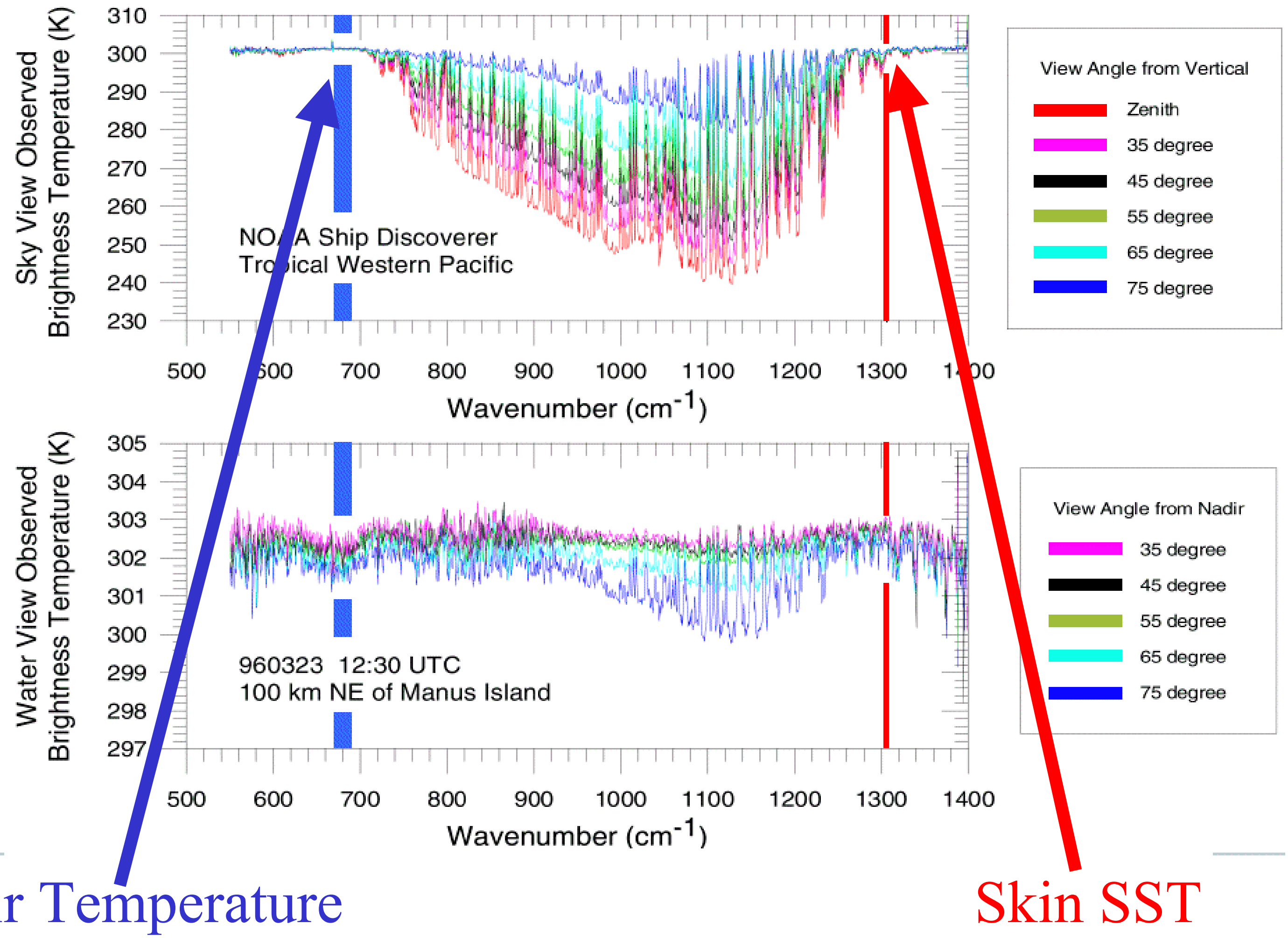
Target Temp.	LW (980-985 cm^{-1})	SW (2510-2515 cm^{-1})
20^oC	+0.013 K	+0.010 K
30^oC	-0.024 K	-0.030 K
60^oC	-0.122 K	-0.086 K

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.

M-AERI at sea



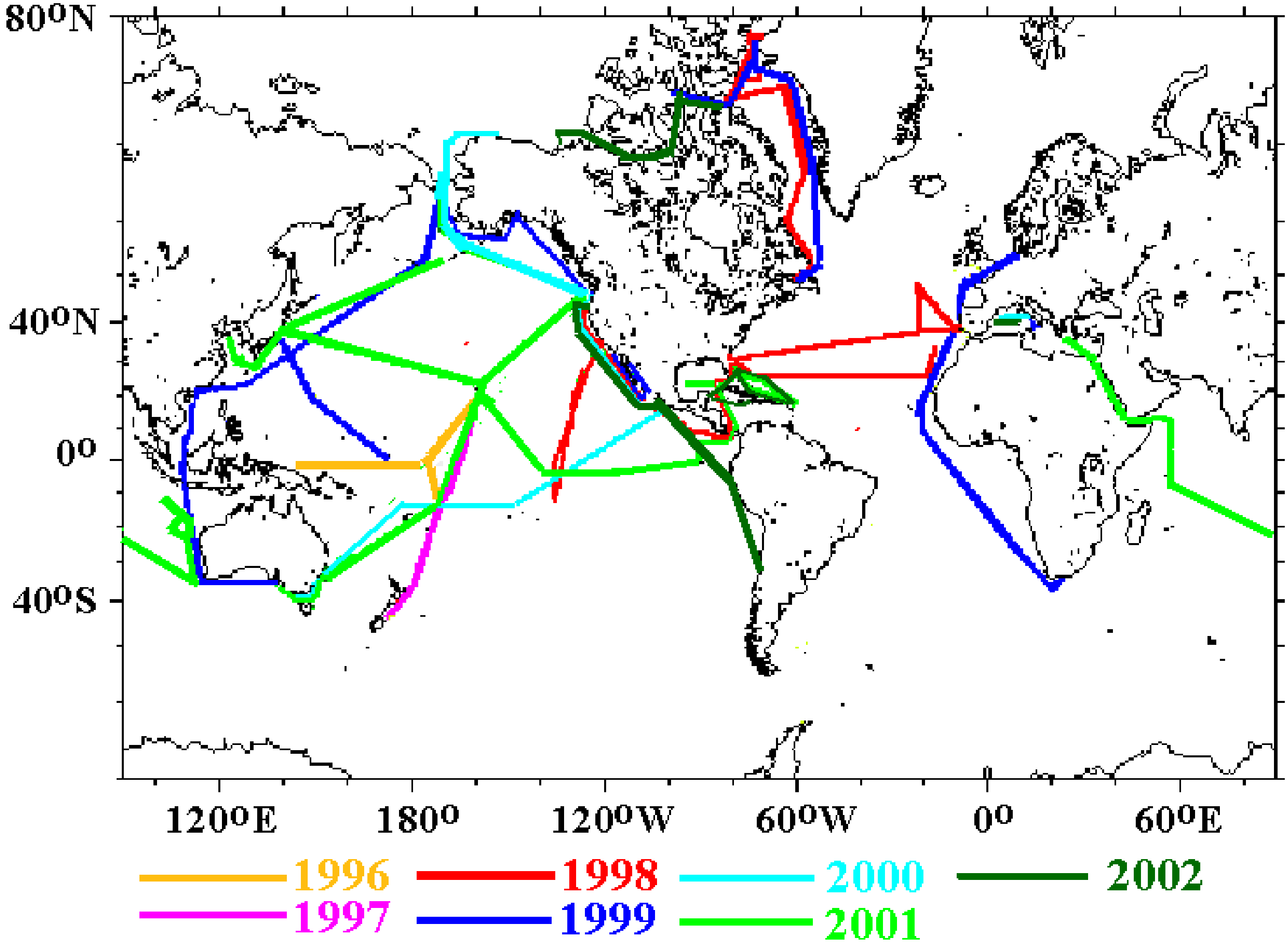
M-AERI spectra



Both temperatures measured by one instrument, one calibration.

From Minnett, P. J., R. O. Knuteson, F. A. Best, B. J. Osborne, J. A. Hanafin and O. B. Brown (2001). "The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI), a high-accuracy, sea-going infrared spectroradiometer." Journal of Atmospheric and Oceanic Technology. 18(6): 994-1013.

M-AERI cruises



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

The *Explorer of the Seas* is a Royal Caribbean Cruise Liner, operating a bi-weekly schedule out of Miami. It is outfitted as an oceanographic and atmospheric research vessel, very suitable for satellite validation. For more details see http://www.rsmas.miami.edu/rccl/

INSTRUMENT LOCATION AND FUNCTIONS ABOARD EXPLORER OF THE SEAS

Multi-Filter Rotating Shadowband Radiometer

This instrument takes spectral measurements of direct normal, diffuse horizontal, and total horizontal solar irradiances. The main mast also has two Weatherpak 2000 meteorologic stations- see the foremast description.

All Sky Imager

An automated imager used for assessing and documenting cloud fields and cloud field dynamics.

Optical Precipitation Sensor

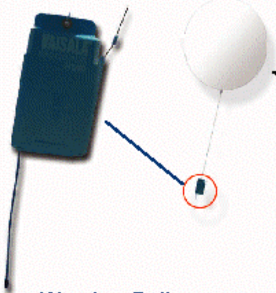
A high tech rain sensor that uses a light beam to detect precipitation particles as they fall.

Ceilometer

Remote-sensing device designed to measure cloud-base height at up to three levels and potential backscatter by aerosols.

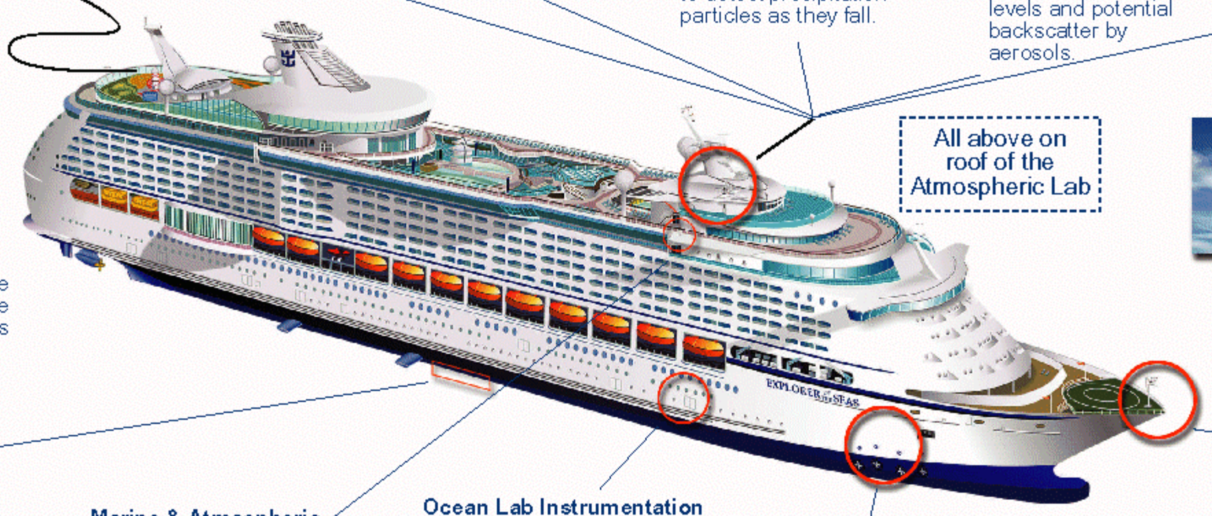
Radian Wind Profiler

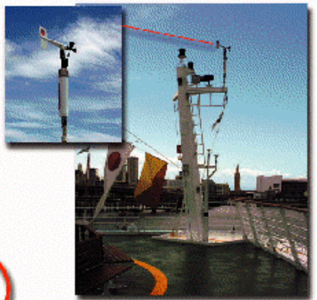
This device measures wind profiles. It operates by transmitting electromagnetic energy into the atmosphere and measuring the strength and frequency of back-scattered energy.



Weather Balloon and Radiosonde

When conditions permit, a weather balloon with attached radiosonde is released from the rear of the ship. The radiosonde transmits atmospheric conditions back to the Atmospheric Lab. The balloon can reach heights in excess of 20,000 meters.

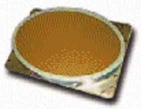




WeatherPak 2000

This surface meteorologic station uses sensors to obtain statistics of surface wind speed, wind direction, air temperature, relative humidity, and barometric pressure. (Also on main mast).

The forward mast also has 4 air sample intakes which send air to equipment under the helipad to measure parameters such as aerosol concentration, light absorption, and light scattering.



Acoustic Doppler Current Profiler

The ship is outfitted with two Acoustic Doppler Current Profilers that provide real-time, three dimensional observations of the currents under the vessel and estimates for suspended materials (including organisms) in the water column.

Marine & Atmospheric Emitted Radiance Interferometer

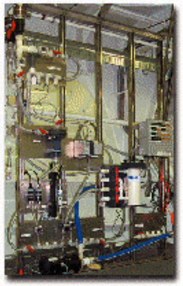
This device precisely measures the temperature of the ocean's thin surface layer or skin.

Ocean Lab Instrumentation

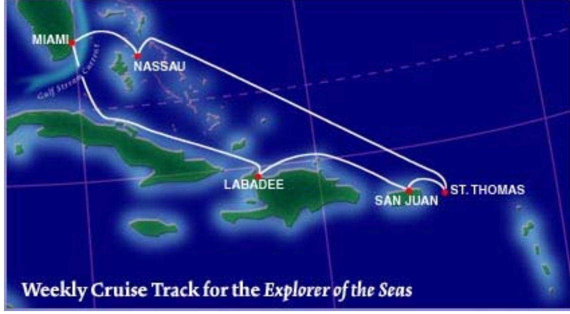
The PCO_2 System is one of the many instruments in the Ocean Lab used to precisely measure seawater characteristics - in this case carbon dioxide. Seawater is supplied to the lab by an intake in the bow of the ship.

Bow Thruster Space - Seawater Intake

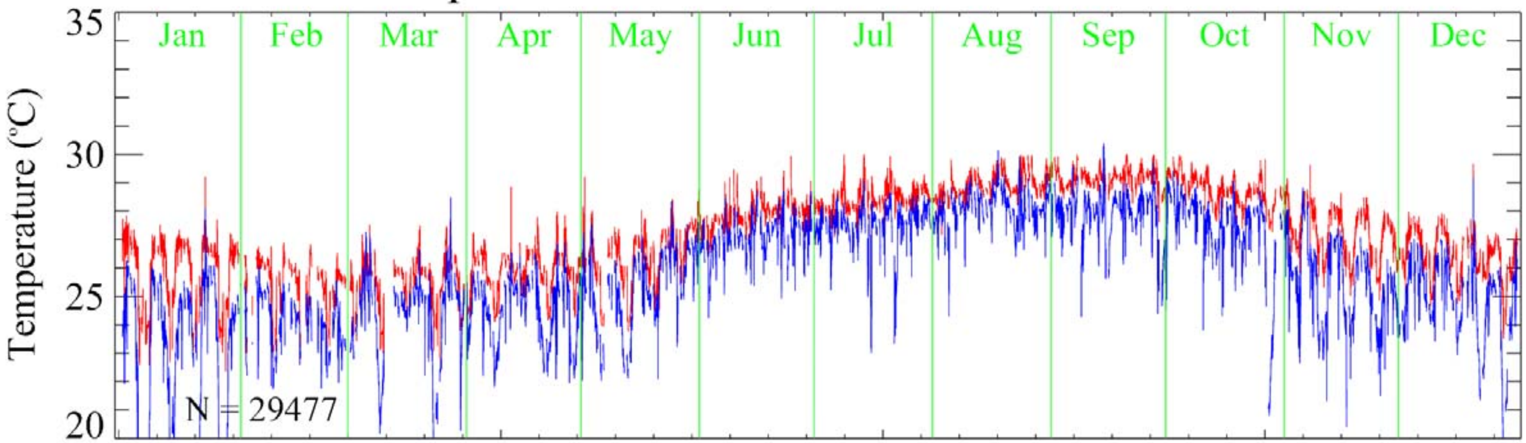
The Bow Thruster Space has a near-surface intake that supplies flowing seawater to the instruments in this space (shown) and to the Ocean Lab. These instruments measure a number of physical, chemical and bio- optical parameters, e.g., temperature, salinity, dissolved oxygen, dissolved organic matter, fluorescence, etc.



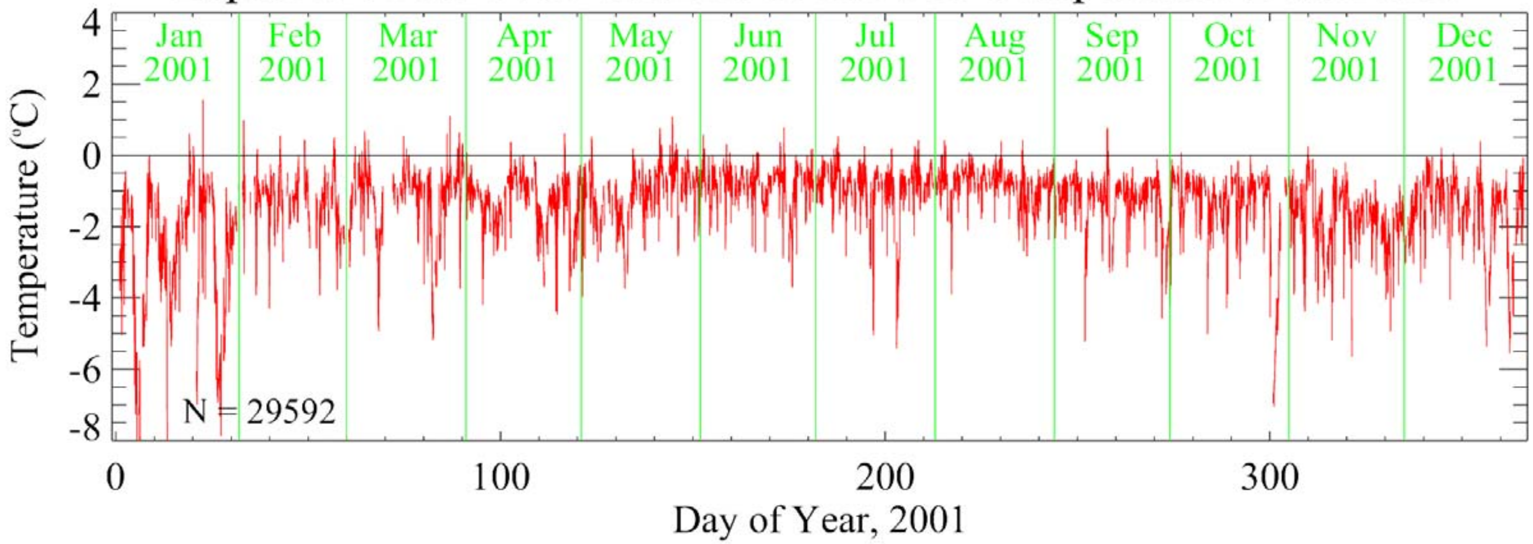
Seasonal effects in radiometric air sea temperature differences



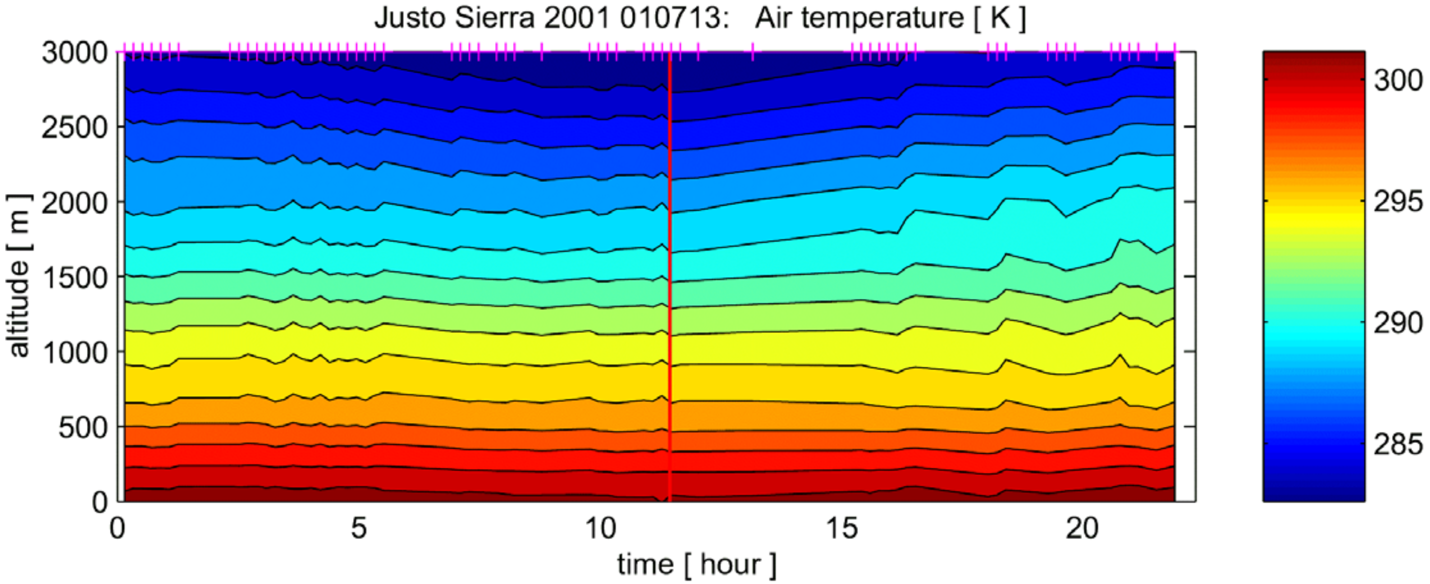
Explorer of the Seas MAERI-1. Skin SST.

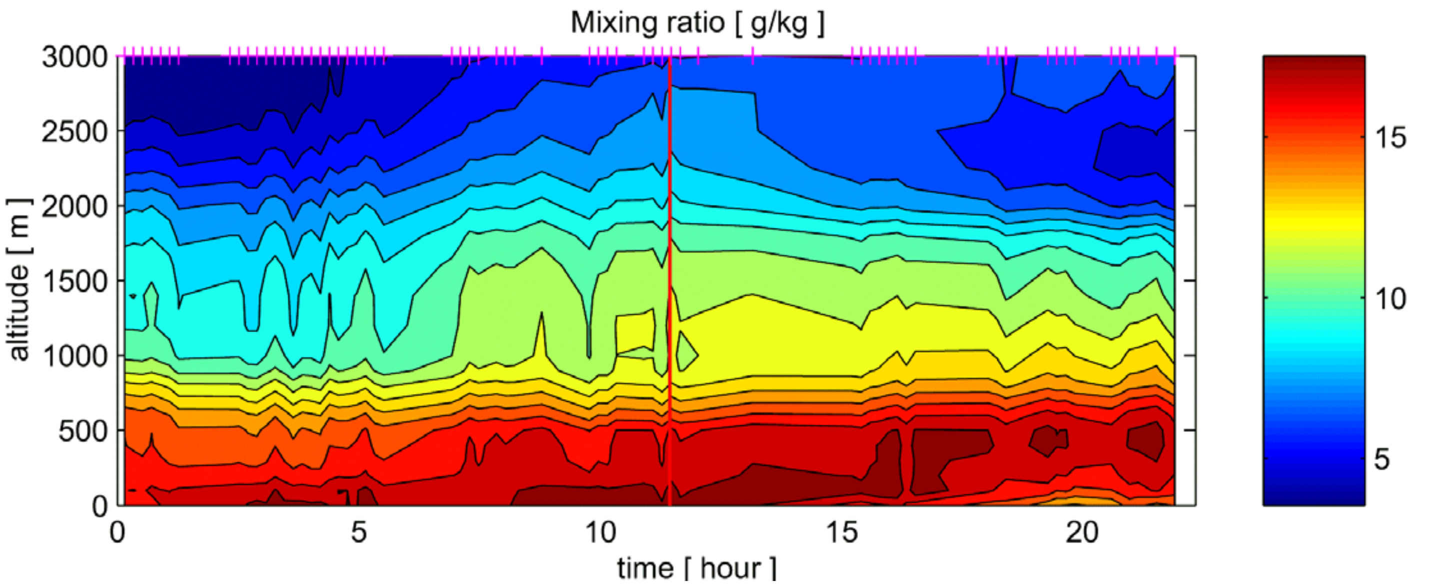


Explorer of the Seas MAERI-1. Air-Sea Temperature Difference

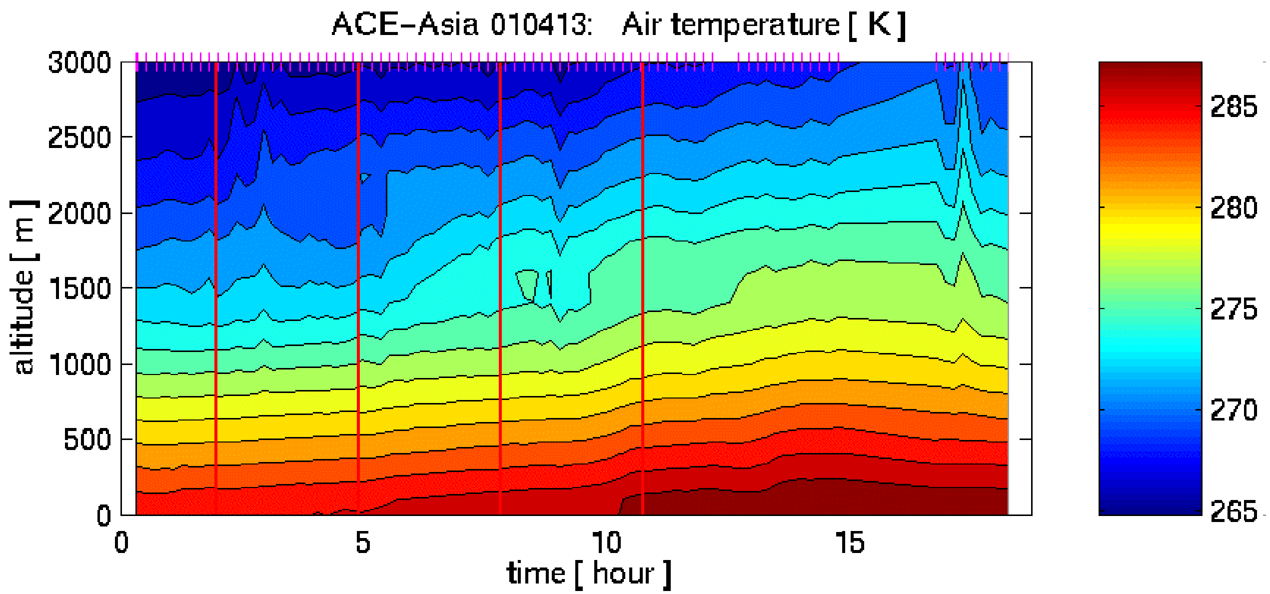


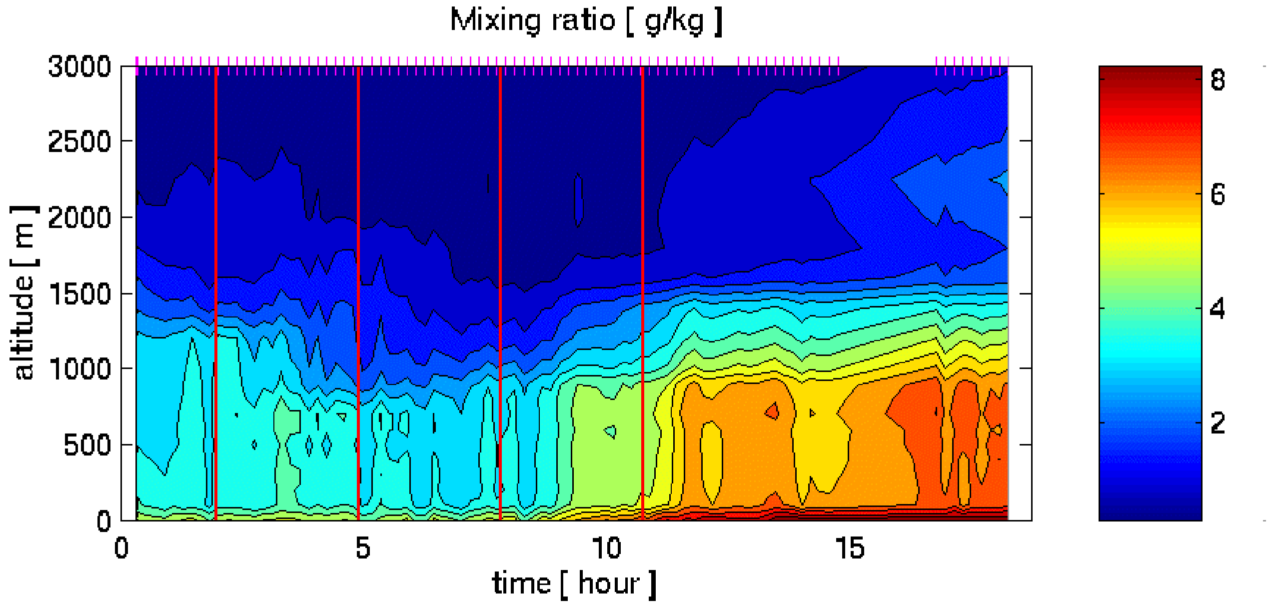
Profiles – W. Caribbean





Profiles – NW Pacific





Miami-2001Radiometer Intercalibration Workshop.

To calibrate and compare infrared radiometers used in the validation of the different surface temperature products derived from earth observation satellites. These aims included an assessment of the relative performance of each instrument as well as ensuring that surface measurements used in satellite product validation are traceable to SI standard units.

Participants

Dr. Ali Abtahi	NASA Jet Propulsion Laboratory, Pasadena, CA, USA
Dr. Ian Barton	CSIRO Marine Research, Hobart, Australia
Dr. Jim Butler	NASA GSFC, Greenbelt, MD, USA
Dr. Craig Donlon	EEC Joint Research Centre, Ispra, Italy
Dr. Marianne Edwards	Leicester University, UK
Ms. Ruth Fogelberg	Applied Physics Laboratory, U. Washington, Seattle, WA,USA
Ms. Jenny Hanafin	RSMAS-MPO, University of Miami, FL, USA
Dr. Simon Hook	NASA Jet Propulsion Laboratory, Pasadena, Ca., USA
Dr. Andy Jessup	Applied Physics Laboratory, U. Washington, Seattle, WA, USA
Dr. Carol Johnson	NIST, Gaithersburg, MD, USA
Ms. Erica Key	RSMAS-MPO, University of Miami, FL, USA
Ms. Trina Lichtendorf	Applied Physics Laboratory, U. Washington, Seattle, WA, USA
Mr. Kevin Maillet	RSMAS-MPO, University of Miami, FL, USA
Dr. Peter Minnett	RSMAS-MPO, University of Miami, FL, USA
Dr. Tim Nightingale	Rutherford Appleton Laboratory, Chilton, UK.
Dr. Mike Reynolds	Brookhaven National Laboratory, USA
Dr. Joe Rice	NIST, Gaithersburg, MD,USA
Dr. Goshka Szczodrak	RSMAS-MPO, University of Miami, FL, USA
Dr. Brian Ward	NOAA, AOML, Miami, FL, USA
Dr. Gary Wick	NOAA, ETL, Boulder, CO., USA

Instruments

Infrared radiometers that participated in the campaign

Instrument	Institution	Lab.	Sea	P.I.
EOS TXR (Transfer radiometer)	NIST, USA	Yes	No	J. Rice
M-AERI	RSMAS, U. Miami.	No	Yes	P. Minnett
SISTeR	RAL,UK.	Yes	Yes	T. Nightingale
DAR011	CSIRO, Australia.	Yes	Yes	I. Barton
CIRIMS	APL, U. Washington.	No	Yes	A. Jessup
ISAR-5	JRC, EEC.	Yes	Yes	C. Donlon
Nulling radiometers	NASA JPL	Yes	Yes	S. Hook
Tasco (off-the-shelf)	CSIRO, Australia	Yes	Yes	I. Barton

Black bodies used for laboratory calibration.

Instrument	Institution	P.I.
NIST-Certified & Designed Black Body Target	RSMAS, U. Miami	P. Minnett
NIST Standard Black Body Target	NIST, USA	C. Johnston
CASOTS black body	JRC, EEC	C. Donlon
Hart Scientific Portable Black Body Target	APL, U. Washington	A. Jessup
JPL Black Body Calibrator	NASA-JPL	S. Hook

Radiometers

Radiometer	Full name
M-AERI	Marine-Atmospheric Emitted Radiance Interferometer
CIRIMS	Calibrated InfraRed In situ Measurement System
SISTeR	Scanning Infrared Sea Surface Temperature Radiometer
ISAR-5	Infrared SST Autonomous Radiometer -5
DAR011	CSIRO Division of Atmospheric Research 011
JPL	Jet Propulsion Laboratory Near-Nulling Radiometer
Tasco	"Lunchbox"

Radiometer Characteristics

Radiometer	Pass-band µm	Detectors	Black-bodies	Sky correction	Notes
M-AERI	3-18	HgCdTe – In Sb Cooled to 78K	Two large cavities – SSEC design	Scan mirror	SST derived at 7.7µm
CIRIMS	9.6 - 11.5	Heitronics KT-11.85*	Hart Scientific mini-water bath black body	Dedicated radiometer	Mismatch of pass-bands of two radiometers during the workshop
SISTeR	10.8	Pyroelectric	Two small cavities.	Scan mirror	
ISAR	9.6-11.5	Heitronics KT-11.85D *#	Two small cavities	Scan mirror	
DAR011	10.5-11.5	Pyroelectric	Two small cavities	Scan mirror	Sky view in opposite quadrant
JPL	7.8 -13.6	Thermopile	One cavity, actively controlled	Modelled	Uses ‘nulling’ of signal to internal black body
Tasco	??	??	External	None	Hand-held

*The Heitronics uses a chopped pyroelectric detector.

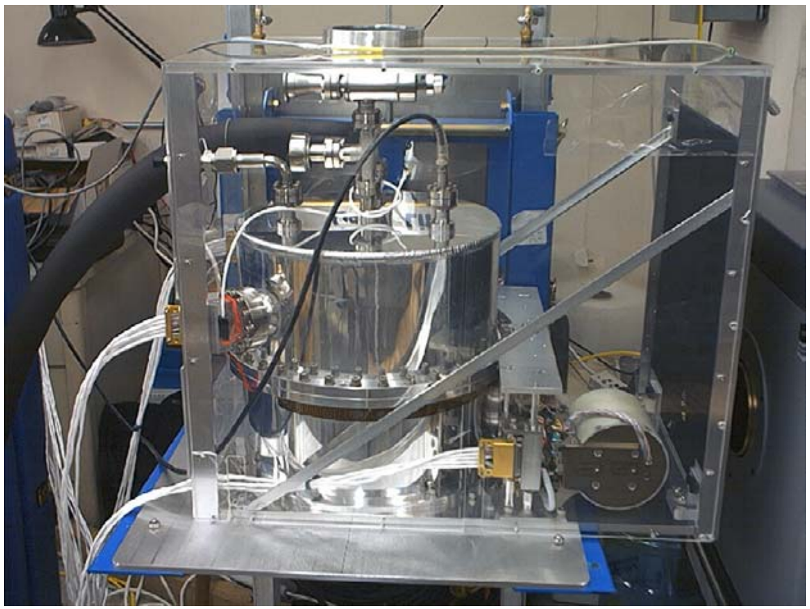
#The ISAR Heitronics is modified to allow the measurement of temperatures down to –100 ^{o}C.

Objectives of laboratory measurements

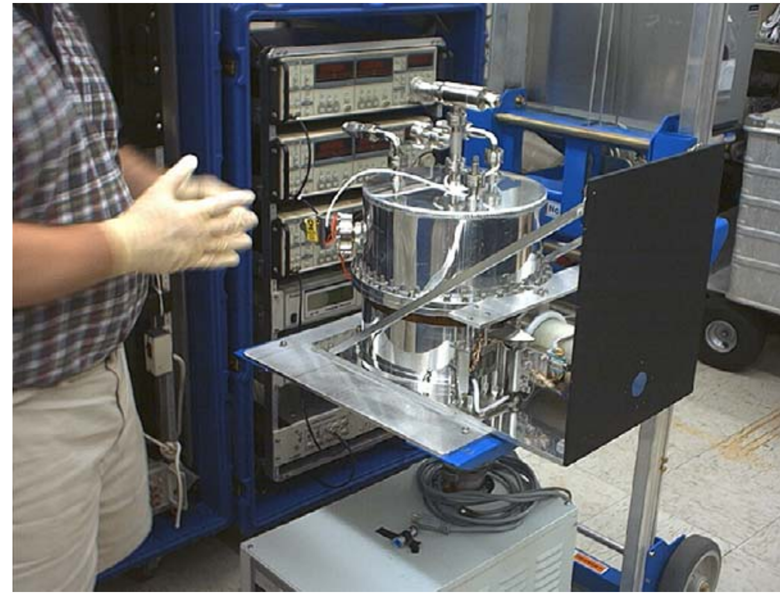
To characterize all black-body calibration targets by NIST EOS TXR, leading to an estimate of emissivity of black body cavities as a function of temperature, wavelength (5 and 10μm) and aperture.

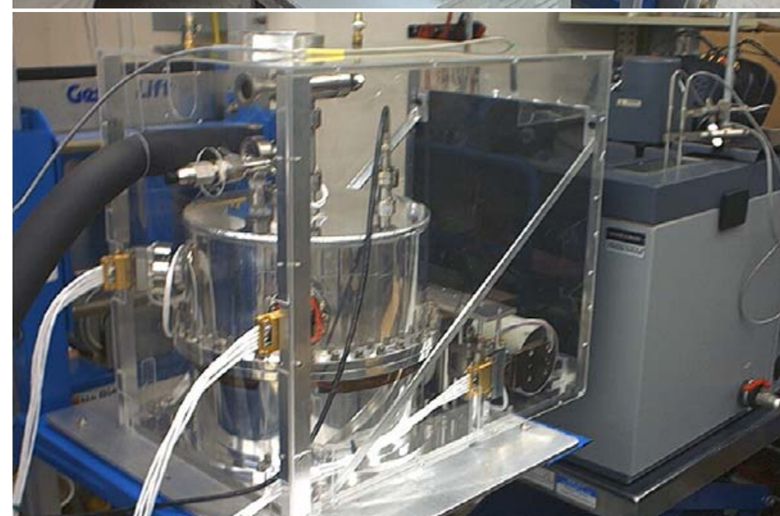
The NIST EOS TXR

EOS Standard
Cryogenic detectors (liquid N_2)
λ= 5 & 10μm



See:Rice, J. P. and B. C. Johnson, 1998. The NIST EOS Thermal-Infrared Transfer Radiometer, *Metrologia*, 35, 505-509

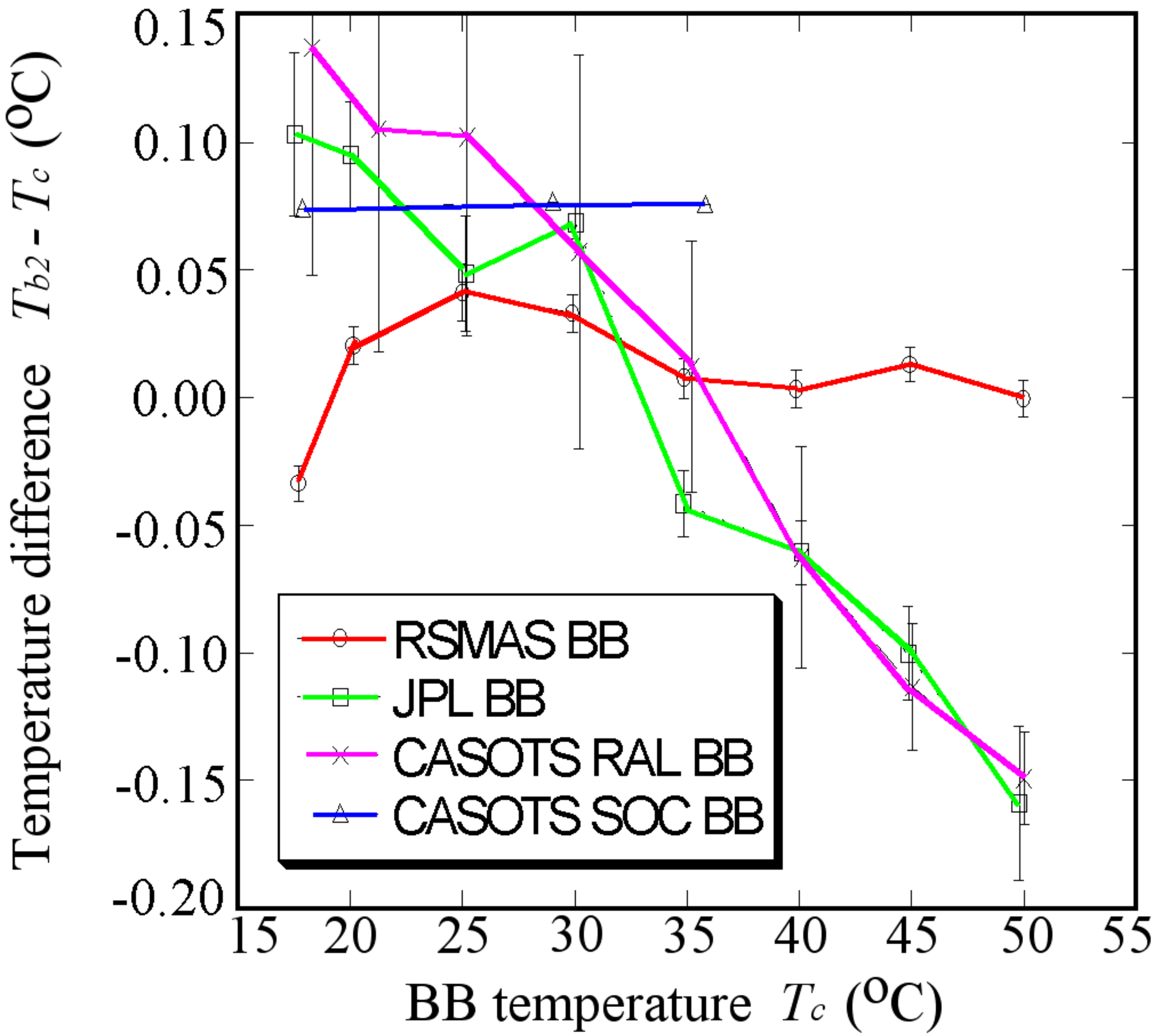




Black-body calibrators

Quantity	RSMAS BB	JPL BB	CASOTS RAL BB
Spacing (mm)	64	128	114
$1-\varepsilon_{BBX}$	1×10^{-5}	8.379×10^{-3}	9.457×10^{-3}
$1-\varepsilon_{BBX}$ fitting uncertainty	7×10^{-4}	8.43×10^{-4}	6.44×10^{-4}
ε_{BBX}	**1.0000**	**0.9916**	**0.9905**
ε_{BBX} fitting uncertainty	**0.0007**	**0.0008**	**0.0006**
Intercept (W cm^{-2} sr^{-1})	-1.9×10^{-7}	-8.96×10^{-6}	-1.047×10^{-5}
Intercept fitting uncertainty (W cm^{-2} sr^{-1})	8×10^{-7}	9.4×10^{-7}	7.2×10^{-7}
T_s (°C)	N/A	31.57	33.82
T_s fitting uncertainty (°C)	N/A	0.28	0.05

Black – body calibration errors



Radiometer calibration errors

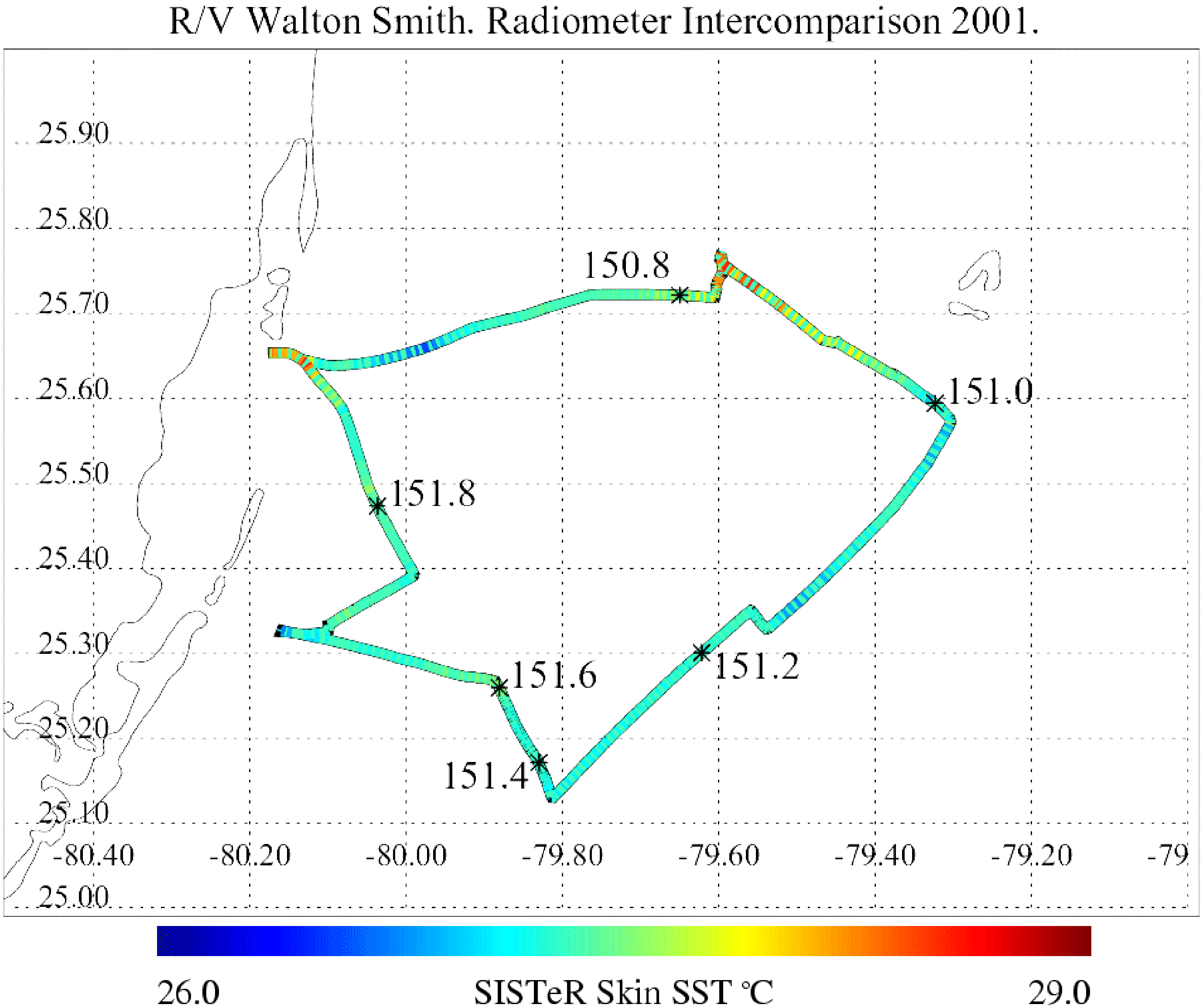
Temperature (°C)	ISAR - WBBB (°C)	DAR011-WBBB (°C)	DAR011-RSMAS BB (°C)	TASCO - RSMAS BB (°C)	JPL005 - RSMAS BB (°C)	JPL007 - RSMAS BB (°C)	JPL009 - RSMAS BB (°C)
15			0.032	0.12			
17		-0.017					
20	0.097			0.00			
25	-0.105		-0.005	-0.12	-0.041	-0.017	
30	-0.120						
35	-0.020	0.001		-0.34	-0.051		0.008
40	0.008						
50	0.007	0.009					

And so to sea…….

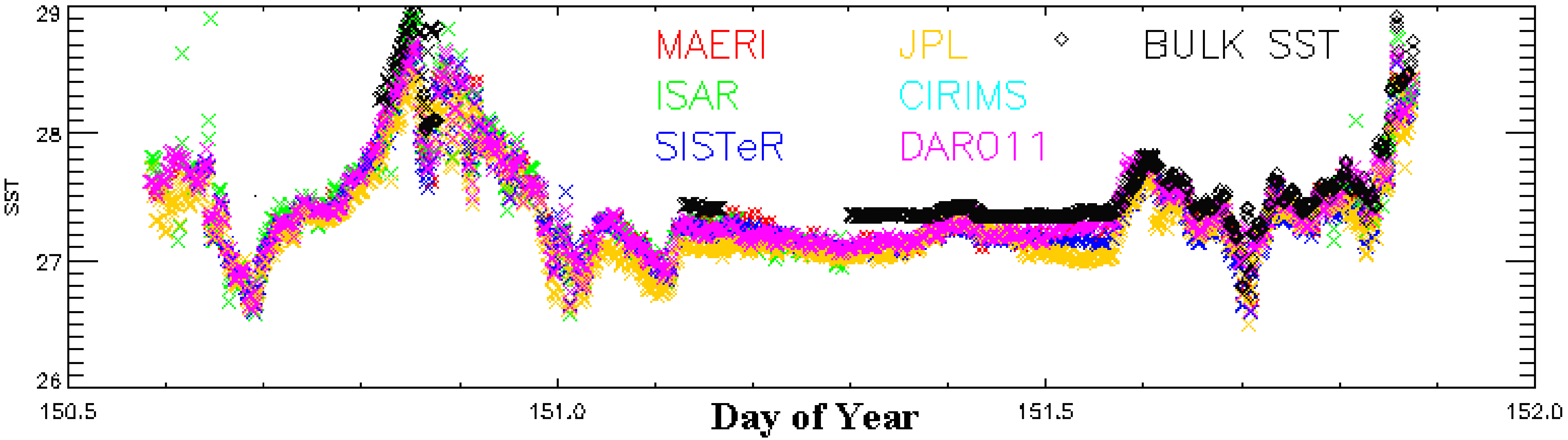
On the R/V *F.G. Walton-Smith*

The SST radiometers

Cruise track



Time series of measurements



Results of at-sea comparisons

Means and standard deviations of the estimated skin SST differences between pairs of radiometers for the entire cruise period, and for each half of the cruise.

Time	150.50 to 152.00			150.50 to 151.25			151.25 to 152.00		
Radiometer Pair	Mean (K)	Std.Dev (K)	N	Mean (K)	Std.Dev (K)	N	Mean (K)	Std.Dev (K)	N
MAE-ISA	0.002	0.135	80	0.005	0.135	69	–0.015	0.135	11
MAE-SIS	0.046	0.066	144	0.046	0.066	74	0.045	0.068	70
MAE-JPL	0.007	0.114	148	0.052	0.111	77	-0.042	0.096	71
MAE-DAR	-0.008	0.076	149	0.022	0.071	78	-0.041	0.067	71
ISA-SIS	0.038	0.101	79	0.030	0.101	67	0.085	0.093	12
ISA-JPL	0.026	0.142	81	0.027	0.141	70	0.018	0.150	11
ISA-DAR	0.007	0.114	80	0.019	0.112	69	-0.064	0.107	11
SIS-JPL	-0.048	0.099	144	-0.009	0.103	74	-0.088	0.078	70
SIS-DAR	-0.053	0.074	144	-0.019	0.054	74	-0.088	0.076	70
JPL-DAR	-0.014	0.103	148	-0.028	0.102	77	0.000	0.102	71

Miami-2001Radiometer Intercalibration Workshop.

- Following the radiometer calibration, intercomparison, and testing under field conditions, the international community has increased confidence in the results to be provided for validation of satellite-derived SSTs from the participating instruments.
- Radiometers work to ~0.1K uncertainty levels in the field
- Black body calibrators have been characterized with reference to NIST standard

R/V Mirai

Ship-board sensors

The M-AERI was installed on a foremast platform giving it a clear view of the sea-surface and atmosphere ahead of the influence of the ship.

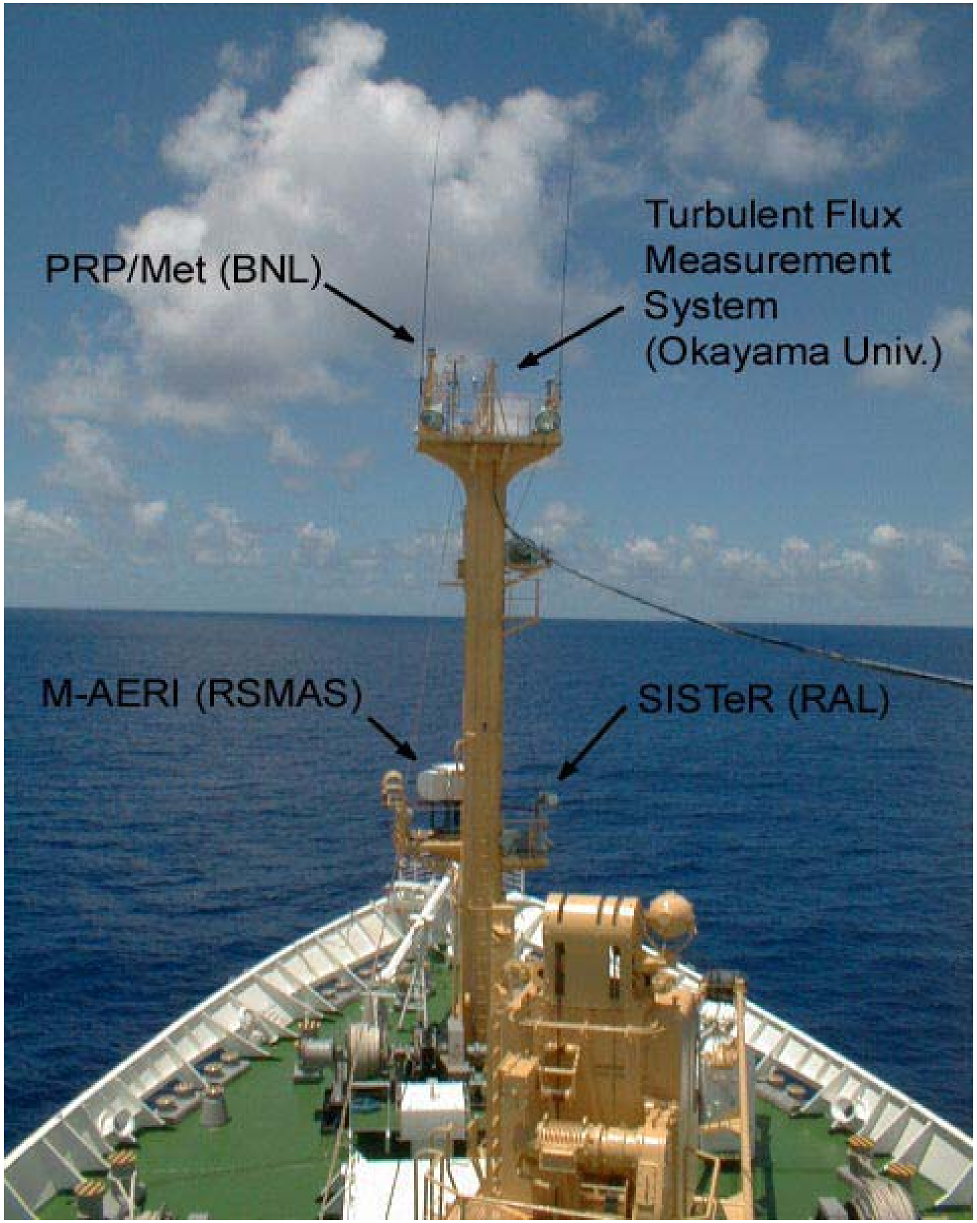
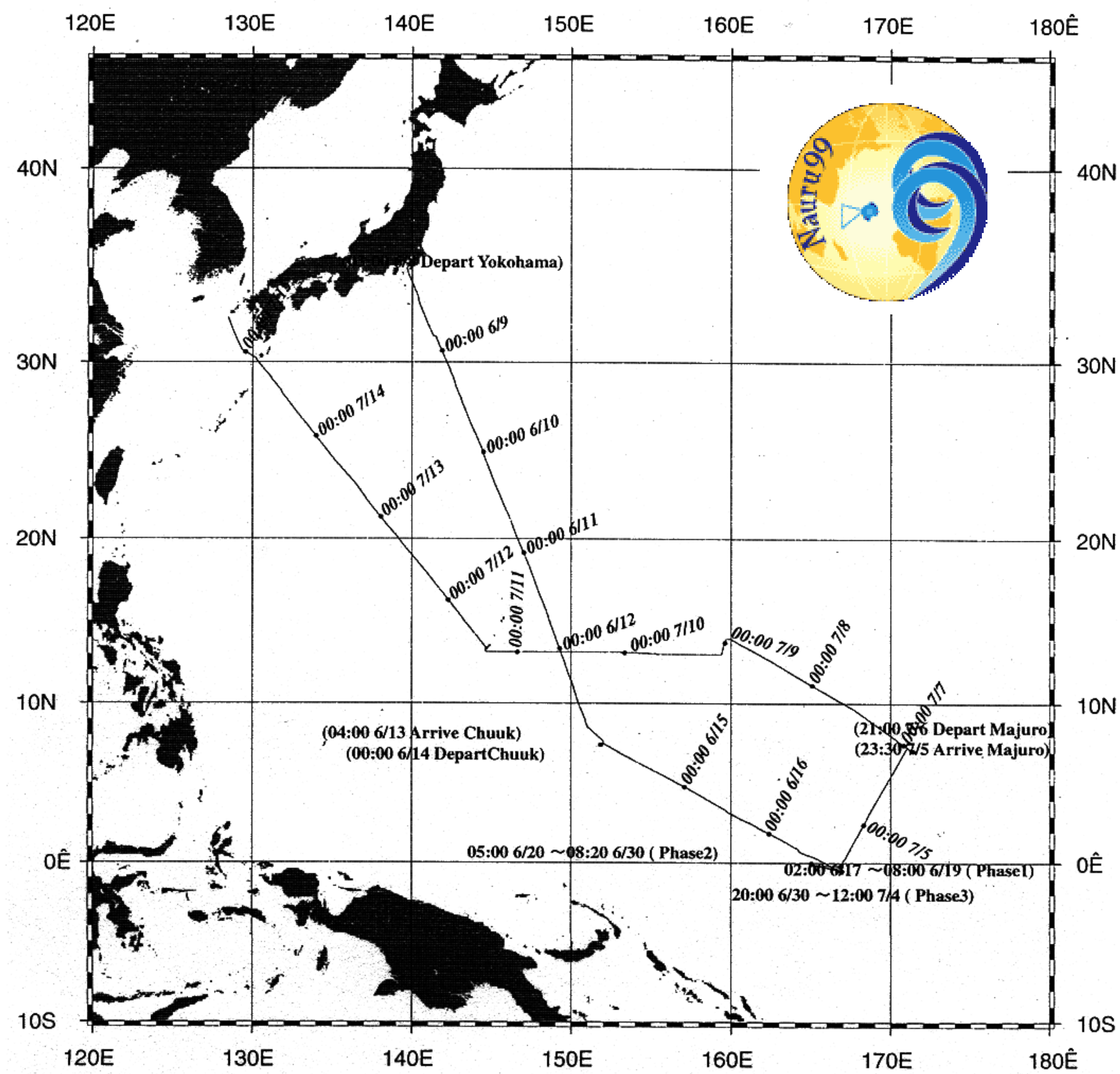


Figure courtesy of Dr. R.M. Reynolds, BNL

Ship track

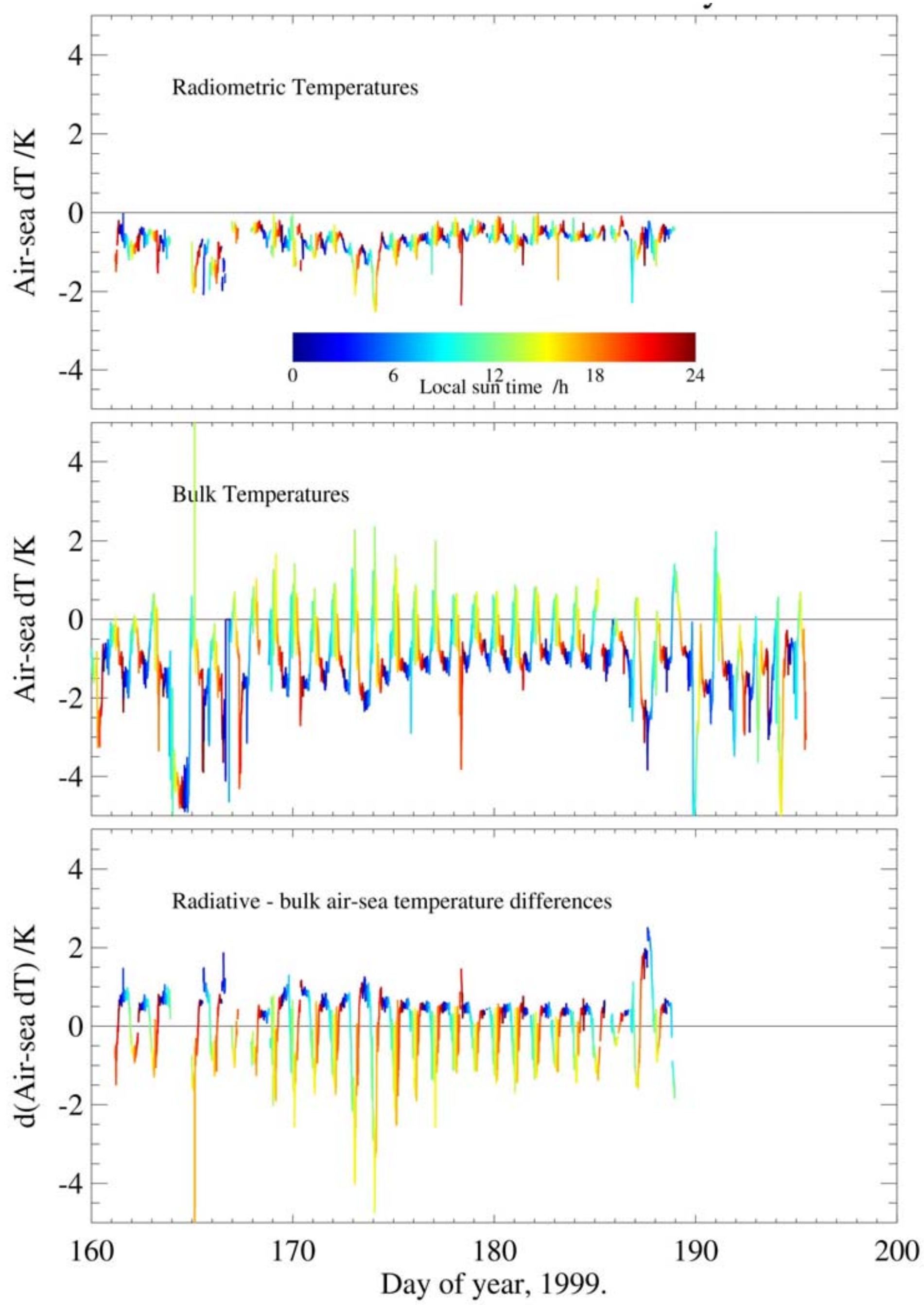
The cruise began and ended in Japan. The data shown here were taken on passage from Japan, Japan, and close to the Equator; 6 June to 7 July, 1999.



Nauru99 air-sea temperature differences

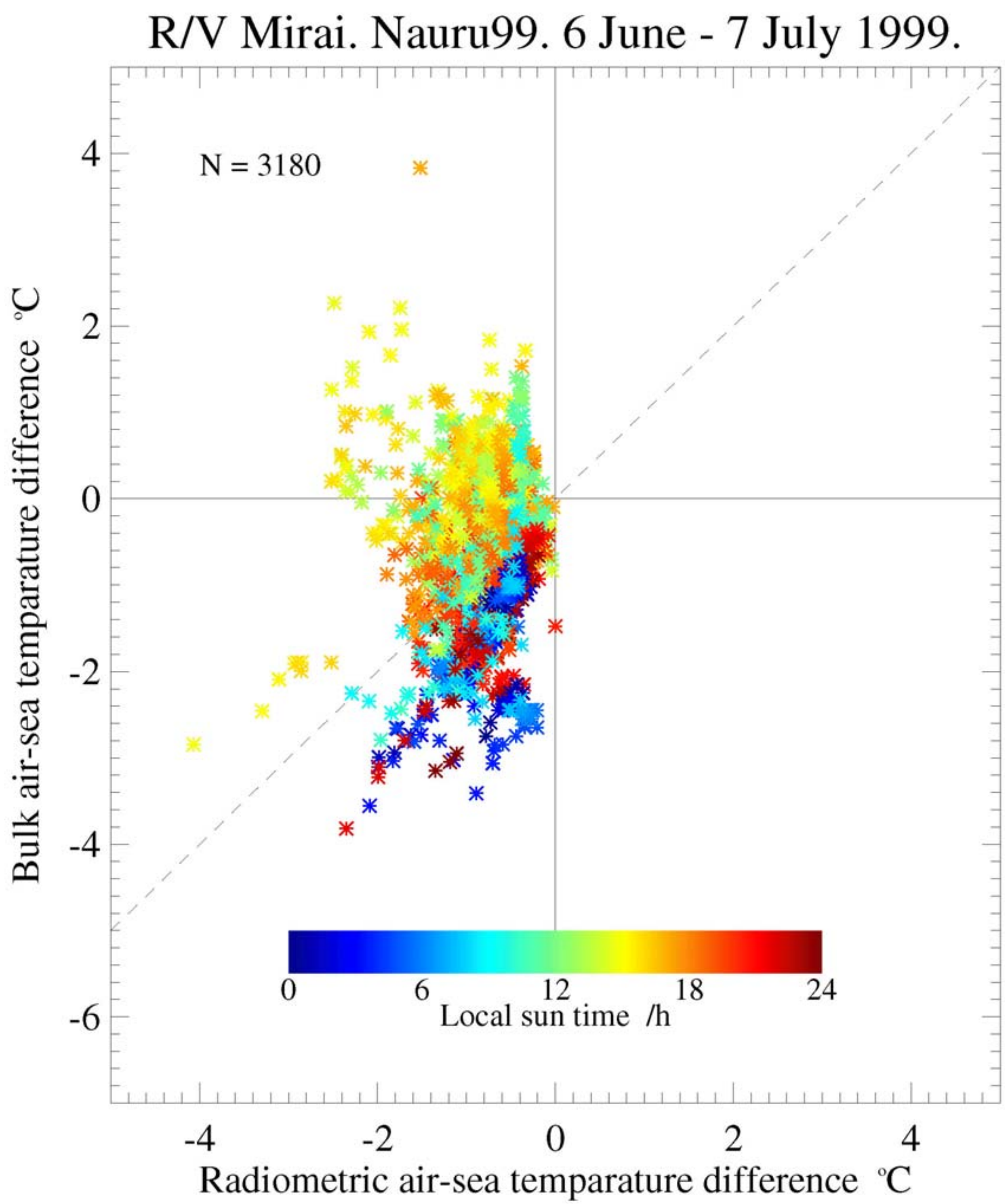
Air-sea temperature differences are generally <2K. There are some diurnal fluctuations, especially in clear sky conditions.

Radiometric measurements show marked differences to those from conventional sensors.



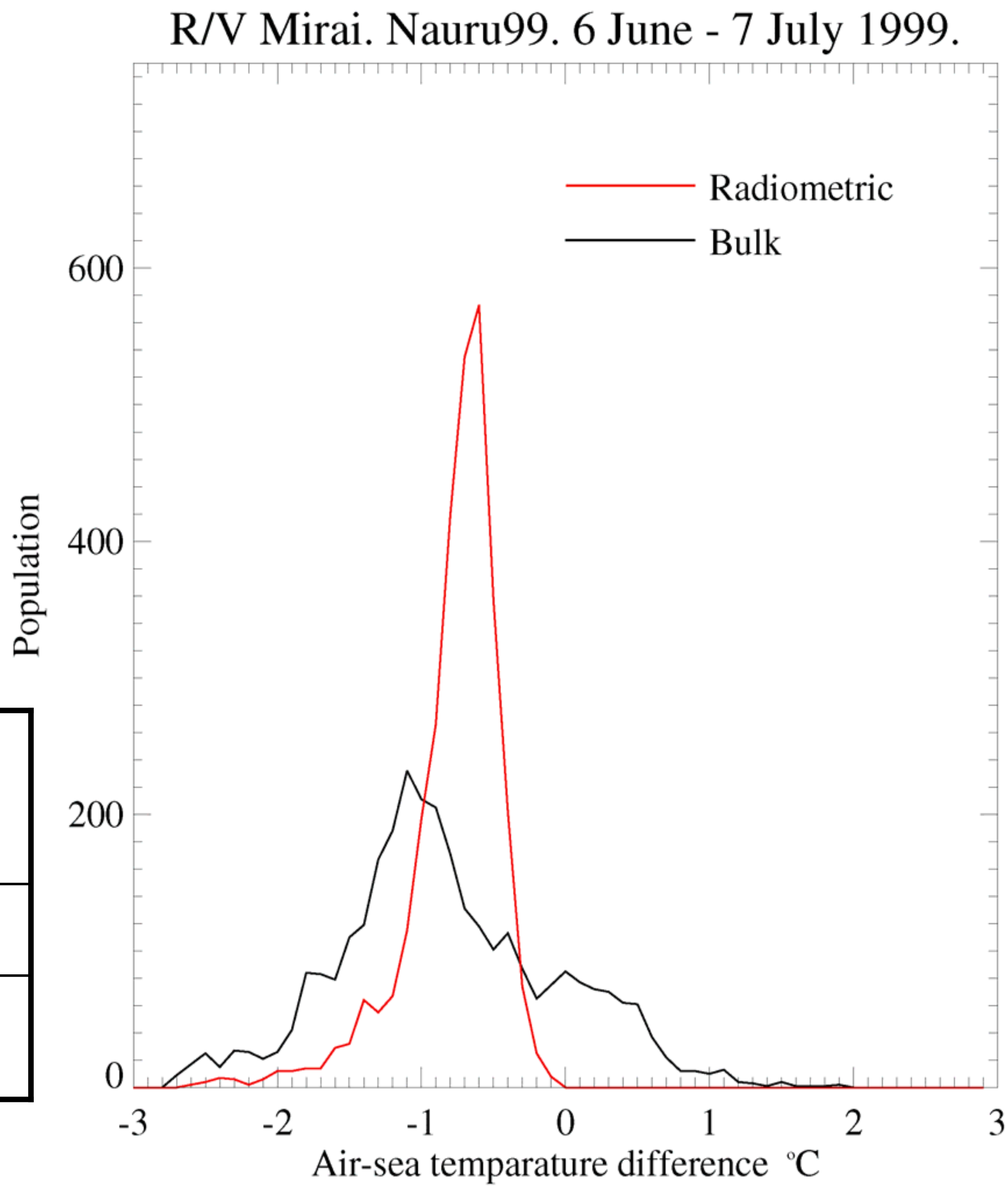
Bulk *vs.* radiometric air-sea temperature differences

Perfect correspondence is indicated by the dashed line. Diurnal effects are apparent.

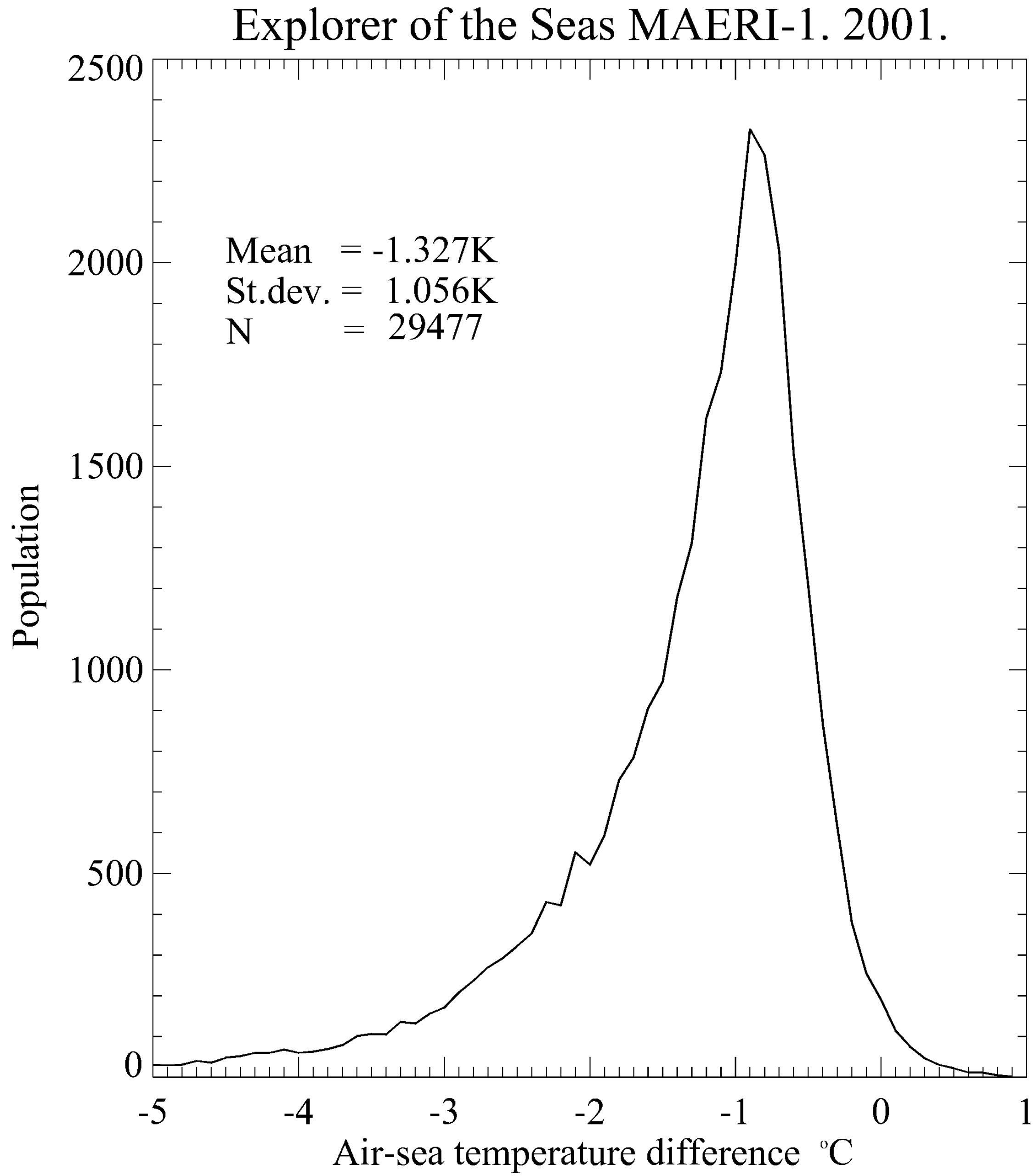


Bulk *vs.* radiometric air-sea temperature differences – statistics

	Mean K	St.dev. K
Bulk	-0.772	0.566
Radio-metric	-0.721	0.113



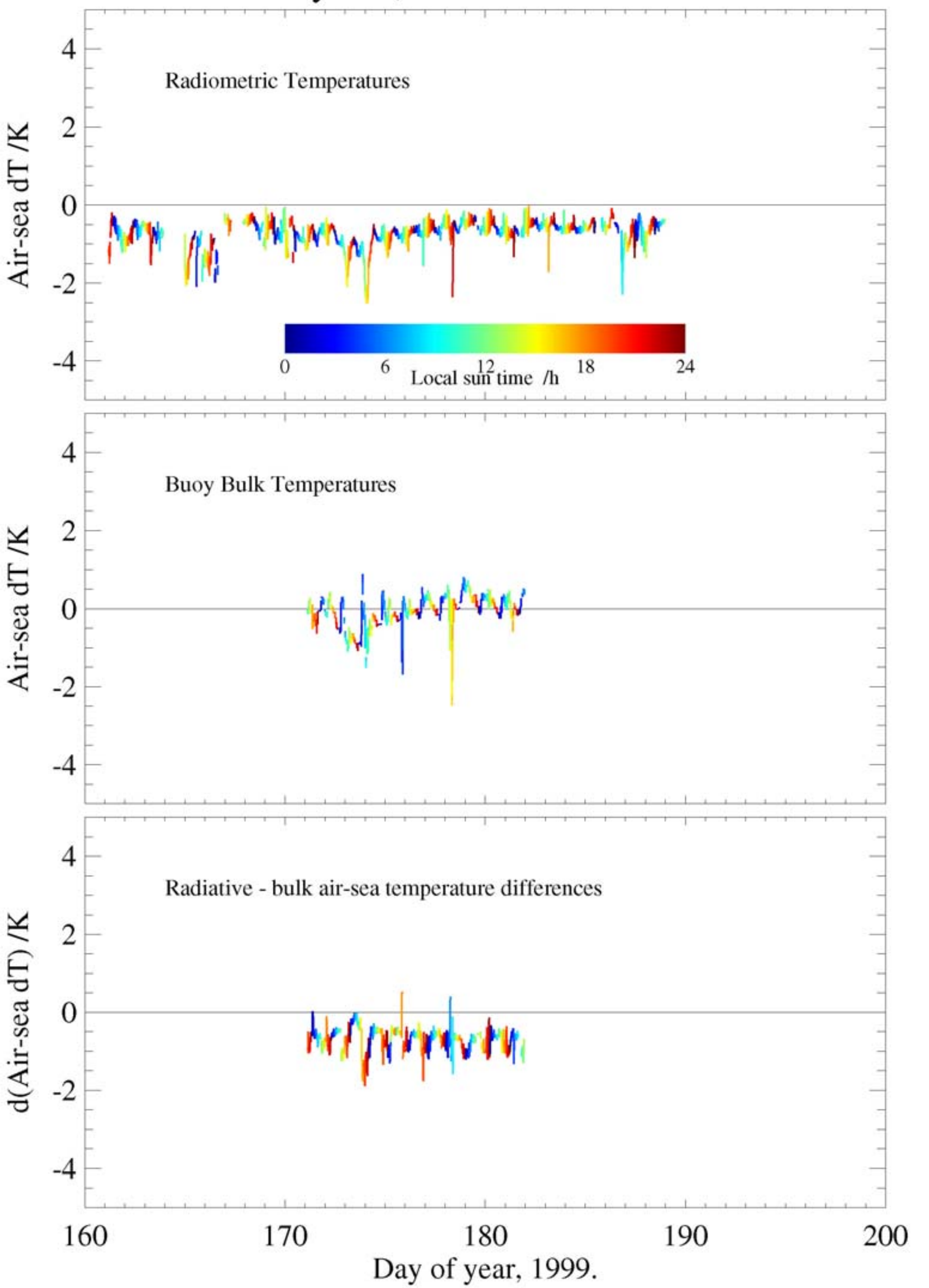
Explorer of the Seas – radiometric air-sea temperature differences



What about buoy data?

For eleven days the *Mirai* loitered close to the TAO mooring at 0°N, 165°E.

Similar diurnal features found, with change of sign of air-sea temperature difference.

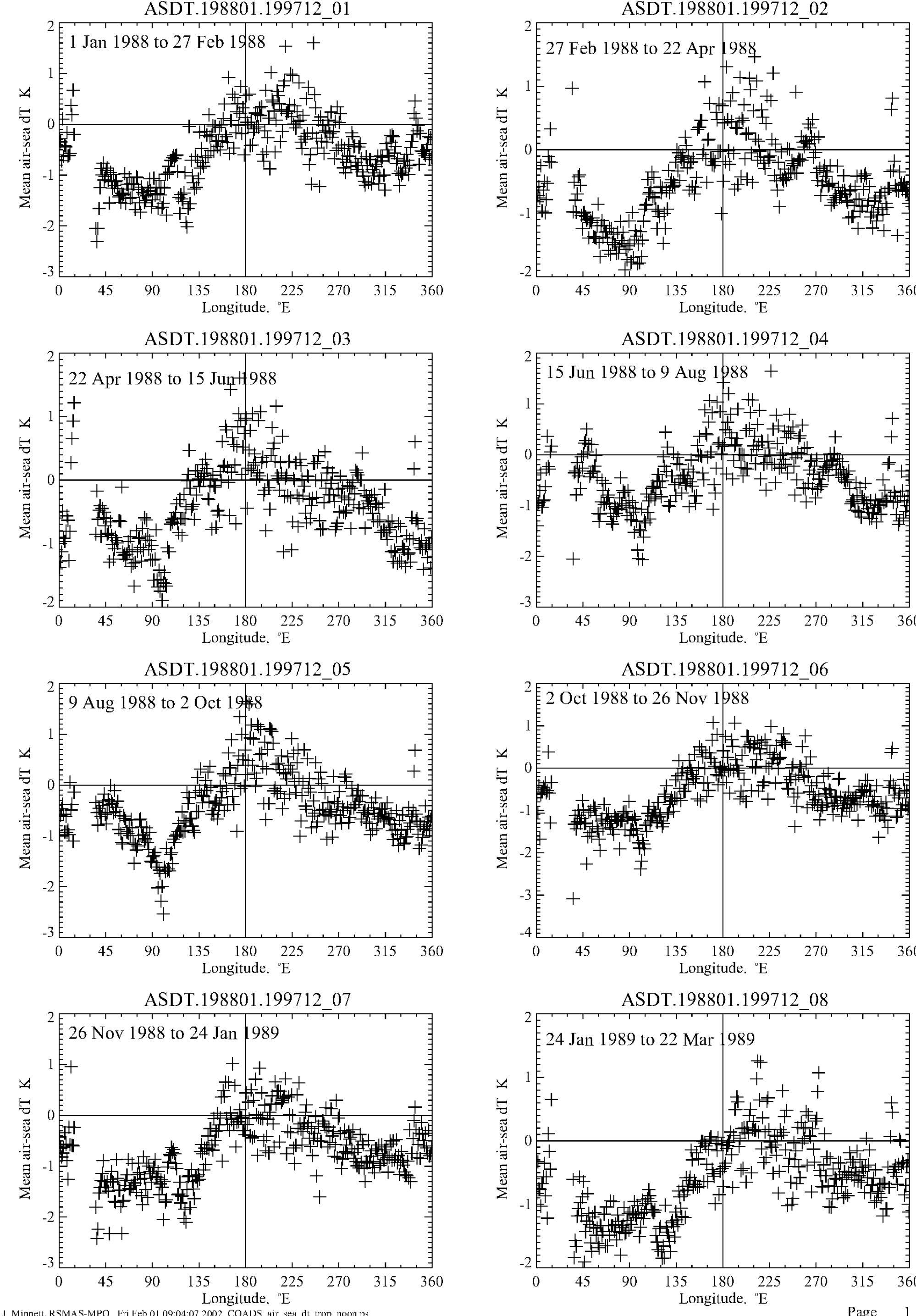


What about archived data?

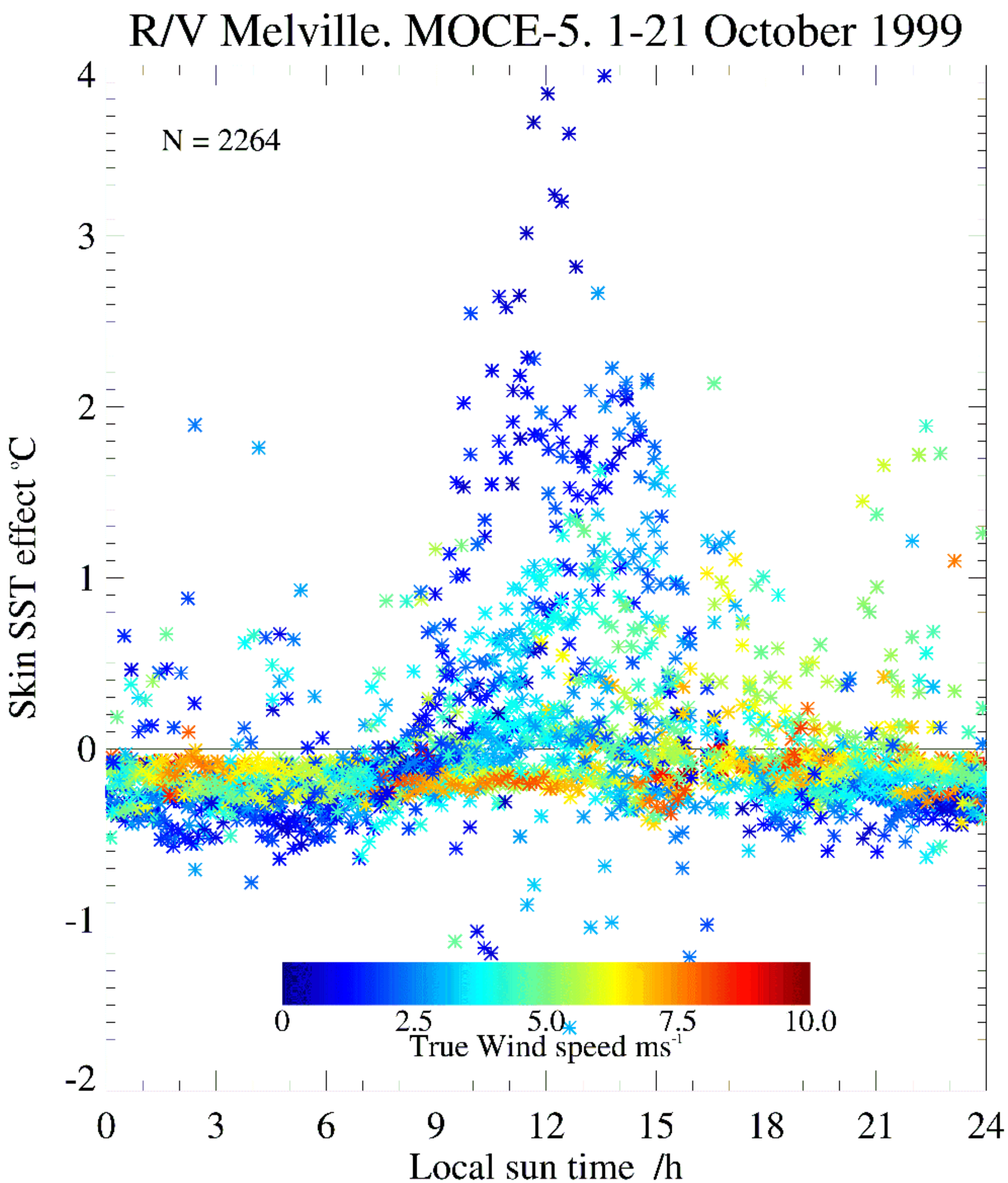
10 years of COADS data where air and sea temperatures reported and pass qa. Includes ships and buoys.

Data within 25° of Equator, taken within 30 minutes of 00Z (noon at 180°) show strong diurnal signal that is mapped into a longitudinal feature.

At synoptic hours, there are longitudinal changes in sign of air-sea temperature difference.



Example of wind speed dependence of diurnal & skin effects – off Baja California



SST Radiometers for the VOS

POSITIV :

Prototype Operational System – ISAR – Temperature Instrumentation for the VOS fleet.

A NOPP Partnership for Skin Sea Surface Temperature.

NOPP Partners

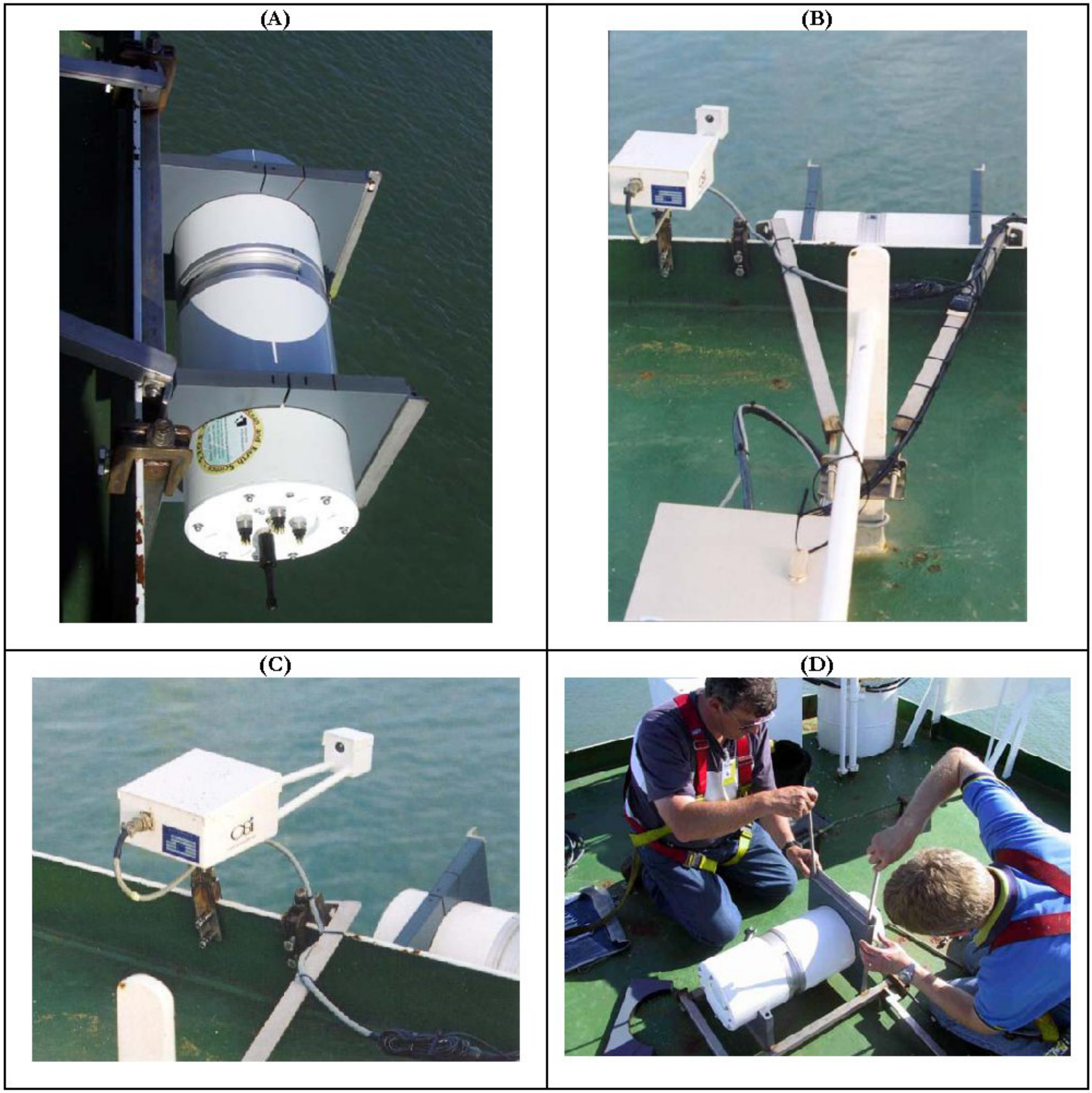
- P.J. Minnett, RSMAS, University of Miami
- D. Stammer, SIO – University of California San Diego
- F. Wentz, C. Gentemann, Remote Sensing Systems Inc.
- M. Reynolds, RMR Co.
- A. T. Jessup, APL, University of Washington
- S. Castro, University of Colorado
- G. A. Wick, NOAA-ETL
- J. Cummings, S. Wang, NRL Monterey
- O. Brown, Royal Caribbean International
- R. Zika, E. Kearns, T. Houston, International SeaKeepers Society
- A. Harris, NOAA-NESDIS
- D. May, NAVOCEANO
- P. McGillivary, US Coast Guard
- C. Donlon, Joint Research Centre, Italy
- I. Robinson, Southampton Oceanography Centre, UK
- R. Saunders, Meteorological Office, UK
- T. Nightingale, Rutherford Appleton Laboratory, UK
- D. Llewellyn-Jones, University of Leicester, UK

ISAR

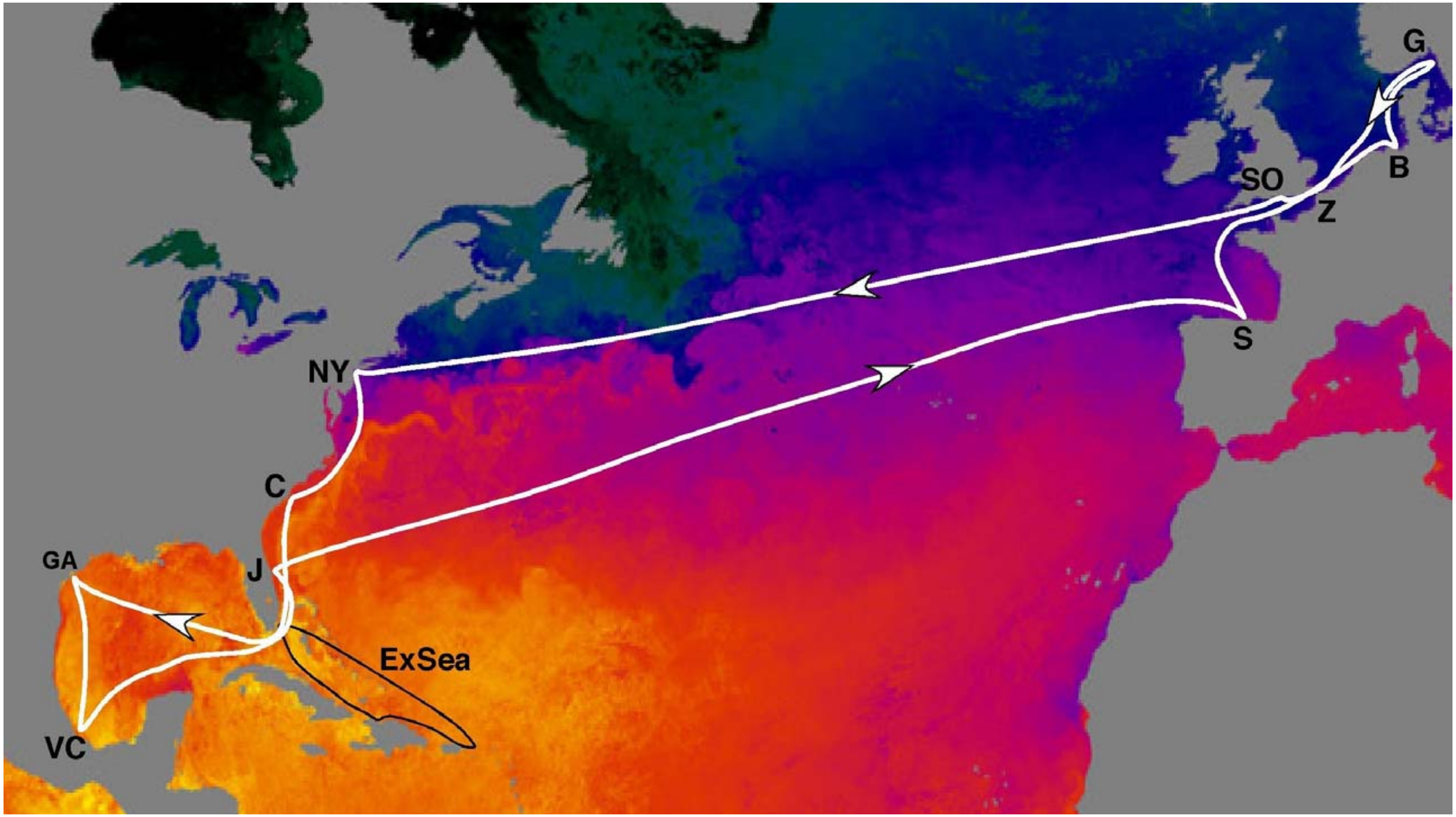
ISAR - Infrared Scanning Autonomous Radiometer

Developed by Craig Donlon, Ian Robinson & Michael Reynolds – validation of Skin SST from AATSR on *Envisat.*

Installed on *Pride of Bilbao*



Falstaff



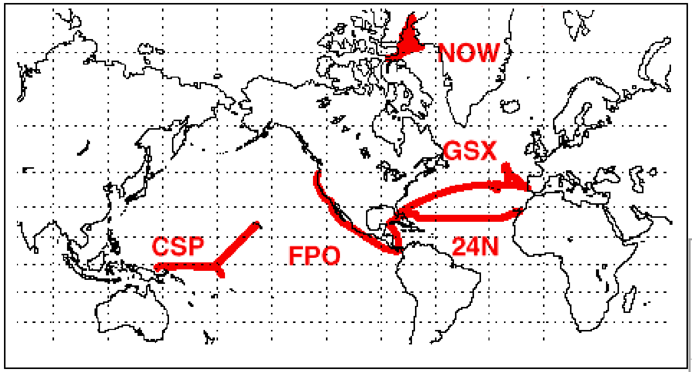
Other NOPP–SST ships

- *Explorer of the Seas*
- USCG Icebreakers *Polar Sea, Polar Star*
- NOAA S *Ronald H. Brown*
- *Pride of Bilbao*
- ……

GHRSST-PP

- GODAE – High Resolution Sea-Surface Temperature –Pilot Project
- Validated satellite-derived SST, <10km, <6hr delay, 6hr time step
- Starting 2003 for three years
- Requires uncertainty estimates for each data point

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

MODIS SST Buoy and M-AERI retrieval Statistics Version 4.5 (new delivery)

median = satellite - reference [MAERI or BUOY]

BUOY

- SST - new coefficients

	Median	StdDev	Number of Points
– Terra all	-0.07	0.48	11027
– Terra night	0.01	0.42	4387
– Terra day	-0.14	0.51	6643
– Aqua all	-0.05	0.48	3821
– Aqua night	-0.10	0.43	1628
– Aqua day	-0.01	0.51	2203

- SST4 new coeffs, new formulation

	Median	StdDev	Number of Points
– Terra night	-0.05	0.41	4096
– Aqua night	-0.10	0.39	1319

M-AERI

- SST - new coefficients

	Median	StdDev	Number of Points
–Terra all	0.10	0.40	439
–Terra night	0.04	0.35	235
–Terra day	0.16	0.42	204
–Aqua all	0.06	0.40	105
–Aqua night	0.02	0.37	59
–Aqua day	0.11	0.45	46

- SST4 new coeffs, new formulation

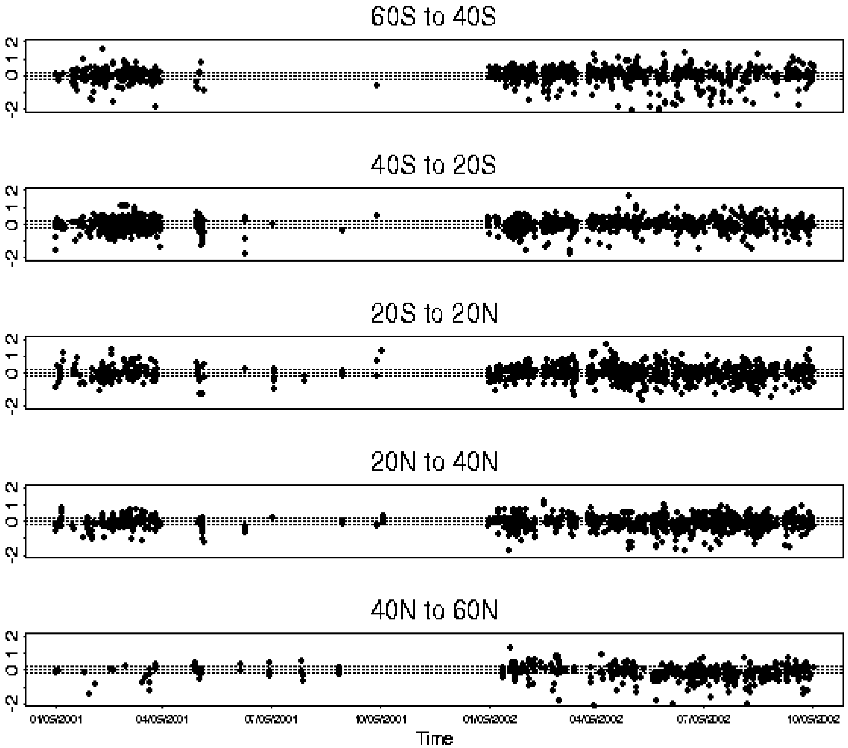
	Median	StdDev	Number of Points
–Terra night	0.02	0.34	278
–Aqua night	-0.01	0.31	52

TERRA MODIS SST Validation

Both SST and SST4 products show no trends with time (Jan 01-Sept 02), temperature, satellite zenith angle (not shown) or latitude *vs* drifting buoys. Dotted lines are ± 0.2K and enclose 50% of the retrievals

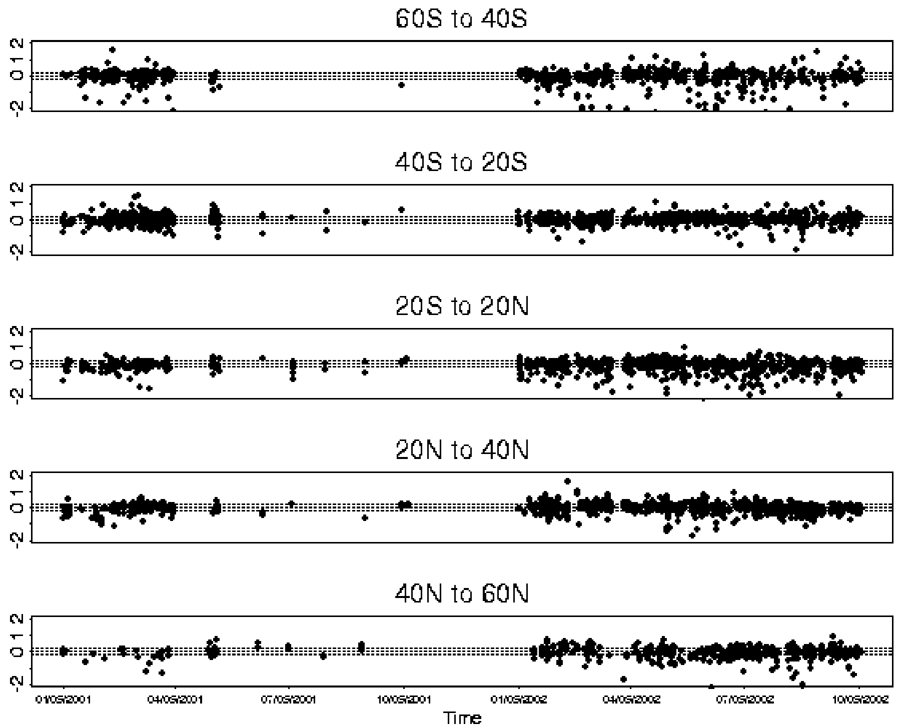
Thermal, 10-11 μm SST

SST residual *vs* time by lat band



Mid-wave, 4 μm SST

SST4 residual *vs* time by lat band



RSMAS

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