

Infrared (IR) Instrument Comparison Workshop at the Rosenstiel School of Marine & Atmospheric Science (RSMAS)

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Sea Surface Temperature (SST) and Global Change

El Niño has received more ongoing media coverage than perhaps any other weather phenomenon in recent memory, although this coverage tends to focus on the aftermath of severe weather systems attributed to this phenomenon. By now it is commonly known that El Niño's development is related to a change in sea surface temperature (SST), as warm water spreads from the western Pacific towards the east. What is not as well-publicized is the fact that the SST change associated with El Niño is only a matter of roughly 3°C. This change seems trivial to most of us, as we typically think about temperature in terms of the air and its daily fluctuation; to the oceanographic community, however, a change of 3°C is extremely significant. The expected average change in SST due to global warming is only about .03°C per year. Understanding the triggers of El Niño, and indeed global climate change as a whole, requires the ability to make extremely precise and reliable measurements of SST, ideally with an accuracy of better than 0.2°C.

Validation of MODIS SST Measurements

The Moderate Resolution Imaging Spectroradiometer (MODIS), scheduled to fly aboard the EOS AM-1 and PM-1 satellites, will measure SST with an absolute accuracy of 0.3 to 0.5 Kelvin (K). (The Kelvin scale begins at absolute zero [-273.15°C], and is defined as °C + 273.15.) So far the most accurate satellite-based SST measurements (~0.3 K) have come from the Along Track Scanning Radiometer (ATSR), although ATSR does not provide daily global coverage like MODIS will. MODIS SST data will of course have to be validated with ship- and aircraft-mounted instruments that can provide a comparable level of accuracy. "There are very few variables that are unequivocal indications of possible climate change, and one of these is SST," explains MODIS Science Team member Peter Minnett of the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS). "Because of the high innate spatial and temporal variability of SST, large areas have to be considered, and time-series of global, or ocean-basin, scale SST fields are a potentially crucial parameter for the study of global change. Satellite instruments offer the only mechanism for providing these large-scale fields, and self-calibrating infrared (IR) radiometers produce the most accurate SST retrievals." Covering the "large areas" that Minnett refers to would require thousands of daily SST retrievals to be made by IR radiometers mounted aboard ships-of-opportunity and other available platforms. Currently the most accurate ship-based radiometers, such as the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), are prohibitively expensive for this kind of wide deployment. The harsh marine environment (e.g., saline aerosol contamination of optics, extreme temperature and humidity changes) to which the widely-deployed radiometers will be exposed requires them to be extremely durable and, in the worst cases, expendable.

Bulk vs. Skin SST Measurements

Researchers deriving SST algorithms have typically not used IR radiometer SST measurements but, rather, in situ bulk SST (BSST) measurements obtained from thermometers on buoys or ships. BSST measurements are made at a depth of perhaps a couple of meters. However, what is measured from a satellite is the sea surface skin temperature (SSST). The difference between the

skin and bulk temperature can differ by a degree or more, and it is crucial to quantify that difference. So far nearly all satellite measurements have been validated with BSST measurements, and scientists at RSMAS and the University of Wisconsin are leading the effort to use SSST measurements to validate satellite measurements. Minnett states that, "The absolute accuracy of the SST retrievals must be determined to establish whether apparent signals in time-series of SST are real or noise. Radiometers mounted on ships, and aircraft, provide the best method of comparing "like with like" and removing the uncertainties resulting from variations in the thermal skin effect and near-surface temperature gradients that are folded into conventional comparisons of satellite-derived SST and in-situ measurements of bulk temperatures."

IR Instrument Workshop

In order to compare and gauge the accuracy of the various IR radiometers available, and discuss their applications in validation activities, Minnett and Otis Brown, MODIS Science Team member and Dean at RSMAS, hosted two workshops March 2 - 6, 1998. The first was a 3-day instrument comparison workshop, or "round robin," whose purpose was to provide a framework in which investigators using IR radiometers, spectrometers and imaging devices could meet to compare instruments, calibration targets and measurement protocols. This is to ensure consistent and accurate data sets for future use in validating IR retrievals of surface temperature from current and future satellite measurements. The instruments compared will have applications in the validation of surface temperatures over land as well as oceans. Immediately following the 3-day instrument workshop, a 2-day validation workshop was held, and this was conducted by MODIS Science Team member Ian Barton of the Commonwealth Scientific and Industrial Research Organization (CSIRO) Marine Labs of Australia. (For a summary of discussion at the validation workshop, refer to page xx).

In addition to the RSMAS/MODIS and CSIRO/MODIS participants already mentioned, the instrument comparison workshop included representatives from the following organizations: the EOS Project Office at Goddard Space Flight Center (GSFC); the Advanced Spaceborne and Thermal Emission and Reflection Radiometer (ASTER) at the Jet Propulsion Laboratory (JPL); the Space Science and Engineering Center (SSEC) at the University of Wisconsin; the University of Colorado; the Applied Physics Laboratory (APL) at the University of Washington; the University of Leicester; the University of British Columbia; the National Institute of Standards and Technology (NIST); the Naval Research Lab (NRL); Rutherford Appleton Lab; the UK MET Office; and the National Physical Laboratory (NPL). Over the course of the workshop participants used a wide range of radiometers, of varying degrees of cost and accuracy, to take turns making temperature measurements in the laboratory against five different blackbody calibration sources, also of varying degrees of cost and accuracy. At the beginning of the workshop it was agreed that lab measurements would be taken with the blackbodies at temperatures of 20° and 30° C. (Supplementary measurements were taken by some participants at other temperatures [e.g., 60°C], or over a range of temperatures while a blackbody source was ramped up from one temperature to another.) In addition to making measurements inside the lab, participants mounted instruments on a platform on the roof of the laboratory building, overlooking the ocean.

Blackbodies at the Workshop

Blackbodies were brought to the workshop by NIST, APL, JPL, CSIRO, and the European Union's Combined Action for the Study of the Ocean Thermal Skin (CASOTS). The common central component to all of these blackbodies is a cavity containing a copper cone which is gold-plated on the outside and painted black on the inside (for high emissivity). IR instruments are focused on the aperture of the cone, whose temperature is controlled by a surrounding water bath.

It is primarily the sophistication of the water bath thermometry, heating, cooling and mixing equipment that separated the blackbodies at the workshop according to temperature stability and cost. The NIST and APL blackbodies represented the most sophisticated units and are intended primarily for laboratory use. (The APL unit copied the NIST design.) According to Joe Rice of NIST, the standard deviation of their blackbody's water bath is stable to roughly 200 microKelvin, or 0.0002°C. The JPL blackbody, developed by Frank Palluconi, is actually intended to be filled with lake water and used as a one-point calibration source for buoys; the aperture is located on the bottom of the unit, and Palluconi used a hand-held drill to drive the water-stirring mechanism. Barton supplied the CSIRO blackbody, a portable unit intended for use at sea, with neither water temperature control nor stirring mechanism. The CASOTS blackbody unit, provided by Craig Donlon of the University of Colorado, is also intended for use at sea. The blackbody is housed within an insulated plastic beverage cooler. This unit has a stirring mechanism but no water temperature control. Measurements taken with the M-AERI indicated hardly any difference in precision between the CASOTS blackbody and the NIST blackbody. Donlon anticipates using the M-AERI as a transfer standard so that the CASOTS units can be "NIST-traceable."

Radiometers at the Workshop

Radiometers measured against the blackbodies ranged from relatively inexpensive, hand-held models to the very expensive and extremely accurate M-AERI. Radiometer data are still being compiled, and Minnett will publish the data on the Web as it is received. (A complete listing of the radiometers brought to the workshop is now available on the Web at:

<http://www.rsmas.miami.edu/ir>. Radiometer data will also be posted at this site.) Fred Prata of the CSIRO Division of Atmospheric Research has already made available measurements he made with four radiometers; three of these were inexpensive, hand-held models (one made by Tasco, the other two by Everest). The fourth radiometer was a more expensive, home-grown Airborne Hazard Detection System (AHDS) 5-channel filter model. (The AHDS was originally designed to utilize IR radiation in the detection of hazardous volcanic ash, clear air turbulence and low-level wind shear.) After plotting the data from all four models, Prata concluded that the AHDS can easily achieve an accuracy of 0.02 K. The other three models could not achieve this level of accuracy; there appears to be a level of magnitude difference between the AHDS and the others. Prata's data indicates that good internal calibration (i.e., good internal blackbodies) provides better accuracy but costs more. Prata suggested that the AHDS, while not suitable for a wide deployment, might be used as a traveling standard against which cheaper radiometers are frequently compared.

Other home-grown radiometer designs brought to the workshop included the CASOTS ship of opportunity sea surface temperature radiometer (SOSSTR) and the University of Washington's "dual-Heimann" model. Both of these designs are intended for use at sea, and employ two radiometers (CASOTS uses Tasco THI-500L models, while Washington uses Heimann KT-15 models) and two blackbodies (one ambient and one hot) within their housing. One radiometer looks at the sea, while the other looks at the sky, to provide data with which to correct for the small component of reflected sky radiance in the sea measurement. Andy Jessup from the University of Washington would like to take the design one step further, and enclose the radiometers and blackbodies within a sealed, temperature-controlled housing. The housing would be filled with dry nitrogen, and the sensors would look out through an IR-transparent window equipped with a wiper and fluid reservoir to periodically clean sea spray and other contaminants. Jessup hopes to find a window that can be very accurately characterized, so that the protection it would afford the sensors could more than account for the added uncertainty it introduces.

M-AERI

The most accurate and expensive radiometer at the workshop was the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI). The M-AERI is a ship-based instrument designed and built at the University of Wisconsin's Space Science and Engineering Center, and one of its applications is the validation of MODIS SST algorithms. (For more information on the M-AERI, go to the RSMAS Web site referenced earlier.) Minnett explains the importance of the M-AERI to the MODIS validation effort as follows: "The essence of post-launch validation of SST derived from the MODIS thermal infrared channels is in determining the accuracy of the correction for the effect of the intervening atmosphere. By using an accurate infrared spectroradiometer close to the sea surface the effects of near-surface vertical temperature gradients, caused by heat exchange between the ocean and atmosphere (the thermal skin effect) and by the absorption of solar radiation in the upper few meters of the ocean on days of low wind speeds (the diurnal thermocline), can be removed from the comparison. The conventional approach of comparing the satellite-derived SST with bulk sea temperatures taken at a depth of a meter or more includes the effects of variation in these gradients, and these are included in the estimate of the inaccuracies of the satellite retrievals. The size of these effects is comparable, and larger in some cases, to the target accuracy of the MODIS SST retrievals (~0.3K rms), and so cannot be ignored. The M-AERI is a spectroradiometer that can achieve both the high absolute accuracy necessary for the comparison and the good spectral resolution (~1cm⁻¹) necessary to resolve the effects of absorption and emission spectra of the atmospheric gasses. In addition, the spectral resolution permits the synthesis of the precise wavelength response of each of the MODIS channels, which would be very difficult to match accurately using filter radiometers." At the Miami workshop the M-AERI achieved excellent results when compared to the NIST blackbody. M-AERI agreement with the NIST blackbody was better than 0.03° C at the 30° C test point, and better than 0.02° C at the 20° C test point. (More M-AERI results can be found at: http://arm1.ssec.wisc.edu/~bobk/miami_ir/miami_ir.htm.) Commenting on the M-AERI results, Bob Knuteson from the University of Wisconsin said that, "The fact that the NIST blackbody and M-AERI agree as well as they do seems like the way it has to turn out if both NIST and Wisconsin are doing their jobs correctly. So it's really a consistency check on our calibration procedures more than anything else." Wayne Esaias, MODIS Ocean (MOCEAN) Group leader, enthused that, "The M-AERI is completely revamping the way SST is validated. It has demonstrated a level of accuracy that is nearly an order of magnitude better than some scientists thought possible for a radiometer."

Results and Future Activities

Overall the results of the radiometer workshop were very encouraging, and participants are already talking about the applications of lessons learned, as well as future workshops. Walt McKeown of NRL was impressed by the radiometer designs of Jessup, Donlon and others, and will recommend to the Navy that the best design be implemented on the National Buoy System. McKeown was also impressed by the large amount and quality of the research cruise data, especially that from RSMAS and Wisconsin, and he is proposing to the Navy that a National Radiometric Library of this research cruise data be collected along with the colocated satellite data. This could be used to radiometrically calibrate the world's satellites as well as to study other phenomena that affect SST, such as the thermal skin effect and diurnal thermocline. Prata suggested that the results of the Miami workshop are also beneficial to the Land community, and stated that, "At the moment there have been (and still are) some large field programs (e.g. FIFE, BOREAS, HAPEX) which made use of IR radiometry but perhaps lacked the kind of calibration and validation protocols that are being pursued by the SST people. I believe that both communities (Land and Ocean) can benefit from some closer collaboration and exchange of ideas." It is likely

that another IR radiometer workshop will be held within the next two years, and may include additional measurement environments, such as aboard a ship or in a lab environment where the ambient temperature is precisely controlled. If new models of radiometers are introduced prior to the next workshop, it is hoped that these will be available for comparison purposes. Barton concluded that, "The radiometers calibrated and compared at the Miami workshop are those that will be used to validate the data products derived from IR measurements from space over the next 5 to 10 years. It is thus important that these are calibrated against NIST and other standards to ensure that consistency is obtained with the different measurements. It will also be important to again compare these instruments in 1 to 2 years time, after they have been used to validate products from EOS and other Earth observing systems."