Measurements of the Skin Effect and Diurnal Thermocline in the Tropical Western Pacific Ocean

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Scientific Background

A fundamental problem in evaluating the exchange of heat, momentum, and gases (including water vapor and carbon dioxide) across the ocean-atmosphere interface is the "cool skin of the ocean." Inherently a transient phenomenon because of the breaking of waves, boundary-layer turbulence, rainfall, and other disturbances, the skin layer re-establishes itself quickly so that it is present under most conditions. Located at the upper limit of the molecular boundary layer, the skin temperature is generally a few tenths of a degree cooler than the temperature a few millimeters below it because of heat loss by sensible and latent heat fluxes as well as outgoing longwave radiative fluxes (Robinson et al. 1984).

The recent results of Van Scoy et al. (1995) show that failure to account for the skin effect leads to an underestimation of the global air-sea CO_2 flux of between 0.17 and 0.4 GtC yr^{-1}, which is a significant fraction of the total exchange, estimated to be ~2.2 GtC yr^{-1} (Tans et al. 1990). This is a consequence of the temperature dependence of the solubility of CO_2 in sea water. There are two main reasons for the spread in the results of Van Scoy et al.: knowledge of the surface wind speed distributions and the response of the skin temperature gradients (and the attendant exchange coefficients).

The turbulent heat exchange between the ocean and atmosphere (sensible and latent, i.e., evaporative) is controlled by the skin temperature, whereas the conventional parameterizations are applied to bulk temperatures, simply because these are more readily available. The parameterizations (the bulk aerodynamic formulae) are strongly dependent on the air-sea temperature difference, which is generally only a few degrees over much of the world's oceans. Discrepancies between the bulk and skin measurements may be comparable and therefore propagate into very large errors in the measurements of the fluxes.

Relevance to the Atmospheric Radiation Measurement Program

The ARM Tropical Western Pacific (TWP) Ocean is a very large oceanic locale in which the atmospheric thermodynamic and radiative conditions are largely dominated by the deep convective activity fueled by the atmospheric water vapor convergence over the warmest sea-surface temperatures (SSTs) on the planet. The intimate coupling between atmospheric convection and SST is graphically demonstrated by the El Niño events in which the migration of deep convection and elevated SSTs across the Pacific Ocean goes hand-in-hand.

Failure to account for the skin-bulk temperature differences in ARM studies of atmospheric radiation and cloud convection obscures the physical insight being sought (e.g., Webster et al. 1996).

Combined Sensor Cruise

The Combined Sensor Cruise of the National Oceanic and Atmospheric Administration (NOAA) ship *Discoverer* took place in the TWP in spring 1996. The *Discoverer* sailed from Pago-Pago in American Samoa on Thursday, 14 March 1996, and headed northwest to a point at 2°S, 180°W where the cruise track turned due west until a point was reached about 100 km off the island of Manus, Papua New Guinea, site of the first island-based facility in the ARM-TWP. The following 10 days were spent occupying five, 2-day stations at varying distances from the island. The ship returned along a line at ~1°S to the date line, and then headed northeast to arrive at Honolulu on Saturday, 13 April.

One of the objectives of this cruise was to test the use of the prototype Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), which is a development of the AERI—a key component in the ARM-TWP instrument suite, and to demonstrate the derivation of accurate SST. The area of the cruise included the "warm-pool" of the tropical Pacific where both the SST and the atmospheric water-vapor loading exhibit global maxima. Thus the cruise conditions are at a climatological extreme. The high air temperatures and strong insolation also meant that the instruments were being stressed towards their upper operating temperatures.

The M-AERI, a Fourier-Transform Interferometric Radiometer (FTIR) operates in the range of infrared wavelengths from ~3 to ~18μm and measures spectra with a resolution of ~0.5 cm^{-1}. It uses a sandwich of two infrared detectors (Indium Antimonide and Mercury Cadmium Telluride) to achieve the wide spectral range, and these are cooled to 77K by a liquid nitrogen dewar to reduce the noise equivalent temperature difference to levels below 0.1K. The M-AERI includes two internal black-body targets for accurate real-time calibration. A scan mirror directs the field of view from the interferometer to either of the black-body calibration targets or to the environment from nadir to zenith. The mirror is programmed to step through a pre-selected range of angles. When the mirror is angled below the horizon, the instrument measures the spectra of radiation emitted by the sea-surface, and when it is directed above the horizon, it measures the radiation emitted by the atmosphere. The instrument was mounted under the flying bridge of the ship, on the port side, so that when pointed at the ocean surface, the field of view was ahead of the ship's bow wave. The interferometer integrates measurements over about 2 minutes per view to obtain a satisfactory signal-to-noise ratio. It was programmed to view a sequence of angles covering the ocean and sky, as well as the two calibration targets; this cycle took about 20 minutes to complete. From these measurements it is possible to derive the oceanic skin temperature to absolute accuracies of ~0.1K and spectra of the infrared emissivity of sea water at the range of observation angles under the environmental conditions that prevailed during the cruise (Smith et al. 1996).

While the ship was on station off Manus, a surface-following float carrying a precision thermistor was deployed forward of the bow-wave to provide in situ measurements of the sea temperature at a depth of ~0.1 m. Throughout the cruise, a bulk temperature measurement from a depth of ~5 m was provided by the ship's thermosalinograph system.

Figure 1 shows the average skin -5 m bulk sea surface temperatures measured by the M-AERI and the ship's system

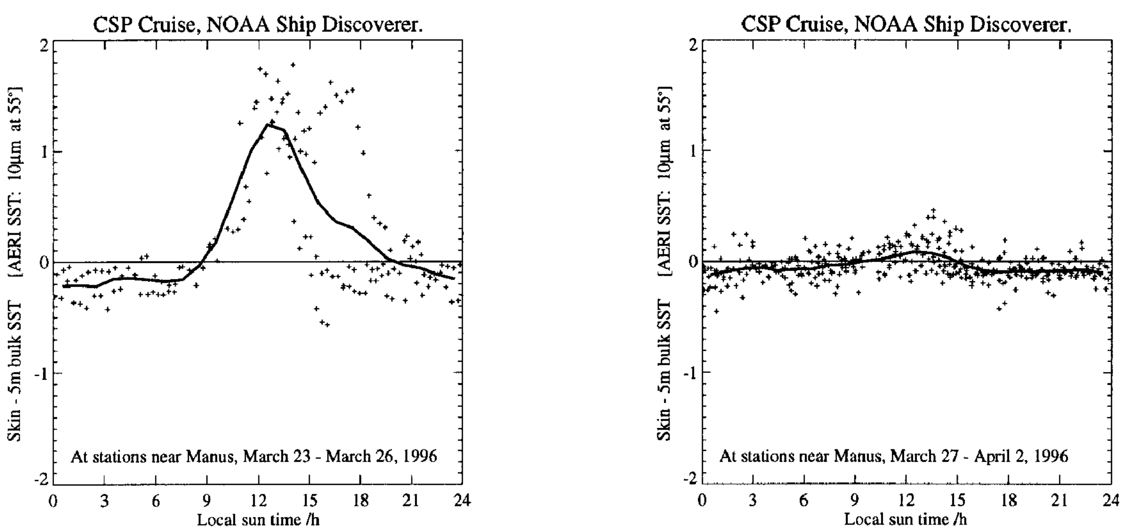

Figure 1. Average Skin -5 m Sea Surface Temperatures Measured off Manus Island. Left-hand panel shows days when wind speed was less than ~5 m/s; right-hand panel shows days when winds were stronger.

while on station off Manus Island (~148°E, ~1.5°S). The measurements are shown as a function of local sun time. The left hand panel is for days when the wind speed was less than about 5 m/s, and the right hand panel for stronger winds. The crosses are individual measurements, and the solid line is a 3-hour running mean. The effect of stronger winds is very noticeable in restricting the amplitude of the diurnal thermocline. The skin effect, observable at night, but present at all times, is ~0.1 to 0.2K in the mean.

Conclusions

The deployment of the M-AERI on the *Discoverer* showed that it can function successfully in the harsh tropical marine environment, where the operating temperatures are high. The ocean skin temperature measurements it provided are consistent with the in situ bulk measurements and reveal the cool skin effect that results from ocean-atmosphere heat transfer.

Webster et al. (1996) show that a 1K error in the specification of the SST leads to errors of 6.3 Wm^{-2} (i.e., typically 1.3%) in the emitted upwelling longwave radiation, 2.3 Wm^{-2} (i.e., typically 23.3%) in sensible heat flux, and 18.7 Wm^{-2} (i.e., typically 16.2%) in latent heat flux. Since the sea-surface is generally warmer than the atmospheric boundary layer, these errors combine systematically to an error of 25-30 Wm^{-2}. The sea-surface temperature is generally measured in the TWP using fixed and drifting buoys that provide a measurement at a depth of 1 m or more. The persistent discrepancy of the cool skin effect, as found in the measurements off Manus, produces an error of typically ~5 Wm^{-2} with a small diurnal modulation when winds are above ~5 ms^{-1}; when winds are below this level, the errors may peak at 45-50 Wm^{-2}. These are with respect to an estimate based on a bulk temperature measurement below the level of the diurnal thermocline. These errors are sufficiently large to significantly contaminate the estimates of heat and moisture fluxes from the ocean to the atmosphere. (For comparison, the target accuracy of the net heat flux measurements for the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment [TOGA COARE] program is 10 Wm^{-2}.)

For the goals of ARM, such errors are important in the description of the atmosphere as regards convective cloud formation, the application of single-column models, and the calculation of atmospheric instantaneous radiative fluxes. To avoid unnecessary error sources, the ocean skin temperature should be used in calculating the air-sea heat and moisture exchanges, and this can best be measured over the extended area of the TWP site using satellites.

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