Turbulent Surface Flux Measurements from Nauru99

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Introduction

The National Oceanic and Atmospheric Administration (NOAA) Research Vessel (R/V) *Ronald H. Brown* conducted a series of measurements in transit to and in the vicinity of the U.S. Department of Energy (DOE) Cloud and Radiation Testbed (CART) site on Nauru in June-July 1999 as part of a joint NOAA-Atmospheric Radiation Measurement (ARM) intensive study of air-sea interaction and cloud/ radiative processes in the tropical western Pacific. This cruise, which has been designated Nauru99, was preceded by a cruise in a monsoon region (Jasmine) and followed by two cruise legs near the island of Kwajalein (Kwajex). Also participating in the Nauru99 study, were the Japanese R/V *Mirai*, the Flinders University research aircraft, and a host of investigators at the ARM Tropical Western Pacific (TWP) site on Nauru. See http://www.etl.noaa.gov/nauru99/ and associated links for more detail.

The ARM effort on the R/V *Ronald H. Brown* for Nauru99 featured an ensemble of instruments to conduct measurements in the ocean and atmosphere with a combination of in situ and remote sensing methods. On the atmospheric and near-surface ocean side, measurements included rawinsondes, bulk near-surface meteorology, air-sea turbulent fluxes, radiative fluxes, numerous rain gauges, three profiling Doppler radars, microwave and infrared radiometers, a cloud ceilometer, and a scanning C-band Doppler precipitation radar.

In this paper we will focus on one set of measurements made with the NOAA Environmental Technology Laboratory (ETL) air-sea flux system. We will compare direct covariance fluxes with estimates from the Coupled Ocean Atmosphere Response Experiment (COARE) algorithm Version 2.6 to evaluate the accuracy of the algorithm for ARM TWP purposes. Cruise averages will be compared with the three other tropical cruises in the sequence.

ETL Flux Measurement Systems

The ETL ship-based air-sea interaction system was used for bulk meteorology, radiative, and turbulent fluxes with additional measurements provided by the ship's operational instruments and the Commonwealth Scientific and Industrial Research Organization (CSIRO). The majority of the sensors were mounted on a scaffold unit just aft of the bow; the turbulence sensors were mounted on a forward-facing boom on the ship's jackstaff at the most forward and best-exposed location on the ship (Fairall et al. 2000). The ETL measurement system is described in detail by Fairall et al. (1997). A sonic anemometer/thermometer is used to make turbulent measurements of stress and buoyancy flux; a high-speed infrared hygrometer is used with the sonic velocity data to obtain latent heat flux. An inertial navigation system is used to correct for ship motions. Fluxes are computed using covariance, inertial-dissipation, and bulk techniques (Fairall et al. 1996). Sea-surface temperature is derived from bulk water measurements at a depth of 5 cm with a floating thermistor. Mean air temperature and humidity are derived from a conventional aspirated T/RH sensor; the infrared hygrometer provided redundant information.

Air-Sea Flux Results

The ship entered the Jasmine experimental area in the Indian Ocean on May 5 and completed Kwajex on September 12 (Figure 1). Site details and observed net radiative fluxes are show in Table 1.

Cruise averages for surface flux components (Hs = sensible heat, Hl = latent heat, and Tau = stress) are given in Table 2; bulk fluxes are designated by 'b' and turbulent (direct) fluxes by 't.' The number of 1-hr values used to compute the averages are given by N. The cruise mean wind speed (U) is also given; all units are standard (W/m^2; Nt/m^2; m/s).

Table 1. Observed net radiative fluxes.

Cruise Name	Jul. Day	Dates	Hrs	Nominal Latitude/ Longitude	Rsn	Rln
Jasmine	124-151	5/5-5/31	654	8 N 89 E	215	-43
Nauru99	166-199	6/15-7/18	794	0.5 S 167 E	220	-51
Kwajex1	209-235	7/28-8/23	511	8 N 167.5 E	237	-46
Kwajex2	236-255	8/24-9/12	363	8 N 167.5 E	232	-44

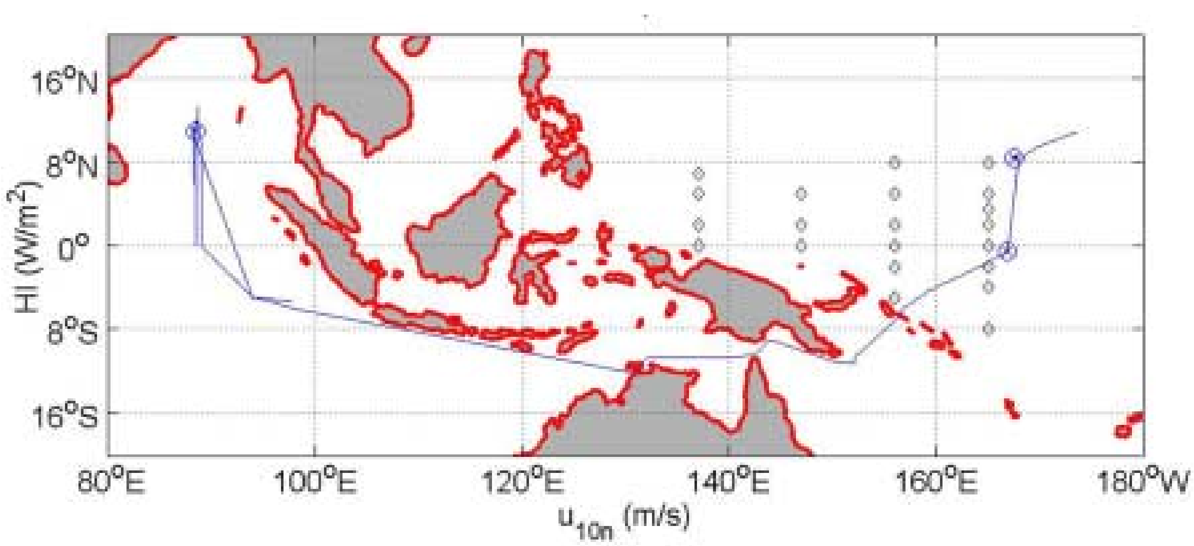

Figure 1. Cruise track of R/V *Ronald H. Brown* during Jasmine, Nauru99, and Kwajex. The diamonds represent Tropical Atmospheric Ocean (TAO) buoy locations.

Table 2. Cruise averages for surface flux components.

	Ns	Hsb	Hst	Nl	Hlb	Hlt	Ntau	Taub	Taut	Nu	U
Jasmine	536	5.6	6.4	331	109	108	528	0.055	0.069	654	5.9
Nauru99	713	5.5	6.5	612	117	117	708	0.054	0.058	794	5.9
Kwajex1	500	6.4	6.8	422	88	89	503	0.031	0.029	511	4.5
Kwajex2	354	7.6	7.7	305	97	99	356	0.036	0.035	363	4.9
Total	2104	6.1	6.7	1671	104	104	2096	0.046	0.050	2323	5.4

The Nauru99 experiment shows very close average agreement between algorithm-derived and directly measured fluxes. When we examine the fluxes as a function of wind speed, some interesting disagreements emerge. We averaged bulk and flux variables from all four cruise legs in wind speed bins. Results are shown for Hl in Figure 2 and stress in Figure 3. There is a tendency for the bulk algorithm to overestimate at low winds and underestimate at high winds. We can get a more detailed look by computing the 10-m neutral transfer coefficients from the direct measurements (this effectively removes the strong dependence on wind speed, sea-air humidity difference, and stability). Below about 5 m/s wind speed, the moisture transfer is about 10% lower than the algorithm (Figure 4). The biases for momentum transfer are significantly larger (Figure 5), showing the classic pattern of good agreement only for wind speeds near the regional mean wind speed. This is usually interpreted as resulting from mesoscale variations in the local mean wind vector that are too fast to be followed by the surface gravity wave "climate." Thus, during short periods of light winds the decay of the wave field reduces the local drag while in short periods of strong winds the growth of the wave field increases the local drag. This affects surface stress more strongly than scalar fluxes. If we boldly dismiss the possibility of some unknown experimental problem, then mesoscale processes are significantly problematical for standard bulk algorithms of air-sea fluxes.

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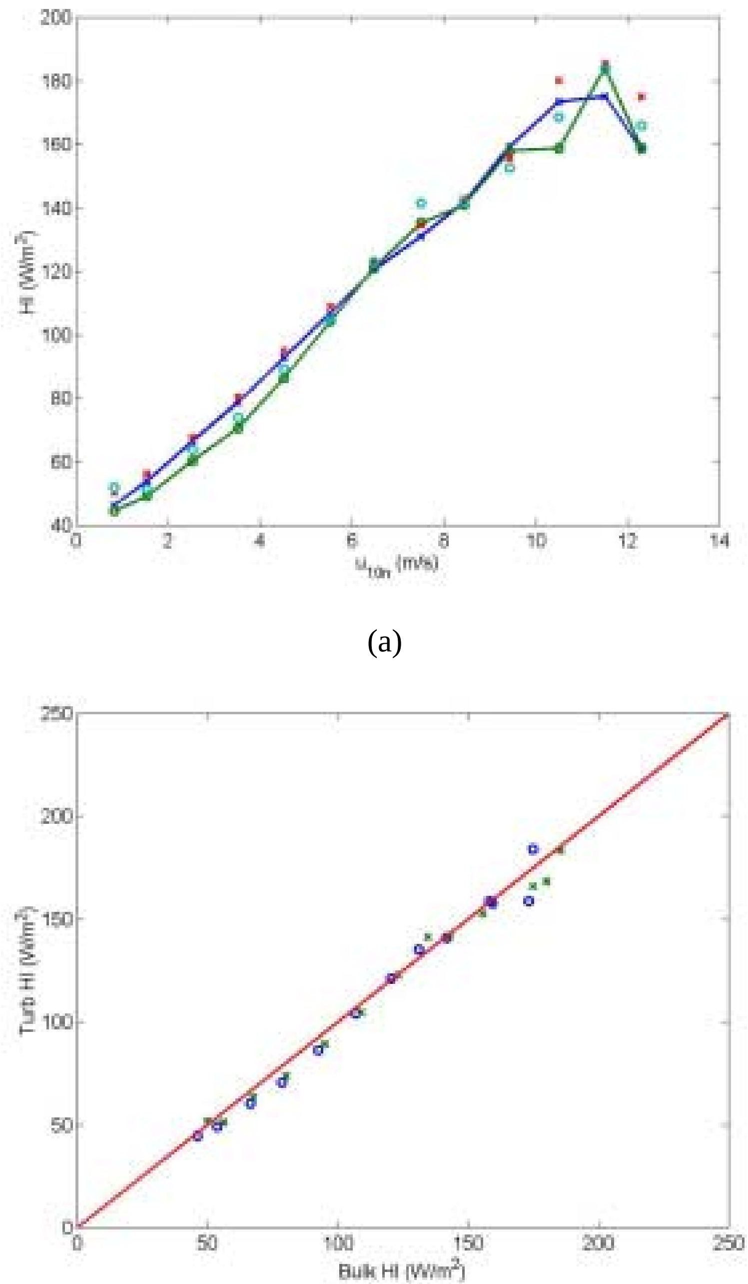

(a)

(b)

Figure 2. Comparisons of bulk and direct turbulence estimates of latent heat flux in 10-m neutral wind speed bins: (a) Flux as a function of wind speed: x's are bulk and o's are direct; symbols connected by lines are medians, while those without lines are means, (b) bulk flux estimates versus direct turbulent estimates: x's are means and o's are medians.

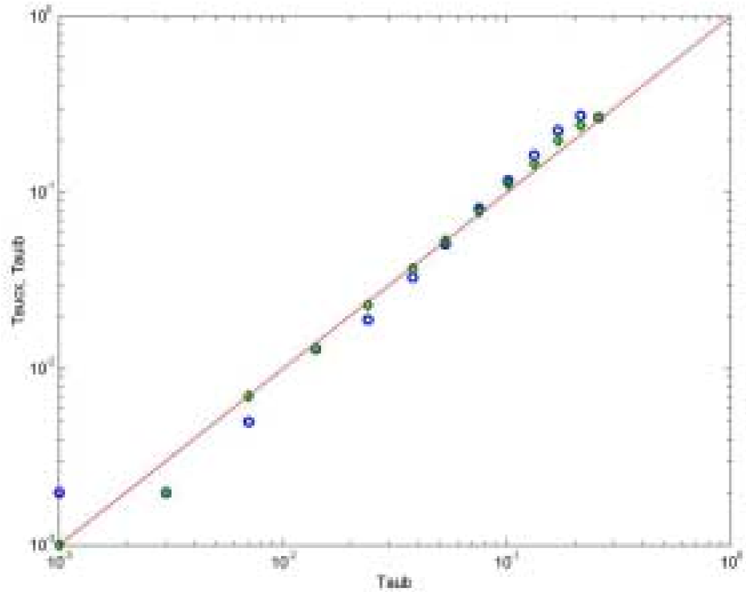

Figure 3. Comparisons of bulk and direct turbulence estimates of stress in 10-m neutral wind speed bins. The diamonds are inertial-dissipation estimates; the circles are covariance estimates.

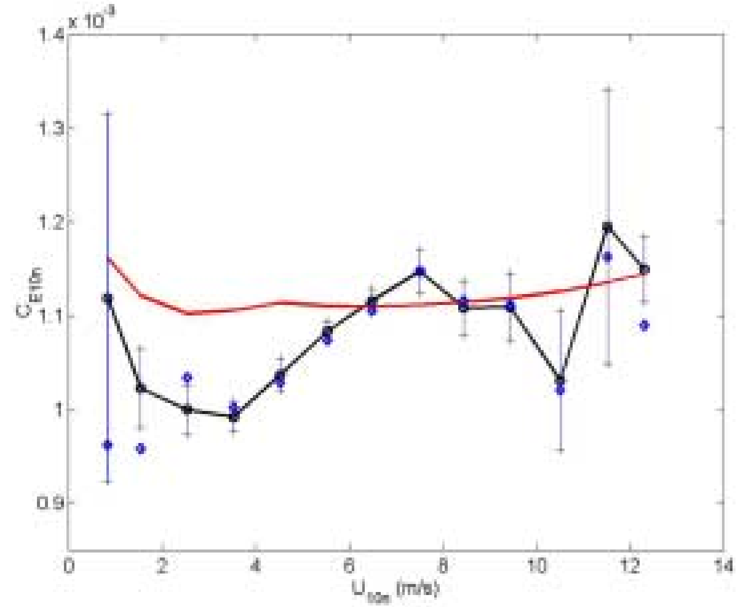

Figure 4. 10-m neutral moisture transfer coefficient (C_{E10n}) versus 10-m neutral wind speed. The direct measurements are given using medians (circles) and means (diamonds); the red line is COARE Version 2.6. The bars indicate the statistical uncertainty in the mean estimate.

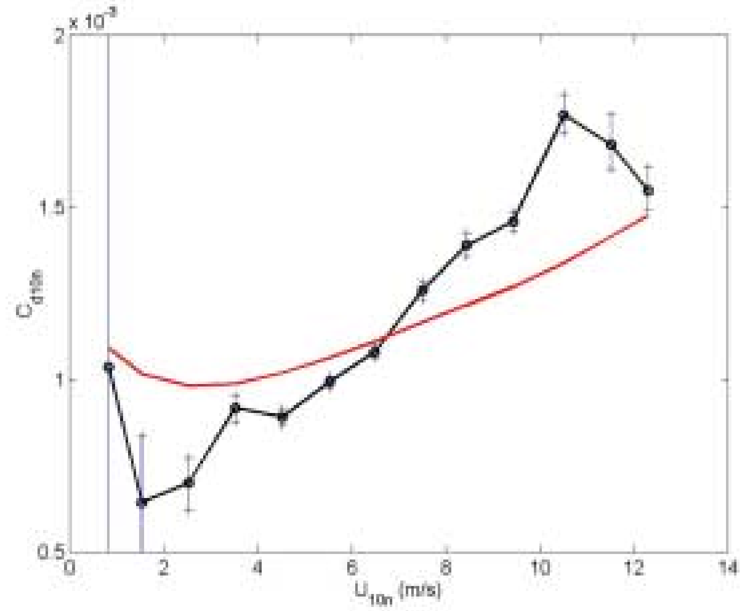

Figure 5. 10-m neutral momentum transfer coefficient (Cd_{10n}) versus 10-m neutral wind speed. The direct measurements are given using medians of the combined covariance and ID values (circles); the red line is COARE Version 2.6. The bars indicate the statistical uncertainty in the mean estimate.