Can Shipboard Measurements Reveal Secular Changes in Tropical Air–Sea Heat Flux?[1]

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ABSTRACT

A new Comprehensive Ocean-Atmosphere Data Set for the period 1854–1979 will soon become available for studies of secular climate changes in ocean surface heat flux. Of the observed variables from which heat flux is calculated, wind speed and sea surface temperature have undergone indeterminate spurious changes due to modifications in estimating and measuring.

Analysis of a summertime ocean data set for the Philippine Sea revealed unacceptably large increases in air temperature and dew point readings resulting from daytime heating of the ship. Differences between ocean skin temperatures and subsurface temperatures lead to positive heat flux errors with light winds. Computing heat fluxes for individual ship reports and then averaging them improves matters.

These errors, as well as those arising from spatial and temporal inhomogeneities of individual monthly averages, require that studies of ocean climate change first be confined to the most heavily traveled ship routes. Criteria of consistency, pattern persistence and physical reasonableness would need to be satisfied before one could accept evidence of secular changes in surface heat flux.

1. Introduction

As interest in detecting secular changes in climate grows, investigators seek clues in long period compilations of ship observations (Fletcher *et al.*, 1982). The recently completed international Historical Sea Surface Temperature Project (HSSTP) for the period 1854–1969 will soon be surpassed. Together, the Cooperative Institute for Research in Environmental Sciences (CIRES), the National Climatic Data Center (NCDC) and the National Center for Atmospheric Research (NCAR) are incorporating additional data sets and updating the collection through 1979. This new Comprehensive Ocean–Atmosphere Data Set (COADS) will comprise more than 100 million ship observations (Fletcher *et al.*, 1983).

Bretherton (1981) has pointed out that fluxes of heat at the ocean surface are a key to understanding climate and climate change. He thinks that for climate change signals to be recognized, the heat flux must be estimated to a precision of "±10–15 W m^{-2} on space scales of several hundreds to thousands of km, and time scales of a few weeks or longer."

Numerous theoretical and numerical studies, summarized by Haney (1979), suggest that atmospheric response to ocean surface thermal anomalies is much stronger in low than in high latitudes, and Webster (1981) has tried to explain this theory. Whether or not these findings are valid, the tropical part of COADS will be eagerly studied for evidence of secular heat flux changes. Will COADS divulge the evidence, will it yield only noise or might change signals be recognizable where observations are plentiful?

In what follows I try to partly answer this question by focusing on the components of the bulk aerodynamic equations. After a discussion of changes since 1854 in measurement and estimating procedures, I assess errors of representativeness inherent in the observations, and finally suggest a possible way to obtain information on secular change from COADS.

2. Bulk aerodynamic equations

The bulk aerodynamic equations for heat flux from the ocean may be written:

Sensible heat flux

$$Q_s = \rho_a C_D C_p (T_w - T_a) V,$$

Latent heat flux

$$Q_e = \rho_a C_D L (q_w - q_a) V,$$

where

ρ_a air density (1.21×10^{-3} g cm^{-3})
C_D drag coefficient (1.55×10^{-3})
C_p specific heat of air at constant pressure (1.00×10^3 J kg^{-1} $°C^{-1}$)
T_W sea surface temperature (°C)
T_a shipboard air temperature (°C)
V surface wind speed (m s^{-1})
L latent heat of vaporization (2.45×10^6 J kg^{-1})

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q_w saturation specific humidity of air at temperature of the sea surface (gm kg^{-1})
q_a specific humidity of air on shipboard (gm kg^{-1}).

Transforming specific humidities into vapor pressures e_w and e_a (mb) and allowing for the effect of salinity by multiplying e_w by 0.98 (Miyake, 1952) leads to the following working formulas:

$$\left.\begin{aligned} Q_s &= 1.87(T_w - T_a)V \\ Q_e &= 2.82(0.98e_w - e_a)V \end{aligned}\right\} \text{in W m}^{-2}.$$

3. Estimates and measurements since 1854

a. *Surface winds*

Over the period of COADS surface winds (V) were first estimated from 1) the response of ships under sail, then from 2) the character of the sea surface as observed from steamer decks and more recently from 3) shipboard anemometer readings (Ramage, 1982). Unfortunately, sailing ship officers, using the original Beaufort Scale, underestimated with following winds and overestimated with head winds while many more used their own scales. As observed from steamships, sea state depends not only on V but also on boundary-layer stability and is hard to estimate at night. Various instrument heights and exposures and corrosion problems introduce unknown inconsistencies into anemometer readings. The only link between the original Beaufort Scale and present wind speed equivalents is through the sea state scale. But from 1854 to 1947, no recognized sea state scale existed. In the tropics (T_w = 29°C, T_a = 28°C, T_d = 25°C), since an error of only 0.5 m s^{-1} in estimating V leads to an error of 12 W m^{-2} in estimating surface heat flux, unknown systematic differences among the three methods of estimating V may be misleading in identifying long-term fluctuations. In any case, there is no basis for correcting or adjusting the record.

b. *Air temperature and moisture content*

By 1854 the principles and practice of wet bulb hygrometry had been well established (Middleton, 1969). On ships, dry and wet bulb thermometers were housed in louvered shelters or were whirled in sling psychrometers. Poor ventilation with light winds resulted in spuriously high shelter readings leading to spuriously low estimates of surface heat flux. Since COADS is mute on the measurement method used for each observation, we must remain ignorant of the ratio of the numbers of shelter to sling measurements or of any secular change in the ratio. The most common error leading to a spuriously high wet bulb reading occurs when the muslin around the wet bulb and the wick leading to the distilled water reservoir are not changed at least weekly and become salt encrusted. Consequently, if the meteorological skill and devotion of ships' officers have fluctuated over the past 125 years, then our calculations of latent heat flux could be contaminated.

c. *Sea surface temperature*

Sea surface temperature (T_w) has been measured from ships by 1) immersing a thermometer in a bucket of water drawn from the upper several centimeters of the ocean or by 2) reading "a thermometer in the engine room mounted at some location in the sea-water injection system of the ship" (Saur, 1963). Several studies comparing bucket and injection temperatures (Saur, 1963; Walden, 1966; James and Fox, 1972; Collins *et al.*, 1975; Tabata, 1978) agree that on average, the latter are higher than the former by about half a degree Celsius. The bucket method was almost always used prior to World War II while the injection method has increasingly predominated since; this sets the stage for a spurious secular rise in T_w. According to Barnett (1984), "the bias so introduced constitutes approximately 30–50% of the observed change in sea surface temperature since the turn of the century." Ideally, only those observations incorporating bucket measurements should be used, but this would unacceptably diminish the totals in recent decades.

d. *Representativeness*

Data from perfectly calibrated instruments and excellently designed and executed estimation methods can still lead to wrong calculations of surface heat flux if they prove not to be representative of the period for which the observations are averaged, of the area surrounding the ship, or of the ocean skin that the atmosphere senses.

In climate change studies using ship observations, a serious lack of representativeness arises from data scarcity over much of the ocean. This forces averaging over a season and over a large area (5° × 5° or even 10° × 10° latitude–longitude rectangles). Consequently, spurious differences between one year and another due to differences in the time and location distributions of the observations may often mask true interannual differences. However, before trying to solve this problem one should first identify sources of local unrepresentativeness. Thus, averages over a period (June–October 1944–69) and a region (the Philippine Sea, 10–20°N, 130–150°E) with small seasonal variations in meteorological elements and ship latitudes were chosen. The data comprise 51 895 observations, being a subset of the revised Marine Climatic Atlas of the World (U.S. Navy, 1977). Sea state was used almost exclusively in estimating wind speed.

4. Philippine Sea data set

a. *Surface wind*

In this file the World Meteorological Organization's (1969) table is applied to estimates of Beaufort Force (sea state) to translate them into m s^{-1}. In the mean, V (daytime) exceeded V (nighttime) by $\sim$0.2 m s^{-1}. This may reflect a slight tendency to underestimate at night since measurements made on oceanographic expeditions and on small coral islands give a range of day minus night of +0.1 to −0.3 m s^{-1}.

b. *Diurnal variation of temperatures (Table 1)*

Average T_w was only 0.1°C higher during the day than during the night. But for air temperature (T_a), the difference amounted to 1.4°C and for dew point (T_d), to 0.4°C, both due to insolational heating of the ship. The difference duplicates findings by Godshall *et al.* (1976) and Goerss and Duchon (1980) for the GATE area and by Kondo and Miura (1982) for the tropical west Pacific. The differences are wind speed-dependent since shelter ventilation improves as the wind increases. Assuming that the nighttime observations are correct, including the daytime observations would contribute an error of −8 W m^{-2} to surface heat flux calculations. Even at night with no insolation, a steamship may act as a heat source in light winds.

c. *Skin effect*

Downward-pointing infrared radiometers sense true T_w and have revealed that the ocean "skin" is cooler than the layers sampled by the bucket or injection pipe (Ball, 1954; Sanders, 1967; Tauber, 1969; Hasse, 1971; Stevenson and Miller, 1972). The difference is largest in light winds when the evaporatively cooled skin is mixing least with the underlying layer. Table 2 suggests just a slight overall effect since only 3% of the observations reported calm. However, in individual months an error of 10–15 W m^{-2} might be produced were the heat fluxes calculated from averaged observations rather than averaged from calculations first made for individual sets of observations.

d. *Effect of winds on temperatures*

Verploegh (1960) found that, on average, over the Indian Ocean "an increase of the wind force by one degree of the Beaufort Scale is accompanied by a decrease of both the air and sea temperature of 0.17°C." For the Philippine Sea the corresponding decreases are 0.21°C for T_a and 0.14°C for T_w.

e. *Computation procedures*

Nelson and Husby (1983) calculated heat fluxes over the California Current region and found that compared to computations from individual ship reports, computations that used monthly means of atmospheric properties underestimated Q_e by 1–8% and Q_s by 3–13%. To the contrary, nighttime averages for the Philippine Sea computed from the individual reports were less by 5.5 W m^{-2} (4%) for Q_e and by 0.9 W m^{-2} (7%) for Q_s. This is so because of the positive errors introduced by spreading the calm-wind skin effect through averaging the atmospheric properties before computing the heat fluxes. Esbensen and Reynolds (1981) found the same relationship for Q_e in subtropical weather ship data with the average difference < 10%.

f. *Role of rain*

Palmer *et al.* (1955) used a dramatic example from Canton Island to emphasize that in the deep tropics, cool dry downdrafts associated both with showers and with rain from altostratus cause the only significant drops in T_a and T_d. Later, adducing the same mechanism, Garstang (1967) found that in disturbed trade winds, Q_s may increase by orders of magnitude and Q_e may double. Although such events are rare, missing them may result in underestimating the surface heat flux. To test this hypothesis I stratified the nighttime Philippine Sea data (Table 3) by wind direction (trade wind and nontrade wind), wind force and weather with a wet-weather observation reporting precipitation either in sight, occurring or occurring within the last hour. Average T_w was the same in dry and wet weather. On the scale of this comparison, rain cooled the air by about half a degree Celsius, while at the same time leaving T_d essentially unchanged and diminishing the

TABLE 1. Day-minus-night air temperature, dew point (°C) and sensible and latent heat fluxes from the sea surface (W m^{-2}), averaged by Beaufort Force intervals (June–October, 1944–69; 10–20°N, 130–150°E calculations made for individual ship reports then averaged).

	Beaufort Force										
Day minus night	0	1	2	3	4	5	6	7	8	9	Average
Temperature	1.8	1.6	1.7	1.5	1.4	1.0	0.7	0.7	0.2	0.3	1.4
Dew point	0.5	0.6	0.6	0.5	0.4	0.3	0.2	0.1	−0.2	0.2	0.4
Q_s	0	−3	−7	−11	−17	−17	−15	−14	−7	−7	−12
Q_e	0	−3	−5	−6	−11	−10	−5	−14	31	2	−3
Number of observations											
Day	447	1707	4618	8612	8811	2948	979	373	154	30	
Night	720	1292	4082	7150	6424	2305	782	279	135	29	

TABLE 2. Average nighttime sea surface temperature minus air temperature and dew point (°C) and frequency of rain (%) by Beaufort Force categories (June–October 1944–69; 10–20°N, 130–150°E).

Sea surface temperature minus	Beaufort Force 0	1	2	3	4	5	6	7	8	9
Air temperature	1.5	1.2	1.3	1.1	1.2	1.2	1.3	1.4	1.3	1.5
Dew point	5.0	4.6	4.5	4.3	4.2	4.1	3.9	3.7	3.5	3.4
% frequency of rain	13	12	17	18	22	31	41	51	52	

dew point depression. This suggests that cold dry downdrafts are not very important on the climatological scale and that the effect of rain is confined to cooling somewhat the surface air by evaporation and therefore enhancing Q_s by about 75%. Evaporation also effectively maintains T_d against dry incursions. Table 2 confirms this. Here, T_w minus T_a is largest with calms (skin effect) and with strong winds (more rain), while T_w minus T_d shows no double maximum. The differences in Q_e can be accounted for by slight differences in average wind speed within the Beaufort Force categories.

In analyzing climatological elements over the Indian Ocean, Verploegh (1960) found for every 10% increase in monthly precipitation frequency, monthly mean T_a is reduced by 0.7°C. This compares to 0.15°C for the Philippine Sea.

g. *Bucket and injection methods for measuring sea surface temperature*

To check on Barnett's (1984) contention that increasing use of injection methods has introduced an apparent positive change in T_w, readings of T_w made over the Philippine Sea for 1910–39 and for 1944–69 were compared. Respective averages amounted to 27.56°C and 28.43°C and standard deviations, to 1.41°C and 1.49°C. Assuming no data independence over the whole area through a year (very restrictive) and data independence between one year and another

TABLE 3. Nighttime meteorological data and surface heat flux averages stratified according to wind direction, weather and wind force (June–October, 1944–69; 10–20°N, 130–150°E; calculations made for individual ship reports, then averaged).

Wind direction (deg)	Number of observations	Weather	Element	Beaufort Force 0	1–2	3–4	≥5
315–135	11 549	dry	$T_w - T_a$ (°C)	1.4	1.1	0.9	0.9
			$T_w - T_d$	5.0	4.5	4.2	4.1
			$T_a - T_d$	3.6	3.4	3.3	3.2
			V (m s^{-1})	0	2.3	5.7	10.0
			Q_s (W m^{-2})	0	5	10	18
			Q_e (W m^{-2})	0	57	130	221
315–135	2708	wet	$T_w - T_a$ (°C)	1.7	1.7	1.5	1.6
			$T_w - T_d$	4.8	4.4	4.2	4.1
			$T_a - T_d$	3.1	2.7	2.7	2.5
			V (m s^{-1})	0	2.4	5.8	10.9
			Q_s (W m^{-2})	0	7	16	34
			Q_e (W m^{-2})	0	57	130	231
135–315	5910	dry	$T_w - T_a$ (°C)	1.4	1.2	1.3	0.9
			$T_w - T_d$	5.0	4.6	4.3	3.7
			$T_a - T_d$	3.6	3.4	3.0	2.8
			V (m s^{-1})	0	2.3	5.6	11.5
			Q_s (W m^{-2})	0	5	13	19
			Q_e (W m^{-2})	0	56	131	229
135–315	2249	wet	$T_w - T_a$ (°C)	1.7	2.0	2.0	1.8
			$T_w - T_d$	4.8	4.6	4.4	3.9
			$T_a - T_d$	3.1	2.6	2.4	2.1
			V (m s^{-1})	0	2.4	6.0	12.2
			Q_s (W m^{-2})	0	9	23	39
			Q_e (W m^{-2})	0	60	138	237

(somewhat liberal) implies about a 100-to-1 chance that the averages come from different populations. The difference between the two periods is too great to be attributable only to the injection measurement effect. However, the result does not contradict Barnett. With reference to COADS which does not differentiate bucket and injection methods prior to 1973, one might assume that only the bucket method was used in 1939 and only the injection method by 1979. This would lead to a spurious rise of about 0.5°C in T_w, equivalent in the Philippine Sea to increases of 18 W m^{-2} in Q_e and 5 W m^{-2} in Q_s.

h. Time series 1944–69

Some of the points made above are illustrated (Fig. 1) by a time-series of the Philippine Sea June–October nighttime observations. Here, T_w minus T_a failed to increase with time suggesting that between 1944 and 1969 the ratio of the numbers of bucket to injection temperatures remained about the same.

Heat flux is most highly correlated with $V (r = 0.82)$ and T_w (r = 0.72). Contrary to Section 4d, V is positively correlated with T_w (r = 0.37), though the correlation of V and T_a is only 0.19. As in the years discussed as follows, an explanation must be sought in the individual observations.

In 1946 (202 observations) V, T_w, T_a and heat flux were higher than in any other year. High V resulted from ships encountering tropical cyclones. Here, T_w was at least 0.6°C too high because of 60 hourly measurements made from a single ship during six days in October, including one day within the circulation of a typhoon. Neighboring measurements suggested an average error of +2.5°C; T_a was at least 0.2°C too high because another ship made 26 hourly observations of T_a 1–3°C above T_w. Because T_d remained near normal, a very high calculated heat flux was ensured.

In 1962 (471 observations) though V, T_w and heat flux were all relatively high, the observations appeared to be reasonably good. The largest T_w minus T_a of any

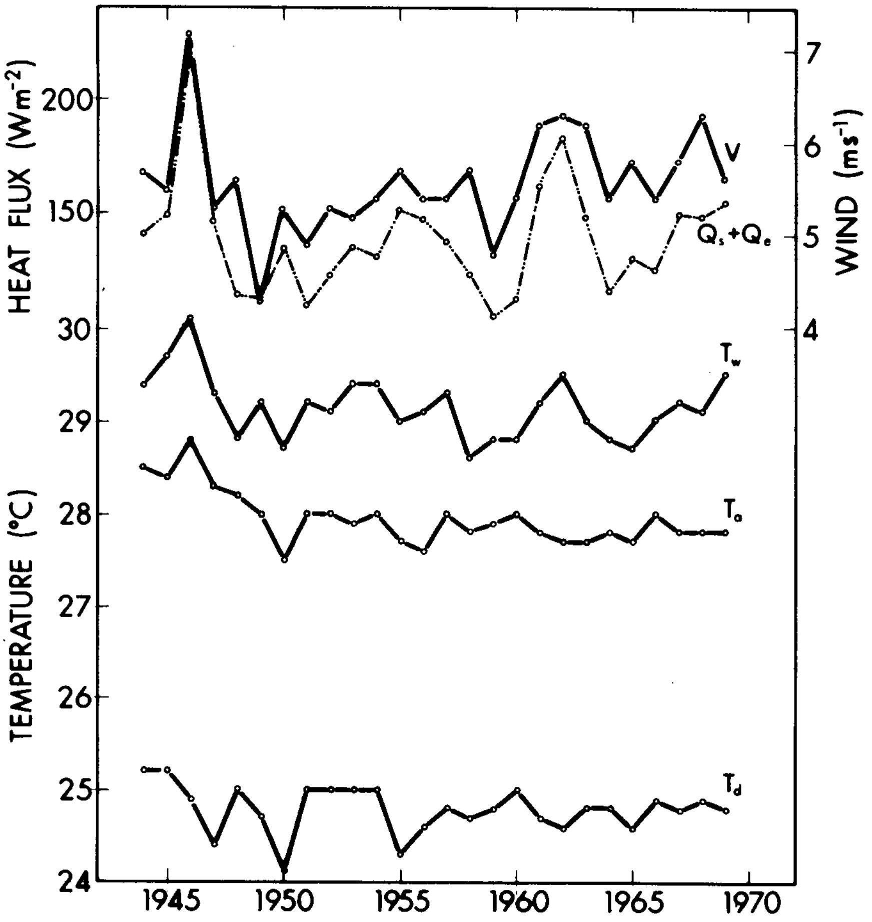

FIG. 1. Averages for the individual years 1944–69 of wind (m s^{-1}), sea surface, air and dew-point temperatures (°C) and surface heat flux (Q_s + Q_e; W m^{-2}) for nighttime observations, June–October; 10–20°N, 139–150°E (flux calculations made for individual ship reports, then averaged).

year could be accounted for here because 27% of the observations reported rain compared to 13% for climatology (U.S. Navy, 1977).

5. Conclusions

a. Spurious secular changes

These may have occurred in wind estimates and measurements but there is no way of finding out. The increasing use of injection measurements of sea surface temperature has imposed a spurious change since 1941; the large errors inherent in the injection method (Saur, 1963) probably preclude estimating the magnitude of the effect. Spurious secular changes in air temperature and dew point are even harder to identify. They may include differences in local heating between sailing ships and steamers and in relative changes in the use of shelters and slings.

b. Spurious diurnal variations

Insolational heating of the ship significantly increases air temperature and wet-bulb readings. The effect is greatest with light winds. Preferably, only nighttime observations should be used. Failing that, wind speed-dependent corrections should be applied to the daytime observations.

The difference between the temperature of the cool ocean skin (that the atmosphere senses) and the ocean layer immediately beneath (that the bucket or injection intake samples) leads to positive heat flux errors with light winds. Computing heat fluxes for individual ship reports and then averaging, reduces the errors by eliminating the effects of calms.

6. Recommendations

My analysis of the total Philippine Sea summer data set was untroubled by data scarcity. But over most of the ocean, spatial and temporal inhomogeneities of individual monthly averages (the basis of climate change studies) could well give rise to spurious secular changes as large as or larger than those that have been discussed. To mitigate this problem, I recommend that tropical climate change studies based on COADS first concentrate on four ship routes that have been heavily traveled since 1854 (Fig. 2)

- Europe–South America
- Europe–Cape of Good Hope
- Gulf of Aden–Malacca Straits
- Malacca Straits–South China/Taiwan.

For each route, distance–time sections of individual monthly means of nighttime observation elements should be prepared and scrutinized for consistency, pattern persistence and physical reasonableness. For example, in the equatorial tropics, sea and air temperatures should fluctuate in parallel; in the winter monsoon, sea surface temperature should be lower with higher winds; air temperature should be lower in wet than in dry weather; averages at neighboring island stations should fit the patterns. If the outcome is satisfactory, the derived fields of Q_e and Q_s should be computed, long-term monthly means prepared and anomalies determined. Absence of secular changes in all fields would probably be conclusive. Apparent secular changes would require further detective work to test their validity, for biases might persist.

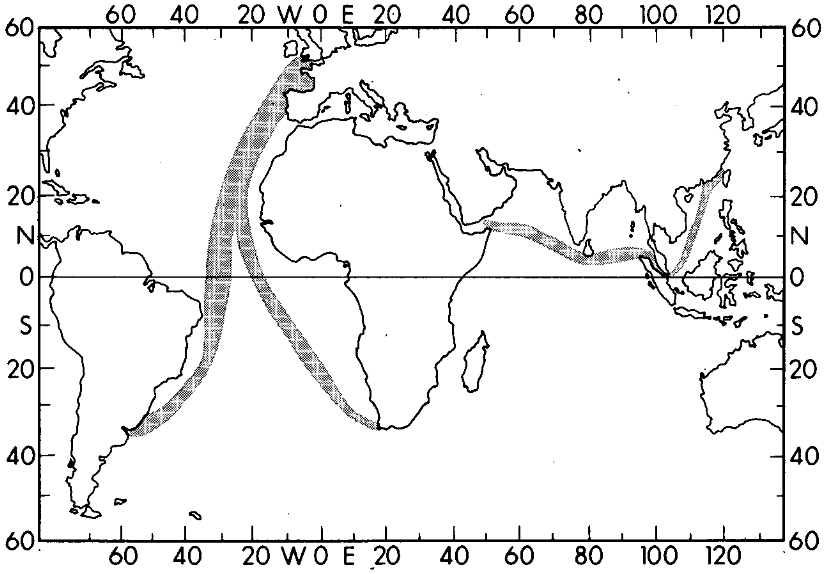

FIG. 2. Tropical ship routes that have been heavily traveled since 1854.

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