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Uncertainties in estimates of surface heat fluxes derived from marine reports over the tropical and subtropical oceans

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ABSTRACT

Estimates are made of the uncertainties in calculations of the heat fluxes at the surface of the tropical and subtropical oceans based upon the bulk formulae and archived marine weather reports. Major contributions are identified not only in the basic observations of such variables as temperature and wind but also in uncertainties in parameters in the bulk formulae themselves. All identified factors are defined as either random or systematic. The potential effects of archiving and sampling errors are also explored. The total uncertainties for individual observations of the net solar and infrared irradiances and the latent and sensible heat fluxes are about 80, 10, 83 and 12 W m^{-2}, respectively. Because uncertainties associated with random errors decrease when many observations are averaged, the uncertainties in the fluxes decrease substantially when fifty or more observations are averaged together. However, since all of the surface fluxes have some systematic uncertainties associated with them, sizeable uncertainties remain, especially in the latent heat flux, even if an unlimited number of observations is available for calculating the means. Representative maps of uncertainties in 20-year monthly means of the component fluxes over the tropical Pacific show large uncertainties in the equatorial and southeastern oceans. Elsewhere, the net solar and infrared irradiance and sensible heat flux have uncertainties of 10 W m^{-2} or less. Unfortunately, the uncertainties in the latent heat flux exceed 30 W m^{-2} everywhere, because of the large systematic component. Total uncertainties in the net heating of the ocean surface are relatively large over the entire tropical Pacific with the smallest relative values in the eastern tropical region.

1. Introduction

In the past 25 years, there have been a large number of authors who have used summaries of the marine weather observations and so-called bulk formulae to estimate the fluxes of heat at the ocean surface (e.g., Budyko, 1963; Wyrtki, 1965; Bunker, 1976; Hastenrath and Lamb, 1978; Weare et al., 1981; Esbensen and Reynolds, 1981). There are three main reasons for all of these studies. The first is the obvious importance of the fluxes of net solar and infrared radiation and latent and sensible heat on the energy budgets of both the oceans and atmosphere. Their importance has been highlighted recently by the strong effort to develop coupled ocean–atmosphere models, which require accurate estimates of these fluxes for initialization and verification. Other uses of the calculations include estimates of the meridional heat transports of the world oceans (Talley, 1984; Hastenrath, 1982) and estimates of the atmospheric water budget (Peixóto and Oort, 1983).

The second reason for so many different estimates is that the data sets available to authors for the calculations have improved considerably over time. Budyko (1963) had to rely upon climatological summaries of temperatures, winds and cloudiness at a relatively limited number of oceanic locations. Most of the latter authors based their analyses upon the mammoth archive of individual marine weather reports compiled by the National Climatic Center. This includes far more data than was available to Budyko, an ability to estimate correlations important to the flux estimate such as those between sea temperature and wind variations, and direct counts of the numbers of observations available upon which to make estimates of the uncertainties in the flux calculations.

The third reason for the various flux calculations, was that improved direct observations of the various fluxes at sea led to revisions and presumably improvements in the bulk formulae. However, progress seems to be almost painfully slow. A recent review by Blanc (1985) of direct estimates of the exchange coefficient C_E, associated with the latent heat flux, shows differences in best fit curves of more than 10%. While the best choice is unclear, it is clear that the strong dependence of C_E on wind speed, used by Bunker (1976) and others is unwarranted. The situation for the net solar flux seems better. A recent review by Dobson and Smith (1988) indicates that the formula suggested by Reed (1977) and used by many of the recent authors seems the best available one, although it still leads to very large random errors. Because there have been few direct observations of net infrared radiation at sea, uncertainties in the associated bulk formula are unclear.

A nagging problem that has been associated with all of the estimates of oceanic heat fluxes is the assertion that the uncertainties in data quality and bulk formulae are so great as to make the estimates nearly meaningless. Indeed the error analysis of Weare et al. (1981) suggests quite large uncertainties ranging between 10 and 100% of the mean values. The qualitative analyses of Sarachik (1984) and Taylor (1984) also conclude that the uncertainties are unacceptably large. In this paper a simple methodology for more carefully estimating the uncertainties in the fluxes will be presented and applied to the fluxes summarized in Weare et al. (1981). While the method will be applied only to this particular data set, it will be evident that the general conclusions will be applicable for other estimates of heat fluxes over the tropical and subtropical oceans.

2. Methodology

The general methodology of estimating uncertainties in the fluxes will be the formal error analyses of Beers (1957) described in Weare et al. (1981). For specificity and convenience the bulk formulae considered will be those of Weare et al.

$$Q_s = Q_{so}(1 - AC + 0.0019\beta), \qquad (1)$$

$$Q_I = \varepsilon\sigma T_s^3[T_s(0.39 - 0.05e^{1/2}) + (T_s - T_a)](1 - BC), \qquad (2)$$

$$Q_L = \rho L C_E V(q_s - q_a), \qquad (3)$$

$$Q_H = \rho C_p C_E V(T_s - T_a), \qquad (4)$$

where Q_s, Q_I, Q_L, Q_H are the net solar and infrared irradiances and latent and sensible turbulent fluxes at the ocean surface. In eq. (1), Q_{so} is the clear sky radiance (Reed, 1977), C is the cloudiness, A an empirical coefficient and β the noon solar altitude (degrees). In eq. (2), ε is the emissivity of the ocean, σ the Stefan-Boltzmann constant, e the atmospheric vapor pressure and T_s and T_a the sea and air temperatures. In eqs. (3) and (4) ρ is the air density, C_E an exchange coefficient, L the latent heat of vaporization, C_p the heat capacity of air at constant pressure, V the wind speed, q_s the specific humidity saturated at the sea temperature and q_a the specific humidity of the air near the surface.

The formulae for the latent and sensible fluxes are essentially identical to those used by all other authors. The net solar flux equation is that of Reed (1977) and was judged among the best in the recent review by Dobson and Smith (1988). The net infrared flux formula is similar to that due to Berliand and Berliand (1952) and is similar to most of those used in the literature.

A large number of possible factors contribute to uncertainties in area-time mean estimates of the heat fluxes using these formulae and archives of the marine weather reports. Generally, these include basic errors in the observations, sampling and archiving errors and uncertainties in the bulk formulae themselves. In this paper, careful attention will be given to categorizing these errors or uncertainties as random or systematic. Random errors are those which will be reduced in space-time averages involving many individual observations. Systematic errors will be those which will remain the same regardless of how many observations are averaged together. An important notion with respect to the establishment of systematic errors, is that such errors exist only if the observational data or the averaging methods used in applying marine weather reports to the bulk formulae differ from the data or the averaging methods used originally to derive the bulk formulae. Thus 10 m level wind speeds do not necessarily have systematic errors in estimating the surface sensible heat flux, since the bulk formulae were derived with the 10 m rather than near surface winds.

To illustrate the methods to be used, consider eq. (1) for the net solar flux at the ocean surface. Let us assume that there is a random error in the estimate of cloudiness C and a systematic error in the formula associated with the parameter A. The uncertainty in the flux associated with each error may be estimated by differentiating eq. (1) with respect to the variable of interest and multiplying by the independently estimated errors in C or A. The total uncertainty in the flux then will be given by

$$\sigma_{Q_s} = \sqrt{\left(\frac{\partial Q_s}{\partial A}\Delta A\right)^2 + \left(\frac{\partial Q_s}{\partial C}\Delta C\right)^2} \tag{5}$$

where ΔA and ΔC are the assumed uncertainties in A and C. This σ_s would be the uncertainty for an individual flux estimate. The uncertainty for an average flux made up of N observations would be given by

$$\overline{\sigma_{Q_s}} = \sqrt{\left(\frac{\partial Q_s}{\partial A}\Delta A\right)^2 + \left(\frac{\partial Q_s}{\partial C}\Delta C f(N)\right)^2}, \tag{6}$$

where $f(N)$ is a function giving the reduction of the random error associated with N observations. Note that the term associated with the systematic uncertainties in the formula represented by ΔA does not have the $f(N)$ reduction factor.

3. Basic measurement and estimation errors

From eqs. (1)–(4), it can be seen that the basic data used to calculate the energy fluxes are T_a, T_s, T_d (dew point temperature), V and C. There have been a number of reports, which have estimated the largely random uncertainties associated with for instance the thermometer readings. From Sarachik (1984) errors for T_a, T_s and T_d have all been assigned as ± 1.0; those for V as ± 2 m s^{-1} and those for C as ± 0.2.

Whereas there is general agreement as to the nature and magnitude of these random errors for regular ship-derived measurements, there are many more questions and considerable disagreements as to the nature of magnitude of any systematic errors. The best known candidate is that of T_s. Saur (1963) compared T_s observations taken from a weather ship using carefully calibrated insulated buckets for a number of months with the means derived from engine-intake temperature observations taken by nearby ships. He concluded that the ships were systematically too warm by ~ 0.7°C. Subsequent papers (e.g., James and Fox, 1972) come to similar conclusions but find that the differences are quite strong functions of location and season. Since the ship records which Saur and the other authors utilized, were largely derived from engine-intake water temperature measurements, it has often been assumed that this error is absent for the earlier measurements (pre 1950) which mainly used bucket-derived temperatures. However, this is presently quite uncertain because of uncertainties in just what fraction of recent measurements are from engine intake or buckets and because the buckets which were often used in the past were often uninsulated and thus also subject to considerable errors, especially in regions of high winds and large air–sea temperature differences. For the present the systematic measurement uncertainty in T_s is assigned to be ± 0.5°C.

For many years it was generally assumed that the T_a measurements did not have systematic errors comparable to those in T_s. Recently, however, Barnett (1983) and Weber (1985) have shown shifts in decadal T_a means, which seem to be related to changes in the methods of measuring T_a. In particular, Weber (1985) showed that the mean diurnal cycle of T_a has changed quite dramatically, suggesting that many daytime measurements are improperly shaded from direct sunlight. While at the present time it is difficult to assign a definitive uncertainty to T_a, it seems that it is likely to be around ± 0.5°C. This value will be used here.

If T_a has systematic errors, it might seem likely that T_d would also have these errors. However, this does not seem to be the case. T_d is generally measured by using a sling psychrometer which usually will be well ventilated and thus unlikely to lead to systematic errors. Thus the systematic error in T_d is assigned to be $\pm 0°C$.

Wind measurements over the ocean are taken from Beaufort estimates of sea state or direct anemometer observations. It would seem that the latter, a direct observation, would be unbiased. However, uncertainties do exist concerning systematic errors from poor corrections to the 10 meter level assumed in the bulk formulae and due inadequate correction for ship motion in the observations. Even today, the majority of wind measurements are from Beaufort estimates of the sea state. A number of earlier studies have found these to be remarkably accurate and thus the World Meteorological Organization has defined a scale to convert these to the wind speeds in m s^{-1}, which are used in the formulae. Taylor (1984) has summarized several studies which compared these Beaufort derived wind speeds and those from anemometer measurements on weather ships and exposed land stations and has found systematic differences of about 1 m s^{-1}. These differences seem to be a function of mean wind speed. In the present calculations a systematic uncertainty in all wind estimates of ± 1 m s^{-1} is assumed.

Estimates of fractional cloudiness by surface observers are notoriously difficult to make. Systematic differences between surface based estimates and those from satellites or aircraft are inevitable due to the different fields of view and the obscuring of high clouds by lower clouds for the surface observer and low clouds by high clouds for the satellite observation. On the other hand these problems do not lead to a systematic error in the radiation formulae, because all such formulae were derived originally using only surface-based observer estimates. Thus the systematic uncertainty in C is assigned to be ± 0.

Table 1 shows the uncertainties of individual estimates of each of the fluxes due to random and systematic errors or uncertainties in the basic observations. Also included in Table 1 are means of each of the fluxes representative of the tropical Pacific Ocean. The random errors for all four fluxes are relatively large, those for the latent heat being the largest. The systematic errors are smaller, but here, too, the largest contribution is in the latent heat flux.

Table 1. *Uncertainties in the heat fluxes associated with basic measurements of T_s, T_a, T_d, V and C and typical mean values of the four fluxes*

		Q_S	Q_I	Q_E	Q_H
random	(W m^{-2})	± 34	± 7.7	± 67	± 10.7
systematic	(W m^{-2})	0	± 1.0	± 28	± 5.4
typical values	(W m^{-2})	220	35	150	10

4. Parameterization errors

A large number of both random and systematic errors are possibly arising from the use of the bulk formulae. This is especially true because the number of high-quality direct observations of the fluxes used to develop the parameterizations is relatively small. Also making these measurements over the open sea is extremely difficult so that the direct measurements themselves may be relatively uncertain.

Simpson and Paulson (1979) have discussed some of the problems in measuring net solar and infrared radiation at the sea surface. These include difficulties in calibrating sensors, the effects of ship motion, shadowing effects of the hull and problems due to inadequate sampling of the large variations of cloudiness seen in nature. They estimate experimental errors of the highest quality measurements to be about $\pm 5\%$.

A number of intercomparisons of the various sensors used to make eddy-correlation measurements of the moisture flux have been made. For instance, Takeuchi et al. (1980) have compared latent heat flux measurements using a sonic anemometer and two different moisture sensors, a fine-wire thermocouple psychrometer and an infrared hygrometer. They conclude that the slower response psychronometer underestimates the moisture flux by about 10%. Several unpublished intercomparisons of the sonic anemometer-fast-response-moisture-sensor fluxes suggest random errors of half-hourly measurements of about 10% (R. H. Shaw and T. Maitani, personal communication).

Dobson and Smith (1988) have carefully compared various bulk formulae for Q_s with weather ship and island observations and found for monthly averages that the formula proposed by Reed (1977) was the best. However, the uncertainties of individual estimates due to the variations in cloudiness was large, giving rise to random uncertainties of single observations of about 70 W m^{-2}. Formulae, which attempted to use cloud type information were incapable of substantially reducing the errors. In an average of a large number of observations the Reed formula was found to give a systematic difference of only about 1 W m^{-2}. In the current analysis both of these uncertainties are ascribed to the cloudiness coefficient A in eq. (1).

Simpson and Paulson (1979) and Fung et al. (1984) have made fairly comprehensive reviews of the uncertainties in the formulae for the net infrared flux. All such studies are hampered by the extreme lack of direct observations over the oceans. The authors of both papers find that the formula proposed by Berliand and Berliand (1952) is probably the best for clear sky conditions. From the Simpson and Paulson results one may assume random errors under cloudy conditions of about ± 5 W m^{-2}. Fung et al. (1984) suggest that the Berliand formula under clear sky conditions has systematic differences compared to exact radiative transfer calculations under wet and dry atmospheric conditions of approximately ± 5 W m^{-2}. In the uncertainty analysis the random errors are associated with the cloudiness factor B in eq. (2) and the systematic uncertainties are for convenience associated with the emissivity ε in the same equation.

Blanc (1985) has undertaken a complete review of all of the parameterization of the latent and sensible heat exchange coefficients, C_E and C_H, based upon direct observations. He found that the values of C_E plotted against wind speed differ substantially so that the range of coefficients based upon apparently equally good data vary by about 12% of the mean. This value is assumed to be the magnitude of the systematic uncertainty in C_E in eqs. (3) and (4).

Anderson and Smith (1981) looked at the random uncertainties in one of the formulae reviewed by Blanc. Using most of the direct measurements available at that time, they conclude that the exchange coefficient adjusted to neutral stability is 1.27 ± 0.26 and that it has therefore an uncertainty of about 20%. Unfortunately, the limitations of the direct measurements have allowed few comparisons at wind speeds greater than 11 m s^{-1} or over the open ocean. Here it is assumed that the Anderson and Smith results are representative of the random errors in C_E in both eqs. (3) and (4).

Table 2. *Uncertainties in the heat fluxes associated with the uncertainties in the bulk formulae parameterization*

		Q_S	Q_I	Q_E	Q_H
random	(W m^{-2})	± 72	± 5.0	± 35	± 2.0
systematic	(W m^{-2})	± 5.0	± 5.0	± 21	± 1.2

Table 2 gives the random and systematic uncertainties in each of the heat fluxes due to the uncertainties and scatter associated with using the bulk formulae, even if the meteorological data base were perfect. In this case the random uncertainty for the net solar flux is very large with that for the latent heat flux also comparable to that of the random uncertainty associated with errors in the observations. In all cases the systematic uncertainties associated with deriving the formulae are relatively small, although that for the latent heat is likely to be important. Blanc (1987) has provided complementary estimates of these uncertainties.

5. Sampling

A basic question is how many observations are required for acceptable uncertainties in the basic observations and heat fluxes? This question may be approached from a variety of tacks.

The simplest way to estimate the minimum number of observations required is to use simple sampling theory. As verified by Hanawa (1987), if the observational errors are all random, the uncertainties should decrease by the factor $1/\sqrt{N}$, where N is the number of observations. However, it is quite clear that the actual observations may not be truly random so that uncertainties may not decrease this quickly with additional observations. Other tests are necessary.

Ramage (1986) has analyzed the data at Ship N (30°N, 145°W) comparing average observations taken aboard this weather ship every three hours with those of varying numbers of commercial ship observations. He concludes that for T_s and T_a there is no relation between number of commercial ship observations and the correlations with the weather ship monthly means. However, for wind speed correlations increased from 0.11 to 0.69 to 0.80 when the number of monthly observations increased from less than 10 to 11–20 to greater than 20. Thus it can be concluded that very few temperature measurements are probably adequate, but greater than 20 wind measurements in a month are required. Although Ramage did not look at cloudiness, the number of required measurements is probably intermediate.

The intramonthly variances of T_s, T_a and the zonal component of the wind have been compared for each month for 5° grids in the tropical Pacific. In general, as found by Ramage, there does not seem to be a clear cut relationship between the variances for T_s and T_a and the number of observations. However, for the zonal wind over sizable regions of the tropical Pacific the average intramonthly variance, when there are between 2 and 11 observations, is about 5 $m^2 s^{-2}$ greater than when there are between 11 and 20 observations. More observations do not seem to further reduce the variance. These results would suggest that when there are less than 11 observations the uncertainties in monthly mean wind are increased by around 2 $m s^{-1}$.

Fissel et al. (1977) used time spectra of Ship P (50° N, 145° W) to estimate the required interval of observations to sample all important periodicities. They found that sampling frequencies of greater than once a day are adequate for this middle latitude region. It would require more than 50 observations per month to guarantee this sampling at the 95% confidence level. Less observations would presumably be required at low latitudes, but no equivalent study has been done for these latitudes.

While it is difficult to definitely state how random errors decrease with increasing numbers of observations, the studies mentioned above lead one to conclude that the simple sampling theory is generally correct, except perhaps for wind observations. In any case it will be assumed that all random errors will be reduced by $1/\sqrt{N}$.

In addition to uncertainties associated with random sampling errors, systematic sampling errors may also be present. Such errors could arise if, for instance, there is a significant diurnal variation and the local night times are undersampled. Weare and Strub (1981) found that in sample coastal regions cloudiness may have the largest systematic diurnal errors. Nevertheless, they conclude that such systematic errors are likely to be small. In another study, Ramage (1986) has found substantial differences at several weather ship locations in the number of commercial marine reports in various pentads of a month. He made no estimate of the effects on the results. In conclusion, if the averages of concern are for a month over grids of 5° × 5° or smaller and if there are at least 10 observations in the sample, then in the tropics there seems to be little systematic bias due to sampling.

For a number of years there was considerable debate as to the proper method of treating the observations in order to arrive at proper monthly averages of the heat fluxes. The problems arise in the inherently nonlinear latent and sensible heat formulae. Esbensen and Reynolds (1981) compared flux calculations in which the basic meteorological observations were first averaged with calculations where individual flux estimates were averaged. They found the differences between monthly means of the fluxes to be less than 10% and thus concluded that the simpler preaveraging method was appropriate. However, more recently Hanawa and Toba (1987) have concluded that preaveraging of the latent heat flux results in an overestimate of about 5% compared to the more appropriate average flux method. After the fact corrections could reduce this error to near zero.

6. Total uncertainties

Table 3 shows the total estimated uncertainties due to random and systematic errors in the

Table 3. *Total uncertainties in the heat fluxes associated with both random and systematic uncertainties and errors in the basic observations and parameterizations for averages of N observations; all uncertainties are in W m⁻²*

	Q_S	Q_I	Q_E	Q_H
$N = 1$	±80	±10.5	±83	±12.4
$N = 10$	±26	±5.9	±42	±6.8
$N = 50$	±12	±5.3	±36	±6.1
$N = \infty$	±5	±5.1	±35	±5.9

observational data used in the formulae and in the parameterizations of the formulae themselves for averages of 1, 10, 50 and an infinite number of observations. The latter case corresponds to the contribution of the systematic uncertainties alone. One interesting fact in Table 3 is that for a single observation the uncertainties in the two most important flux terms, the net solar radiation and the latent heat flux, are nearly the same, i.e., approximately 80 W m^{-2}. As the numbers of observations included in an average increase, the uncertainty in the solar flux decreases much more rapidly than that of the latent heat flux. Therefore, for 50 observations the uncertainty for the solar irradiance is down to around the ± 15 W m^{-2}, established as a target by the Tropical Ocean Global Atmosphere (Webster and Fieux, 1984). On the other hand, the uncertainty of the latent heat flux is unacceptably large even with a very large number of observations, due to the large systematic uncertainties in this term.

While estimates such as in Table 3 are useful, it is known that data densities vary considerably over the world ocean contributing to substantial variations in uncertainties. Fig. 1 shows the square root of $\frac{1}{12}$ of the total number of observations over the tropical Pacific in the 1957–76 period used in the analyses of Weare et al. (1981). The total number has been divided by 12 to give numbers representative of those available for each calendar month in the 20-year monthly means of the heat fluxes. Obvious data-void exist along much of the equator and in the southeastern ocean.

Figs. 2–5 show the total uncertainties, random and systematic, of each of the heat fluxes based upon the error analyses of Sections 3–5 and the numbers of observations indicated in Fig. 1. Figs. 2–5 also show the mean annual heat fluxes. These mean fluxes are identical to those in Weare et al. (1981), except for the latent and sensible heat fluxes. In these cases the fluxes have been multiplied by $1.3 \times 10^{-3}/\overline{C}_E$ where $\overline{C}_E$ is the mean exchange coefficient used in calculating the original results. This adjustment seems appropriate, since the analyses of Blanc (1985) showed that the tabulated C_E's suggested by Bunker (1976) and used by Weare et al. were systematically too large and varied too strongly as a function of wind speed. Blanc suggested that a better estimate of C_E is a constant value of 1.3×10^{-3}, which is what this adjustment results in.

Looking at the important solar and latent fluxes shown in Figs. 2 and 4, several conclusions are evident. Outside of the near equatorial zone and the southeastern ocean uncertainties in the mean net solar flux are 5–10% of the mean. Those for the latent heat flux are approximately 20–35% of the mean regardless of location. Again, the large systematic component of the uncertainties in the latent heat flux is evident. The uncertainties in the less important net infrared and sensible heat fluxes are also substantial when viewed as percents of the mean values. However, the relatively small absolute values of these latter uncertainties will mean that they have a small effect on the total uncertainty in the net heating at the ocean surface or in estimates of the meridional transport of energy by the oceans.

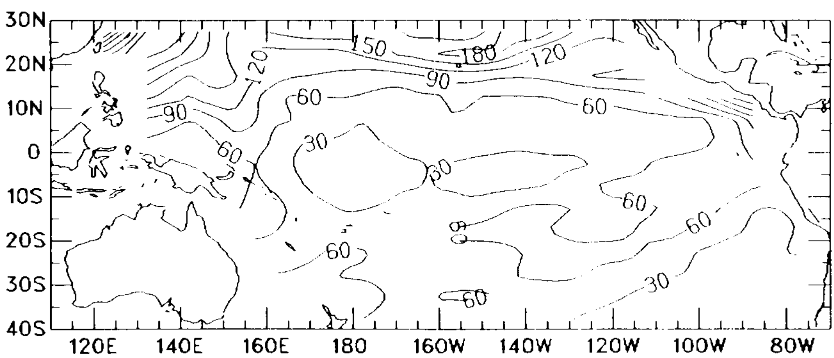

Fig. 1. Square root of the total number of marine observations N divided by twelve ($\sqrt{N/12}$) for the 1957–76 period from Weare et al. (1981).

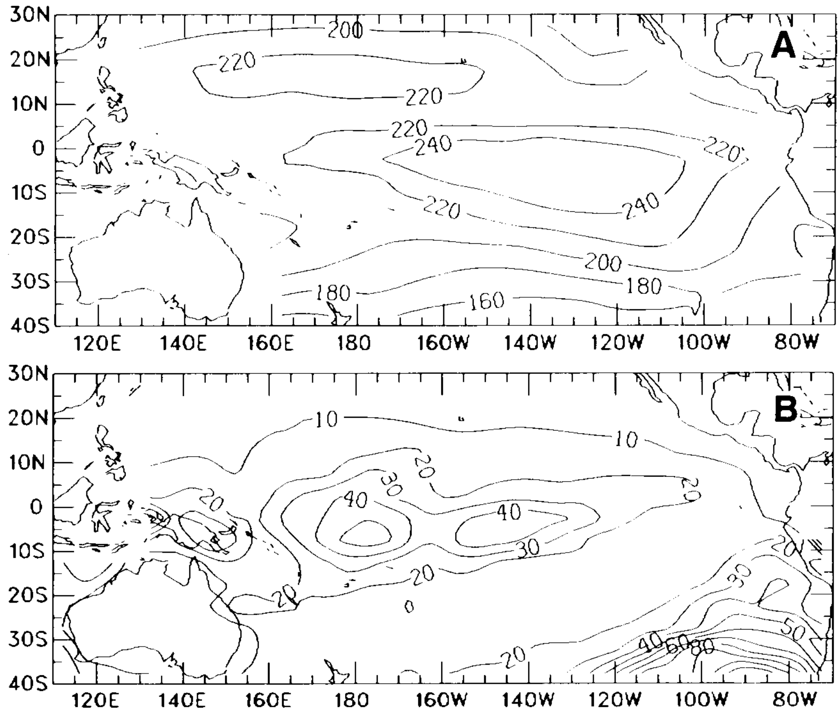

Fig. 2. (a) Annual mean net solar irradiance at the surface of the tropical Pacific Ocean from Weare et al. (1981). (b) Total uncertainty in the net solar irradiance based upon the analyses in Sections 2–5 and the number of observations illustrated in Fig. 1 (W m^{-2}).

That net heating of the ocean surface is given by

$$Q_N = Q_S - Q_I - Q_L - Q_H. \tag{7}$$

The total uncertainty in the net heating is found by

$$\sigma_N = \sqrt{\sigma_s^2 + \sigma_I^2 + \sigma_L^2 + \sigma_H^2}, \tag{8}$$

where σ_s, σ_I, σ_L and σ_H are the total uncertainties of the solar, infrared, latent and sensible heat fluxes, respectively. The 1957–76 annual mean net heating and total uncertainty were calculated from the results illustrated in Figs. 2–5 and are shown in Fig. 6. It should be noted that the Q_N illustrated here differs somewhat from that in Weare et al. (1981) because of the changes in Q_L and Q_H mentioned above. In general the current map has larger areas of net heating and fewer regions with cooling greater than 30 W m^{-2} compared to the earlier map. The total uncertainties (Fig. 6b) are generally larger than the net heating itself, with the exception of the eastern equatorial and possibly the western equatorial zones. Perhaps most discouraging is the fact that north of 10° N where the number of observations is relatively large and the individual heat fluxes are relatively certain the net heating is very uncertain even as to its sign.

The results illustrated in Figs. 2–6 have so far been compared with the absolute values of the fluxes. Often one is concerned with differences of a flux value from the long-term annual or monthly mean, in which case the systematic errors are assumed to largely cancel. Figs. 7 and 8 show the total random uncertainties of the solar and latent heat fluxes based upon the conclusions in Sections 3–5 and the number of observations illustrated in Fig. 1. Also shown in Figs. 7 and 8 for comparison are the standard deviations σ of the 1957–76 monthly means. These were calculated using

$$\sigma^2 = \sum_{m=1}^{12} (F_m - F_A)^2/11, \tag{9}$$

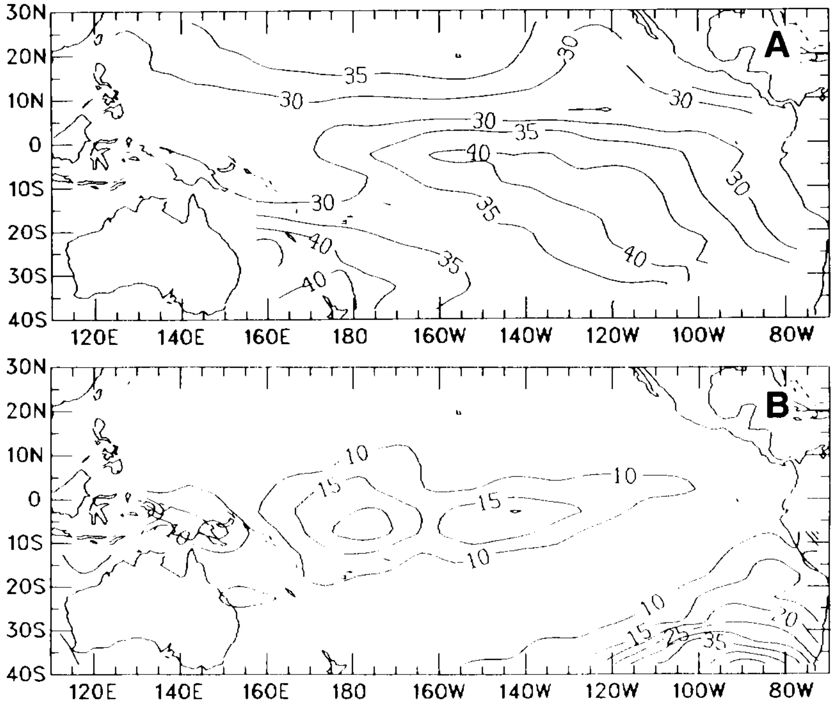

Fig. 3. (a) Annual mean net infrared irradiance and (b) total uncertainty as in Fig. 2.

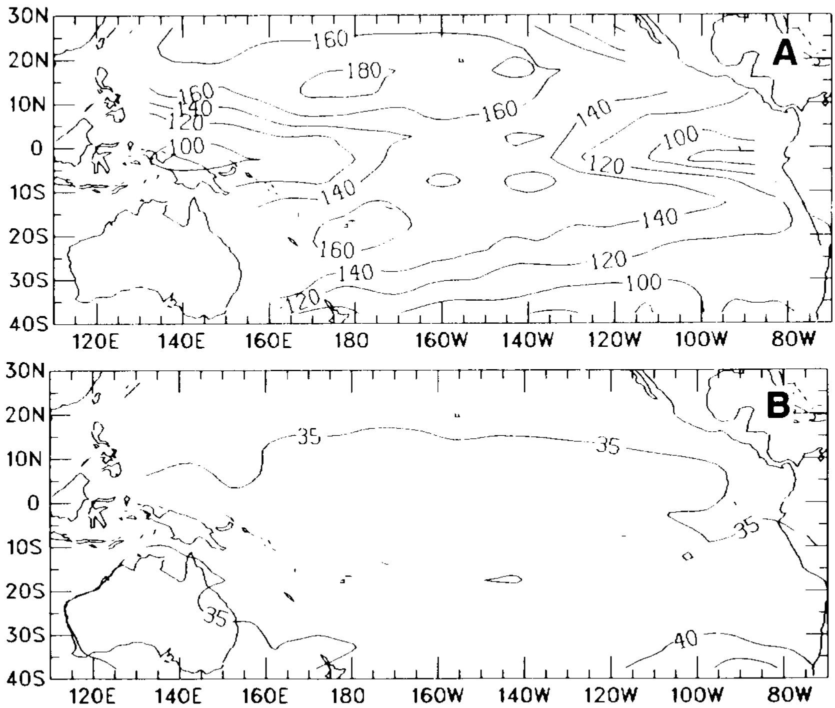

Fig. 4. (a) Annual mean latent heat flux and (b) total uncertainty as in Fig. 2.

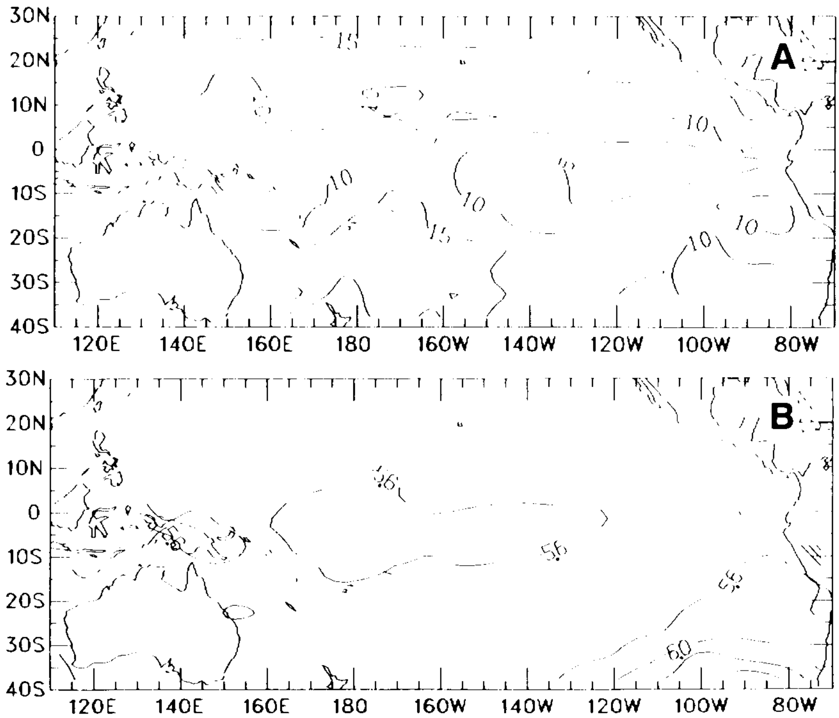

Fig. 5. (a) Annual mean sensible heat flux and (b) total uncertainty as in Fig. 2.

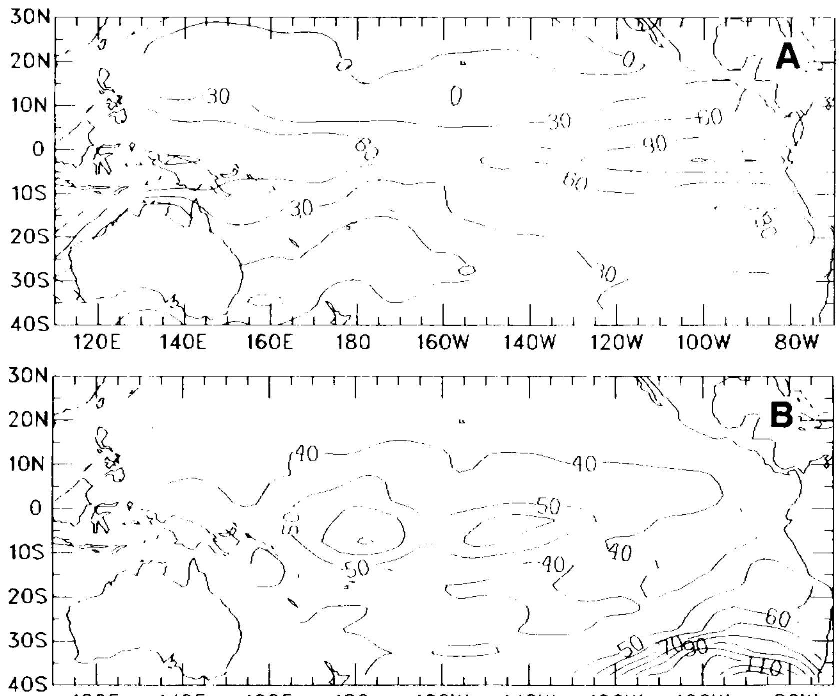

Fig. 6. (a) Annual mean net heat flux and (b) total uncertainty as in Fig. 2.

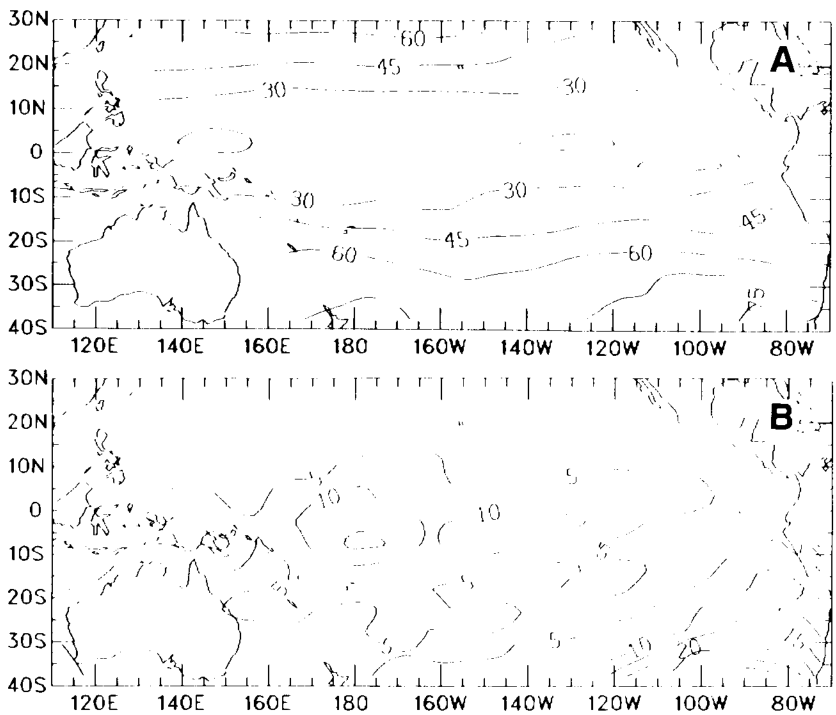

Fig. 7. (a) Standard deviation of the seasonal cycle of net solar irradiance at the surface of the tropical Pacific Ocean as calculated from eq. 7. (b) Total random uncertainty in the solar irradiance, based upon the analyses in Sections 2–5 and the number of observations in Fig. 1 (W m^{-2}).

where F_m is the 20-year mean flux for a particular calendar month and F_A is the annual mean flux. Fig. 7 suggests that the variations of monthly means of net solar irradiance about the long term annual means have uncertainties of about 8–20% of these standard deviations poleward of about 10°N and 10°S. Those for the latent heat fluxes (Fig. 8) away from the data sparse regions are between approximately 10 and 30% of the standard deviations. Thus random uncertainties relative to the annual cycles of the latent heat and solar fluxes are comparable.

7. Discussion

Many random and systematic sources of uncertainties in the heat fluxes at the ocean surface have been identified. A simple error analysis has been used to estimate their contributions to the flux estimates based upon vastly variable numbers of basic observations. In general it can be concluded that estimates of climatological mean fluxes have uncertainties of approximately 15 W m^{-2} in those regions of the tropical oceans which are reasonably well sampled. The exception to this statement is the surface flux of latent heat which has uncertainties in the climatological means of greater than 30 W m^{-2} everywhere.

Estimates of any of the surface fluxes for individual months will have total uncertainties greater than 15 W m^{-2}, since the number of observations in the means will be relatively small and thus the random uncertainties will be relatively large. If for monthly means, changes in the fluxes and not absolute values are desired, then the systematic uncertainties should be inconsequential and only random uncertainties would remain. Under these circumstances with 10 observations the solar and latent heat fluxes would have uncertainties of about 25 W m^{-2} and the other two smaller fluxes uncertainties of about 3 W m^{-2}.

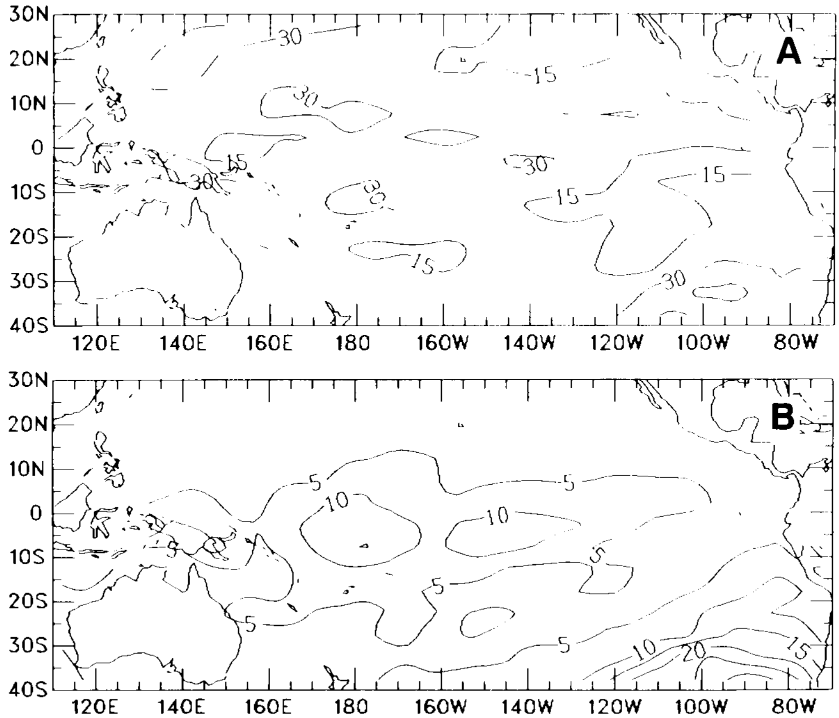

Fig. 8. (a) Standard deviation of the seasonal cycle of latent heat flux and (b) total random uncertainty as in Fig. 7.

All of the conclusions thus far have been assumed to be appropriate for the tropical and subtropical oceans. However, most of the assumptions and conclusions made concerning basic measurement errors and parameterization uncertainties are probably equally applicable to higher latitudes. The factor that may not be appropriate for higher latitudes is the assumption that the reduction of random errors during averaging would follow simple sampling theory. The known large day to day variability in middle latitudes could easily make this assumption inappropriate. Thus it seems necessary to derive a more relevant sampling theory for such regions and test that theory in areas of large numbers of observations, such as in the vicinity of weather ships. This new theory may also be more applicable than the one employed here at low latitudes as well.

A major conclusion of this study is that for averages involving modest numbers of observations the systematic errors introduced by uncertainties in basic measurements and the parameterization are comparable to the random errors. This conclusion is on the one hand encouraging and on the other hand discouraging. It is discouraging because it implies that even many more observations, for instance from additional ships whose data are presently not archived or from special drifting buoys, may not appreciably improve the uncertainties in our estimates, except in a few regions of very low numbers of observations. However, the conclusion is also encouraging because these systematic errors, in principle at least, may be investigated and corrected. Thus it would seem very important, for once and for all, to fully quantify the apparent bias in sea surface temperatures in terms of such factors as whether the basic measurement is an uninsulated bucket or engine intake temperature, the latitude, season, reporting hour and cloudiness. Similar statements could be made about the apparent biases in air temperature and wind speed. Also, stronger efforts might be made to remove the biases at the time of the measurements by improving the observational methods, rather than trying to remove the biases after the fact.

The systematic uncertainties in the parameterization of the bulk formulae are equally or even more important problems. More high quality direct observations of all fluxes must be made in order to assure unbiased formulae with minimal variance. The latent heat flux measurements are especially problematic. Its uncertainties are large and even current experimental methods using satellite data (Liu, 1984) rely upon this bulk formula. More direct observations must be made over the open ocean with a larger range of wind speeds and sea states. Also consideration should be given to measurements in convective regimes of very low mean winds where intercloud dry downdrafts may contribute substantially to the overall flux of latent heat.

Finally, it seems imperative that in all observational studies, either using traditional or satellite observations based upon multiple measurements and complex empirical formulae, formal error estimates as well as mean values should be presented.

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