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The significance of sampling biases on calculated monthly mean oceanic surface heat fluxes

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ABSTRACT

The possible influence of spatial gradients and seasonal and diurnal cycles in basic meteorological parameters on the accuracy of monthly five degree latitude–longitude mean ocean surface flux calculations is explored. A simple formalism for assessing the importance of these possible biases is outlined. Data for two sample eastern Pacific regions shows possibly significant biases in one or more variables. The effect of the bias on the 20-year means of the fluxes would appear to be less than 1% of the variance or about 10% of the mean. The influence of the biases on individual monthly means could be far greater depending upon the number and distribution of available observations. It is suggested that in tropical and subtropical regions free of tropical storms about eleven observations is the minimum number of observations to assure the accuracy of individual monthly fluxes.

1. Introduction

Vertical surface fluxes of energy and momentum are the primary means of communication between the oceans and atmosphere. Climatological averages of these fluxes over large regions of the world oceans have been calculated and displayed by a number of authors (e.g., Budyko, 1963; Wyrtki, 1965; Bunker and Worthington, 1976; Hastenrath, 1977). These have been computed for each calendar month for grids varying from one degree latitude–longitude to approximately ten degrees latitude–longitude using summaries of marine weather observations. Accurate determination of the climatological means is essential in providing proper boundary conditions for both oceanic and atmosphere general circulation models as well as diagnostic analyses of the mass and energy budgets of each system. Individual monthly means of the fluxes averaged over 5° or 10° grids have also been calculated (e.g., Clark, 1967; Ramage et al., 1972; Bunker, 1976). These computed heat flux analyses may help to elucidate the spatial and temporal patterns of such large-scale air–sea interaction phenomena as El Niño and the Indian summer monsoon.

Although the above-mentioned authors have calculated the fluxes slightly differently, they have all relied upon similar formulations of the so-called bulk formulae. In the present paper we shall refer to the following set

$$LE = \rho L C_E |\vec{V}| (q_s - q_a) \quad (1)$$

$$H = \rho C_p C_E |\vec{V}| (T_s - T_a) \quad (2)$$

$$S = S_0(1 - 0.62C + 0.0019\alpha) \quad (3)$$

$$I = \varepsilon\sigma T_s^4(0.39 - 0.05e^{1/2}) + 4\varepsilon\sigma T_s^3(T_s - T_a) \quad (4)$$

$$\tau = \rho C_D U^2 \quad (5)$$

LE, H, S, I and τ are the vertical surface fluxes of latent heat, sensible heat, solar radiation, infrared radiation and wind stress, respectively. The other symbols generally follow the usual meteorological conventions. In addition, C is the fractional cloud cover, α the noon solar altitude and S_0 the clear sky solar flux at the surface. The important meteorological parameters, derived from meteorological reports from an assortment of merchant,

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naval and research vessels, are windspeed, air, sea and dewpoint temperatures, and observer estimates of cloud cover. Generally, observations made at any reporting hour are included in the calculations.

The accuracy of the derived areal average climatological and year–month fluxes are of concern. Errors, sufficient to cast doubt on their validity, may arise from a number of important causes.

1. The bulk formulae themselves, especially those for the radiative fluxes, are subject to considerable uncertainty. This is in part because marine reports do not give sufficient information to discern the profile of the lower atmosphere as well as a lack of adequate verification of formulae, largely derived for continental conditions, over open ocean. The latter is especially true of the very important solar flux under cloudy conditions (see Simpson and Paulson, 1979).

2. The number of marine reports available from commercial shipping may often be insufficient to sample all the weather events that may be encountered in a given month in say a 5° grid. In high or middle latitudes storms are often insufficiently sampled which would tend to give rise to underestimates of the sensible and latent heat and wind stress fluxes, the so-called fair weather bias. A less important bias certainly exists in tropical regions with respect to tropical cyclones.

3. The marine weather reports, often made by ill-trained observers using sometimes poorly calibrated equipment, may have important systematic errors. Saur (1963), who compared reported temperatures taken from the cooling intake for the engines with simultaneously measured "bucket" temperatures, found an average difference of 0.6*C*. There is also reason to believe that the air flow over a ship superstructure would perturb wind velocity and air and dewpoint temperatures (Bunker, 1976). Clark (private communication) has also suggested that ship observer cloud estimates are significantly different from those derived from satellites.

4. Systematic errors may also arise from irregular sampling of weather parameters within a day, within a month, or spatially within the chosen grid. The first bias would arise if there were an important diurnal variation and if the four primary reporting hours were not equally sampled. Similarly in a region with a strong season cycle, uneven sampling throughout a month could give rise to an error in the calculated mean of the meteorological parameters and the energy or momentum fluxes. Spatial gradients could give rise to unrepresentative fluxes if, for instance, a shipping lane crossed only one corner of the grid.

5. Excessive random errors in the weather parameters could arise because of gross observer mistakes or transmission or archival problems. A review of the marine reports of the world shows a number of observations in the middle of the Sahara desert.

During the process of calculating a set of monthly mean heat and momentum fluxes for the tropical Pacific, we have become interested in ascertaining the contribution of each of the above errors to the final computed fluxes. In this paper we will concentrate on the possible significance of sampling biases on *monthly means over a 5° grid*, e.g. those which might arise from the combination of substantial diurnal variation together with an uneven sampling with respect to hour or from a strong seasonal trend within a month and an oversampling of the earlier or latter part of the month or a strong spatial gradient and observations primarily in one region of the grid. In the remainder of this paper we will refer to all of these possible errors as "bias". We have chosen to concentrate on them because they may easily be analyzed using long-term statistics of individual observations and because they may, in principle at least, be largely rectified by a proper weighting of the observations.

2. Method of analysis

In order to derive the most clearcut estimate of the importance of one or more of the systematic errors, we have chosen to follow the formal error analysis outlined by Beers (1957). Given a function H of sampled independent variables x and y in which the mean of H is given by $\overline{H}(x, y) = H(\bar{x}, \bar{y})$, the standard deviations of x and y by s_x and s_y and the correlation between x and y by ρ_{xy}, the variance of H is

$$V_H = \left(\frac{\partial H}{dx}\right)^2 s_x^2 + \left(\frac{\partial H}{\partial y}\right)^2 s_y^2 + 2\rho_{xy}\left(\frac{\partial H}{\partial x}\right) \times \left(\frac{\partial H}{\partial y}\right) s_x s_y \quad (6)$$

It may be assumed that the variances of variables x and y are due to both random and systematic variations. In the present context, systematic variations are those which might be attributable to the temporal or spatial biases. Labelling the random and systematic standard deviations with subscripts r and s, respectively,

$$s_x^2 = s_{xr}^2 + s_{xs}^2 \quad s_y^2 = s_{yr}^2 + s_{ys}^2$$

If one assumes

$$s_{xr}\, s_{ys} - s_{xs}\, s_{yr} \ll s_{xr}\, s_{yr} + s_{xs}\, s_{ys}$$

then the variance of H due to the systematic errors is

$$V_{Hs} = \left(\frac{\partial H}{\partial x}\right)^2 s_{xs}^2 + \left(\frac{\partial H}{\partial y}\right)^2 s_{ys}^2 + 2\rho_{xy}\left(\frac{\partial H}{\partial X}\right)\left(\frac{\partial H}{\partial y}\right) s_{xs}\, s_{ys} \tag{7}$$

The fraction of variance due to systematic errors is given by the ratio of eq. (7) over eq. (6)

$$F_s = V_{Hs}/V_H$$

The systematic standard deviations may be estimated from the average deviation (Beers, 1957). For example, if x and y are linear functions of a third variable z, then

$$s_{xs} = \overline{\frac{\partial x}{\partial z}}\, \overline{\Delta z}(1.25) \quad s_{ys} = \overline{\frac{\partial y}{\partial z}}\, \overline{\Delta z}(1.25) \tag{8}$$

where the overbars denote means of the gradients and departures. The factor 1.25 is that which relates an average deviation to a standard deviation for a normally distributed variable (Beers, 1957).

In order to estimate the effect of the systematic errors the data for a number of 5° grids in the equatorial Pacific were analyzed. The data used were the individual marine weather reports archived at the U.S. National Climatic Center for 1957–74 which were kindly supplied by the U.S. Fleet Numerical Weather Central. These were merged with the ship radio weather reports for 1972–76 archived by the Southwest Fisheries Center. Duplicates and gross errors were eliminated and observations were sorted chronologically within each 1° grid.

We have chosen to concentrate on the two heat fluxes which are numerically the most important, the latent heat and solar radiation. If, as is generally true, one assumes that ρ, L, C_E and S_0 are nearly independent of the marine weather measurements, then the important variables are the magnitude of the wind (V), the difference between the saturation humidity at the sea temperature and the measured humidity (Δq) and the fractional cloudiness (C). The total variance of LE is given by

$$V_{LE} = \rho^2\, C_E^2\, L^2 \times [\overline{\Delta q}^2 s_V^2 + \overline{V}^2 s_{\Delta q}^2 + 2\rho_{V\Delta q}\, \overline{V}\, \overline{\Delta q} s_V\, s_{\Delta q}] \tag{9}$$

The total variance of S is given by

$$V_S = S_0^2 (0.62)^2\, s_C^2 \tag{10}$$

The variance due only to the systematic errors in V, Δq and C is expressed by equations similar to eqs. (9) and (10) except that the standard deviations are replaced by the estimated standard deviations which result from the biases.

In order to compute the interannual variance in the estimates of latent heat or solar fluxes from eqs. (9) or (10), a number of statistical properties must be derived for the calendar month in question. These include the 20-year monthly mean values of the windspeed, fractional cloudiness and the difference between the saturation specific humidity for the ocean surface temperature and the specific humidity measured on board ship. This latter quantity will be referred to as the humidity difference. One must also have measurements of the standard deviation of these three parameters as well as the correlation between deviations in windspeed and those in humidity difference. In addition, in order to estimate possible average deviations due to systematic biases in sampling, it is necessary to generate long-term statistics of the variations of V, C, Δq with respect to observing hour, season and location within the grid and the likely biases in the number of observations in a particular areal or time interval.

3. Data

Fig. 1 illustrates the regions for which the entire record of individual observations for the months of January, April, July and October were analyzed. These regions were chosen in part because they are quite representative of the different temperature, wind and cloudiness regimes over the ocean and in part because these grids were known to have a sufficiently large number of observations to give reliable estimates of means, standard deviations and correlations. Many of the grids illustrated

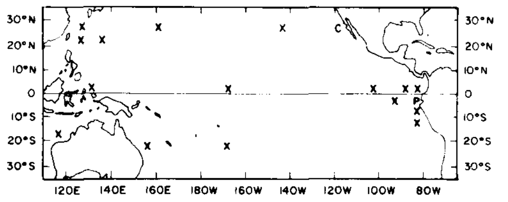

Fig. 1. Crossed regions are those locations for which preliminary bias analyses were carried out. Regions C and P are those used in the more detailed study described in the text.

possibly significant biases in one or more seasons. However, we have chosen to illustrate the results for only two regions, one near the coast of Baja California labeled C on Fig. 1 and one in the equatorial Pacific just west of Peru labeled P. These were chosen because they seemed typical of middle latitude and equatorial regions which displayed important spatial or temporal biases.

Figs. 2, 3 and 4 show for area C the variation of the means of the windspeed, humidity difference, and total cloudiness respectively, with respect to

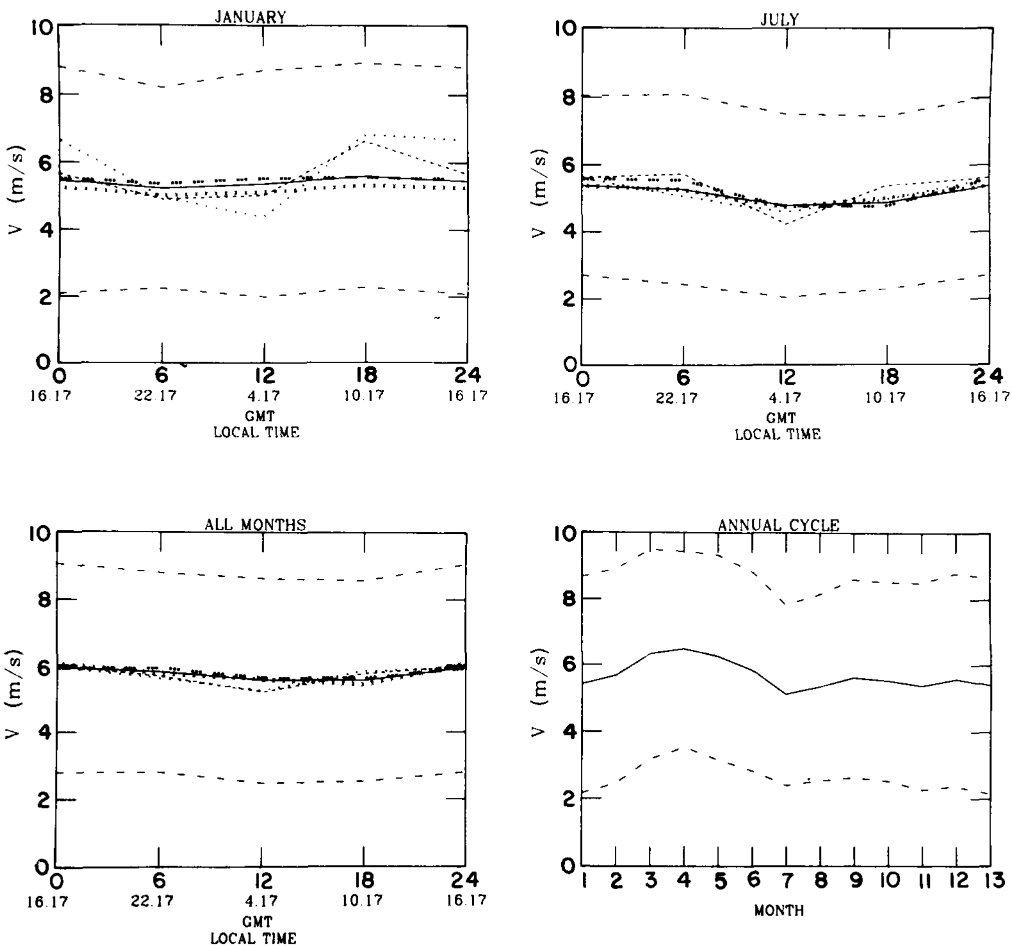

Fig. 2. Diurnal and annual variations of region C windspeed. Twenty year means and standard deviations are shown as a function of reporting hour for (a) January, (b) July and (c) all months. The solid line is the mean value using all data within the square. The large dashed patterns each show one standard deviation from this mean. The other dashed patterns show the means for the five 1° grids at the north (× × ×), south (+ + +), east (*** ***) and west (– – –) edges. In (d), twelve long-term monthly means found using all data from all hours and locations within the region are plotted to show the annual cycle. The dashed lines each show one standard deviation from the mean.

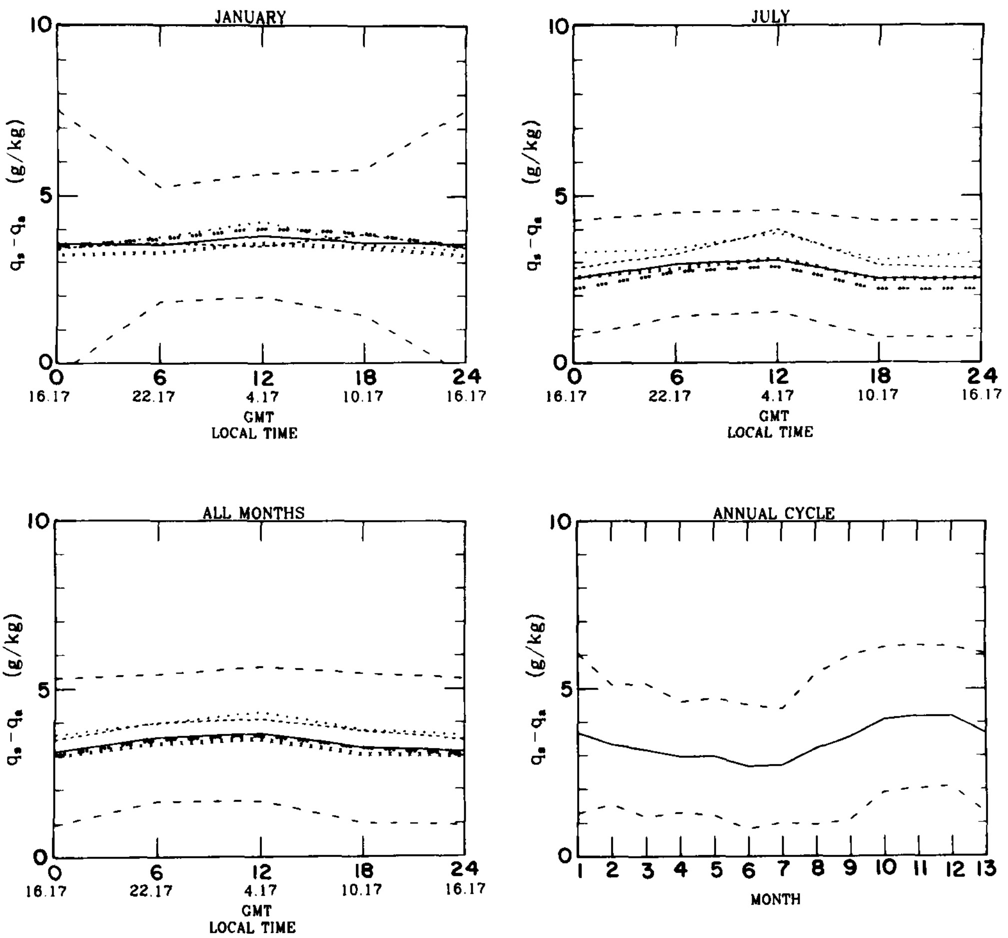

Fig. 3. As in Fig. 2 but for humidity differences in region C.

reporting hour, location within the 5° grid and season. The first two variations are illustrated for two sample months and for an annual average. Spatial variations within a grid are examined by comparing the average of the five one-degree squares in the northernmost, southernmost, westernmost and easternmost parts of the 5° grid. Estimates of the standard deviation for each reporting hour are also illustrated in the plots. The seasonal cycle is represented by the monthly means.

It may be noted that the wind data for this region shows very little diurnal or spatial variation. The winds do exhibit a modest season cycle with a maximum in April. The amplitude of this cycle is approximately 1 m/s. The means of the humidity difference exhibit somewhat greater spatial and temporal variability than those of windspeed. In particular, it appears that in spring and summer the southern and western edge of the grid have humidity differences which are approximately 1 g/kg greater than the mean. There also appears to be a significant diurnal variation, especially in summer, in the southwestern portions of the grid. The 4 a.m. local time reports have humidity differences which are up to 1 g/kg greater than the reports at 10 a.m. There is also a rather large seasonal cycle in the humidity difference which has an amplitude of about 1.5 g/kg with a maximum in December and a minimum in June. The cloudiness estimates also have discernible diurnal, seasonal and spatial biases. Generally cloudiness is greatest around 10 a.m. local time in summer and in the

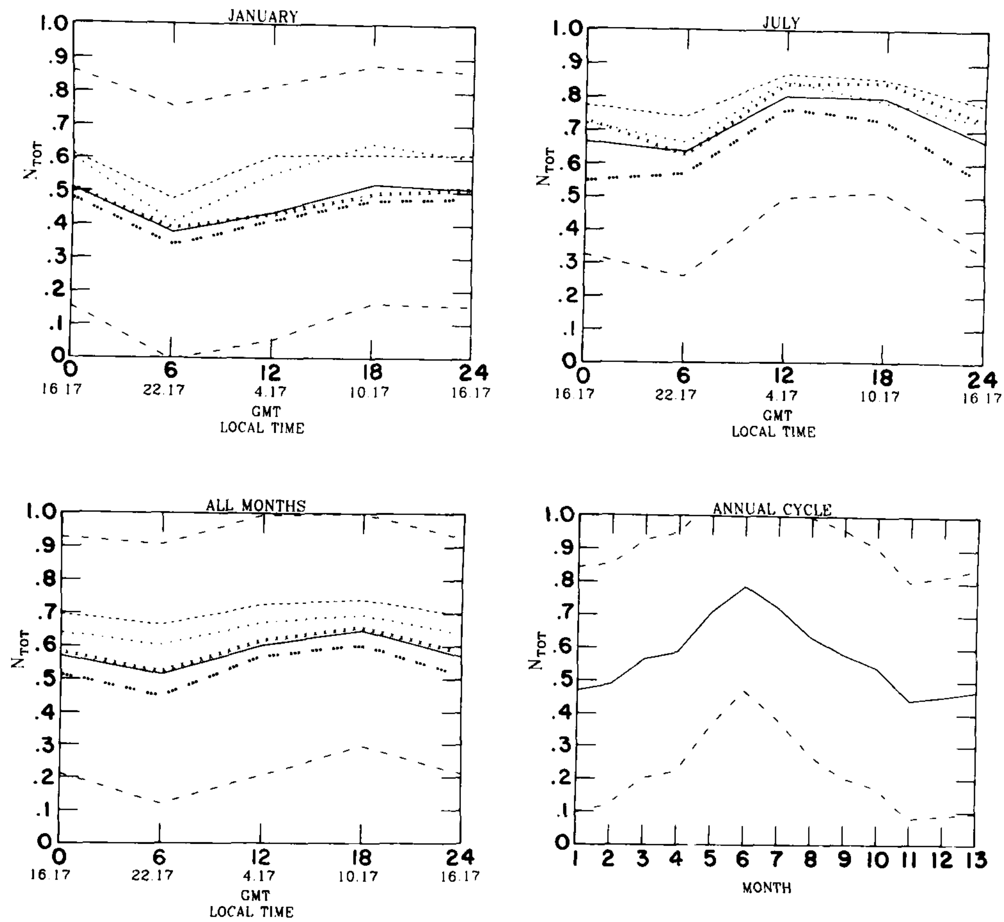

Fig. 4. As in Fig. 2 but for total cloudiness in region C.

southwestern part of the grid. The maximum differences are between 0.1 and 0.2.

Figs. 5, 6 and 7 show for area P the variations for the same variables as just discussed for area C. Because there are only a total of 16,000 observations for this grid compared with more than 47,000 for grid C, the estimates of variations with respect to time of day, portion of grid or month of year tend to be "noisier". Nevertheless, significant biases are apparent for this grid as well. For instance, windspeed has a spatial bias such that winds in the southwestern region are up to 1.5 or 2.0 m/s greater than those in the northeastern region. This probably arises out of the fact that this grid is bounded by land in the northeast. There is also a considerable seasonal cycle in windspeed with a minimum in March and maximum in October. The humidity difference has an especially pronounced northeast–southwest gradient with the maximum in the near-shore region to the northeast. The differences are up to 2.0–3.0 g/kg across the grid. Both the season and diurnal cycles seem small. The total cloudiness estimates show a rather strong diurnal bias with estimates at 9 a.m. local time approximately 0.1 greater than at the other three reporting hours. This is in agreement with Clark's (personal communication) finding for selected grids of the north Pacific that daytime estimates are about 0.1 greater than nighttime estimates. The diurnal bias for region P appears to be similar in all seasons. The cloudiness estimates also have sizable spatial departures. The coastal region appears to have an average at 0.1 more of the sky obscured than the open ocean region in the southwestern

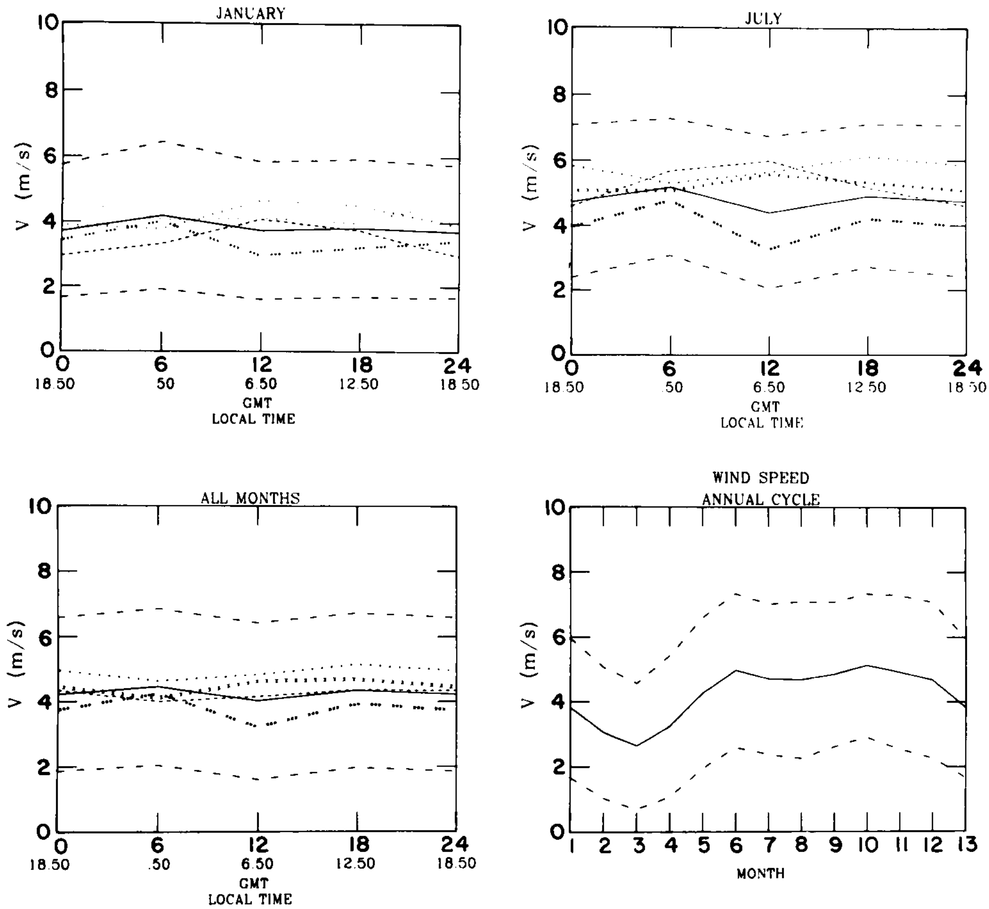

Fig. 5. As in Fig. 2 but for windspeed in region P.

corner of the square. Finally, there are considerable season differences in the estimates with a maximum of 0.85 in October and a minimum of 0.56 in April.

Figs. 2–7 illustrate that the means of important parameters may vary considerably depending upon the time of day, day within a month or subsection of the grid. For these variations to contribute to the variance of the climatological monthly mean fluxes, there must be an inequity in the number of reported observations. For example, for the diurnal variation to contribute to the variance, one or more reporting hours must have on average substantially more or less observations than the other hours.

Fig. 8 shows for grid "C" the average number of reports per month for each reporting hour and for each third of a sample month and the average relative longitude and latitude of the observations for each year from 1957 through 1976. Observations were generally well distributed with respect to reporting hour until 1972, after which the marine reports are largely radioed reports. In 1975 there was an average of only eight reports at 12 GMT (4 a.m. local time) and sixty reports at 18 GMT (10 a.m.). Fig. 8b shows that observations were generally well distributed between the first, second and third thirds of a month. The most extreme departure occurred in 1967 when April had eight observations in the first 10-day period and approximately twenty observations in each of the latter two 10-day periods. Fig. 8c and d shows that the mean position of the observations within a grid is quite constant except for 1964 when the average number of observations in a month was less than ten. The

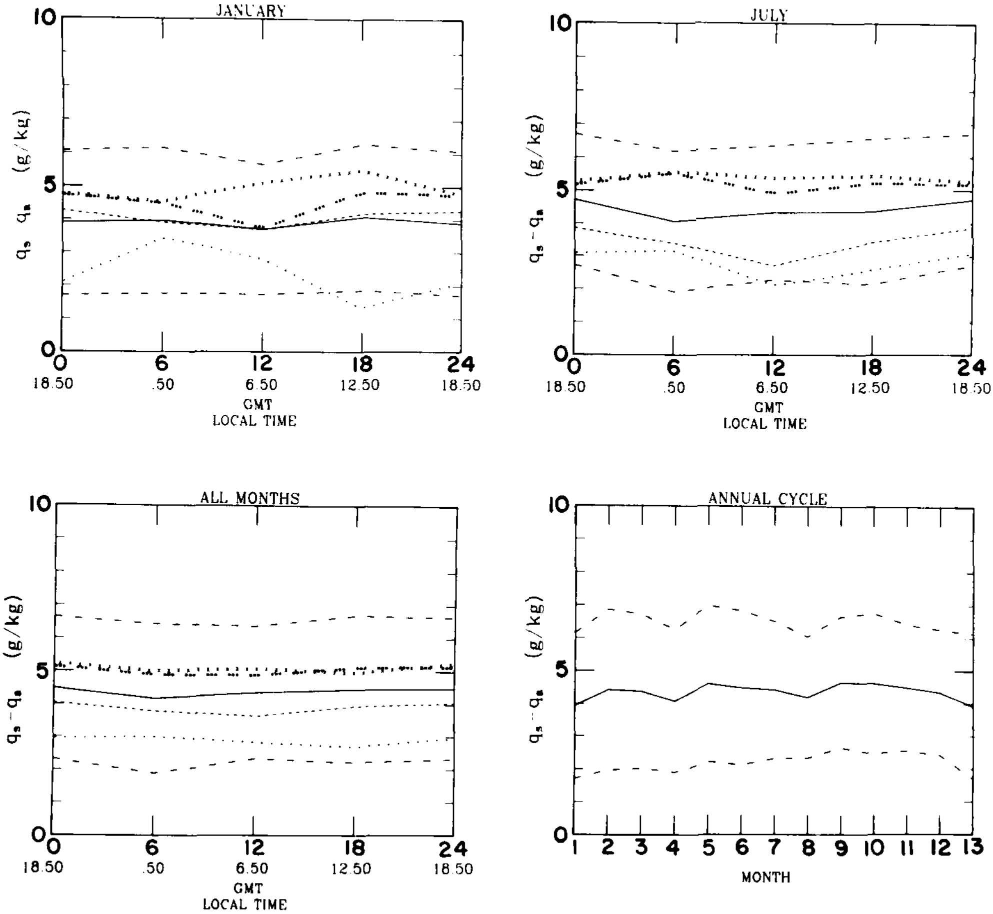

Fig. 6. As in Fig. 2 but for humidity difference in region P.

figure does, however, show a perceptible trend in average position during 1957–76. The mean position moved from west to east nearly 1° and from north to south a similar amount.

Fig. 9 shows the average report numbers in each reporting hour and triad and average latitude and longitude for grid P. Fig. 9a suggests that 6 GMT (1 a.m. local time) was generally undersampled relative to other times, especially in 1972. Fig. 9b suggests a considerable imbalance in the number of observations taken in each third of a month such that, for instance, in 1966 there are more than twice as many observations in the first third of the month than in the whole rest of the month. Fig. 9c and d do not show any long-term trend in the mean position of the observations and only rather small departures from the mean, primarily in years with less than ten observations per month.

The only additional data necessary to measure the contribution to the variance of the latent heat or solar fluxes using eqns. (9) or (10) are the correlations between windspeed and humidity difference. These correlations, together with those between windspeed and air–sea temperature differences and sea temperature and cloudiness, are listed in Table 1 for all months for grids C and P. It will be noted that all the correlations are less than 0.11.

4. Results

The monthly variance averaged over all calendar months of the latent and solar fluxes at C and P has been computed using eqs. (9) and (10) and the annual average of the monthly means and standard

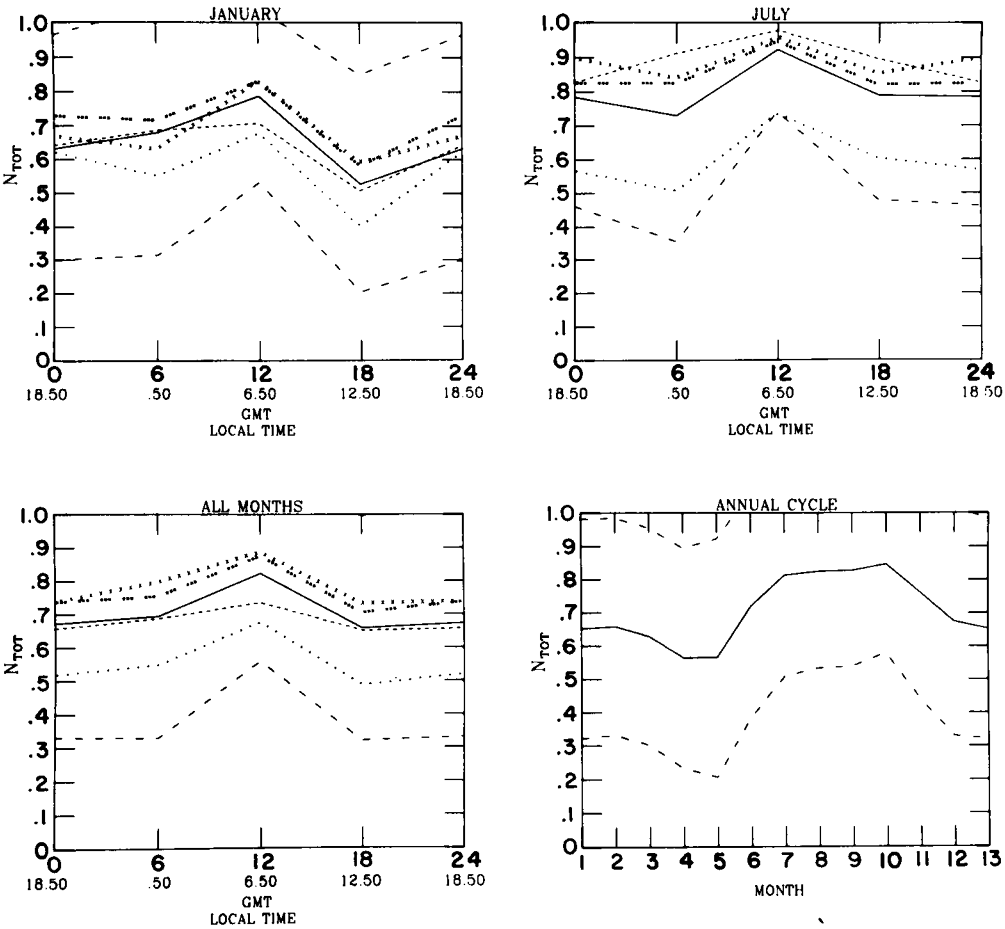

Fig. 7. As in Fig. 2 but for total cloudiness in region P.

deviations, some of which are illustrated in Figs. 2–7. This provides a single variance for each parameter and region in which to compare the contribution of each of the proposed biases. The computed variance of the latent heat flux in region C is 4660 W^2/m^4, equalling a standard deviation of 68 W/m^2. This standard deviation is almost equal to the annual mean of 86 W/m^2, indicating the rather large degree of variability of estimates of these fluxes within the sampling period. The variance of the solar flux is 3122 W^2/m^4, giving a standard deviation of 56 W/m^2, compared to a mean of 189 W/m^2. Clearly, solar flux estimates are generally relatively less variable than those of latent heat.

The results for region P are quite similar. The variance and standard deviation of the latent flux are 3415 W^2/m^4 and 58 W/m^2 compared to a mean of 85 W/m^2. The variance and standard deviation of the solar flux are 3317 W^2/m^4 and 58 W/m^2 compared to a mean of 201 W/m^2. Again the standard deviation of the latent flux is much larger compared to its mean than that deviation of the solar flux compared to its mean.

Two sets of estimates of the contribution of the biases to the flux variances were calculated. One set was based upon "typical" average deviations resulting from, for instance, an average spatial gradient and an average of the relative over- or undersampling of areas within the grid. A second set of estimates is meant to represent a practical upper limit of the bias contribution to the variances. These calculations used the average spatial or temporal gradients inferred from Figs. 2–7 and the

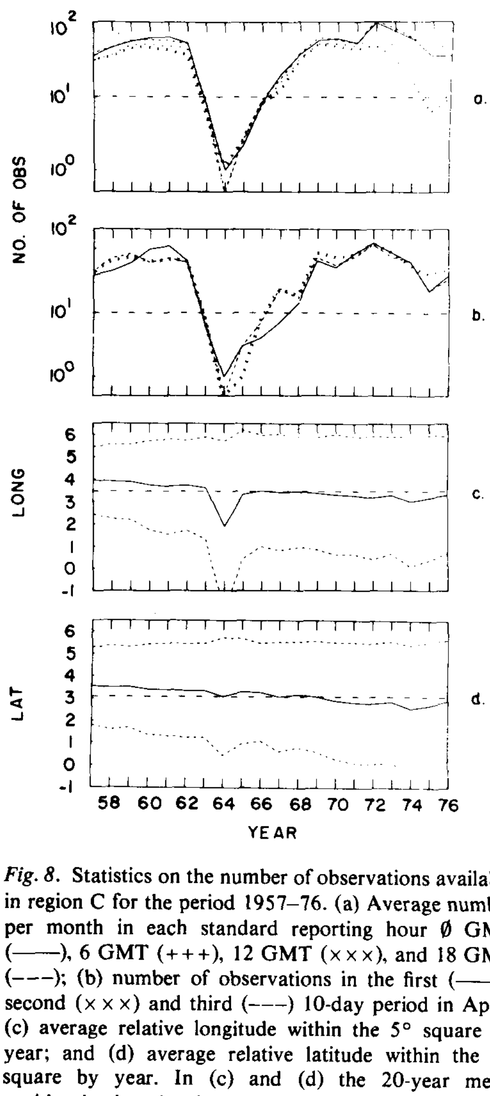

Fig. 8. Statistics on the number of observations available in region C for the period 1957–76. (a) Average number per month in each standard reporting hour Ø GMT (——), 6 GMT (+++), 12 GMT (×××), and 18 GMT (---); (b) number of observations in the first (——), second (×××) and third (---) 10-day period in April; (c) average relative longitude within the 5° square by year; and (d) average relative latitude within the 5° square by year. In (c) and (d) the 20-year mean position is given by the large dashed pattern, the yearly mean by the solid line, and the small dashed patterns show two standard deviations from the year mean.

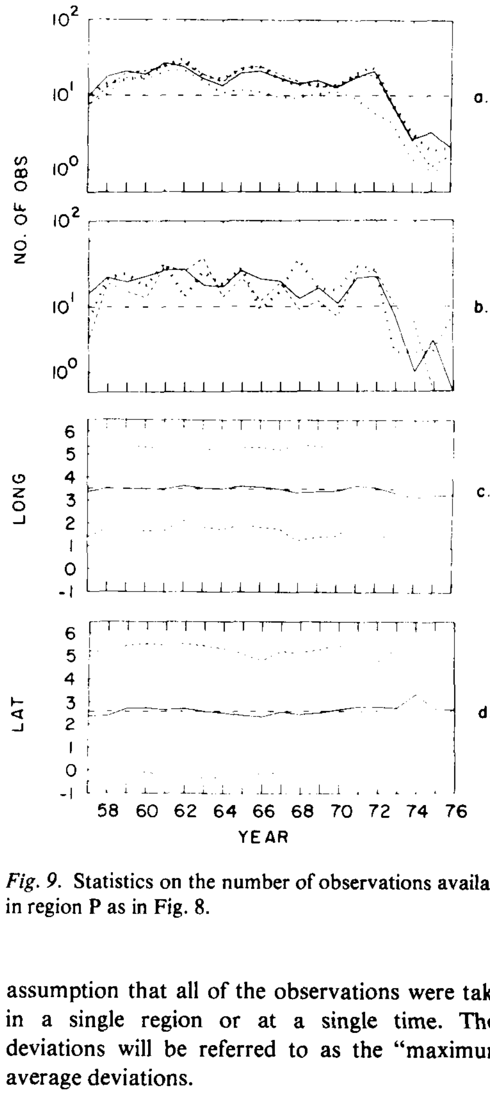

Fig. 9. Statistics on the number of observations available in region P as in Fig. 8.

Table 1. *Correlations between marine weather observations. Notation as in text plus T_s sea temperature, T_a air temperature and $\Delta T = T_s - T_a$. Correlations based on data for all months during 1957–76*

	V vs. Δq	V vs. ΔT	T_s vs. C
Region C	0.044	0.062	−0.021
Region P	0.006	0.109	0.069

assumption that all of the observations were taken in a single region or at a single time. These deviations will be referred to as the "maximum" average deviations.

Table 2 shows the resultant average deviations (multiplied by 1.25) and percent contribution of those deviations to the total variance for biases in mean windspeed and humidity difference contributing to errors in the latent flux estimates and in cloud cover estimates leading to errors in solar insulation. The correlation between windspeed and humidity difference biases were assumed to be zero. In general, the "typical" average deviation contributes less than 1% of the variance. The only exception for both C and P is the longitudinal bias in the humidity difference in these two coastal regions. This implies that this bias may result in an error of about −5.8 W/m² or 7% of the mean in

Table 2. *"Typical" and "maximum" average deviations as described in text and the percent of total variance each contributes. Symbols are as used in text: LE and S are the latent and solar fluxes. V, Δq and C are windspeed, humidity difference and total cloudiness, respectively. Percent values less than 1% are omitted*

	Region C				Region P			
	"Typical" average deviation	Percent of variance	"Maximum" average deviation	Percent of variance	"Typical" average deviation	Percent of variance	"Maximum" average deviation	Percent of variance
	V	LE	V	LE	V	LE	V	LE
Longitudinal gradient	0	—	0	—	0.1	—	0.2	—
Latitudinal gradient	0	—	0	—	0.01	—	0.2	—
Hour bias	0.004	—	0.12	—	0.02	—	0.5	4
Day within month bias	0.056	—	0.90	3	0.01	—	0.3	1
	Δq	LE	Δq	LE	Δq	LE	Δq	LE
Longitudinal gradient	0.12	1	0.25	—	0.25	1	0.5	3
Latitudinal gradient	0.15	—	0.37	1	0.05	—	0.1	14
Hour bias	0.027	—	0.25	—	0.002	—	0.5	3
Day within month bias	0.04	—	0.62	4	0.003	—	0.17	—
	C	S	C	S	C	S	C	S
Longitudinal gradient	0.06	3	0.12	11	0.02	—	0.02	—
Latitudinal gradient	0.02	—	0.06	3	0.005	—	0.10	9
Hour bias	0.004	—	0.06	3	0.002	—	0.06	3
Day within month bias	0.009	—	0.15	18	0.002	—	0.05	2

the estimate of the long-term mean latent fluxes at both C and P. This error in the calculated long-term mean arises because of the generally lower sea temperature near the coast giving rise to a smaller humidity difference than over the open sea coupled with the larger number of observations near the coast.

The "maximum" average deviations generally result in a far greater possible contribution to the variance. However, spatial gradients of windspeed are still insignificant. For region C the "maximum" average deviations due to cloudiness biases lead to errors in the solar flux estimates accounting for up to 18% of the total variance. The most important possible error would result from only a single third of a transition month being sampled. Another important error contribution would result if data for only longitudes near or far away from the coastline were sampled. Since these two errors are independent it is possible, especially if there were less than ten observations in a month, that both biases might occur leading to a misestimate of the solar flux of nearly 30 W/m^2 out of a mean of about 192 W/m^2. The most important bias in the latent heat estimates appears to also be that arising from sampling only a single third of a month.

The results are similar for region P. In this case, however, the bias resulting from sampling in only the northern or southern portion of the grid is the most important. The resulting bias in humidity difference could give rise to an error of 14% of the total variance in the latent flux; that in cloudiness could lead to a 9% error in the solar flux. Bias resulting from diurnal variation in all three parameters, windspeed, humidity difference and cloudiness, may also lead to significant errors in the latent and solar fluxes.

Although the contributions of the "maximum" average deviations are meant to be upper bounds, similar departures are probably not unlikely in the calculations of individual monthly mean fluxes for grids having few observations in a month. Sampling only one region, one reporting hour or one part of a month becomes increasingly likely with decreasing numbers of observations. In some cases proper weighting of the calculated fluxes with respect to the position, day within a month and hour of the observation could result in considerably improved estimates of the actual spatially averaged monthly mean value.

A partial test of these results was made by comparing mean values of the latent heat and solar fluxes calculated by two different methods. The first involved computing flux estimates from individual marine reports and then averaging all such estimates in a given month and 5° latitude–longitude grid. In the second method the individual estimates were first averaged in nine spatial subgrids and triads of the month and then the means of these averages were computed over the entire month and grid. The latter method was designed to compensate in part for spatial and temporal biases. Although detailed synoptic studies are probably necessary to know which method derives a flux estimate more representative of the actual physical situation in a given year–month, the previous analysis suggests that the latter should do so *on average*.

The two methods were contrasted by comparing annual average of monthly means for 1957–76 at both C and P. In region C the 20-year averages of the latent heat and solar fluxes differed by about 2% and 4%, respectively. The differences in P were about 5% and 2%, respectively. These differences were generally found to be consistent with the greater weight given in method two to the relatively few far offshore observations. Differences in flux estimates made by the two methods for individual years were sometimes greater than 10% of the mean. Overall, the estimates of the latent and solar fluxes computed by the two methods had correlations of 0.83 and 0.90 at C and 0.77 and 0.70 at P. As might be expected the two methods were in better agreement in the region C in which there are many more observations available. One somewhat disconcerting result of our comparisons was that the interannual variances of the flux values were generally slightly greater when the second computational method was used. This can apparently be attributed to occasionally giving far greater weight to a single unrepresentative observation far offshore in the second method.

5. Discussion

In the previous sections it has been shown that for two regions of the Pacific Ocean large errors in the estimate of spatially average monthly means fluxes of latent heat and absorbed solar radiation may arise because of spatial gradients, seasonal trends or a diurnal cycle if all data are averaged as a single sample. Whether or not this conclusion holds for a given month depends in part on whether the observed gradients, trends or cycles are relatively stable attributes of the regions or primarily the residuals of the 20-year averaging process. Rather simple physical arguments suggest that the former is much more likely. The spatial gradients at both C and P clearly arise because of the proximity to and frequent wind flow from the American continents. The diurnal cycle in cloudiness, windspeed and humidity difference is likely related to the sea–land breeze regime in both coastal regions.

Perhaps a more important question is, how applicable are these results to other oceanic regions? Are important biases due to spatial gradients, seasonal trends or diurnal cycles likely to be significant over a large part of the world ocean? There are two general arguments which imply the answer is yes. The chosen regions, C and P, are probably quite representative of most of the near-shore regions on the eastern boundary of the tropical Atlantic or Pacific. Many features of these regions are probably representative of western boundary regions as well. In addition our subjective analyses of the regions outlined on Fig. 1 suggest that significant biases also exist at many of the other grids although perhaps to a lesser extent.

With these conclusions in mind it seems possible to make some generalizations from the results. Errors in long-term (e.g., 10 or more years) monthly mean fluxes resulting from gradients, trends or cycles are likely to be approximately 1% of the long-term variance or less. This suggests that such means would be in error because of such biases by less than 10%. On the other hand, possible errors in estimates of individual monthly means of the fluxes may be far greater. Errors of up to 50% of the mean seem possible. How many observations would be necessary to reduce this possible error to, say, 10% of the mean depends critically how they are distributed in space and time. If, however, one assumes that the observations are randomly distributed, one can estimate a minimum number of observations necessary for an unbiased sampling of the data. For instance, if one wishes to sample all three triads of a month at least once, elementary probability theory (see, e.g., Brunk, 1965) shows that nine observations are necessary for 95% confidence. To obtain at least one report in all four reporting hours, eleven reports are necessary to achieve the same confidence. If the spatial gradient could be largely compensated by sampling at least once in each of four subregions, then again eleven reports are necessary. This implies that to be confident at the 95% level that one has observations which are uniformly sampled in space and time requires about eleven observations per month. If these observations were then used to calculate mean fluxes in each triad, hour and subregion of the grid, the resulting errors due to the biases in the overall spatial and time average would be comparable to those of the long-term means, about 1% of the variance. If, however, one calculated average fluxes by lumping data for all days of the month, reporting hours and spatial subregions, then one could expect larger errors because sampling differences would become more significant.

Although the above argument suggests that approximately eleven observations properly weighed should provide a relatively unbiased estimate of year–month mean fluxes, it is not meant to imply that only eleven observations are necessarily enough to provide accurate estimates. This is certainly not true in higher latitude regions in the winter. In such cases most of the latent flux occurs during relatively short periods of intense flux associated with baroclinic disturbances (Fissel et al., 1977). Accurate flux estimates, therefore, require sufficient observation to sample periods of such disturbances. Clark (personal communication) suggests that in the region of Ship P (50° N) about 50–75 observations per month are necessary in winter. Because cyclonic systems are much less frequent in subtropical and tropical latitudes, probably many less observations are required in these regions. This is not to downgrade the importance of sampling the occasional tropical cyclone.

Finally, there is a third criterion for establishing the minimum number of observations which are likely to give rise to accurate year–month flux estimates. This is the necessity of having a sufficient number of data points to reduce the contributions of the presumably random instrumental, observer and archiving errors. Well-known sampling theory (Laurman, 1976) shows that the contribution of the associated "observer" variance to the overall variance of a variable is one over the number of observations. If, for instance, this "observer" variance in windspeed is 1 m/s, then only about ten observations are necessary to reduce the standard deviation to 0.3, which as is shown on Table 3 leads to an error in the latent flux of about 1% of the total variance.

In the previous discussion we have assumed that data are randomly distributed in space and time. If this is not true, for instance if data are largely confined to narrow ship routes, the number of data points necessary to produce an unbiased estimate with sufficiently reduced random noise will be larger than eleven. In actual practice the number of necessary observations may be much greater than eleven when large regions of the grid are rarely sampled.

In conclusion, spatial gradients and temporal biases may contribute to significant errors in the estimates of individual monthly mean fluxes for 5° latitude–longitude grids. The contribution of these biases is up to about 10% of the mean flux estimate in regions of relatively large spatial or temporal gradients. This possible error is probably of the same order as that resulting from random measurement or archiving errors. The other major factors contributing to errors in the flux estimates are the uncertainties in the bulk formulae themselves. Although this contribution is difficult to accurately assess, it would also seem to be about 10% of the mean. However, it should be noted that as the number of observations increase the contribution of random errors and systematic biases will generally decrease, whereas that of improper empirical formulation will remain quite fixed. Furthermore, bias errors will also decrease in regions of smaller temporal or spatial gradients. This suggests that bulk formula formulation errors will dominate in the estimates of long-term mean fluxes whereas all three sources may contribute significantly in the uncertainties associated with short-term (e.g. monthly) mean fluxes.

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ВАЖНОСТЬ ВЫБОРОЧНЫХ СМЕЩЕНИЙ ДЛЯ РАССЧИТЫВАЕМЫХ ЕЖЕМЕСЯЧНЫХ СРЕДНИХ ПОТОКОВ ТЕПЛА НАД ОКЕАНИЧЕСКОЙ ПОВЕРХНОСТЬЮ

Исследуется возможное влияние пространственных градиентов и сезонного и суточного циклов в основных метеорологических параметрах на точность рассчетов среднемесячных осредненных по пяти градусам по широте и долготе потоков тепла с поверхности океана. Намечается в общих чертах простой формализм для оценки важности этих возможных смещений. Данные для двух пробных областей в Тихом океане показывают возможно значительные смещения в одной или более переменных. Влияние смещений на 20-летние средние потоки, если бы они проявлялись, меньше 1% изменчивости или около 10% от среднего. Влияние смещений на индивидуальные ежемесячные средние могли бы быть много больше в зависимости от числа и распределения доступных наблюдений. Предполагается, что в тропических и субтропических областях, свободных от тропических штормов, около 11 наблюдений являются минимальным числом наблюдений, чтобы гарантировать точность индивидуальных ежемесячных потоков.