~~Comm~~ Merchant Ships vs Moored Buoys

Comparison of Observations of Sea Surface Temperatures at Ocean Station P and NOAA Buoy Stations and Those Made by Merchant Ships Traveling in Their Vicinities, in the Northeast Pacific Ocean

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(Manuscript received 25 July 1977, in final form 28 November 1977)

ABSTRACT

An analysis of the 6 h observations of sea surface temperatures made at Station P and the eight NOAA buoy stations in the northeast Pacific Ocean indicates that the buoys appear to be providing data that are as reliable as from Station P. On the basis of the total number of observations available for each station, the mean standard deviation associated with the 3½-day average temperatures varied from ±0.1 to ±0.2°C. There are indications that the summer values of the standard deviation are somewhat higher than during the remaining months. This is attributed to the effect of diurnal heating and cooling of the surface waters. The larger values noted for autumn and winter are attributed to the effect of the rapid rate of cooling of surface waters and/or to the influence of water mass movements. A comparison has been made between the temperatures obtained at the time-series stations and by merchant ships in their vicinities. The results show that the ships' temperatures are 0.2±1.5°C greater than those of the time-series stations. The quality of the ships' temperatures is not as good as it ought to be and efforts should be directed to improving it. For some locations there is some evidence that the horizontal temperature gradient present in the localities might be affecting the temperature differences between the time-series stations and ships' observations. An improvement of the quality of the ships' data by reducing the standard deviation from ½ to ⅓ of the presently determined values should be sufficient to determine this at the 95% confidence level.

1. Introduction

A number of studies have been conducted in the past to show the relationship between the sea surface temperatures measured with a variety of instruments and techniques, in particular, by the use of the bucket and the engine-intake methods. They range from an examination of data obtained from a single merchant ship or specialized vessels (Brooks, 1926; Roll, 1951; Knudsen, 1966; Wolff, 1963; Tauber, 1969; Tabata, 1977) to those collected from a large number of merchant or naval vessels (Saur, 1963; Walden, 1966; James and Fox, 1972). Others include the comparison of data taken by one fleet of ships to another fleet or to those taken by research vessels (Franceschini, 1955; Collins *et al.*, 1975). However, to date, there appears to be no study conducted to evaluate the general quality of the sea surface temperatures observed by the merchant ships and reported daily to the meteorological centers. The temperatures observed reliably at the various ocean weather stations and the recently established NOAA fixed-buoy stations should provide an opportunity to compare these with those observed by the merchant ships in their vicinities to determine the efficacy of the latter observations.

In the northeast Pacific Ocean there are a number of locations where sea surface temperatures are measured regularly. They include Ocean Station P where such measurements have been made for over 25 years and the NOAA fixed-buoy stations. There are a large number of ships' observations made in their neighborhood and it is these data that are compared with those made at these stations. From this, an assessment is made of the present-day quality of the ships' data.

2. Location of stations

The position of the fixed stations from which sea surface temperatures are observed regularly are shown in Fig. 1. Ocean Station P is located at latitude 50°N, longitude 145°W and is situated in the path of the eastward-flowing Subarctic Current which diverges in this very general vicinity to form the northward-flowing Alaska Current and the southward flowing California Current. The buoy, EB-17, lies west-northwest of Station P and is situated between the Subarctic Current to the south and the Alaskan Stream to the north. EB-19 lies between Station P and the Queen Charlotte Islands and is in the path of the Alaska Current. EB-21 lies south of EB-19 and is located in the general area of the origin of the California Current while EB-16 situated south of

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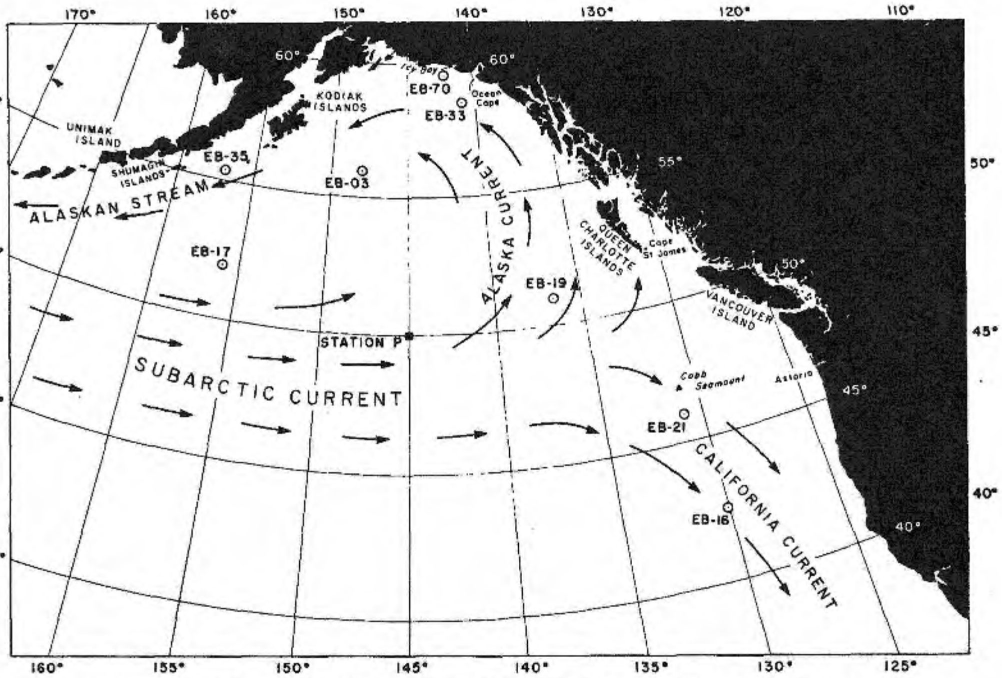

FIG. 1. Chart showing location of Ocean Station P and the NOAA fixed-buoy stations in the northeast Pacific Ocean.

TABLE 1. Particulars associated with time-series stations in northeast Pacific Ocean.

Station no.	Latitude (°N)	Longitude (°W)	Depth (m)	General location	Type of platform	Status of observations
P	50.0	145.0	4000	Approximately 1000 km WSW of Queen Charlotte Islands, British Columbia	Weatherships	Started December 1949. Observations continuing.
EB-03	56.0	148.0	4400	Approximately 340 km SE of Kodiak, Alaska	Engineering experimental phase 12.2 m discus buoy	First NOAA buoy deployed in northeast Pacific Ocean in autumn 1973. Retrieved in summer 1974; redeployed in December 1974; retrieved in June 1976; redeployed in July 1976. Started receiving data in July 1976.
EB-33	58.5	141.0	3400	Approximately 140 km SW of Ocean Cape, Alaska	NOMAD 6 m boat-shaped buoy	Deployed in autumn 1974. Started receiving data in November 1974.
EB-16	42.5	130.0	3400	Approximately 630 km SW of Astoria, Oreg.	Prototype environmental (10 m discus) buoy	Deployed in summer 1975. Started receiving data in July 1975.
EB-17	52.0	156.0	4700	Approximately 380 km SE of Shumagin I., Alaska. Halfway between Station P and Unimak K., Alaska	Prototype environmental (10 m discus) buoy	Deployed in summer 1976. Started receiving data in July 1976.
EB-19	51.0	136.0	3300	Approximately 360 km WSW of Cape St. James, B.C.	Prototype environmental (10 m discus) buoy	Deployed in summer 1976. Started receiving data in August 1976.
EB-21	46.0	131.0	3000	Approximately 550 km W of Astoria, Oreg., 80 km S of Cobb seamount	Prototype environmental (10 m discus) buoy	Deployed in autumn 1976. Started receiving data in September 1976.
EB-35	55.3	157.0	90	Approximately 140 km E of Shumagin I., Alaska	Modified NOMAD 6 m boat-shaped buoy	Deployed in summer 1976. Started receiving data in August 1976.
EB-70	59.5	142.2	180	56 km SW off Icy Bay, Alaska	12.2 m discus buoy	Deployed in autumn 1976. Started receiving data in September 1976.

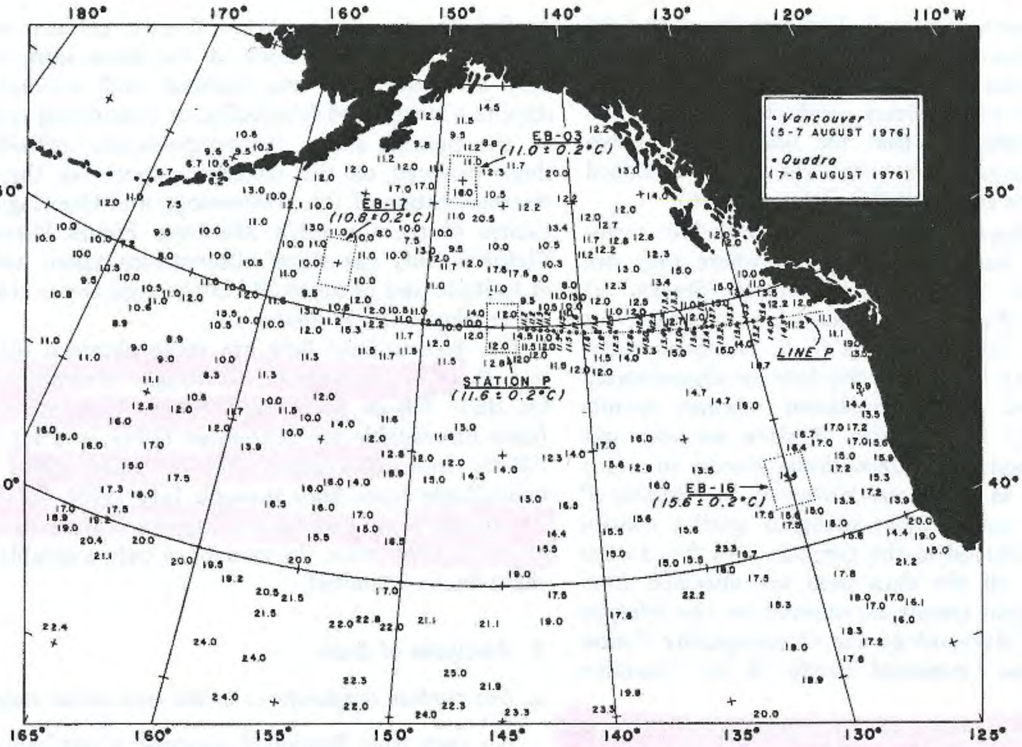

FIG. 2. An example of 3½-day sea surface temperature (°C) chart (5–8 August 1976) showing the temperatures from both the time-series stations and merchant ships as received at the local weather station. For each time-series station the mean and the standard deviation of the 3½-day temperatures are indicated. Temperatures taken by the weatherships CCGS *Vancouver* and CCGS *Quadra* are also shown.

EB-21 is well within the area of this Current. EB-03 and EB-33 off Alaska are both within the confines of the Alaska Current, while EB-35 which lies southwest of the Kodiak Islands is in the area of the westward flowing Alaskan Stream. EB-70 is located close to the Pacific coast of Alaska, and like EB-35, is anchored in the relatively shallow continental shelf of Alaska.

While EB-03 has been deployed in the northeast Pacific Ocean as early as 1973, most of the others were put into operation during 1976. The particulars of these stations are given in more detail in Table 1.

3. Location of ships in northeast Pacific Ocean

The majority of ships reporting sea surface temperatures are merchant ships that ply the shipping lanes along the great circle routes between major seaports. The others are the naval and research ships as well as special fishing vessels. In the northeast Pacific, the lanes are between major seaports situated along the Pacific coast of North America and the Orient. Even the route between Panama Canal and the Orient passes, at the longitude of Station P, north of latitude 40°N. There are, of course, other lanes such as the one between the Orient and North America via Hawaii and others between Alaska and other ports of Pacific coast of United States and also the Orient. At any one time during the 3½ days, it is not uncommon to receive a few hundred sea surface temperature reports from the northeast Pacific, say in an area bounded by the Pacific coast of North America and longitude 160°W to the west and latitude 40°N to the south. As is shown in an example in Fig. 2, there is an extensive coverage of temperature in the northeast Pacific.

4. Data

Sea surface temperatures at Station P are measured with bucket thermometers encased in specially designed thermally insulated buckets. They are calibrated to read within ±0.05°C but they are reported only to one decimal place. Temperatures observed at Station P are accurate to ±0.1°C (Tabata, 1978).

The NOAA buoys deployed in the northeast Pacific Ocean employ either a platinum-resistance bulb or a thermistor to measure the sea surface temperature. Buoys EB-03, EB-16, EB-17, EB-19 and EB-21 use a platinum-resistance bulb that is mounted on the tube which slides into a fixed standpipe mounted on the hull bottom plate while the others (EB-33, EB-43 and EB-70) use a thermistor placed in direct contact with the inside of the buoy bottom hull (Winchester, 1977, private communication). Although thorough field tests have not been conducted in the Pacific to assess the reliability and accuracy of the temperatures obtained by these buoys, tests conducted in the laboratories have indicated that the buoys are capable of providing temperature with errors (one standard deviation) of less than $\pm 0.2°C$ (Withee, 1976).

The data collected at these buoys are first radiotransmitted to San Francisco, from where they are relayed to the Shore Communication Station at Miami, where they are formatted and analyzed for validity before delivery to the U. S. National Meteorological Center. From here the data are disseminated on the national and international weather circuits (Beasley, 1976). The Station P data are also put into the national and international circuit in much the same way as in above. However, the Station P data are later put to more stringent quality control before being archived in the climatic data file. In the present study, all the data used are obtained from the meteorological circuit as received on the teletype receiver at the Meteorology and Oceanography Center of the Maritime Command Pacific of the Canadian Forces.

The merchant ships, on the other hand, measure sea surface temperatures by either one of the two main methods, bucket or engine-intake. The former was the main method many years ago but nowadays it is more common to use the second method. The bucket method involves observation of the temperature of surface water collected with an ordinary canvas, metal or plastic bucket in which a thermometer is fitted. Special buckets such as the Crawford bucket (Crawford, 1969) designed to reduce errors in the reading are not widely used yet. Perhaps the most common method used currently is the engine-intake method, especially by larger merchant ships that find it difficult to collect bucket samples. The intake method may vary from observations with direct-reading thermometers fitted into the large intake pipe or well to the remote reading of data based on platinum or thermistor sensors fitted into the pipe or well. Specially designed bucket thermometers such as the Crawford bucket thermometer (Crawford, 1969) or those used by the Atmospheric Environment Service of Canada aboard its weatherships are capable of yielding temperatures that are accurate to $\pm 0.1°C$ (Tauber, 1969; Tabata, 1978) but it is doubtful if many of the merchant ships' temperatures are measured to this accuracy, even if the instruments themselves are capable of doing it. There is no reason why the intake thermometers cannot provide values that are equally as accurate as those measured with bucket thermometers, as the former have been shown to yield temperatures that are accurate to within $\pm 0.1°C$ (Brooks, 1926; Tabata, 1978).

The temperatures obtained by the ships are forwarded to the major meteorological centers within radio communication reach of the ships from where they are distributed via national and international circuits to interested forecasting or monitoring centers. In the present study the temperatures utilized are those received on the teletype receiver at the local weather station of the Meteorology and Oceanography Centre of the Canadian Maritime Forces Pacific in Victoria. Only the ships' observations taken with 1° of latitude and of longitude of the time-series stations are employed in the analysis.

The data utilized here are those obtained for Station P, from January 1975 through December 1976; for Buoy EB-16, from July 1975 to December 1976 (data unavailable for September 1976); and for Buoy EB-33, from November 1974 to April 1976 (data unavailable from April through July 1975). All of the remaining buoys had been in operation for six months or less in 1976; thus, the amount of data available from these buoys is limited.

5. Analysis of data

a. Sea surface temperatures at the time-series stations

The data from Station P comprise about half of the total number of data utilized in this study. Of the total of eight buoy stations only two (EB-16 and EB-33) had more than $1\frac{1}{2}$ years of data. The combined number of observations from these three stations constituted two-thirds of the total number of data used in the analyses. As a result any conclusions drawn from the analysis of all the data would necessarily be colored by the results from these three stations, and are therefore considered as preliminary only. However, it would be unlikely for major changes in the conclusions to result from the consideration of more data.

For each station the mean and the standard deviation of sea surface temperature were calculated for each $3\frac{1}{2}$ days of 6 h observations. Fig. 3 shows the distribution of the frequency of occurrences of the values of the standard deviations for each of these stations. Considering the data from all the stations, approximately three-fourths of the standard deviations are less than $\pm 0.2°C$. However, values as large as $\pm 0.5°C$ are present, though infrequently ($<2\%$ of data). From the figure it can be seen that more than twice the number of these large values occurred during the heating season, April–September, than during the remainder of the year. There is also some indication that the standard deviations for the heating season are also greater than during the remainder of the year. This becomes slightly clearer when the monthly mean standard deviations are compared, as is shown in Fig. 4. While it is evident that the larger values of standard deviations occurred more frequently during the heating season than during the remainder

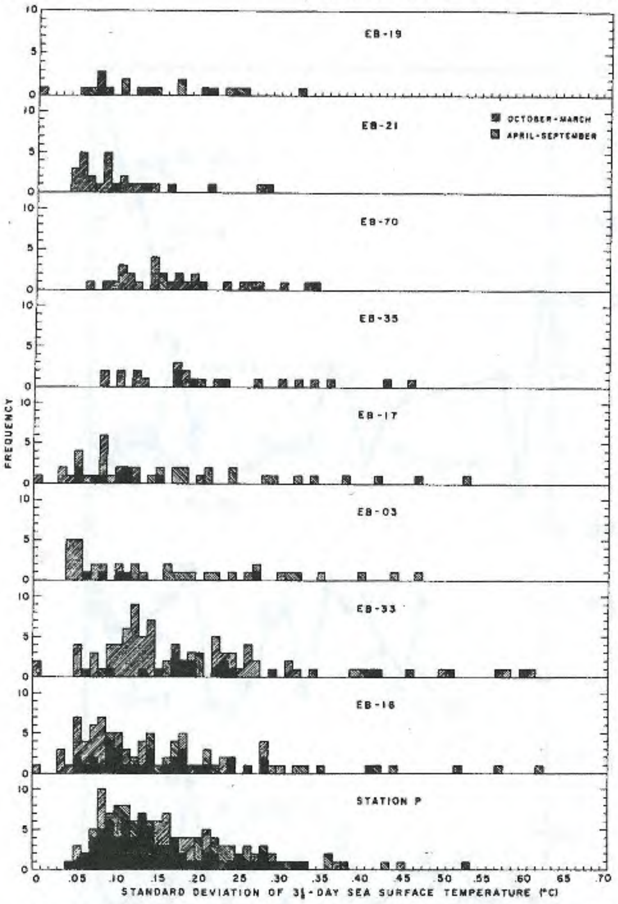

FIG. 3. Distribution of standard deviations associated with the 3½-day mean sea surface temperatures (°C) at the time-series stations (Station P, Buoys EB-16, EB-33, EB-03, EB-17, EB-35, EB-70, EB-21 and EB-19).

of the year, such large values were also present during some months in the cooling season. They occurred at Station P in October 1975 and at EB-33 in November and December 1975 and October 1976.

The annual mean of the standard deviations at the three stations was ± 0.17°C ($n=200$), ± 0.17°C ($n=112$) and ± 0.21°C ($n=110$), respectively, for Station P, EB-16 and EB-33. At the remainder of the stations where only less than one-half year of data was available, the mean standard deviations were also approximately ± 0.2°C except at EB-21 where it was only half as large.

b. Comparison between sea surface temperatures of time-series stations and merchant ships

The sea surface temperatures observed by the merchant ships in the vicinities of the time-series stations are, in general, within a few degrees of those observed at the latter. However, only 60% of the ships' observations are within ± 1.0°C of the latter, while 75% are within ± 1.5°C and 85% within ± 2.0°C. As is shown in Fig. 5, the sea surface temperature difference between the ships' observations and those of the time-series stations (hereafter simply called temperature difference) can well exceed several degrees occasionally, but such large differences are likely to be associated with large errors in the ships' reports. There is indication that the ships' temperatures are, on the average 0.2°C ($n=1150$) larger than those of the time-series stations. The 95% confidence limit for this value is ± 0.1°C and therefore, the overestimate of temperatures by the ships is real. With respect to the individual stations, this overestimate was particularly noticeable at EB-03 and EB-17, and perhaps at EB-33. The underestimates at EB-21 and EB-35 are not statistically significant at the 95% confidence interval.

The standard deviations of the temperature differences using data from all the stations ($n=1150$) was ± 1.5°C, and ranged from a minimum of ± 1.1°C for EB-17 to a maximum of ± 2.6°C for EB-70 (Fig. 5).

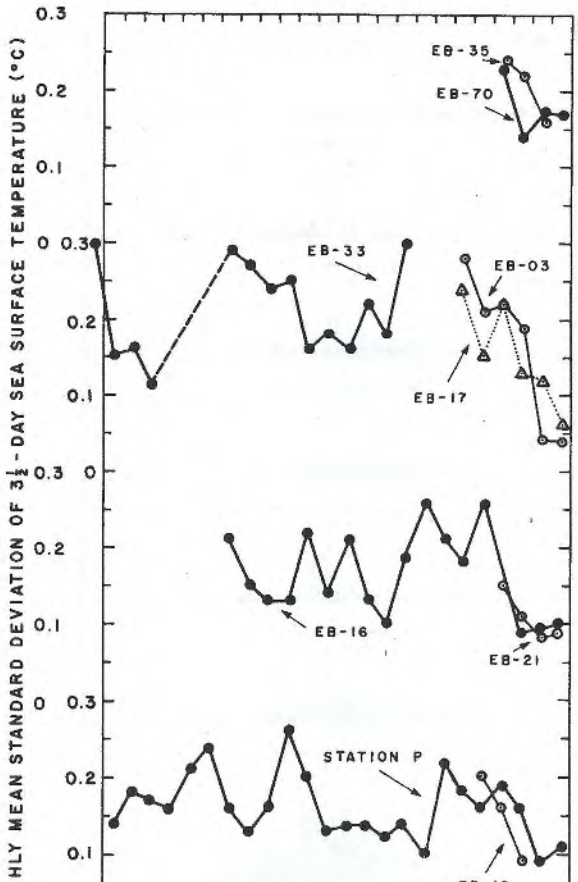

FIG. 4. Monthly mean standard deviations associated with the 3½-day sea surface temperatures ($\pm$°C) at the time-series stations (Station P, Buoys EB-16, EB-33, EB-03, EB-17, EB-35, EB-70, EB-21 and EB-19). They are based mainly on eight or nine observations for each 3½-day period.

There was no perceptible seasonal variation of the standard deviations for any of the stations as can be seen from Fig. 6. It was anticipated that for the summer months the deviation might be larger than for the winter because the diurnal range of temperatures is usually larger during the summer. However, only twice were the deviations appreciably larger in the summer (at Station P in July 1976 and at EB-03 during August 1976). For some stations the winter values were even larger than those for the summer (EB-33 in January 1975 and EB-70 in December 1976) (Fig. 6).

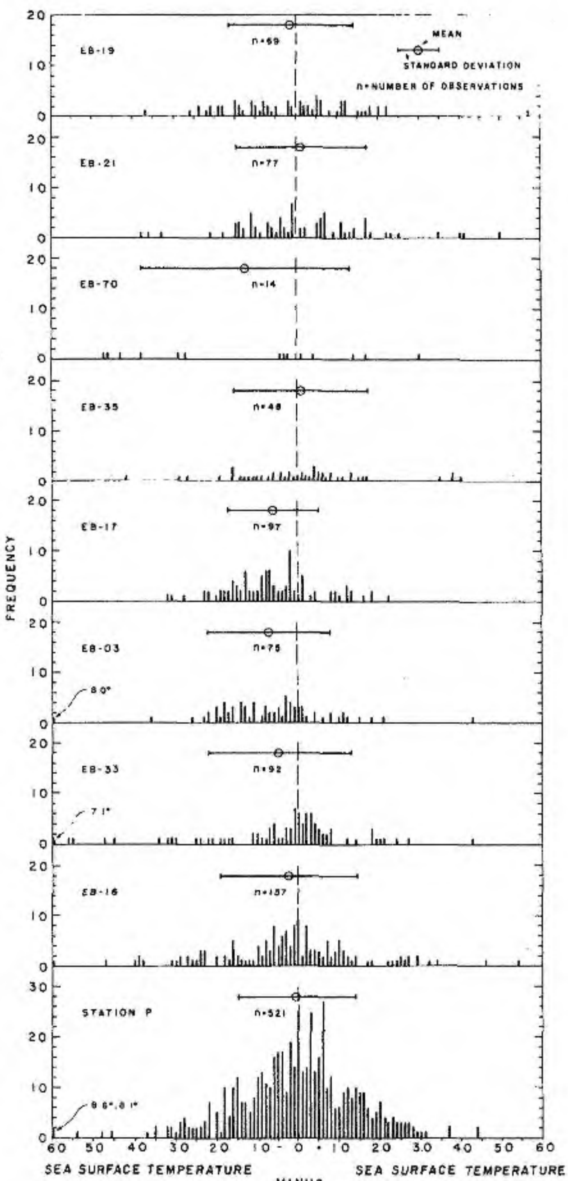

FIG. 5. Distribution of the differences between the 3½-day mean sea surface temperatures of the time-series stations (Station P, Buoys EB-16, EB-33, EB-03, EB-17, EB-35, EB-70, EB-21 and EB-19) and observations made by the merchant ships with 1° of latitude or longitude of these stations during the 3½-day interval.

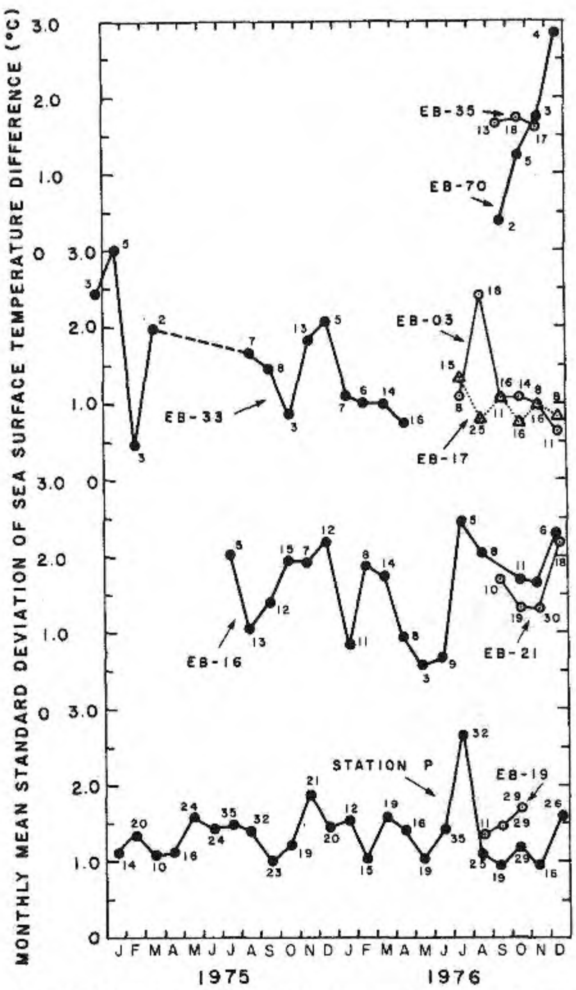

FIG. 6. Monthly mean standard deviations of differences between sea surface temperatures of the time-series stations and of the merchant ships.

c. Effect of horizontal temperature gradient on sea surface temperature differences between time-series stations' and ships' observations

It was thought that part of the reason for the occurrence of large differences between the sea surface temperatures observed by the time-series stations and the ships was the effect of the presence of a horizontal temperature gradient in the vicinity of the time-series stations. For this reason, the temperature ranges in the 2° quadrangle for each station were estimated from the climatological sea temperature charts published recently by Robinson (1976), and are shown in Table 2. It is evident from this table that the monthly temperature range can vary from a little less than 0.5°C to as large as 2.0°C, the gradient being smallest at EB-03 and EB-17 and largest at EB-33 and EB-70.

TABLE 2. Climatic monthly mean horizontal sea surface temperature range (°C) within 2° of latitude and longitude, in the vicinity of time-series stations. Based on Robinson's (1976) charts.

Station no.		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
P	Temperature range	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5	0.5	1.0	1.0	0.5
	Orientation of isotherms	NNE–SSW	NE–SW	ENE–WSW	ENE–WSW	NE–SW	E–W, N–S	NE–SW	NE–SW	E–W	E–W	E–W	NE–SW
	Location of warmer water relative to station location	E	SE	S	S	S	S	S	S	S	S	S	S
EB-16	Temperature range	2.0	2.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	1.0	1.0	2.0
	Orientation of isotherms	NW–SE	NW–SE	ESE–WNW	ESE–WNW	NW–SE	NW–SE	N–S, NW–SE	N–S, E–W	N–S, E–W	NW–SE	NW–SE	NW–SE
	Location of warmer water relative to station location	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	SW	
EB-33	Temperature range	1.0	0.5	0.5	1.5	1.5	2.0	1.5	0.5	2.0	1.5	1.0	1.0
	Orientation of isotherms	E–W	E–W	NW–SE	NW–SE	NW–SE	NW–SE	NW–SE	E–W	NW–SE	E–W	E–W	E–W
	Location of warmer water relative to station location	S	S	NE	NE	NE, SE	NE	NE	SE	S	S	S	S
EB-03	Temperature range	0.5	<0.5	<0.5	<0.5	<0.5	0.5	<0.5	0.5	0.5	0.5	0.5	<0.5
	Orientation of isotherms	N–S	N–S	N–S	N–S	N–S	N–S	NNW–SSE	NW–SE	N–S	N–S	N–S	N–S
	Location of warmer water relative to station location	E	E	E,S	E,S	E	E	E	NE	E	E	E	E
EB-17	Temperature range	<0.5	<0.5	<0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	0.5	0.5
	Orientation of isotherms	E–W	E–W	E–W	E–W, N–S	NE–SW	NE–SW	NE–SW	NE–SW	NE–SW	NE–SW	E–W	E–W
	Location of warmer water relative to station location	S	S	S	S,E	SE	SE	S	SE	SE	SE	S	S
EB-35	Temperature range	<0.5	<0.5	<0.5	1.0	0.5	<0.5	<0.5	0.5	1.5	1.0	<0.5	<0.5
	Orientation of isotherms	E–W, N–S	various	NE–SW	NE–SW	E–W	N–S	N–S	NE–SW	NE–SW	NE–SW	NE–SW	NE–SW
	Location of warmer water relative to station location	S	E,S	NW	NW	N	E	E	NW	SE	SE	SE	W
EB-70	Temperature range	1.5	0.5	0.5	1.5	1.5	1.5	1.0	1.0	2.0	1.0	1.0	1.0
	Orientation of isotherms	E–W	NE–SW	NW–SE	NW–SE	NW–SE	WNW–ESE	NW–SE	E–W	E–W	E–W	E–W	E–W
	Location of warmer water relative to station location	S	SE	NE	NE	NE	N	NE	S	S	S	S	S
EB-21	Temperature range	1.5	1.0	0.5	1.0	0.5	0.5	1.0	1.0	1.0	1.0	1.0	1.0
	Orientation of isotherms	E–W	E–W	E–W	E–W	E–W	E–W, N–S	NE–SW	NE–SW	E–W	E–W	E–W	E–W
	Location of warmer water relative to station location	S	S	S	S	S	S,E	SE	S,E	S	S	S	S
EB-19	Temperature range	<0.5	0.5	1.0	1.0	<0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Orientation of isotherms	N–S	N–S	N–S	N–S	NE–SW	NW–SE	E–W, N–S	N–S	N–S	various	various	various
	Location of warmer water relative to station location	E	E	E	E	SE	SW	S,E	SE	SE	SE	SE	SE

These gradients are based on climatological means from 28 years (1941–69) of data and it is likely that they are larger or smaller for individual years. However, some of these mean gradients may be used to obtain a rough idea of their effect since four of the eight stations examined (Station P, EB-16, EB-19 and EB-21) were in areas where the isotherm orientations were consistent enough throughout the year that it was possible to examine the effect of temperature gradients on the observed temperature differences.

At Station P the isotherms were oriented in a general northeast–southwest direction with the higher temperature occurring southeast of the station. Here, the temperature from the merchant-ship observations in the northwest quadrant was, on the average, 0.1°C higher than in the southeast quadrant, which is contrary to what one should expect if it were due to the effect of the gradient. However, this difference was not statistically significant even at the 70% confidence level and therefore the significance of this difference can be ignored. At EB-16 the isotherms were oriented in a northwest–southeast direction and the higher temperatures were located in the southwest quadrant. Here the ships' temperatures observed in the southwest quadrant were larger by 1.0°C, on the average, than in the northeast quadrant. Although this difference was not statistically significant at the 95% confidence level, it was at the 80% level. At EB-21 isotherms were oriented in sectors from northeast through east to southwest through west with warmer water laying in the south to southeast sector. Here the ships' observations indicated that the warmer water in the southern sector was 0.6°C higher than in the opposite side, but this difference was only significant at the 70% level. Finally, at EB-19 the isotherms were oriented northwest–southeast so that the warmer water lay in the southeast sector. Here again, this difference was not significant even at the 70% level.

6. Discussion

It has been shown that the variations in the 3½-day sea surface temperatures of Station P and the NOAA buoy stations are of the same magnitude (standard deviation = ±0.2°C). Considering that Station P sea surface temperatures have already been established to be reliable (Tabata, 1978), the similarity of the variations of these temperatures of the buoy stations to those of Station P suggests that the buoy stations are producing reliable data, at least to the same degree as at Station P. It may be argued because no suitable data are available at the buoy stations to verify each of their observations, that there is some doubt as to the reliability of their data. However, since the temperature-sensing devices [platinum-resistance thermometers (except thermistors for EB-35 and EB-70)] had been calibrated before at the base laboratory and immediately after the buoys were deployed (Mueller, private communication, 1977), there is no reason to believe that their absolute temperatures are not reliable. Further, at least with the *Nomad*-type buoys, their sea surface temperatures have been found to be quite dependable. For instance, when the buoy-observed temperatures were compared with those obtained from detailed map analysis based on ships' reports, the former, while providing values that were initially (1959–61) smaller by 1.40°C on the average (Marcus, 1964), yielded values that were within 0.1°C in later years (1965–66) (Marcus, 1967, 1969).

The variations of temperatures at these stations are somewhat larger during the heating season, April through September (Tabata, 1961), than during the cooling season, October through March. This is not a surprising result, for during the former period the upper mixed layer of the ocean is much thinner (<30 m) than during the latter period (>100 m) (see, e.g., Tabata, 1976) and is therefore more sensitive to the heat exchange across the air-sea boundary. This may have a pronounced effect in the surface layer when the weather is characterized by cloud-free sky and by calm or light winds during the summer. Diurnal temperature changes as much as 1.5°C can occur under such conditions (Tabata and Giovando, 1962). On the other hand, the occasional occurrence of relatively large variations during the cooling season is less easy to explain. It is more likely that they are due to the rapid cooling of water that takes place in autumn and winter. This may account for the large values of standard deviations for Station P and EB-33 during October 1975, EB-16 during November 1975, and EB-35 during October 1976 when the temperature decreased at an average rate of approximately 0.1°C per day. For others such as for EB-16 during January 1976 and EB-33 during February 1976, a satisfactory explanation for the larger variations is not readily available except perhaps for EB-33 where a possible intrusion of cold water into the area during the mid-month could have affected the data.

The sea surface temperatures reported by the ships and utilized here are those taken directly from the meteorological teletype circuit and therefore have not been put through rigorous quality control. A small percentage of such data are known to contain errors due to faulty radio transmissions (Gibson, 1962a) and also to incorrect reporting of ships' positions (McLain, 1977, private communication). The possibility of the presence of such errors in the present data suggests the advisability of using archived data rather than real-time data. However, it is to be noted that the latter is of more interest to the great majority of users and the utilization of such data is therefore, warranted.

The main characteristics of the differences between the sea surface temperature observed by the merchant ships and the time-series stations have been examined. The results indicate that the ships' temperatures were, on the average, 0.2°C higher than those of the time-series stations. While this difference was statistically significant at the 95% confidence level using all the data for all nine stations, the difference for the individual stations was significant at the same level for only two stations, EB-17 and EB-03. The fact that the ships' temperatures were higher suggests that the majority of the ships' observations were based on the engine-intake method as this method has been shown to yield a slightly higher than the actual temperature (Saur, 1963).

There is a possibility that the horizontal temperature gradient present in the vicinities of the time-series stations might affect the temperature difference between the ships' and time-series stations. At four stations (Station P, EB-19, EB-16 and EB-21) the gradients appeared to be relatively well defined, at least on the climatic charts. Its effect was not perceptible at Station P and EB-19 but was evident at EB-16 and EB-21, although only at the 80 and 70% confidence levels, respectively. The implication is that the present data are not generally capable of discerning the effect of the horizontal temperature gradients in the vicinity of the time-series stations. Nevertheless, it would only require an improvement of the quality of the ships' observations, by reducing the standard deviation of the ships' data from the present ± 1.7°C to ± 1.3°C (25% reduction) and from the present ± 1.6°C to 0.8°C (50% reduction), at EB-16 and EB-21, respectively, to detect whether or not such an effect can be shown with 95% confidence.

The occurrence of the relatively large temperature differences between the time-series stations and the ships indicates that the ships' data are still not as accurate as they ought to be for utilization in oceanographic or large-scale ocean-atmosphere interaction studies. Had they been, the monthly standard deviation of the temperature difference should be better than one-third of the value (± 1.5°C) determined from the present data. During the summer months, differences as large as ± 1.5°C can be expected on some individual days during calm or light wind conditions or when there has been a difference in the spatial variations of wind mixing. But such conditions are unlikely to occur often in the northeast Pacific, at least not at Station P, where calm periods occur, on the average, only 3% of the time during a year (Tabata, 1964). Thus, even for the summer months, monthly mean differences exceeding ± 1.0°C are likely to be excessive. Further, if the diurnal variations of temperatures during the summer months had any appreciable effect on the observations, one would have expected to see some correlation between the monthly standard deviations of the $3\frac{1}{2}$-day temperatures at the time-series stations and the corresponding standard deviations of the temperature differences. However, the lack of any correlation suggests that this summer effect did not exist in the present series of measurements.

It is rather surprising, given the long history of measurements by merchant ships, that the present study is the first of its kind to compare the time-series stations data with those observed by the ships, in the time frame of few days. In the past, there have been some studies of one kind or another that are related to the present study. For example, Franceschini (1955) compared the $1\frac{1}{2}$–$2\frac{1}{2}$ weekly average ships' temperature in 1° quadrangles in the Gulf of Mexico to the individual temperatures observed by a research ship within the corresponding quadrangles during the abovementioned time interval and found that a good correlation indeed existed between the two sets of data. After discarding the large differences that were suspected to be in error, he found the merchant ships' temperatures to be reliable to within ± 0.9°C (standard error of estimate) of the research ships' values. Considering that the comparison of temperature was between the $1\frac{1}{2}$–$2\frac{1}{2}$ week averages and the individual values over this time interval, the agreement is remarkably good. In the present study the corresponding "error" was ± 1.5°C on the average. Only for EB-17 was it as small as ± 1.1°C; for the rest it was $>\pm 1.5$°C. It is suspected that the small "error" estimated by Franceschini resulted from the omission of ships' observations that were suspected to be erroneous whereas in the present study, no attempt was made to exclude any of the ships' data principally because it was the quality of the ships' data, as reported, that was considered.

More recently, studies conducted to evaluate the data taken by the Gulf of Mexico *Nomad* buoys (Marcus, 1964; Marcus and Smith, 1966; Marcus, 1967, 1969) have shown, among other things, that temperatures based on synoptic ships' reports were generally higher than the corresponding buoy-observed values, though only marginally for the later years (1965–66). Both the mean difference between the buoys' and ships' temperatures and the associated standard deviation calculated in these studies show much similarity to the respective values computed in the present study.

Although a study of the comparison of data such as in the above-mentioned case has been rarely attempted, there has been a number of well-conducted studies comparing bucket and engine-intake temperatures from the same ship. Brooks (1926), in one of the earliest of such studies, conducted several experiments aboard the S.S. *Empress of Britain* during her West Indies cruise during February–March 1924. He found, among other things, that the intake method was capable of measuring surface temperatures to within ± 0.1°C of the carefully observed bucket temperatures, but that the engine room crew recorded data that were 0.3°C too high. Roll (1951) later found also that, on the average, the engine-intake temperatures were only 0.1°C larger than those of the bucket. More recently, Knudsen (1966) has arrived at the same result but found that the difference was not statistically significant. Later, Saur (1963) concluded, from an analysis of extensive series of comparisons between bucket temperatures observed from specially designed bucket thermometers and intake temperatures from 12 military ships plying the North Pacific during 1959–62, that the intake temperatures were, on the average, 0.7°C±0.9°C higher than the corresponding bucket temperatures, after the ships' data had been filtered to exclude suspected values. At about the same time Wolff (1963) conducted experiments from a U. S. Navy Liberty-type ship in the eastern North Pacific during January–May 1957, using a specially designed water intake system fitted with a series of thermocouples to measure the intake temperatures. He found that its system was capable of measuring temperatures to within ±0.06°C of the corresponding bucket temperatures. (The system incorporates a pump drawing water at a rate of 230 l min^{-1} through a 5 cm inside diameter pipe from an intake located 0.6 m below the water line.) More recently James and Fox (1972) have made a comparative study based on a large volume of data comprising matched pairs of bucket and intake temperatures obtained from various ships in the world oceans during 1968–70. Their results showed that, on the average, the intake temperatures were 0.3±1.3°C higher than the bucket temperatures. Similarly, Walden (1966) found that the intake temperatures were also 0.3°C higher than those taken with the bucket. In another recent study (but using old data from 1927–33) Collins *et al.* (1975) have compared the monthly mean temperatures, based on an unspecified number of bucket observations, made by Japanese ships in a 5° quadrangle in the vicinity of the present Station P to those based generally on two observations per month obtained by use of the intake method by the Canadian ships in the same area. From these data they were able to conclude that the engine intake temperatures were, on the average, 0.3±0.7°C higher than the bucket temperatures. Most of these studies do indicate that the intake temperatures, as observed and reported by the merchant and naval ships, are higher by 0.3 to 0.7°C than the bucket temperatures.

In the present study the ships' temperatures were found to be only greater by 0.2°±1.5°C than those of the time-series stations. This value is somewhat smaller than the difference between intake and bucket temperatures estimated by others using a variety of data. There may be a number of reasons for this. First, it is possible that the ships' data utilized here may contain some temperatures that are based on the bucket method which has a tendency to give lower than actual temperature values particularly in the presence of cold air over the ocean (Brooks, 1926; Tauber, 1969; Collins *et al.*, 1975) or during windy days (Roll, 1951), unless of course the bucket is of a special design such as the Crawford bucket (Crawford, 1969). Also, the fact that the data used here were not filtered to exclude possible erroneous values may have resulted in influencing the estimates made. Alternately, the differences between the intake and bucket temperatures reported by the previous investigators (Saur, 1963; Collins *et al.*, 1975; James and Fox, 1972; Walden, 1966) might have been influenced by bucket temperatures that were too low.

One of the difficulties of making a proper assessment of the reliability of either the bucket or the intake temperatures by the comparison of the two, of course, has been the lack of good, reliable reference temperatures such as can be obtained from deep-sea reversing thermometers or the modern-day salinity-temperature-depth recorder. In a few cases such reliable instruments have been used for this purpose. Tauber (1969), for example, has compared the temperatures obtained with Crawford bucket thermometers and with reversing thermometers and has concluded that the former was capable of providing temperatures that are reliable to within ±0.1°C. Similarly, the specially designed bucket thermometers used by Canadian weatherships also have been shown to yield temperatures that are reliable to within ±0.1°C when observations are made by adequately trained observers (Tabata, 1978). It is when such information is available that a meaningful assessment of the relative merits of bucket or intake temperatures can be made.

When the comparison is between one set of observations made by one type of platform, say fixed stations as in the present study or a research ship as was the case for Franceschini's (1955) study, and another by merchant ships, two additional difficulties arise. One is the lack of simultaneity of the observations. Very seldom is it possible to compare a sufficiently large number of temperature observations made from one platform to that of the other concurrently, unless the two sets of observations are made from the same ship or from a coordinated observational program involving more than one platform. In the present study, the $3\frac{1}{2}$-day mean temperatures observed at the time-series stations are related to the instantaneous ships' observations made at any time during this $3\frac{1}{2}$-day period. In Franceschini's case, the comparison is between the $1\frac{1}{2}$–$2\frac{1}{2}$ week averages and the research ship's observations during any time in this interval. Such comparisons can be affected by the diurnal changes of temperatures or by changes resulting from the rapid heating or cooling during the averaging time. The other difficulty is associated with the presence of horizontal temperature gradients in the ocean. The average temperatures based on the ships' observations may have been estimated from a relatively small area, such as from a 1° quadrangle as considered by Franceschini (1955), or from a larger area, such as the 5° quadrangle utilized by Collins *et al.*, 1975. In the present study it is intermediate between the two considered by the above investigators. Such an area may be still too large and it would have been preferable to consider a 1° quadrangle. But this would have resulted in the loss of approximately three-fourths of the total number of the ships' data and would have reduced the statistical significance of the estimated results. Further, even within a 1° quadrangle, a temperature range of a few degrees can be present (Gibson, 1962b; Marcus, 1964). Thus, a comparison of a point observation with those even within the 1° quadrangle is not necessarily the best one. As has been shown earlier it is possible that the horizontal temperature gradient may have some influence on the differences between observations from the time-series stations and the ships; therefore, it is desirable to keep the area under consideration as small as practicable when a field comparison of temperatures is made.

7. Conclusions

The sea surface temperatures observed by NOAA buoys in the northeast Pacific appear to be as reliable as those of Station P. On the basis of the total number of observations available for each station, the mean standard deviation associated with the $3\frac{1}{2}$-day temperatures varied from ± 0.1 to $\pm 0.2°C$, the average based on observations from all stations being $\pm 0.17°C$. The occurrence of somewhat higher values of standard deviation for the summer months is attributed to the effect of the diurnal heating and cooling of the surface layers of the ocean. On the other hand, it is believed that the higher values for the remaining period are associated with the rapid rate of cooling of the water or are due to the effect of movement of water masses. The temperatures observed by the merchant ships were, on the average, $0.2° \pm 1.5°C$ larger than at the time-series stations. This positive bias of the ships' temperatures is probably due to the overestimate of their temperatures by the engine-intake method. There is some suggestion that part of the differences between the ships and time-series stations might be caused by the presence of a horizontal temperature gradient at the location of some stations.

A reduction of the standard deviation of the ships' data by 25% and 50% would be sufficient to determine this effect at the 95% confidence level at the two stations (EB-16 and EB-21, respectively). The magnitude of the variations of the temperature differences between the ships and time-series stations, as expressed by the standard deviation of $\pm 1.5°C$, indicates that the ships' observations are still not as accurate as they ought to be and require improvements. Studies conducted elsewhere have demonstrated that both the bucket and intake temperatures can be measured to an accuracy of $\pm 0.1°C$ when measurements are made with care. There is no apparent reason why this level of achievement has not been reached despite the fact that previous investigators have been voicing concern over the quality of ships' observations since 1926. In the present study no attempt has been made to screen the ships' data as the purpose of the study was to assess the data as received. No doubt there could be errors in the data due to faulty temperature measurements or even errors in reporting the position of the observations as well as those due to radio transmission and reception.

A knowledge of sea surface temperatures is becoming increasingly important in the study of the influence of ocean temperatures upon weather and climate since the difference of even a few degrees appears to be important enough to affect weather and climatic patterns (Bjerknes, 1966; Namias, 1969). Further, ships' data are currently being used a great deal as ground truth for satellite observations. However, the standard deviations routinely found in the comparisons of ship and satellite data are of the order of $\pm 2°C$ (see, e.g., Brown, 1975) which is too coarse to make reliable estimates of sea surface temperatures from satellite observations. Therefore, there is an urgent need for acquiring accurate sea surface temperatures now. Platforms are available to make these observations, methods are also available to make reliable observations; all that is needed is a concerted effort directed to obtaining such data.

Acknowledgments. I am grateful to Mr. M. Blake and his staff of the Meteorology and Oceanography Centre of the Maritime Forces Pacific for providing the necessary materials used in the study and to Dr. J. W. Winchester and his staff of the NOAA Data Buoy Office for supplying detailed information on the instrument package of the NOAA buoys deployed in the Pacific and to Freda Alexandria Hartley for assisting in the analysis of the data and to Patricia Kimber for making the illustrations. Finally, I wish to thank Drs. R. W. Stewart and J. F. Garrett for their kind and constructive comments.

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