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A Comparison of Ship Drift, Drifting Buoy, and Current Meter Mooring Velocities in the Pacific South Equatorial Current

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In this note we compare mean seasonal cycles of zonal and meridional velocity in the Pacific South Equatorial Current based on current meter mooring data, drifting buoy data, and ship drift data. Monthly averages of ship drift and drifting buoy data were computed over 2° latitude by 10° longitude rectangles centered at the positions of multiyear current meter moorings near 0°, 110°W, and 0°, 140°W. All three representations of the flow field show the basic character of the annual mean and its variations, provided that the sampling characteristics associated with each measurement technique are taken into account. In particular we find that more than 15 days of drifter data (regardless of year) are required on a 2° latitude by 10° longitude basis to produce monthly mean estimates that agree with moored estimates to within about 5–10 cm s^{-1} rms. We also infer that windage affects climatological monthly mean ship drift velocities, although uncertainties in the data limit a precise determination of the windage magnitude. An upper bound appears to be about 3% of the surface wind speed, though the actual effect of windage may be considerably smaller.

1. INTRODUCTION

The surface circulation of the equatorial Pacific Ocean consists of a series of powerful wind-driven zonal currents extending over nearly one-third the circumference of the globe. The strength and variability of these currents are important in determining large scale climatic variations through their effects on sea surface temperature. In particular, interannual variations along the equator in the South Equatorial Current are associated with El Niño, in which there is a large scale eastward displacement of warm surface water during periods of anomalously weak tradewinds [*Wyrtki*, 1975; *McPhaden and Hayes*, 1990]. The impact of El Niño is felt worldwide through air-sea interactions in the equatorial Pacific which remotely affect the general circulation of the atmosphere and disrupt normal weather patterns [*Rasmusson and Wallace*, 1983]. Accurate determination of the surface circulation in the equatorial Pacific is therefore crucial for understanding and predicting climate variations both regionally and globally.

Much of what is known about the large-scale surface circulation of the equatorial Pacific Ocean derives from ship drift data, drifting buoy data, and current meter mooring data. Though the sampling characteristics of these measurement techniques are distinctly different, we expect that each technique will provide a measure of the surface velocity field consistent with the others if the data overlap sufficiently in space and time and if known instrumental biases (such as windage in ship drift and drifter data) can be suitably accounted for. It is difficult to corroborate our expectations about the consistency of these three measurement techniques in a particular flow regime, however, because seldom are there enough coincident data. One therefore often relies on the comparison of averaged quantities (e.g., monthly or seasonal means) for which meaningful conclusions can be drawn provided that the observed variability is stationary over the time period encompassing the measurements. Even so, there are few locations where all three measurement techniques can be sensibly compared, and in particular, there have been no systematic evaluations of these techniques in relation to one another in the equatorial Pacific. However, a significant amount of mooring and drifter data now exist in the South Equatorial Current as the result of large-scale measurement programs beginning in the late 1970s [*Hansen and Paul*, 1987; *McPhaden and Hayes*, 1990]. Also, monthly mean ship drift data in the tropics have recently been edited and recompiled on a 1° by 1° grid for studies of the general circulation [*Richardson and McKee*, 1989]. The purpose of this note therefore is to evaluate the extent to which the mean seasonal cycles based on these data sources agree with one another in the vicinity of two long-term mooring sites in the eastern equatorial Pacific.

The paper is outlined as follows. In section 2 we describe each data set and its processing to a mean seasonal cycle. Results are then presented in section 3, followed by a summary of major conclusions in section 4.

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2. DATA SOURCES AND PROCESSING

2.1. *Moored Current Measurements*

The moored current measurements used in this study were collected as part of the NOAA's Equatorial Pacific Ocean

TABLE 1. Annual Mean Zonal Velocity and Meridional Velocity Based on Current Meter Mooring, Drifting Buoy, and Ship Drift Data Near 0°, 110°W and 0°, 140°W

	Zonal Velocity u, cm s^{-1}	Meridional Velocity v, cm s^{-1}	Latitude x	Longitude y	Number of Observations n
		110°W			
Mooring	−11.1	0.3	109°46′W	0°01′N	2174
Drifting buoy	−22.4	−1.0	109°52′W	0°05′N	269
Ship drift	−22.8	5.1	108°55′W	0°07′S	250
		140°W			
Mooring	−11.8	−0.7	140°03′W	0°02′S	1180
Drifting buoy	3.7	16.8	139°02′W	0°08′S	92
Ship drift	−29.7	−0.7	141°10′W	0°01′S	177

Annual mean velocity is calculated as the average of the monthly means in Figures 1 and 2 and is plotted as vectors in Figure 3. The mean longitude (x) and latitude (y) of all the current meter moorings, drifting buoys and ship drift observations is shown to the nearest minute; n is the total number of days of mooring and drifting buoy data, or the number of ship drift observations, available for calculation of the annual means.

Climate Studies (EPOCS) program in the vicinity of 0°, 110°W, and 0°, 140°W. Measurements were obtained with EG&G vector-averaging current meters at typically 7 depths in the upper 250 m from taut-wire surface moorings. The shallowest depth instrumented was 10–20 m at 110°W and 10 m at 140°W. The moorings were recovered and redeployed on a 6-month schedule beginning in March 1980 at 110°W and April 1983 at 140°W.

Climatological monthly means were computed at a nominal depth of 10 m following procedures outlined by *McPhaden and Hayes* [1990]. Daily data were first smoothed to monthly means, which were then averaged over 6 years at 110°W (April 1980 to March 1982 and January 1984 to December 1987) and 4 years at 140°W (January 1984 to December 1987). The 110°W (140°W) data span 14 (9) mooring deployments, mean positions of which are listed in Table 1. Also listed in Table 1 is the total number of daily averaged data that went into the calculation (2174 at 110°W and 1180 at 140°W). Data at 110°W were excluded for the period April 1982 to December 1983 to avoid biasing the mooring analysis by variations that occurred during the strongest El Niño of the century; 1983 data at 140°W were also excluded.

A similar climatology based on mooring data through 1986 is presented by *McPhaden and Hayes* [1990]. The rms differences in monthly means between these two climatologies is 3.2 (4.8) cm s^{-1} in the zonal direction and 1.5 (2.4) cm s^{-1} in the meridional direction at 110°W (140°W). Thus the inclusion of 1987 data does not lead to significant biases in our records due to the moderate 1986–1987 El Niño. Moreover, inclusion of data from 1987 is consistent with the drifting buoy averages (which include data from the entire 1986–1987 El Niño); and with ship drift averages (which presumably include data from several El Niño events of comparable magnitude over the course of more than 100 years).

We have estimated the accuracy of the climatological monthly mean mooring data by computing interannual variance for each month, then averaging these variances over the year at each location. We then used this estimate of average variance to derive a standard error for each month assuming that there are 5 degrees of freedom at 110°W and 3 degrees of freedom at 140°W. These errors are 10.2 (10.9) cm s^{-1} for zonal velocity and 4.4 (4.9) cm s^{-1} for meridional velocity at 110°W (140°W).

2.2. *Drifting Buoy Measurements*

Beginning in 1979, regular deployments of First GARP Global Experiment (FGGE) type drifters manufactured by Polar Research Laboratory were made in the eastern equatorial Pacific as part of the EPOCS program. These buoys were initially equipped with 2 m × 10 m drogues attached by nylon tethers 30 m long to improve their performance as current-following devices. Tether lengths were shortened to 10 m on buoys deployed beginning in 1981 to measure flow nearer the surface. Then in 1985, the buoy design was changed to a low-cost 3-m spar with a 5-m^2 holey sock attached to a 10-m tether. The differing design of these drifters implies differing performance characteristics, such as slippage through the water because of windage and/or upper ocean shear [e.g., *World Climate Research Program (WCRP)*, 1988; *Bitterman and Hansen*, 1989; *Chereskin et al.*, 1989]. Nonetheless, the drifting buoys are likely to follow flow at the center of the drogue depth (35 m for the early deployments, 15 m for the later deployments) to within a few centimeters per second.

The bulk of the drifter data from 110°W (80%), and all the drifter data from 140°W, derive from drifters with drogues centered at 15 m depth. In many cases, drogues were lost but the buoys remained otherwise functional as surface floats. The undrogued buoys contain useful information on the surface circulation; however, we have excluded them from this analysis because they are more subject to windage and waveage effects which degrade their performance relative to drogued drifters [*Hansen and Paul*, 1987].

We computed climatological monthly means in 2° latitude by 10° longitude rectangles centered on the mooring sites using data for the period 1979–1987 (0°, 110°W) and 1985–1987 (0°, 140°W). Data from the 1982–1983 El Niño are included in this ensemble only at 110°W, and then only in August 1982 (12 days of data equivalent to ~80% of the August total). The spatial averaging intervals were chosen to be comparable to the meridional and zonal decorrelation scales for monthly mean drifter data of 300 km and 1600 km, respectively [*Hansen and Paul*, 1987]; 2° meridional averages are also convenient for comparison with the ship drift data, which are on a 1° grid. The mean position of all the drifting buoys within these 2° × 10° rectangles is 13 km for

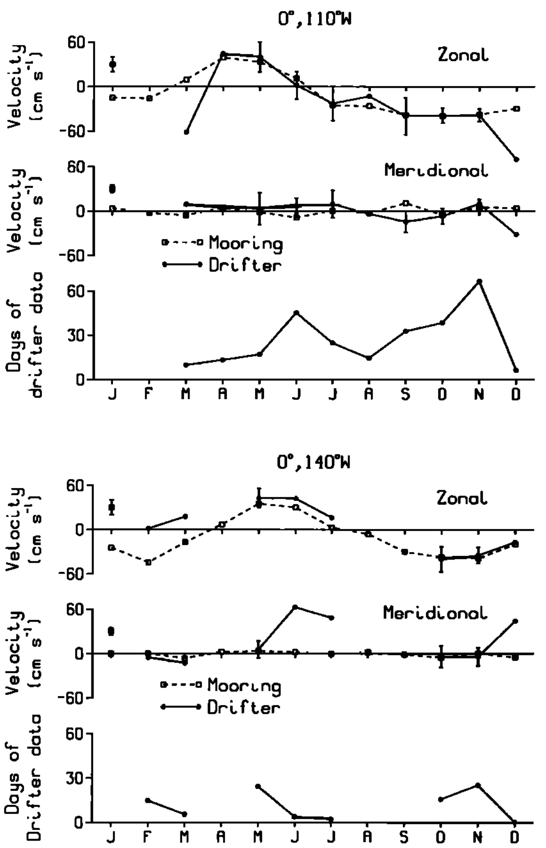

Fig. 1. Climatological monthly mean zonal velocity and meridional velocity based on drifting buoys averaged in 2° latitude by 10° longitude rectangles centered at 0°, 110°W and 0°, 140°W. The number of days of buoy data available for each monthly estimate are also indicated. Standard errors are calculated only when $n > 15$ and are based on the assumption that 1 in 5 days is independent. A monthly mean climatology based on current meter mooring data is also shown (dashed lines). Standard errors for current meter monthly means (approximately ± 10 cm s^{-1} in the zonal direction and ± 5 cm s^{-1} in the meridional direction as discussed in section 2.1) are indicated above the January values.

the mean position of the moorings at 110°W and 113 km east of the mean position of the moorings at 140°W (Figure 3).

The number of buoy days of data (n) available for computation of the mean seasonal cycle at each site is shown in Table 1. Not all these data are independent, however, because the Lagrangian decorrelation time scale of the buoy velocities is about 5 days [*Hansen and Paul*, 1987]. On the other hand, averages for any given month are typically derived from several different buoys passing through the 2° × 10° rectangle. Hence a conservative (low) estimate of the number of degrees of freedom in the drifter data set from Table 1 is $n/5$, or about 55 at 110°W and 18 at 140°W.

Figure 1 shows the monthly mean estimates of zonal and meridional velocity from the drifters. Not all months are represented because the equator is a region of surface Ekman divergence (Figure 4) and buoys are rapidly advected away from the equator [*Hansen and Paul*, 1984]. In some months there are only a few days of data available for forming a monthly mean estimate. The minimum number of days used for the calculation of a monthly mean was 1 (December at 140°W), and the maximum was 67 (November at 110°W). The error bars shown in Figure 1 assume $n/5$ degrees of freedom and are calculated only when $n > 15$.

2.3. *Ship Drift Measurements*

Ship drift data used for equatorial ocean circulation studies have most recently been described by *Richardson and McKee* [1984, 1989]. A ship drift velocity is the vector difference between velocity estimated from successive position fixes 12–24 hours apart, and the estimated velocity of the ship through the water during the same time interval. As such it is an average in time, an average in space over a few hundred kilometers, and an average in depth over the ship's hull (typically a few meters). Ship drift data therefore tend to average out mesoscale and high-frequency variability like small-scale eddies and inertia-gravity waves, emphasizing the larger-scale, lower-frequency aspects of the circulation. However, the data tend to be noisy because of errors in positioning and dead reckoning; also, they are subject to windage and waveage, whose effects are at best only qualitatively understood.

The ship drift data base in the equatorial Pacific encompasses the period 1854–1974, though most of the observations were obtained between 1920 and 1941. *Richardson and McKee* [1989] computed a 1° gridded monthly climatology from these data, which we then used to generate 2° latitude by 10° longitude averages centered on the mooring sites at 0°, 110°W and 0°, 140°W. The total number of ship drift estimates available (250 at 110°W and 177 at 140°W) is listed in Table 1. These are probably all independent because heavily traveled shipping lanes in the eastern equatorial Pacific have a primarily meridional orientation, and ships are likely to traverse the 2° meridional extent of our averaging area in 12–24 hours. The mean position of the ship drift estimates is about 96 km east of the mean mooring site at 110°W and about 123 km west of the mean mooring site at 140°W (Figure 3). Note that our 2° × 10° averaging intervals may be somewhat broader in actuality, since ship drift data locations are given at the mid point of successive position fixes. Hence data points inside the peripheries may include information from outside the explicit averaging domain.

Figure 2 shows the time series of ship drift monthly means for zonal and meridional velocity. The minimum number of estimates used in these calculations was 6 (December at 140°W) whereas the maximum number was 49 (March at 110°W). Standard error estimates are shown assuming that each ship drift estimate is independent.

3. Results

A number of similarities can be found in the annual and monthly means of the ship drift, drifting buoy and current meter mooring data (Figures 1–3). Annual means are predominantly westward at speeds of 10–30 cm s^{-1}, with the exception of the drifting buoy mean at 140°W (Figure 3). All show a pronounced seasonal cycle with eastward or weak westward flow in boreal spring, and westward flow of 30–50 cm s^{-1} later in the year. The springtime reversal of the South Equatorial Current in ship drift measurements near 110°W was first noted by *Puls* [1895] and later commented on by *Wyrtki* [1965]. More recently, *Halpern* [1987] observed the springtime reversal in current meter mooring data at 110°W, and *McPhaden and Taft* [1988] discussed its westward

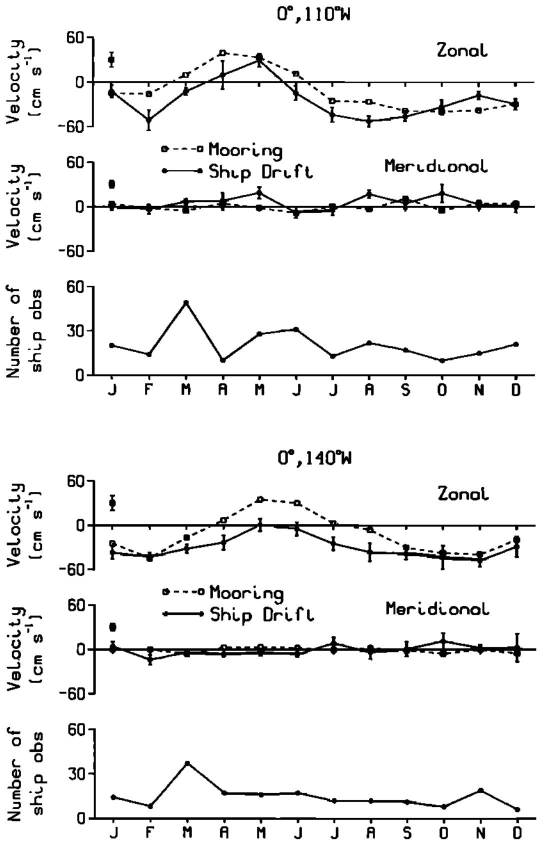

Fig. 2. Climatological monthly mean zonal velocity and meridional velocity based on ship drifts averaged in 2° latitude by 10° longitude rectangles centered at 0°, 110°W and 0°, 140°W. The number of ship drift data per month are also indicated; standard errors are calculated assuming each ship drift estimate is independent. A monthly mean climatology based on current meter mooring data is also shown (dashed lines). Standard errors for current meter monthly means (approximately ±10 cm s^{-1} in the zonal direction and ±5 cm s^{-1} in the meridional direction as discussed in section 2.1) are indicated above the January values.

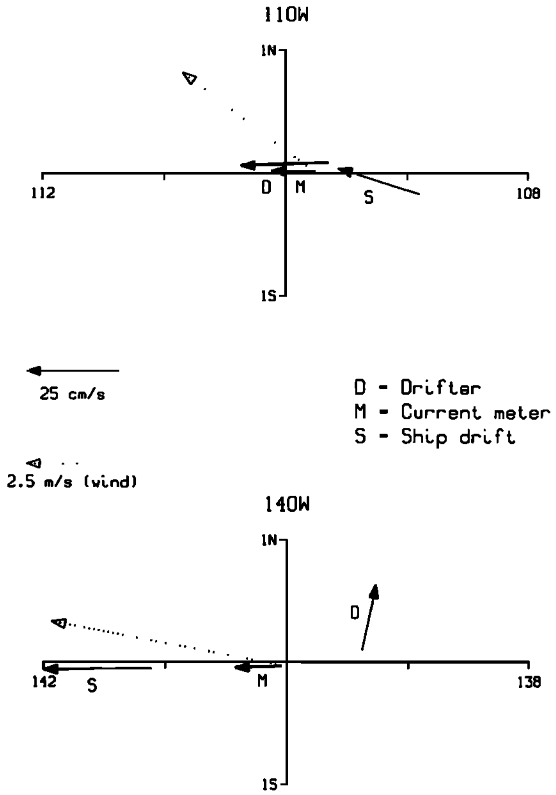

Fig. 3. Annual mean velocity vectors based on averages of the monthly means in Figures 1 and 2. The tail of each vector is at the mean position of the measurements listed in Table 1. Also shown are the mean wind vectors from data listed in Table 3.

progression across an equatorial moored array between 110°W and 140°W. In contrast to these pronounced zonal velocity variations however, none of the three data sets exhibits a significant seasonality in meridional velocity.

There are significant differences between the ship drift, drifting buoy and current meter mooring means as well. These are discussed below, first for the drifting buoy/mooring data sets, then for the ship drift/mooring data sets. We use the mooring means as a baseline in these comparisons because of the relatively large amount of data on which they are based.

3.1. *Drifting Buoy–Mooring Differences*

The most significant differences between the current meter mooring and drifting buoy means are related to drifter data density. The largest differences in zonal velocity in Figure 1 for example occur at 110°W when only 7 and 9 days of data were available for computing December and March means, respectively. Similarly, the largest differences in meridional velocity occur at 140°W when only 1, 2, and 4 days of data were available for computing December, July, and June means.

Data density also explains the largest differences between drifter and mooring annual means at 140°W and 110°W (Figure 3). At both locations there are months with low drifter data density and large deviations from the mooring means (30–60 cm s^{-1}) that when included in the annual average significantly bias the results. The ship drift and mooring annual means do not significantly change when they are computed using only data from the months when drifter data are available (8 at 140°W and 10 at 110°W). Hence the large differences between the mooring and drifter annual means do not result from aliasing of the seasonal cycle in the drifter records.

Table 2 summarizes the dependence of the comparison on data density more concisely. The median number of daily drifter data available for computing monthly means is 15. When more than 15 days of data are available, the mean difference between mooring and drifter velocities is less than 1 cm s^{-1}; and the rms differences are 5.0 cm s^{-1} (zonal direction) and 10.7 cm s^{-1} (meridional direction). In con-

TABLE 2. Drifting Buoy Minus Mooring Velocity Differences Based on Monthly Means

	Zonal Velocity		Meridional Velocity		
	Mean	rms	Mean	rms	Months
$n \leq 15$	−1.3	38.8	14.1	33.4	9
$n > 15$	0.8	5.0	0.7	10.7	9

Here $n > (\leq)$ 15 refers to months with more than (less than or equal to) 15 days of drifter data used to estimate monthly averages.

TABLE 3. Annual Mean Ship Drift Minus Mooring Velocity Differences in the Zonal and Meridional Directions

	Zonal			Meridional		
	Velocity Difference Δu, cm s^{-1}	Wind U, m s^{-1}	$\Delta u/U$, %	Velocity Difference Δv, cm s^{-1}	Wind V, m s^{-1}	$\Delta v/V$, %
110°W	−11.7	−3.4	3.4	4.9	2.5	2.0
140°W	−17.9	−5.9	3.0	0.0	1.1	0.0

Also listed are the annual mean winds in the zonal and meridional directions, and the ratios of velocity difference to wind speed expressed in percent.

trast, when $n \leq 15$, the mean difference in the meridional direction is 14.1 cm s^{-1} and the rms differences in both meridional and zonal directions are 30–40 cm s^{-1}. These values are large in relation to our error estimates for monthly mean mooring data (approximately 5 cm s^{-1} in the meridional direction and 10 cm s^{-1} in the zonal direction) and indicate that more than 15 days of drifter data (regardless of year) are necessary to form reliable monthly climatological averages on a 2° latitude by 10° longitude basis.

The month of August at 110°W may also be biased in the drifter climatology by data from the 1982–1983 El Niño. As was mentioned in the preceding section, this monthly mean is based on only 14.5 days of data, 12 of which are from August 1982. Current meter mooring data from August 1982 indicate westward flow weaker than climatology by 20 cm s^{-1} [*McPhaden and Hayes*, 1990]. This suggests that at least part of the 14 cm s^{-1} difference between the drifter and mooring August means could be due to a reduction in the strength of the South Equatorial Current at the onset of the 1982–1983 El Niño.

It is interesting to note that for months with more than 15 days of drifter data (such that reliable monthly estimates can be computed), there is no significant mean difference between the drifter and mooring velocity estimates (Table 2). One might have expected the buoy averages to be more eastward by at least 5–10 cm s^{-1} in the zonal direction because the buoy drogues are centered at depths below the 10 m in a region of $O(-10^{-2}\ s^{-1})$ vertical shear [e.g., *Bitterman and Hansen*, 1989]. However, several factors probably combine to offset this expected eastward bias. First, drogue-to-buoy area ratio for the drifters in this study is about 10, which, for shears observed in the eastern equatorial Pacific, implies a slippage of the drifters through the water by 2–4 cm s^{-1} toward the west [*Bitterman and Hansen*, 1989]. Second, windage on the buoys is expected to be about 0.5–0.6% of the wind speed [*Richardson and Reverdin*, 1987; *WCRP*, 1988], which for the easterly wind speeds shown in Table 3 implies an additional westward drifter velocity of about 2–4 cm s^{-1}. Third, the mean meridional profile of near surface zonal velocity in the eastern equatorial Pacific is nonlinear [*Hansen and Paul*, 1984] so we expect that zonal velocity averages over 1°N to 1°S will not be identical to velocity measured right at the equator. Figure 4, for example, shows the long-term average (1979–1988) profile of near-equatorial zonal velocity based on drifter data averaged over 80°–130°W. Each 0.5° latitude bin represents an average of between 200 and 400 days of data. The difference between zonal velocity in the bin centered on the equator (−8.2 cm s^{-1}) and the 1°N to 1°S average (−10.6 cm s^{-1}) is −2.4 cm s^{-1}. One expects a bias comparable to this to enter into our comparison of moored and drifting buoy measurements. Finally, in strong vertical shear there may be a tilt and an uplift of the drogue, bringing the center of the drogue closer to the 10-m depth of the moored current meters. Though not well quantified from our measurements, this tilt and uplift may lead to buoy velocities effectively measured at depths 1–2 m shallower than the nominal depth of the drogue center. A similar uplift of O(1 m) has been documented in thermistor chains suspended from drifting buoys in the equatorial Atlantic [*Reverdin and McPhaden*, 1986]. These buoys were designed differently than the circulation drifters discussed in our study; however, in principal the forces acting on the submerged drogue elements are the same in both cases.

3.2. *Ship Drift–Mooring Differences*

The most obvious difference between the mooring data and the ship drift data is the westward bias of both monthly and annual mean ship drift velocities. For example, in the ship drift data the South Equatorial Current reverses for only 2 months in boreal spring at 110°W and not at all at 140°W, whereas the mooring data show a 4-month reversal at both locations (Figure 2). Annually averaged, the westward bias

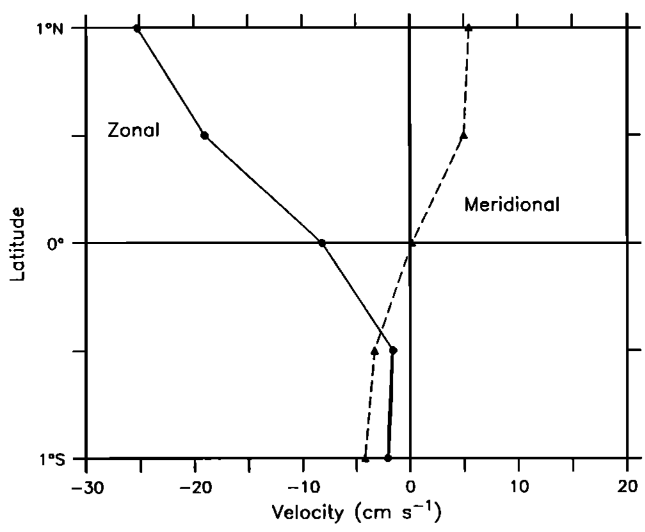

Fig. 4. Meridional profiles of mean zonal velocity (solid line) and meridional velocity (dashed line) based on drifting buoy measurements averaged over 80°–130°W for 1979–1988. Data have been grouped into 0.5 latitude bins, each of which contains 200–400 days of data.

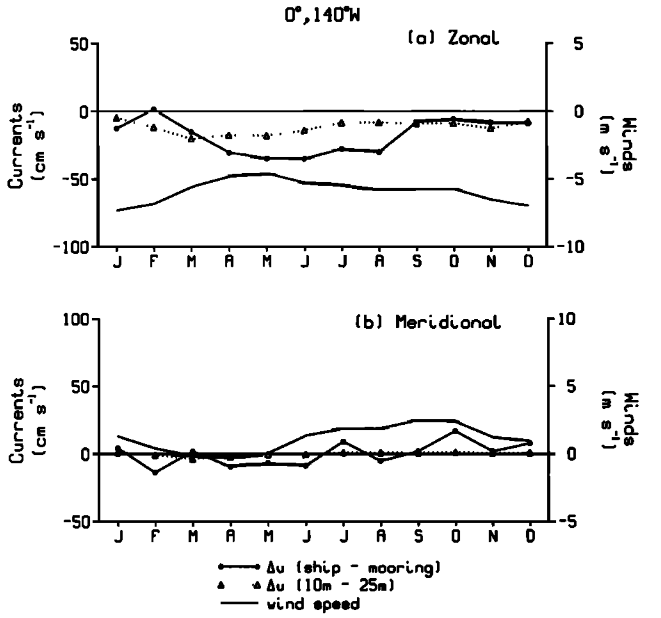

Fig. 5. Time series of climatological monthly mean winds (solid line), 10 m minus 25 m velocity differences (dotted line with triangles), and ship drift minus mooring velocity differences (solid line with circles) at 0°, 140°W. The wind and 10- to 25-m velocity climatologies are based on current meter mooring data collected during 1984–1987.

in zonal velocity relative to mooring means is 11.7 cm s^{-1} at 110°W and 17.9 cm s^{-1} at 140°W (Table 3). In addition, at 110°W there is a significant northward annual mean bias of 4.9 cm s^{-1} relative to the mooring measurements. Table 3 and Figure 3 also show that these biases tend to be in the direction of the winds, which are southeasterly at 110°W and predominantly easterly at 140°W.

The biases between ship drift and moored velocity measurements are probably due in part to the effects of windage in the ship measurements. Expressed as a percentage of the wind speed, these biases range between 2.0 and 3.4% (if we exclude the zero value in the meridional direction at 140°W where the meridional winds are light). Note, however, that not all the ship drift-mooring differences can be ascribed to windage. For example, as was noted in the preceding section, the average velocity over 1°N to 1°S is likely to be different than the velocity measured right on the equator. This effect is most pronounced for zonal velocity where we estimated from Figure 4 that the 1°N to 1°S average is more westward than the equatorial value by 2.4 cm s^{-1}. In the meridional direction on the other hand, the 1°N to 1°S average from Figure 4 (0.6 cm s^{-1}) is different than the equatorial value (0.2 cm s^{-1}) by only 0.4 cm s^{-1}.

The vertical shear in the upper ocean also needs to be accounted for in the ship drift–mooring comparisons. This is illustrated in Figure 5, which shows the seasonal cycle of winds at 4-m height, velocity difference between 10 and 25 m, and the difference between ship drift and mooring monthly means at 140°W. Mean 10- to 25-m velocity difference in the zonal direction is equivalent to a vertical shear of -7.8×10^{-3} s^{-1}, and has the same sign as the ship drift–mooring differences. Moreover, large ship drift–mooring zonal velocity differences occur in boreal spring when the easterlies are weakest and the vertical shear is relatively strong. Linearly extrapolating the 10- to 25-m vertical shear to the surface, we infer a mean 0- to 10-m zonal velocity difference of −7.8 cm s^{-1}, or 44% of the observed mean ship drift–mooring bias of 17.9 cm s^{-1}. This probably overestimates the effects of vertical shear on the ship drift–mooring zonal velocity differences at 140°W because it is based on (1) an extrapolation to the surface of equatorial shear, which is stronger than that to either the north or south, and (2) an assumption that ship drift measurements are made right at the surface rather than averaged over the upper few meters. In the meridional direction in contrast, the 10- to 25-m vertical shear at 140°W is much weaker (e.g., 0.3×10^{-3} s^{-1} on average), and though the difference between the meridional ship drift and moored measurements is noisy, its seasonal cycle tends to track that of the meridional winds (weakly southward in boreal spring and predominantly northward in boreal summer and fall).

At 110°W as at 140°W, mean 10- to 25-m vertical shear is much stronger in the zonal direction (-21.3×10^{-2} s^{-1}) than in the meridional direction (2.0×10^{-2} s^{-1}). Similar to 140°W, the ship drift–mooring differences in the zonal direction tend to be largest in the boreal spring when the winds are weakest and the vertical shear is strongest. An attempt to quantify the effect of vertical shear on the mean zonal velocity ship drift–mooring differences at 110°W by linearly extrapolating the mean 10- to 25-m vertical shear to the surface leads to the result that, on average, mooring zonal velocities would be 10 cm s^{-1} higher to the west than ship drift velocities. This is unrealistic, since we expect ship drifts to be affected in some degree by windage. Rather, it is likely that the high 10- to 25-m zonal velocity vertical shears (which are related to the proximity of the Equatorial Undercurrent core to the surface at 110°W) do not extend linearly to depths shallower than 10 m, or extend off the equator.

Thus from Table 3 and the foregoing discussion, we conclude that an upper bound for windage effects on climatological monthly mean ship drift estimates is about 3% of the wind speed. We would probably find the actual magnitude to be less than this if we could properly account for the effects of meridional and vertical shear in the upper 10 m in the ship drift–mooring differences. It is possible, for example, that windage effects are closer to 2% of the wind speed, as suggested by the value in the meridional direction at 110°W (Table 3), since the ship drift–mooring comparison for meridional flow is less subject to uncertainties associated with vertical and meridional shears. However, more accurate estimates than this are not possible with the data available to us.

4. Summary and Conclusions

In this note we have described the mean seasonal cycle in the South Equatorial Current near 0°, 110°W and 0°, 140°W from current meter mooring data, drifting buoy data, and ship drift data. All three representations of the flow field show the basic character of the annual mean and its variations, provided that the sampling characteristics associated with each measurement technique are taken into account. In particular we find that for the period 1979–1987, more than 15 days of drifter data (regardless of year) are required on a 2° latitude by 10° longitude basis to produce climatological monthly mean estimates that agree with moored estimates to within about 5–10 cm s^{-1} rms. We also estimated an upper bound for the effects of windage on ship drift data of about 3% of the surface wind speed.

It is possible that interdecadal climatic variations affect the comparison of ship drift data (mainly from 1920–1941) and mooring and drifter data (mainly from the 1980s). However, we do not have a compelling hypothesis for a shift toward weaker westward flow in the Pacific South Equatorial Current over the past 50–60 years. Moreover, we cannot completely ignore the effects of the winds on the ship drift measurements, although the magnitude of the windage bias is subject to considerable uncertainty. Hence we have interpreted the differences between the ship drift and current meter mooring data in terms of sampling characteristics rather than interdecadal climatic variations, which if present are not large enough to be detected with certainty in our analysis.

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