Characteristics of Surface Current Flow Inferred from a Global Ocean Current Data Set

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ABSTRACT
A seasonal global ocean-current data set (OCDS) digitized on a 5° grid from long-term mean shipdrift-derived currents from pilot charts is presented and described. Annual zonal means of $v$-component currents show subtropical convergence zones which move closest to the equator during the respective winters in each hemisphere. Net annual $v$-component surface flow at the equator is northward. Zonally averaged $v$-component currents have greatest seasonal variance in the tropics with strongest westward currents in the winter hemisphere. An ensemble of ocean currents measured by buoys and current meters compares favorably with OCDS data in spite of widely varying time and space scales. The OCDS currents and directly measured currents are about twice as large as computed geostrophic currents. An analysis of equatorial Pacific currents suggests that dynamic topography and sea-level changes indicative of the geostrophic flow component cannot be relied on solely to infer absolute strength of surface currents which include a strong Ekman component. Comparison of OCDS $v$-component currents and meridional transports predicted by Ekman theory shows agreement in the sign of transports in the midlatitudes and tropics in both hemispheres. Ekman depths required to scale OCDS $v$-component currents to computed Ekman transports are reasonable at most latitudes with layer depths deepening closer to the equator.

1. Introduction
In 1942, the German Admiralty published a chart of world ocean currents based on shipdrift data accumulated until that time (Schott, 1943). The chart shows world ocean surface currents for the Northern Hemisphere winter and an inset map for 30°N to 20°S depicting currents during the Northern Hemisphere summer. Current speeds and directions are represented by unequally distributed vectors; velocity units are in nautical miles per day.

This one chart has been the basis for many global surface current charts produced since then (e.g., Defant, 1961; Stommel, 1964; Neumann and Pierson, 1966). The recent proliferation of numerical models of ocean circulation and coupled ocean and atmosphere climate models has created the need for a source of observed ocean surface currents more suitable for comparison with gridded seasonal model output as well as for use in diagnostic studies.

In the future, it may become possible to retrieve ocean surface currents directly through remote sensing (Shuchman et al., 1980; TOPEX Science Working Group, 1981). At present, however, long-term mean current flow is usually obtained through analysis of shipdrift records.

Here a data set of long-term mean ocean surface currents derived from shipdrifts (Meehl, 1980) is described and compared to surface currents measured by other methods at various locations. Then, annual zonal mean $v$-component currents are compared to meridional transports predicted by Ekman theory.

2. Data
The basis for inferring ocean surface currents from shipdrift is described by Sverdrup et al. (1942) and Stidd (1974). A shipdrift is the difference between its true position and its predicted position calculated 24 h earlier by dead reckoning. This difference in position can be accounted for by two factors—wind and ocean currents. The exact effects of wind on shipdrift have not been satisfactorily determined, but Stidd (1974) estimates that the drift may be roughly one-quarter wind drag and three-quarters ocean current.

The Ekman component of a surface current due to wind stress is in a direction deviated 45° (to the right in the Northern Hemisphere and to the left in the Southern Hemisphere) from the line of the wind, Ekman drift (Neumann, 1968). However, even though the Ekman component of the surface current and the wind are acting in different directions on the
ship, both have components acting in the same direction which would affect the movement of the ship. Therefore, a current computed from the shipdrift would be greater than the Ekman component of the surface current because of the effect of the wind not being accounted for in the surface current calculation. The degree to which this would actually affect surface-current calculations from shipdrifts would vary in space and time over the global oceans due to many other factors including the effects of the geostrophic component of the current. In spite of the difficulties involved, shipdrift-derived surface currents are the only direct long-term measurements of surface flow and can be useful if the inherent limitations are kept in mind.

Several options are available for constructing an observed seasonal source of global ocean surface currents on a 5° latitude-longitude grid. The first is the original U.S. Naval Oceanographic Office (NAVOCEANO) file of over four million shipdrift observations compiled from a number of countries. NAVOCEANO has also converted these original shipdrift data into a set of 42 surface current atlases. Each atlas lists seven parameters of current flow for each 1° latitude-longitude square, but the amount and type of data in these atlases make them difficult to use for the application of interest here. The National Oceanographic Data Center (NODC) has incorporated the original NAVOCEANO shipdrift data into their Surface Current Data System (SCUDS). The SCUDS file is recorded on eleven computer tapes, but global analysis of the millions of original observations is both costly and time-consuming.

A second option is to seek sources of shipdrift that have already been translated into seasonal surface currents. Stidd (1974) analyzed the NAVOCEANO shipdrift file now incorporated in SCUDS and compiled an atlas of shipdrift components by season on a global grid 5° latitude by 10° longitude, with a separate 5° by 5° grid for the North Pacific. However, problems with quality control of the original data are not adequately resolved, and the tapes on which the data were recorded are inaccessible, thereby necessitating fresh digitization of the data in the atlas for computer use.

A third possibility is non-gridded ocean-current data from existing atlases. Several sources cover limited ocean regions. The Department of Commerce (1959, 1961) published two volumes which include ocean currents based on the NAVOCEANO shipdrift file, but only the North Atlantic and North Pacific are covered. A Dutch atlas gives shipdrift currents for only the Indian Ocean (Koninklijk Nederlands Meteorologisch Instituut, 1952).

A better alternative with global coverage is the set of pilot charts prepared from NAVOCEANO data (U.S. Naval Oceanographic Office, 1955, 1966, 1979a,b,c). Among numerous other quantities, arrows on these charts show surface current directions labeled with current speeds in either knots or nautical miles per day. Data for the pilot charts are based on long-term mean current speeds and directions already derived from the NAVOCEANO shipdrift file. Extracting a gridded ocean-surface-current data set from this source does not require great amounts of time or expense, but involves hand analysis and digitization of the data.

Considering the various requirements, we chose the ocean-current data from the pilot charts. This data set provides the flexibility needed to produce a source of observed surface currents in a suitable format for use in ocean model and diagnostic studies. It must be kept in mind that the shipdrift data recorded on the pilot charts are in the form of mean speeds and mean directions and may not always be representative of vector-averaged currents.

The pilot charts are separated into five sets of ocean-area maps with slightly different characteristics. The North Atlantic, North Pacific and Indian Ocean are shown on 12 monthly charts. January, April, July and October charts represent the four seasons in the OCDS. The South Atlantic and South Pacific have four seasonal maps, and each season is represented in the OCDS. The North Atlantic, South Atlantic and Indian Ocean charts give current speeds in knots; the others are in miles per day. All current speeds, therefore, are converted to centimeters per second for the OCDS. The South Pacific charts depict different ranges of current speeds, and average speeds are used in the OCDS.

The pilot charts give no indication of density of shipdrift observations, but presumably data quality is best in the well-traveled shipping lanes of the North Pacific and North Atlantic. Levitus and Oort (1977) have analyzed a large amount of global oceanographic data and their charts showing geographic density of ship observations indicate areas where shipdrift currents are probably most reliable.

The digitized ocean current data are shown in Fig. 1. Surface currents for the four mid-season months are represented by vectors on a 5° by 5° latitude-longitude grid. The length of each vector is proportional to the speed of the current (cm s⁻¹). South of 45°S in the Atlantic and Indian Oceans and 50°S in the Pacific in the Antarctic Circumpolar Current (ACC) region, there are no data because the pilot charts contain direction but no velocity information. However, current directions from the pilot charts from the far southern oceans are used to give an indication of the direction of current flow and are represented by dashed streamlines in Fig. 2. Elsewhere, the digitized data in Fig. 1 are used to produce schematic streamlines representative of current flow. Similar maps have been drawn for the Northern Hemisphere winter and summer (e.g., Stommel,
1964; Bowditch, 1966). What is new here is that the maps in Fig. 2 were produced from a global, uniformly gridded, seasonal ocean-current data set. It should be emphasized that the schematic streamlines in Fig. 2 depict long-term mean ocean current flow. At any particular instant, the flow pat-
tern would undoubtedly look much different from the mean, and current velocities would also vary. Instantaneous flow would probably show a series of eddies superimposed on the general mean flow to the extent that the mean flow would possibly become unrecognizable in certain areas (Wooster and Reid, 1963; Wyrtki et al., 1976). For this reason, mean surface current charts such as the ones presented
Fig. 2a. Ocean surface-current schematic streamlines analyzed from data in Fig. 1a, January and July. Dashed streamlines south of 50°S indicate that only current direction was available from pilot charts.

Here should be used for oceanographic or climatological studies where long-term averages of ocean or atmospheric variables are of interest.

The pilot charts provide no measure of the standard deviation of the magnitudes of the currents, but studies of dynamic height in the Pacific Ocean have
shown that magnitudinal variation is largest in western boundary currents and equatorial currents (Wyrtki, 1975a).

The two closed gyres in the Pacific north of the equator seen in Fig. 2 agree with Sverdrup et al. (1942) and a modeling study by Kenyon (1975), in
which these features were simulated by varying the longitudinal wind stress. Charts of dynamic height (e.g., Reid, 1961; Wyrtki, 1975a) show only one gyre in the North Pacific. Another feature shown on the charts of dynamic height is a countercurrent at about 10°S in the western Pacific. This current is only faintly present in the OCDS in January (Fig. 2a). The lack of correspondence between shipdrifts and
dynamic heights indicates areas where the wind-driven component of the surface current included in shipdrifts may be more important than the geostrophic component inferred from dynamic heights. Further discussion of this point will follow later in this paper. Figs. 3 and 4 show seasonal $u$- and $v$-component current speeds. Stippled areas indicate positive east-
Fig. 4a. v-component ocean surface currents (cm s⁻¹). Positive values are northward, January and July.

ward and northward components. In these figures, one can follow the seasonal evolution of features such as the equatorial countercurrents in all oceans and monsoonal currents (e.g., the Somali Current in the western Indian Ocean). A discussion of currents south of 45°S based on dynamic topography from Gordon et al. (1978) is given in Meehl (1980). The directional variability of surface currents, as
indicated by changes in sign in Figs. 3 and 4, is shown in Fig. 5. Two sets of two seasons each (January and July, April and October) are chosen to outline areas of current reversals, defined as $180^\circ \pm 30^\circ$ change of direction between respective seasons. Three different reversal criteria were tried: $180^\circ \pm 15^\circ$, $180^\circ \pm 30^\circ$ and $180^\circ \pm 45^\circ$. The size of the affected areas changes slightly with each reversal criterion, but lo-
FIG. 5. Surface current reversals between January and July, April and October. A reversal is defined as $180^\circ \pm 30^\circ$ change of direction between two seasons. Solid arrows indicate current direction for January, dashed arrows for April. Currents flow $150^\circ$ to $210^\circ$ in opposite directions in July and April, respectively.

FIG. 6. Zonally averaged $u$- and $v$-component currents: (a) annual-mean $u$ component; (b) annual-mean $v$ component; (c) January (solid) and July (dashed) $u$-component; (d) January (solid) and July (dashed) $v$-component.
cations remain consistent. The directions of currents in January and April are represented in Fig. 5 by solid and dashed lines, respectively. These current directions change in the opposite seasons of July and October according to the reversal criteria.

The most obvious feature of Fig. 5 is the great directional variability of equatorial currents in all oceans. Current directions also change with slight seasonal shifts of mid-ocean gyre convergence areas.

Annual-mean global zonal averages of $u$- and $v$-component surface currents from the OCDS appear in Figs. 6a and 6b. The $u$-component currents show midlatitude eastward and tropical westward maxima of $\sim +20$ to $+25$ cm s$^{-1}$ and $-20$ to $-25$ cm s$^{-1}$, respectively. An eastward maximum representing the Pacific Equatorial Countercurrent is present at $5^\circ$N associated with low values of eastward wind stress at that latitude (Fig. 7a). The $v$-component currents show subtropical convergence near $25^\circ$N and $30^\circ$S, and a midlatitude divergence at $55^\circ$N. Convergence and divergence here are implied by a change in sign of the $v$-component current. Net annual northward flow occurs at the equator as well as at $5^\circ$S.

Some features of the zonally averaged $v$-component currents in Fig. 6b can be interpreted physically, but several can just as easily be attributed to the inherent variability of the data set, data noise and resolution of the data set. For example, the existence of southward flow at $10^\circ$N implies convergence between 5 and $10^\circ$N and divergence between 15 and $10^\circ$N. This does agree with qualitative explanations of equatorial current systems in the Pacific (e.g., Neumann, 1968) which attribute these convergences and divergences to the mean position of the ITCZ lying between 5 and $10^\circ$N (Fig. 7b). Since the Pacific dominates the zonal means at those latitudes, one may cite the Equatorial Countercurrent as a product of the ocean's response to the wind stress field. However, the width of the Equatorial Countercurrent is less than $5^\circ$ and the pilot charts give the actual maximum at $\sim 7.5^\circ$N. Given the $5^\circ$ resolution of the OCDS, the eastward maximum of the Equatorial Countercurrent appears at $5^\circ$N (Fig. 6a), but this velocity represents only the southern edge of the actual current. Therefore, from the coarse resolution of the OCDS and the fact that it is impossible to assign error bars to the data, it is not clear what significance, if any, to attach to the southward $v$-component flow at $10^\circ$N. Another questionable value in Fig. 6b is the relative minimum of southward $v$-component flow at $40^\circ$N. If two grid points at the respective western edges of the Pacific and Atlantic along $40^\circ$N are omitted from the zonal average to remove the influence of the western boundary currents, the zonal average at $40^\circ$N becomes $-3.68$ cm s$^{-1}$ (compared to the original value of $-2.15$ in Fig. 6b) which is closer to the values immediately to the north and south. Once again it is difficult to determine if this feature is descriptively significant or just an inherent data perturbation.

Other features of zonally averaged $v$-component currents can be explained physically with a bit more confidence. The seasonal shift of the subtropical convergence zones as indicated by January and July $v$-component currents is seen in Fig. 6d. In January, there is convergence at $38^\circ$S and $17^\circ$N suggested by the change in sign of the $v$-component currents, and in July the convergence zones shift northward to $27^\circ$S and $34^\circ$N. These shifts follow the seasonal cycle of climatological wind forcing.

The $u$-component current's seasonal variation is greatest in the tropics with stronger westward currents occurring in the winter hemisphere. The Equatorial Countercurrent is seen as a strong eastward-flowing current in July at $5^\circ$N and a weak westward current in January. It was noted earlier that the actual maximum occurs on the pilot charts at $\sim 7.5^\circ$N since the width of the current is less than $5^\circ$.

The seasonal variation of cross-equatorial surface currents in January and July in Fig. 6d is characterized by northward flow in July and southward flow...
in January. Fig. 8 shows \( u \)-component currents at the equator broken down by ocean areas. In both the Pacific and Atlantic, there is positive \( u \)-component flow in January and July with a very strong positive value in July in the Atlantic due to stronger \( u \)-component flow of the Guiana Current off the coast of South America. The two monsoon ocean areas, the Indian Ocean and South China Sea, show flow reversals between January and July. The positive value for July in the Indian Ocean is relatively low because the large northward flow of the Somali Current is offset somewhat by southward flow in the eastern part of the basin. Net global \( u \)-component surface flow at the equator shown in Fig. 8 is northward because the northward flow in July is greater than the southward flow in January. The annual average for all four seasons in Fig. 6b shows net northward flow at the equator as well.

3. Comparison with other current measurements

Since shipdrifts represent only one method of deriving ocean surface currents, it is of interest to compare the shipdrift-derived currents to currents measured by various other direct methods. The intent here is not to present an exhaustive intercomparison, but to perform a number of spot checks at various locations. The degree to which shipdrift currents correspond to currents measured by other means can be determined in this manner.

One technique utilizes satellite-tracked drifting buoys. The use of buoys to measure surface current flow is not without its own set of difficulties, the most obvious being that buoy programs are infrequent and nonuniform in space and therefore cannot represent long-term mean flow. Nevertheless, such a comparison is instructive to see how the speeds of individual buoys, as well as an ensemble of buoy measurements from different locations, compare with long-term mean shipdrift currents.

Kirwan et al. (1978) report results from a buoy program in 1976-77 in the eastern North Pacific. They present velocity records from two of their 23 buoys. Positions of the two buoys can be determined for velocity comparison to October and January values from the OCDS. The first, which they describe as typical of the records from the subarctic gyre, shows a maximum velocity of 36 cm s\(^{-1}\) and a minimum of 18 cm s\(^{-1}\) for October 1976 near 45°N, 160°W with an average speed of \( \sim 27 \) cm s\(^{-1}\). The OCDS value for October at that location is 26 cm s\(^{-1}\). During January 1977, the buoy was near 50°N, 145°W and had an average velocity of 17 cm s\(^{-1}\) with a minimum of 8 cm s\(^{-1}\) and a maximum of \( \sim 26 \) cm s\(^{-1}\). The OCDS value for that location in January is 26 cm s\(^{-1}\). The other buoy velocity trace, which they consider a typical record from the subtropical gyre, shows an October maximum of 34 cm s\(^{-1}\), a minimum of 2 cm s\(^{-1}\), and an average of \( \sim 18 \) cm s\(^{-1}\) near 150°W, 40°N. For January, the buoy was near 140°W, 40°N, and showed a maximum of 25 cm s\(^{-1}\), a minimum of 2 cm s\(^{-1}\), and an average of roughly 14 cm s\(^{-1}\). Surface currents for those locations in the OCDS are 21 cm s\(^{-1}\) for both months. The OCDS current speeds agree well with the average velocities of the buoys in October and are within the limits of variability in January. Kirwan et al. (1978) note that the speed of their buoy-derived currents is about twice that of the geostrophic currents calculated from mean dynamic heights. Therefore, the shipdrift-derived currents agree more closely with these particular buoy currents than with geostrophic currents from dynamic height.

The direction of the currents indicated by the buoys and OCDS currents is in fairly good agreement in this region with eastward flow in October, northeastward flow in January, and southeastward flow in April.

Results from a satellite-tracked drifting buoy launched in the Southern Hemisphere in 1976 (Harris and Stavropoulos, 1978) indicate mostly zonal flow at 41°S between \( \sim 10° \)W and 15°E with no indication of the strong northeastward flow (not part of the ACC) seen in all seasons in the OCDS data. Based on mean drift for this buoy near 0° longitude, the zonal component for April is \( \sim 17 \) cm s\(^{-1}\) and for July 16 cm s\(^{-1}\). Comparable zonal component currents from the OCDS are 29 cm s\(^{-1}\) in April and 39 cm s\(^{-1}\) in July, with considerably greater meridional component velocities. However, a current maximum distinct from the ACC appears in the southern Atlantic near 35°S on a map of geostrophic surface
currents computed from relative dynamic topography (Gordon, et al., 1982). Also, three FGGE drogued buoys (Nos. 17755, 17760, 17765) launched during 1978–79 agree with the northeastward flow seen in the OCDS (FGGE Buoy Data Control Centre, 1980). Based on beginning and ending positions, two moved with average velocities of about 20 cm s\(^{-1}\) northeastward in January 1979. Long-term mean OCDS velocities for the same area of the South Atlantic in January are stronger—\(\sim 36\) cm s\(^{-1}\)—but in the same direction as those of the three FGGE buoys.

Satellite-tracked drifting buoys launched as part of the Hawaii to Tahiti Shuttle Experiment (Wyrtki et al., 1981) in the Pacific Equatorial Countercurrent near 5\(^\circ\)N and 160–115\(^\circ\)W moved east at an average speed of 45–55 cm s\(^{-1}\) from August through November 1979. Long-term mean currents from the OCDS for October indicate a maximum eastward velocity of 51 cm s\(^{-1}\) at 165\(^\circ\)W, 5\(^\circ\)N, decreasing eastward to 31 cm s\(^{-1}\) at 140\(^\circ\)W, 5\(^\circ\)N.

Wyrtki et al. (1981) note that while the buoys were being carried eastward by the Countercurrent, they also translated slowly from south to north. The plots of \(u\)-component OCDS currents in Fig. 4 confirm this result and show positive or northward \(u\)-component in most areas of the Countercurrent.

Buoys launched during the Indian Ocean Experiment (INDEX) in 1979 showed that the eastward equatorial surface jet extends across the Indian Ocean at the equator during the monsoon transition periods (April and October), is most vigorous in the central Indian Ocean, and reaches speeds of 100 cm s\(^{-1}\) (Luyten et al., 1980). The OCDS currents show positive eastward-component flow occurring across the entire width of the Indian Ocean during April and October. Strongest zonal-component flow in the OCDS occurs in the central Indian Ocean with values \(\sim 66\) cm s\(^{-1}\) between 65–75\(^\circ\)E in April, and about 65–68 cm s\(^{-1}\) near 70–75\(^\circ\)E in October.

Pochapsky (1976) reports results from MODE in 1972–73 where instrumented profiling floats measured currents near 28\(^\circ\)N, 69\(^\circ\)W. In August 1972 and June 1973, currents in the first 50 m were \(\sim 20\) cm s\(^{-1}\) toward the southeast. The OCDS value for 30\(^\circ\)N, 70\(^\circ\)W for July is 26 cm s\(^{-1}\) toward the northeast, and the April current for that location is about the same magnitude toward the southeast.

A current meter is another tool for measuring currents directly. Current-meter measurements are different from buoy measurements in that a current meter represents a Eulerian rather than a Lagrangian method of measurement. Also, current meters are usually placed beneath the surface at depths greater than the draft of a ship. Therefore, wind effects experienced by buoys and shipdrifts are absent. Current meters and drifting buoys share the same problems of occasional and nonuniform measurements scattered around the globe in just a few locations. Like drifting buoys, current meter measurements are not necessarily indicative of the long-term mean flow represented by the OCDS currents.

A series of current meter measurements was made near Addu Atoll in the Indian Ocean at 73\(^\circ\)E near the equator (Knox, 1976). The eastward jets of spring and fall were measured at speeds of \(\sim 100\) cm s\(^{-1}\), and the westward currents of January and July ranged from 75 to 100 cm s\(^{-1}\). The OCDS currents for April and October are also eastward and somewhat weaker at 67 cm s\(^{-1}\). January and July westward currents range from 41 to 46 cm s\(^{-1}\) at that location.

A number of current measurements were made in the tropical Atlantic during GATE in 1974. Bubnov et al. (1976) report surface currents measured by moored current recorders between 1.5\(^\circ\)N and 1.5\(^\circ\)S at 23\(^\circ\), 30\(^\circ\)W during June–September 1974 of 30–50 cm s\(^{-1}\) westward. The OCDS value at 0\(^\circ\), 25\(^\circ\)W for July is 51 cm s\(^{-1}\) westward. Other direct current measurements made during GATE at 9\(^\circ\)N, 23\(^\circ\)W during September 1974 showed currents of 20–40 cm s\(^{-1}\) eastward in the top 50 m (Perkins and Van Leer, 1977). The OCDS value at 10\(^\circ\)N, 25\(^\circ\)W for October is 26 cm s\(^{-1}\) eastward.

Profiling current meter measurements were made in the tropical Pacific during the Hawaii to Tahiti Shuttle Experiment. An example of this type of measurement is given by Wyrtki et al. (1981). Contouring begins at a depth of 10 m and current speeds are relative to the average current between 300 and 500 m which makes this type of measurement difficult to compare to OCDS surface currents. Nevertheless, the sample shown by Wyrtki et al. (1981) gives currents near the surface along 153\(^\circ\)W in January 1980 of \(\sim 40\) cm s\(^{-1}\) westward at the equator and \(\sim 60\) cm s\(^{-1}\) eastward at 5\(^\circ\)N. The OCDS values for January at 155\(^\circ\)W are 36 cm s\(^{-1}\) westward at the equator and 26 cm s\(^{-1}\) eastward increasing to 40 cm s\(^{-1}\) at 140\(^\circ\)W at 5\(^\circ\)N.

As mentioned earlier, dynamic height obtained from hydrographic data has been used to infer geostrophic surface currents (e.g., Gordon et al., 1978). Dynamic height and sea level have been used to infer relative strength of seasonal geostrophic surface current flow in the equatorial Pacific Ocean (Wyrtki, 1974a). That study concludes that the North Equatorial Current and Countercurrent are strong in fall and weak in spring, and the South Equatorial Current is out of phase with the two Northern Hemisphere currents. This result can be compared to zonally averaged OCDS Pacific \(u\)-component currents in Fig. 9a. Three latitudes (15\(^\circ\)N, 5\(^\circ\)N, 5\(^\circ\)S) are chosen as representative of the three major currents defined by Wyrtki (1974a). The OCDS zonal velocities are averaged from 155\(^\circ\)E to 110\(^\circ\)W.

The Equatorial Countercurrent at 5\(^\circ\)N exhibits
the greatest seasonal variation with strongest eastward flow in July. The other two equatorial currents vary much less dramatically throughout the year. Even though the amplitude of the annual cycle of these two currents is slight, the flow pattern does follow the annual cycle of $u$-component wind stress shown in Fig. 9b (Hellerman, 1982). Weak westward tradewinds north of the equator in July are associated with a weak westward North Equatorial Current at $15^\circ$N and a strong eastward Equatorial Coun-
tercurrent at 5°N. The latter relationship, which appears to occur seasonally, has been postulated in anomalous events on interannual time scales as a contributing factor to El Niño (Wyrtki, 1975b). This also agrees with Wyrtki (1974a) in that large interannual anomalies in major currents behave similarly to their seasonal fluctuations.

It was mentioned earlier that the ITCZ lies to the north of the equator in the annual mean, but is farthest north in July when the Equatorial Counter-current is strongest and easterlies are weakest at 5°N. Similarly, weak easterly tradewinds at 5°S in January are associated with weak westward flow in the South Equatorial Current.

A direct relationship between winds and currents at higher latitudes has been studied by van Loon (1971). There are semiannual oscillations of zonal wind at middle and high latitudes in the Southern Hemisphere seen in Fig. 9b and documented by van Loon and Rogers (1981), van Loon (1972) and van Loon (1967). The 12-month annual cycle of shipdrift surface current velocities in the southwestern Indian Ocean presented by van Loon (1971) shows a semiannual component which follows these winds.

Using dynamic topography and sea levels from island stations as indicative of geostrophic current flow, Wyrtki (1974b) saw less direct correspondence between winds and currents in the tropical Pacific. It can be argued that a shipdrift-derived current is biased toward the Ekman or wind-driven flow component due to direct wind effects on ships. Some of these difficulties were addressed earlier. However, Kirwan et al. (1978) and Harris and Stavropoulos (1978) concluded that their buoy speeds were about twice as large as geostrophic currents computed from dynamic height. This difference is still appreciable even when one takes into account the reduction of geostrophic current speeds due to averaging which is not present in point measurements.

The results presented here would at least point to the importance of the wind-driven component and suggest that dynamic topography and sea-level changes cannot be relied on solely to infer the absolute strength of surface currents which include the Ekman component.

4. Comparison with Ekman theory

In addition to comparison with buoys and current meters, the observed surface currents can be compared to transports computed by Ekman theory. Since the OCDS only represents currents in the upper 10 m of the ocean surface layer, it must be assumed in the following discussion that those currents are representative of a depth-averaged current over the thickness of the Ekman layer.

For non-accelerated wind-driven currents where vertical eddy viscosity $A$ is constant with depth, the equations of motion are

$$-fv = \frac{A}{\rho} \frac{\partial^2 u}{\partial z^2},$$

$$fu = \frac{A}{\rho} \frac{\partial^2 v}{\partial z^2},$$

where $f$ is the Coriolis force $(2\omega \sin\phi)$ and $\rho$ is density.

Boundary conditions are

$$\rho A \frac{\partial u}{\partial z} = \tau_x \quad \text{at} \quad z = 0, \quad \frac{\partial u}{\partial z} = 0 \quad \text{at} \quad z = -h$$

$$\rho A \frac{\partial v}{\partial z} = \tau_y \quad \text{at} \quad z = 0, \quad \frac{\partial v}{\partial z} = 0 \quad \text{at} \quad z = -h$$

where $h$ is the Ekman depth and $\tau_x$ and $\tau_y$ are the zonal and meridional components of surface wind stress, respectively.

Integrating from $z = 0$ to $z = -h$, we obtain the Ekman transports

$$\rho \bar{\omega} = -\frac{\tau_x}{f}, \quad (1)$$

$$\rho \bar{u} = \frac{\tau_y}{f}, \quad (2)$$

where $\bar{v}$ and $\bar{u}$ are the depth-averaged velocities over the thickness of the Ekman layer $h$.

Fig. 10 is a plot of the OCDS $v$-component surface currents seen in Fig. 6b and the quantity $-\tau_x/f$ from Eq. (1) using the eastward wind stresses plotted in...
TABLE 1. Ekman depth.

<table>
<thead>
<tr>
<th>Latitude group</th>
<th>$-\tau_x/(f(v \text{ cm}$ s$^{-1}$)</th>
<th>$h$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°-50°N</td>
<td>$-0.52 \times 10^6$</td>
<td>3.06</td>
</tr>
<tr>
<td>5°-25°N</td>
<td>$+1.38 \times 10^6$</td>
<td>2.58</td>
</tr>
<tr>
<td>5°-30°S</td>
<td>$-1.47 \times 10^6$</td>
<td>2.28</td>
</tr>
<tr>
<td>35°-45°S</td>
<td>$+0.83 \times 10^6$</td>
<td>2.76</td>
</tr>
</tbody>
</table>

Fig. 7a. Assuming the OCDS $v$-component currents are in some way indicative of the depth-averaged $v$ in Eq. (1), the agreement of the two curves in Fig. 10 indicates the degree to which the OCDS $v$ currents correspond to Ekman theory. The $v$-currents plotted in Fig. 10 have not been scaled by the Ekman layer depth $h$ in Eq. (1).

To facilitate the comparison and to eliminate some of the noise from the curves, Table 1 gives latitude-grouped averages of the $v$ currents and $-\tau_x/f$ from Fig. 10. The groupings are defined roughly by sign changes of meridional transport. Table 1 also gives the Ekman depth $h$ which is required properly to scale $v$ and $-\tau_x/f$ in Eq. (1). Table 1 shows agreement of sign between the observed OCDS $v$-currents and transports predicted by Ekman theory with equatorward transport at midlatitudes and poleward transport in the tropics creating subtropical convergence near 25°-30° in both hemispheres. The Ekman depth $h$ required to scale the OCDS $v$-component current is on the order of tens of meters in all latitude groups except 5°-25°N. The value of $h$ for that group is reduced if the large negative $v$-component current at 10°N is omitted.

If a constant coefficient of eddy viscosity $A$ is assumed for all latitudes, the Ekman depth $h$ is inversely proportional to the square root of the Coriolis parameter. Therefore, one would expect a deeper Ekman layer in the tropics as compared to that in midlatitudes. This is consistent with the predicted values of $h$ from the OCDS shown in Table 1.

A similar plot (not shown) of $u$-component currents and $\tau_x/f$ from Eq. (2) produced somewhat less agreement, probably because of the effects of the strong geostrophic zonal currents present in the OCDS. The influence of geostrophic western boundary currents on the plot of $v$-component currents in Fig. 10 is assumed to be slight, due to the relatively narrow extent of the boundary currents as compared to the scale for the global zonal averages taken over all ocean basins.

5. Conclusions

A seasonal global ocean current data set (OCDS) digitized on a 5° grid from long-term mean shipdrift-derived currents from pilot charts is presented and described. Annual zonal means of $v$-component surface currents from the OCDS suggest meridional cells with tropical divergence and subtropical convergence. The subtropical convergence zones in each hemisphere move seasonally and are located farthest equatorward during their respective winters. Net annual $v$-component surface flow at the equator is northward with southward flow in January and northward flow in July. The zonally averaged $u$-component currents exhibit greatest seasonal variance in the tropics with strongest westward currents occurring in the winter hemisphere. There is a favorable agreement between OCDS data and an ensemble of ocean currents measured by buoys and current meters, but currents from these sources are about twice as great as currents computed from dynamic heights or sea levels. This result, along with an analysis of equatorial Pacific currents, indicates that dynamic topography and sea-level changes as indicative of the geostrophic flow component cannot be relied on solely to infer the absolute strength of surface currents which include an Ekman component. Comparison of OCDS $v$-component currents with Ekman transport theory shows: 1) agreement in sign of midlatitude and tropical transports in both hemispheres; 2) relatively large but still reasonable Ekman layer depths required to scale the OCDS $v$-component currents to predicted Ekman transports at most latitudes, and 3) deeper predicted Ekman layers in the tropics than in midlatitudes, which is consistent with theory if a constant eddy viscosity coefficient is assumed.

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The ocean current data set described in this paper is available on computer tape. A copy of the tape can be obtained by contacting Wilbur Spangler of the Data Support Section at the National Center for Atmospheric Research, Boulder, Colorado.

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