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The Near-Surface Circulation of the Eastern North Pacific

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ABSTRACT

A description of the near-surface circulation of the eastern North Pacific during 1976–77 is given. The data for the study are obtained from 23 satellite (Nimbus 6) tracked drifters. The large-scale description obtained from the drifter trajectories is in good agreement with the mean annual dynamic topography. In the interior there is eastward zonal flow with a pronounced northward meander centered around 140°W. It is speculated that the meander, which is also seen in the mean annual dynamic topography, is an occasional feature closely connected with large-scale fluctuations of the surface wind. The trajectories define the eastern portion of the subarctic and subtropical gyres and the split between these gyres which occurs at about 50°N. In addition to these large-scale features, the trajectories show ubiquitous mesoscale activity. However, the mesoscale velocity field is not as strong as that reported for the western Atlantic or western Pacific. Separation statistics for the drifters indicate that very little dispersion occurs on time scales longer than 30 days and space scales greater than 300 km.

1. Introduction

Observations of the near-surface circulation have been either inferred indirectly from the field of mass or determined directly from ship drift. These observations are not easily compared. Surface currents determined from the mass field rely on an arbitrary reference level and do not include motions excited by the direct action of the wind. On the other hand, ship drift measures the total current but is strongly biased by the direct influence of the wind on the ship.

Here we report on observations of the surface circulation in the eastern North Pacific made by satellite-tracked drifters. This is a new observational tool which, in principle, is capable of measuring the total near-surface current.

However, there is widespread concern about wind drag causing drogue slippage (Kirwan *et al.*, 1975). In a recent study Kirwan *et al.* (1978a) attempted to correct velocity data obtained from drifters which had lost their drogues. Employing the technique described by Kirwan *et al.* (1975), it was found that the corrected velocities were often much larger and in the opposite direction than the uncorrected. This indicated that for the buoy configuration used here (see Fig. 1 of Kirwan *et al.*, 1978b) the correction technique overestimates the windage effect, even for undrogued buoys. Thus, we have elected not to apply any windage correction to these data. However, this prescription should not be applied to other drifter data sets without careful consideration of the wind data and the drag effects on specific hull designs.

There are a number of descriptions of the surface circulation in the North Pacific. Sverdrup *et al.* (1942) identified two major eastward flowing currents in the interior of the eastern Pacific. These are the Subarctic Current which they located at approximately 45°N and the North Pacific Current located at approximately 38°N. Neumann and Pierson (1966), utilizing Defant's analysis of data acquired prior to World War II, present a similar pattern but identify only the North Pacific Current by name. The Defense Mapping Agency pilot charts as reported by Tabata (1975) show two anticyclonic gyres in the North Pacific. In the winter the eastern gyre is centered about 30°N, 160°W. Roden (1975) shows eastern flow between the subarctic and subtropical fronts which are located along 43 and 30°N, respectively. South of the subtropical front, the flow is to the west. The dynamic topography charts of Reid and Arthur (1975) and Wyrtki (1974, 1975) are

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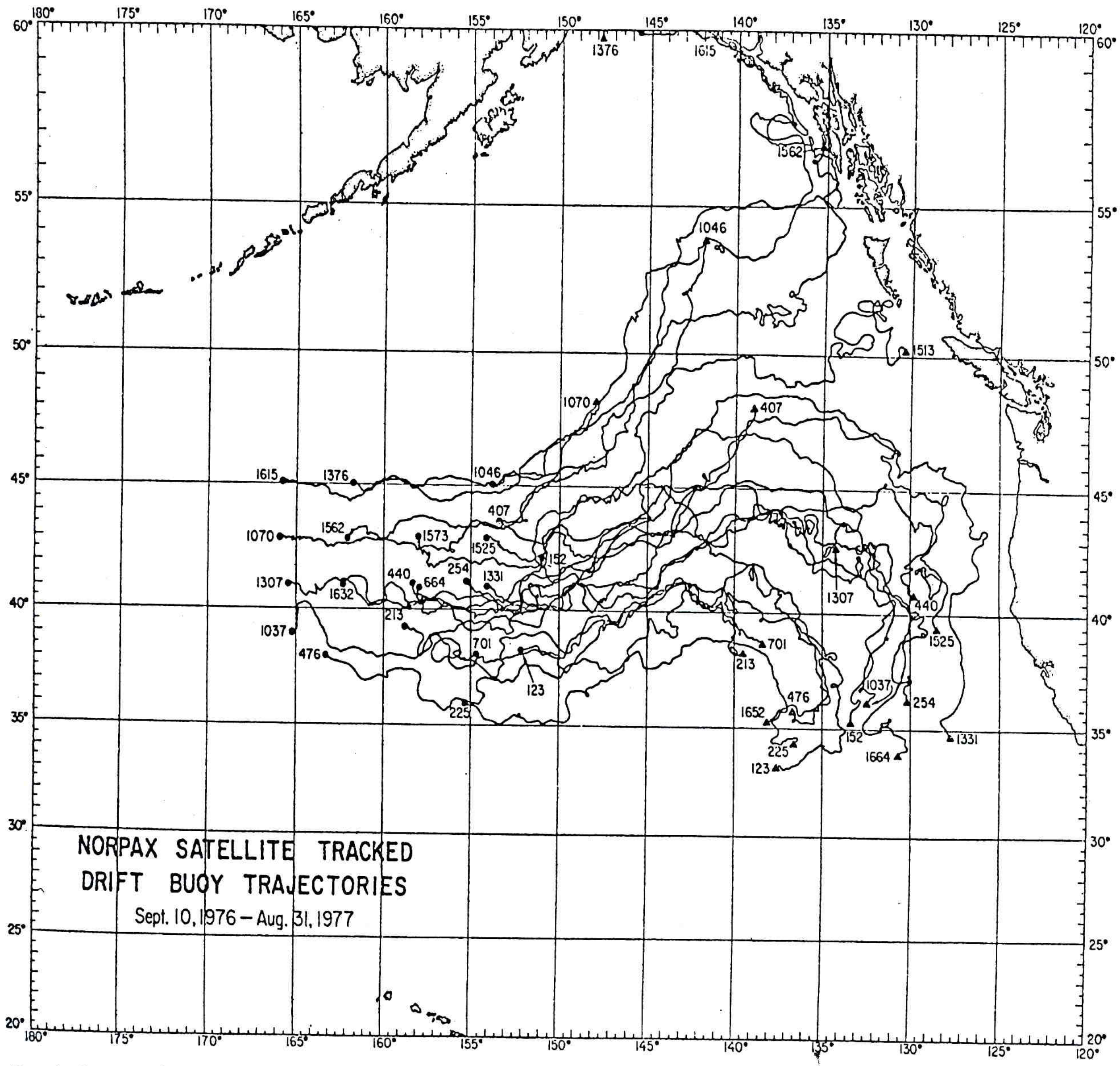

FIG. 1. A composite of the trajectories of 22 drifters deployed during the ADS I and II. The trajectories are from positions fixed by Nimbus 6 during the period 10 September 1976 through 31 August 1977.

generally consistent with these studies. However, specific currents are not well resolved in these latter two climatological studies. Although the climatologies are generally consistent, Tabata (1958, 1965) has reported significant year-to-year variability.

Other than Wyrtki's 1974 study and the pilot charts, no studies have been made on the seasonal variability of the surface currents. Also, no studies have been made of year-to-year surface current variability. However, studies by Namias (1971) and others show considerable interannual variability in the sea surface temperature field. White and Walker (1974) indicate that this thermal variability may extend down to the main thermocline, thus suggesting the possibility of year-to-year fluctuations of the general circulation.

In the experiment described below, a large amount of hydrographic and XBT data in addition to the drifter data was obtained. A synthesis of the drifter data with concurrent hydrographic and wind field data will be the topic of a later report.

2. Description of trajectories

The data set analyzed here comes from the 23 longest trajectories from drifters deployed during the Anomaly Dynamics Study (ADS) I and II experi-

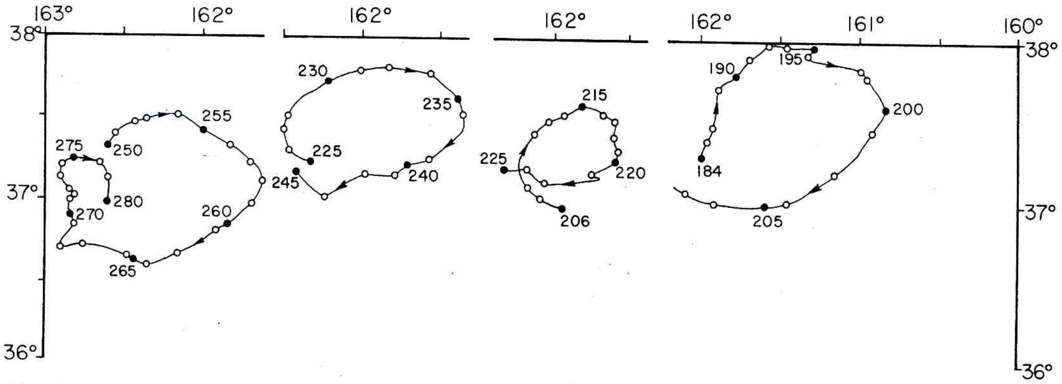

FIG. 2. The trajectory of ID 0115 from day 184 through 280/76. During this period the drifter completed four revolutions about an eddy. This eddy migrated to the west-southwest at about 0.02 m s^{-1}.

ments. The ADS I deployment was made during June 1976 and the ADS II deployment was made during September of the same year. In both deployments all drifters were drogues by 9.2 m diameter parachutes at 30 m. McNally *et al.* (1978) have summarized the technical performance of these drifters. In general, drogue indicators showed that the parachutes stayed on for over 100 days in ADS I and even longer in ADS II. There is no obvious change in the trajectories or velocities when the parachutes fell off.

Fig. 1 is a composite plot of the ADS I and II trajectories. The most striking aspect of this figure is large-scale eastward flow separating at the west coast of North America. Embedded in the main flow field are numerous mesoscale features. Fig. 2 shows a typical mesoscale eddy. The size (~100 km diameter) of the eddy is roughly the same as that reported for Gulf Stream rings. However, the period (three weeks) is about three times longer than the period of eddies or rings reported in western boundary current regions.

Fig. 3 is a plot of some trajectories superimposed on Wyrtki's (1975) mean annual 0/1000 db

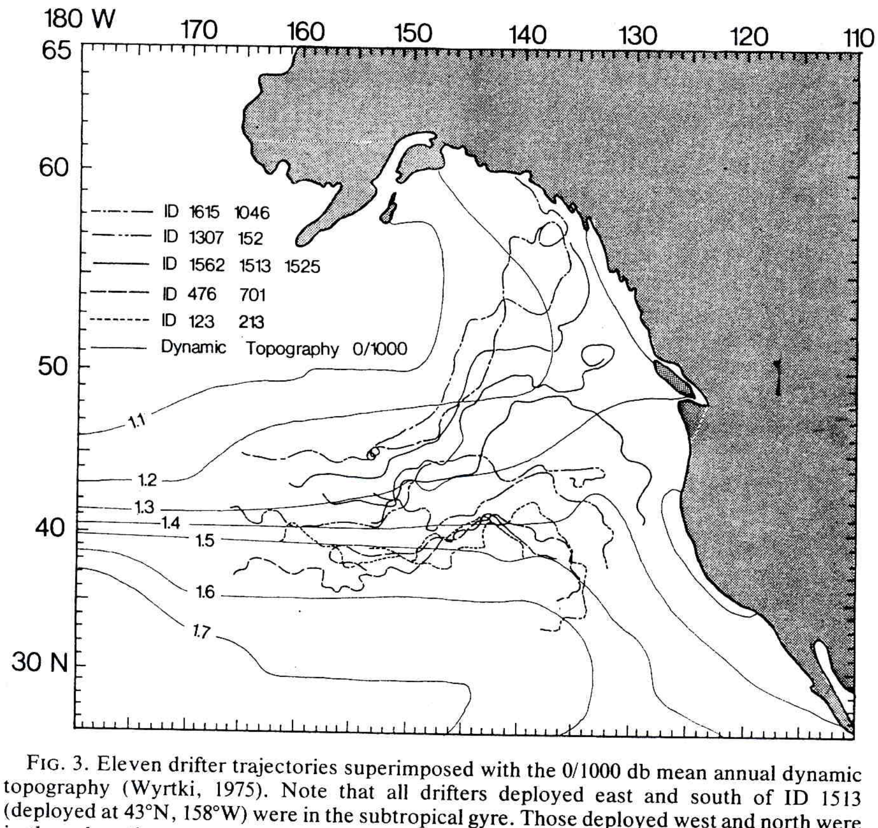

FIG. 3. Eleven drifter trajectories superimposed with the 0/1000 db mean annual dynamic topography (Wyrtki, 1975). Note that all drifters deployed east and south of ID 1513 (deployed at 43°N, 158°W) were in the subtropical gyre. Those deployed west and north were in the subarctic gyre.

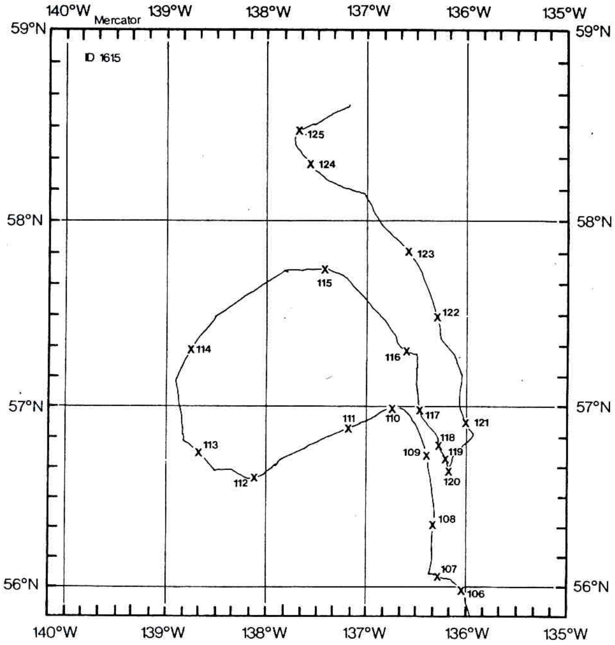

FIG. 4. The trajectory of ID 1615 as it traverses the meander at 57°N, 138°W. The ticks are the interpolated positions at 1200 GMT. Period covered 16 April to 5 May 1977.

dynamic topography. Generally, there is good agreement between the trajectories and the dynamic topography. Both the trajectories and the dynamic topography show the existence of the eastern portions of the subtropical and subarctic gyres, and both data sources agree that the gyres split between 45 and 50°N at 140°W. Also, a close examination of the drifter data reveals that all drifters deployed in or to the north of the subarctic front stay in the subarctic gyre; those deployed south of the subarctic front stay in the subtropical gyre. The lone exception ends up in the stagnation point between the gyres.

Three trajectories of the drifters deployed along 43°N show the sharpness of the split between the gyres. The drifter deployed at 43°N, 162°W (ID 1562) ends up in the subarctic gyre, while ID 1525, deployed at 43°N, 154°W, stops in the subtropical gyre. ID 1513, deployed at 43°N, 158°W, between the first two, spends its last 110 days in aimless excursions centered about 51°N, 133°W, midway between the two gyres.

A curious feature of the subarctic gyre trajectories is the large anticyclonic meander centered at 57°N, 138°W. The meander was observed by three different drifters, the first being ID 1046 near the end of March 1977. The last drifter to detect this feature was ID 1376 in mid-May, about seven weeks later. Curiously, ID 1615, which was deployed 4° west of 1376, arrived at the meander three weeks before. Fig. 4 shows the trajectory of ID 1615 as it traversed the meander. Again the fact that the drifters which detected the meander were all deployed along 45°N is an indication of the smooth nature of the large-scale flow.

Another conspicuous feature of both the trajectories and the mean annual dynamic topography is the northward meander in the eastern portion of the subtropical gyre. However, the northward and westward extent of the meander in the mean annual dynamic topography is not nearly as great as it is in the trajectories. As the drifter observations were made during the development of the largest thermal anomaly ever observed in the North Pacific, it is likely that this meander represents a significant intra-annual variation of the general circulation.

Because the drifters were deployed at different times and in different locations, a comparison of different trajectories can provide some information on the inter-annual variability of the general circulation. The trajectories indicate that the transition from season to season is not smooth.

Over the period of November 1976–March 1977 two large-scale changes in the trajectories occurred. Both were associated with the surface winds. The trajectories in Fig. 5 show that in November the four easternmost drifters developed a significant northward flow and that by January all the drifters were moving to the north. Pazan (1977a) has shown that as early as October the surface winds east of 150°W to the coast were from the south. The implication of this is that in the surface currents east of 150°W a significant northward wind-driven component developed.

The other large-scale change is shown in the last panel in Fig. 5. In March the drifters ceased their northward movement and turned to the east. This coincided with the wind field weakening and veering to the east (Pazan, 1977b).

3. Velocities

Fig. 6 shows velocity records from two drifters. Fig. 6a (ID 1376) is typical of records from the subarctic gyre. The early part of the record shows considerable variability with a period of about 20 days. The average speed up to day 225 is 0.23 m s^{-1}. The rms value of velocity fluctuations in the U and V components is 0.1 m s^{-1} and is seen to be principally associated with the 20-day fluctuations. The high velocities observed around day 240 occur in the anticyclonic meander discussed previously. Note the large westward velocities near the end of the record. This was the result of its westward movement off the coast of Alaska.

Fig. 6b (ID 0152) is typical of the velocity records from the subtropical gyre. The average flow is about 0.1 m s^{-1} to the east for the first 240 days of the deployment. Again, fluctuations with a period of

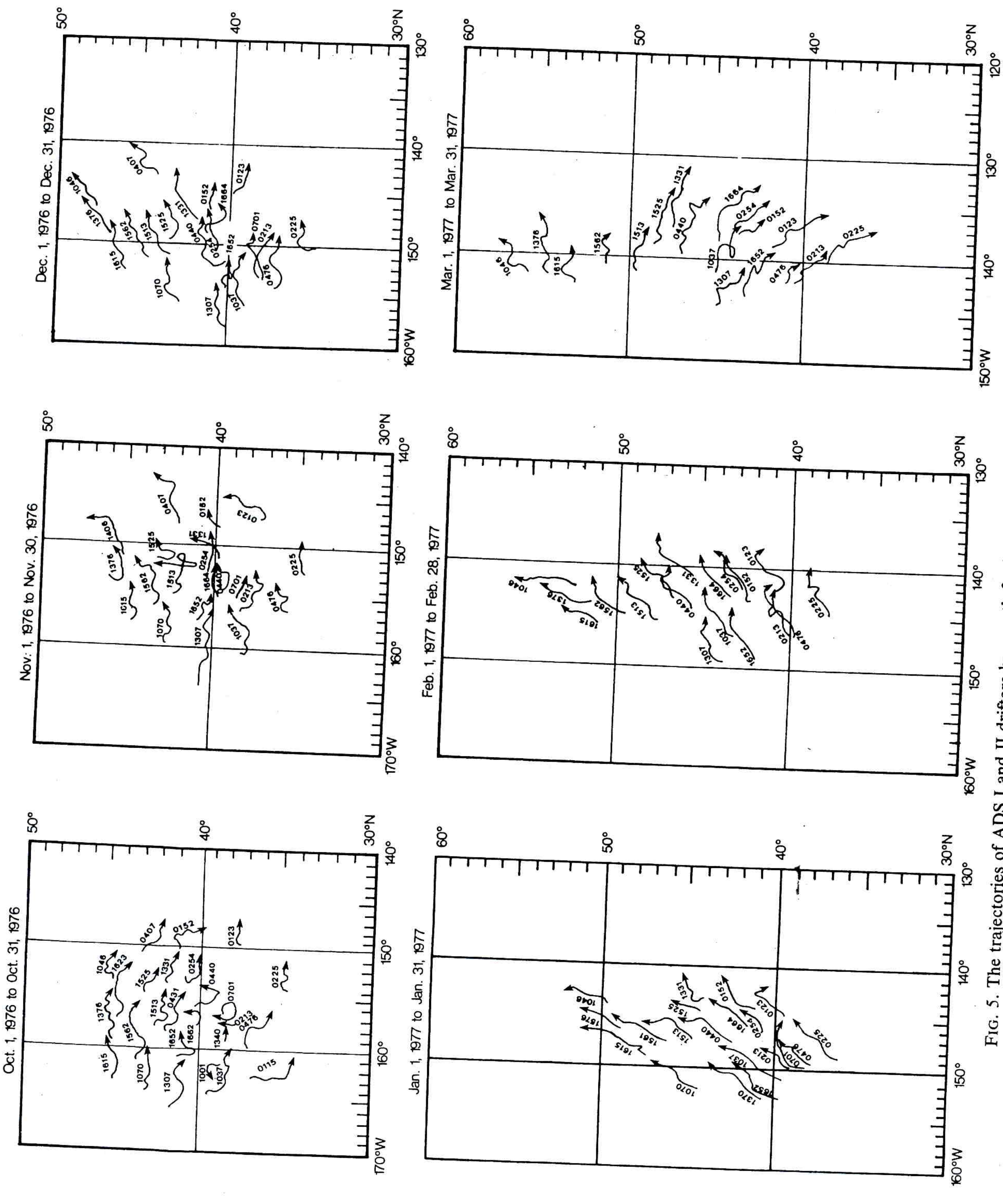

FIG. 5. The trajectories of ADS I and II drifters by month for November 1976 through March 1977. Only drifters which transmitted for the entire month are included for that month.

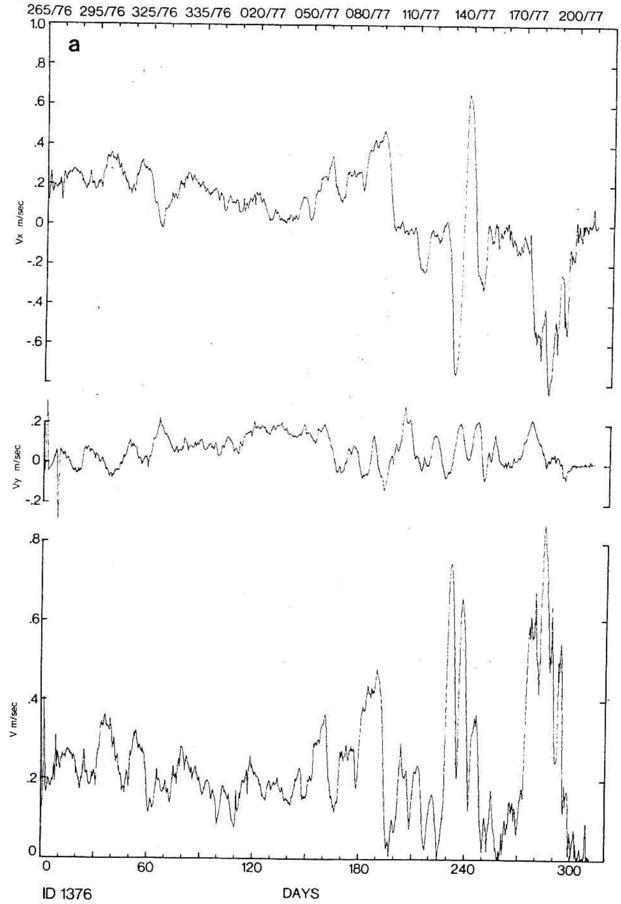

FIG. 6a. The velocity records from ID 1326 deployed in the subarctic gyre. The velocities were computed from the positions interpolated at each synoptic period. The only smoothing applied to the records was a 25-point running average.

about 20 days are present in both *U* and *V* components, and have an rms value of about 0.1 m s^{-1}.

In general, the average eastward velocities are about twice those calculated from the mean annual dynamic heights. This is not surprising. The mean dynamic heights represent time-averaged conditions and do not define the banded structure of the current. Also, there is usually some spatial smearing of the current width due to large hydrographic station spacing. Moreover, since the winds were quite strong throughout the experiment, the drifter velocities contain an appreciable Ekman component. In a study where the drifters all lost their drogues, Kirwan *et al.* (1978b) found that with knowledge of the wind field the drifter velocity could be decomposed into an Ekman and geostrophic component. The latter was in excellent agreement with that obtained from the mean annual dynamic topography. A similar study is in progress for ADS I and II.

4. Separation statistics

Information on the time and space scale of the flow in the eastern North Pacific are contained in relative parcel displacement statistics. For the relative separation of two parcels, Kao and Al-Gain (1968) have developed a general relation between the Lagrangian relative displacement tensor D_{ij} and the Lagrangian correlation function for the relative velocity separation R_{ij}, which generalizes a well-known earlier result of Taylor (1922). Specifically, they found that

$$D_{ij}(t) = \langle [X_i(t)X_j(t) - X_i(0)X_j(0)]^2 \rangle = \int_0^t (t-\tau)\langle R_{ij}(t)\rangle d\tau, \quad (1)$$

where $X_i(\lambda)$ is the relative displacement of two marked parcels at a time λ, and the angle braces are an ensemble average over all pairs.

Two asymptotic limits for the right-hand side of (1) are well known. For early times $R_{ij} \approx 1$, in which case $D_{ij} \approx t^2$. At late times the correlation function is assumed to be zero beyond a maximum correlation time T, in which case $D_{ij} \approx t$. Riley and Corrsin (1974) have extended this analysis to include the effect of a constant mean shear. In their simple model the late-time solution was dominated by the shear effect in which case the growth rate of D_{ij} is generally not linear with time.

Following the method of Kao and Al-Gain (1968), we have calculated the mean-square pair separation, which is the trace of (1), for three clusters of drifters. One cluster was selected from the drifters which were deployed in the subtropical gyre, another from those deployed in the subarctic gyre and the last from drifter pairs which spanned the two gyres. For each cluster, all possible pair separations were calculated. As the minimum initial absolute displacement of any pair was 200 km, any turbulent effect of mesoscale motions would be apparent in the early times behavior. The behavior at late times provides a test of the homogeneity of the flow field.

These calculations are shown in Fig. 7. For the subtropical gyre, the t^2 growth rate is maintained to about 10 days and a rms relative displacement of 60 km. Thereafter, the growth rate is approximately linear to day 150 when a large-scale convergence causes the mean square separation to decrease. This occurs at a rms relative displacement of about 300 km. This convergence and the subsequent rapid separation at the very end of the record must be caused by large-scale shears.

The results for the subarctic gyre cluster are considerably different. The early times growth rate is maintained for about 30 days, at which time

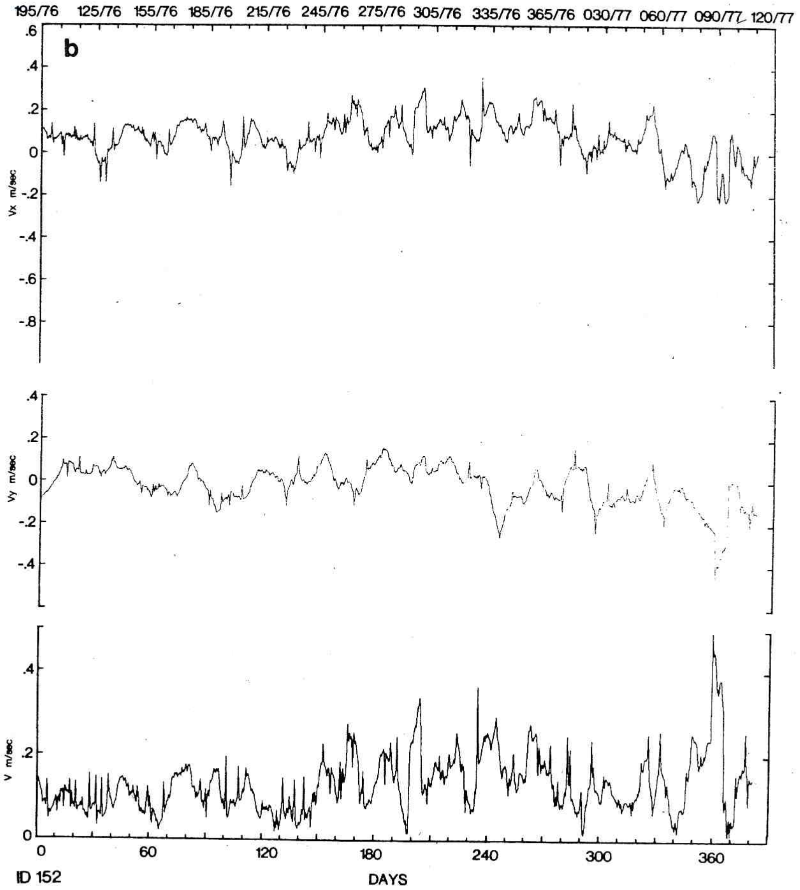

FIG. 6b. As in Fig. 6a except for the records from ID 0152 deployed in the subtropic gyre.

there is an abrupt break followed by little growth in the mean-square pair separation. This too is the result of a large-scale convergence of the subarctic cluster.

The results for the cluster spanning the two gyres are more characteristic of the classic homogeneous turbulence picture. There is the early times growth rate out to about 10 days fading into the late times growth rate which is maintained to about day 120. Toward the end of the record a rapid relative separation occurs. This rapid separation is due to the splitting of the two gyres.

A theoretical analysis for the dispersion of drifter clusters in the North Pacific has been made by Dotson *et al.* (1977). Their model shows a tendency of drifters deployed south of 40°N to migrate via large-scale diffusion into the Gulf of Alaska. However, in ADS I and II no drifter deployed south of 43°N reached the Gulf of Alaska.

During ADS I and II there is remarkably little dispersion of drifters in the mid-ocean eastern Pacific. This is different from drifter observations in the western boundary current regions. However, this result is consistent with those of Bernstein and White (1977), who found a large difference in mesoscale potential energy levels between the Pacific Basin east of the Emperor seamount chain and the Kuroshio extension region. In brief, in the eastern Pacific the drifter and XBT data show fairly smooth flow with the mesoscale motions evidently playing a relatively unimportant role in the large-scale circulation.

5. Conclusions

Allowing for mesoscale variability, the trajectories are reasonably consistent with the mean annual dynamic topography. Both show a split between the subarctic and subtropical gyres at about 50°N. All trajectories show a northward meander in the eastern part of the Pacific. The flow around the meander is consistent with the strong northward winds observed in this region from September 1976 through February 1977. This was a period of

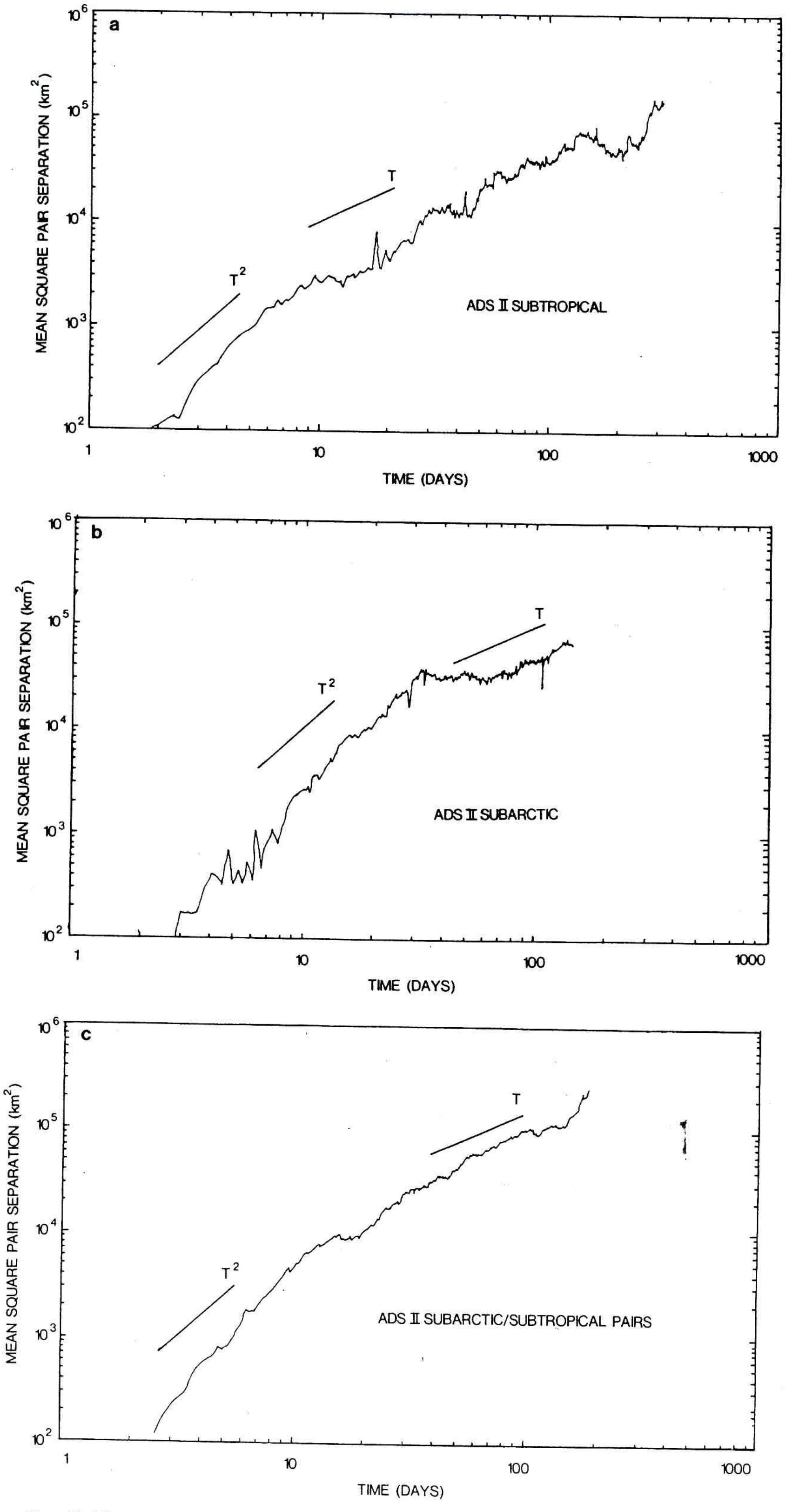

FIG. 7. The mean-square relative separation of drifter pairs from the ADS II subtropical gyre (a) using data from ID's 1037, 1307, 1331, 1525, 1652 and 1664; from the subarctic gyre (b) using data from ID's 1046, 1070, 1376, 1562 and 1615; and from the cluster spanning the two gyres (c) using data from ID's 1037, 1046, 1307, 1376, 1513, 1525, 1562, 1665 and 1652. The curves are the average of all possible pair combinations in each cluster.

anomalous conditions in both the atmosphere and sea surface temperature distribution; however, the connection between these is not yet established. We speculate that these anomalous conditions have occurred enough times to produce a vestige in the mean annual dynamic topography.

The observations show that all drifters deployed in the subarctic front or to the north stay in the subarctic gyre and those deployed in the subtropical front or to the south stay in the subtropical gyre. This seems to be the consequence of the smooth nature of the large-scale flow and the lack of dispersion by the mesoscale.

The drifter data show that the mesoscale produces very little dispersion in the eastern Pacific beyond a 300 km scale. This is in sharp contrast to drifter and hydrographic data from the western Pacific and Atlantic basins. The drifter data do not support the concept of large-scale turbulent motion and random dispersion of clusters of parcels on time and space scales in excess of 30 days and 300 km, respectively. Finally it seems that the drifters tend to find and follow the strongest currents.

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