On the Nongeostrophic Appearance of Some Mean Surface Velocity Observations in the Gulf of Mexico

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ABSTRACT: A previous study by the author concluded that either there were errors in the satellite results or that some long-term means were not in geostrophic balance. Ship-drift results are in good agreement with surface drifters, but these two do not agree with satellite sea surface heights (SSH). The agreement between the first two suggested the possibility that there could be errors in the SSH or that the mean surface flow is not in geostrophic balance. The present results, using the addition of a fourth long-term mean from hydrographic data, which agrees with the SSH, resolves the issue. The lack of agreement between different long-term means is from inadequate coverage in space and time in data from ship drifts and drifters.

KEYWORDS: Convection; Currents; Eddies; Large-scale motions; Ocean circulation

1. Introduction

In a previous paper (Sturges 2020) I compared three sources of data: ship drift, drogued surface drifters, and the results of satellite altimetry (SSH). The first two, explored by Sturges and Kenyon (2008) suggested a north–south mean upper-layer flow into the western Gulf of Mexico, while the third suggested that the mean upper-layer flow was essentially zero. The two direct methods were independent and in agreement as to a mean westward flow, leading me to conclude that there could be a bias in the SSH results—perhaps from uncertainty in the geoid.

The ship-drift data, as discussed by Sturges and Kenyon (2008), show flow to the west (at $\sim 90^{\circ}$ – 92.5° W) at all latitudes except for a narrow region between 23.5° and 25.5° N, with north–south mean speeds of order 5 – 10 cm s^{-1} . Those data have been recorded irregularly since the late 1800s, are available at NOAA web pages and can be purchased on a set of CDs (Enkoji 2010). The U.S. Naval Oceanographic Office (1991) has published many atlases of surface currents based on this dataset. Richardson (1997) found that wind effects could cause an error of less than one percent of wind speed. In the northern Gulf of Mexico, this effect, using mean winds, is small.

The drifter data analyzed by DiMarco et al. (2005) similarly show flow to the west, with a mean speed of order 5 cm s^{-1} , except in a narrow band centered at 26° N. They were careful to include only drifters that were drogued at 50 m and included results from 1989 to 1899. There is little or no overlap with the times of ship-drift data. In both datasets the mean values are dependent on the choices made for the latitude boundaries chosen; the far south and north areas, on the continental shelves, have strong flows to the west. Most of these drifters

were launched as part of an industry study that focused on Loop Current rings.

The purpose of the present paper is to suggest that the logic of the original conclusion was reasonable but was wrong, because the datasets on which it was based turn out to have inadequate seasonal sampling. This result is based largely on the inclusion of a fourth data source, dynamic heights based on hydrographic data.

The comparison between currents, on one hand, and SSH or dynamic heights, on the other, is straightforward. The height of the sea surface rises from south to north with the westward flow. If there is compensating flow back to the east in the northern half of the basin, that is, essentially no net mean flow to the west, the height of the sea surface will decrease from the central high to the northern boundary, to almost the same height as in the south, except for the small change in the Coriolis parameter.

Figure 1 shows the sea surface heights derived primarily from satellites (SSH), based on the long-term mean from the AVISO results. The dominant feature in the east is the Loop Current. The primary feature in the west, for the present purpose, is that there is no net change in height from the southern to the northern borders. Similar results are found in maps of “mean dynamic topography,” such as those shown by Maximenko et al. (2009).

The results of the ship-drift and surface drifter data were thought to be good examples of the near-surface flow patterns, and because they show results similar to each other and were completely independent, their combined result was believed at the time to be reliable. They show speeds to the west that suggest a substantial net transport to the west in the southern part of the basin, with little or no return transport back to the east in the north. The obvious discrepancy from Fig. 1 is that a mean near-surface flow to the west, if it is geostrophic balance, requires a net rise of sea level from south to north of tens of centimeters, which is not found in Fig. 1.

Figure 2 shows the long-term mean dynamic heights from hydrographic data, based on recent work of R. Weisberg and

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FIG. 1. Long-term mean sea surface height from the AVISO results over the Gulf of Mexico, plotted from their means as of 2016. Values are in cm. Note that the longitude values here are shown east of the Greenwich meridian, rather than west as is traditional in oceanography.

A. Nickerson (2021, personal communication) based on data from the *World Ocean Atlas 2018*. Figure 3, based on that data, shows how the heights at the southern and northern edges change in their monthly pattern. The curve of their mean value is similar to the typical annual cycle of height over the whole

Gulf that results from seasonal cycle of heating. Figure 2 is similar to the long-term dynamic height results of Maul and Herman (1985), although the *WOA18* is based on a much larger dataset. Furthermore, recent results by Lilly and Pérez-Brunius (2021) using a much larger set of drifter data also

FIG. 2. Dynamic heights in the Gulf of Mexico based on data from the *World Ocean Atlas 2018* (from R. Weisberg and A. Nickerson 2021, personal communication). All values are relative to 1000 dbar inside the 1000-m depth contour.

FIG. 3. Monthly mean dynamic height relative to 1000 dbar from the results of Weisberg and Nickerson, at 90°, 91°, and 92°W in the Gulf of Mexico. The black dashed curve is the mean of the boundary values at each longitude showing the seasonal variation.

show a return flow in the northern half of the basin. Their results support the idea of no net north–south mean flow. If we were restricted to the winter data only, Fig. 3 would suggest that there is, in fact, a change of order 10 cm from south to north. But the winter season has by far the poorest sampling, and the data in the south, which are the least numerous, do not show the expected winter decrease.

The absolute numerical values in Fig. 2 are not directly comparable with those of Fig. 1, although the differences within the figures are. The essential point is that there is only a small change in sea surface height from the southern to the northern border, and certainly not tens of centimeters.

2. Discussion

Before I made the original comparison between the datasets, I thought there were only two ways the disagreement between the results could be resolved. If there were some unknown error in the geoid for the western gulf, perhaps because the bottom topography near the boundaries is so steep, the SSH could be in error. The other possibility was that the near-surface flow suggested in the earlier maps of surface currents is not in geostrophic balance. Yet we assume that the near-surface flow shown in Figs. 1 and 2 is in geostrophic balance. Because the data going into Fig. 2 span many decades, it is highly likely to be fundamentally the same as the near-surface flow that is represented in Fig. 1. We assume, after averaging the observations over many years, that the transient effects of wind in the near-surface Ekman layer have been lost in the averaging. So the issue remaining is to understand how (or whether) errors could have accumulated in the drifter and ship-drift datasets.

The basic requirement for the means of datasets to be accurate is adequate sampling both in time and in space. The primary SSH maps are constructed from the accumulation of

FIG. 4. The full curve shows the number of Loop Current rings passing 90°W per month, derived from the data of Table 5 in Leben (2005); the dashed curve is a fit to a six-month harmonic for comparison.

results from several satellites collected approximately weekly. SSH tracks are considered uncorrelated if they are 300 km apart or separated by times of 30 days; see, for example, the discussion by Le Traon et al. (2008). Individual weekly SSH maps, therefore, show data from brief, coherent intervals, so velocities computed from the slopes on such SSH maps are considered to be in geostrophic balance. The mean map of Fig. 1 is from a linear combination of such maps, hence is believed to show flows in geostrophic balance.

The inherent time scale of a single dynamic height cross section is that of baroclinic adjustment, so is long enough to be in geostrophic balance. The map of Fig. 2 is an accumulation of hydrographic data over many years, and carefully constructed to be well-sampled in time, so it is believed to show flows in geostrophic balance.

When we examine the data from ship drift, however, we find problems. For example, if we examine a map of ship tracks for September (not shown), a month of better-than-average sampling, we find that the sampling is seriously inadequate in the central latitudes and the return flow in the northern half of the gyre is sampled poorly in deep water.

THE ELUSIVE “ANNUAL CYCLE”

For the drifter data, the problem is more elusive. Figure 4 shows the months of the passages of Loop Current rings in the central Gulf, based on data from Leben's (2005) Table 5. For the 31 years of data he describes, 40 rings were shed beginning in 1973. For a comparison, Fig. 5 shows a spectrum of the SSH from AVISO data, based on times of rings passing 90°W. The spectra show the frequency with which rings pass that central longitude. It is not exactly the same as the frequency of ring shedding, but we expect it to be similar. A six-month sine wave is plotted in Fig. 5 to show how the (quite reasonable) seasons used by DiMarco et al. (2005) do not fit well with the data cycle.

FIG. 5. SSH spectra along 90°W in three latitude bands using daily data from AVISO. The south band is the mean of spectra at 22° and 22.5°N. The north band is the mean of spectra at 28.5° and 29°N. Central is the mean of spectra at 25° and 25.5°N. The vertical lines show periods of one year and six months. The SSH data have not been normalized by their standard deviations. Note the lack of noticeable power near one year.

The monthly data, even for 10 years, apparently do not provide adequate sampling of the 6-month higher harmonic, which is apparent in Fig. 5.

Figures 6–9 in DiMarco et al. (2005) show maps of the flow represented by the drifter data. As they point out, in their “winter season” no rings were shed from the Loop Current during that decade. It is also remarkable that in my earlier study (Sturges 1993) of ring shedding between 1965 and 1990, not a single ring was found to be shed in December (although the data are skimpy). Winter is the only season in which the Loop Current appears in DiMarco’s maps; it is not apparent in the other three-month seasons. If the north–south mean of the east–west flow in the western Gulf is small, as shown in Figs. 1 and 2, the westward flow in the south must be balanced by equal flow to the east in the north. This small difference, therefore, is a second-order result. If the Loop Current itself, which is a zeroth-order feature, was not resolved in three of the four “seasons,” that is a clear indication that the drifter sampling is not adequate in space or time to resolve a second-order result.

3. Conclusions

The primary conclusions, therefore, are first that the long-term mean surface flows indicated from SSH and dynamic heights agree well and are likely to be in geostrophic balance. Second, the flow suggested by earlier results (based on ship drift and drifter data) do not *appear* to be in geostrophic balance because of inadequate sampling. Third, the suggestion

that geoid errors could be responsible for the mismatch between Figs. 1 and 2 is not supported. Fourth, the suggestion of a substantial net upper-layer transport into the western Gulf of Mexico, leading to downwelling in the west, is not borne out by these results.

However, one aspect of the flow remains unresolved. Large nonlinear rings are generally believed to transport mass as they propagate. It is clear that Loop Current rings bring a mass transport into the western Gulf. Whether there is a simultaneous compensating return flow back to the east is unknown, as far as I know, and is not resolved in these data. This issue will be the focus of a further study.

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REFERENCES

DiMarco, S. F., W. D. Nowlin Jr., and R. O. Reid, 2005: A statistical description of the velocity fields from upper ocean drifters

- in the Gulf of Mexico. *Circulation in the Gulf of Mexico: Observations and Models, Geophys. Monogr.*, Vol. 161, Amer. Geophys. Union, 101–110.
- Enkoji, R., 2010: Current-direction and other data from multiple ships from world-wide distribution from 1894 to 1993 (NODC Accession 9400068), version 1.1. NOAA National Oceanographic Data Center.
- Leben, R. R., 2005: Altimeter-derived Loop Current metrics. *Circulation in the Gulf of Mexico: Observations and Models, Geophys. Monogr.*, Vol. 161, Amer. Geophys. Union, 181–201.
- Le Traon, P. Y., P. Klein, B. L. Hua, and G. Dibarboure, 2008: Do altimeter wavenumber spectra agree with the interior or surface quasigeostrophic theory? *J. Phys. Oceanogr.*, **38**, 1137–1142, <https://doi.org/10.1175/2007JPO3806.1>.
- Lilly, J. M., and P. Pérez-Brunius, 2021: A gridded surface current product for the Gulf of Mexico from consolidated drifter measurements. *Earth Syst. Sci. Data*, **13**, 645–669, <https://doi.org/10.5194/essd-13-645-2021>.
- Maul, G. A., and A. Herman, 1985: Mean dynamic topography of the Gulf of Mexico with application to satellite altimetry. *Mar. Geod.*, **9**, 27–44, <https://doi.org/10.1080/15210608509379514>.
- Maximenko, N., P. Niiler, L. Centurioni, M.-H. Rio, O. Melnichenko, D. Chambers, V. Zlotnicki, and B. Galperin, 2009: Mean dynamic topography of the ocean derived from satellite and drifting buoy data using three different techniques. *J. Atmos. Oceanic Technol.*, **26**, 1910–1919, <https://doi.org/10.1175/2009JTECHO672.1>.
- Richardson, P. L., 1997: Drifting in the wind: Estimating the leeway error in shipdrift data. *Deep-Sea Res. I*, **44**, 1877–1903, [https://doi.org/10.1016/S0967-0637\(97\)00059-9](https://doi.org/10.1016/S0967-0637(97)00059-9).
- Sturges, W., 1993: The annual cycle of the western boundary current in the Gulf of Mexico. *J. Geophys. Res.*, **98**, 18 053–18 068, <https://doi.org/10.1029/93JC01730>.
- , 2020: On the mean flow in the western Gulf of Mexico and a reappraisal of errors in ship-drift data. *J. Phys. Oceanogr.*, **50**, 1983–1988, <https://doi.org/10.1175/JPO-D-19-0260.1>.
- , and K. E. Kenyon, 2008: Mean flow in the Gulf of Mexico. *J. Phys. Oceanogr.*, **38**, 1501–1514, <https://doi.org/10.1175/2007JPO3802.1>.
- U.S. Naval Oceanographic Office, 1981: Surface Currents: SW North Atlantic Ocean including the Gulf of Mexico and Caribbean Sea. Special Publ. 1400-NA9, 40 pp.