Frequency of Ring Separations from the Loop Current in the Gulf of Mexico: A Revised Estimate

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7 October 1999 and 3 January 2000

ABSTRACT

The most energetic events in the circulation of the Gulf of Mexico are the separation of large anticyclonic rings from the Loop Current. Building on previous work, the authors examine all the apparent rings since July 1973. This new dataset includes the satellite altimetry since 1992, providing a set of 34 consecutive ring formations. The primary advantage of altimetry is that the data remain available in the summer. One finding is that the ambiguity of whether or not a ring has separated is reduced, but not eliminated; the uncertainty with which separation ''events'' can be specified remains approximately 4 weeks, even with nearly continuous data. Primary peaks in the distribution of separation intervals are found at 6 and 11 months with a smaller peak at 9 months. If the spectrum is smoothed heavily enough, a peak in the distribution can be formed nearer 12 months, but this near-annual peak is a result more of the smoothing than of the data.

1. Introduction

Before the main flow from the Caribbean Sea becomes the Florida Current and then the Gulf Stream, it first passes through the Gulf of Mexico. Figure 1 shows a view of the Loop Current 4 months after a ring has separated.

When the current from the Caribbean first comes into the Gulf, the flow is directed primarily toward the north. This flow must accomplish a 90° turn to the right in order to pass between Cuba and the Florida Keys. The dynamical balance of this turn has been discussed by Pichevin and Nof (1997). In the course of making this turn, the current pattern takes the shape of a portion of a large circle, or loop. Over the course of several months, the part of the flow field in this loop extends farther into the Gulf (see, e.g., Reid 1972) until it becomes sufficiently unstable. At this point a large anticyclonic ring gradually separates from the main flow and drifts to the west. In many respects we suspect that these rings are analogous to Gulf Stream rings, except for the obvious difference that Gulf Stream rings are of both signs.

There are several puzzling features of these ring separation events. They are not quick, simple events, but long and drawn out; the separation process takes several months or more. It is not unusual for observers of some satellite IR images to conclude ''the ring has now separated,'' yet an image several months later may show the ring still attached to the main flow. Clearly, we do not understand the separation process well. Nevertheless, for any representation of Gulf circulation (whether analytical or numerical) to be capable of modeling the circulation competently, it should be able to handle ring separation events correctly. It seems important to us, therefore, to determine this fundamental time scale of ring separation events as accurately as can be done based on the available data.

Since the 1970s, much of our knowledge of ring-shedding behavior has been based heavily on satellite infrared (IR) data (see, e.g., Maul and Vukovich 1993). The IR data continue to be extremely valuable, because the horizontal resolution is unsurpassed. However, the IR data suffer from one primary limitation: the uniformly warm surface temperatures in the Gulf of Mexico during summer allow no inferences about the flow field for 3–4 months.

Data from satellite altimeters, however, are not subject to this summertime limitation. Some unresolved problems with determining a proper geoid surface for interpreting the altimetry data remain, but these are

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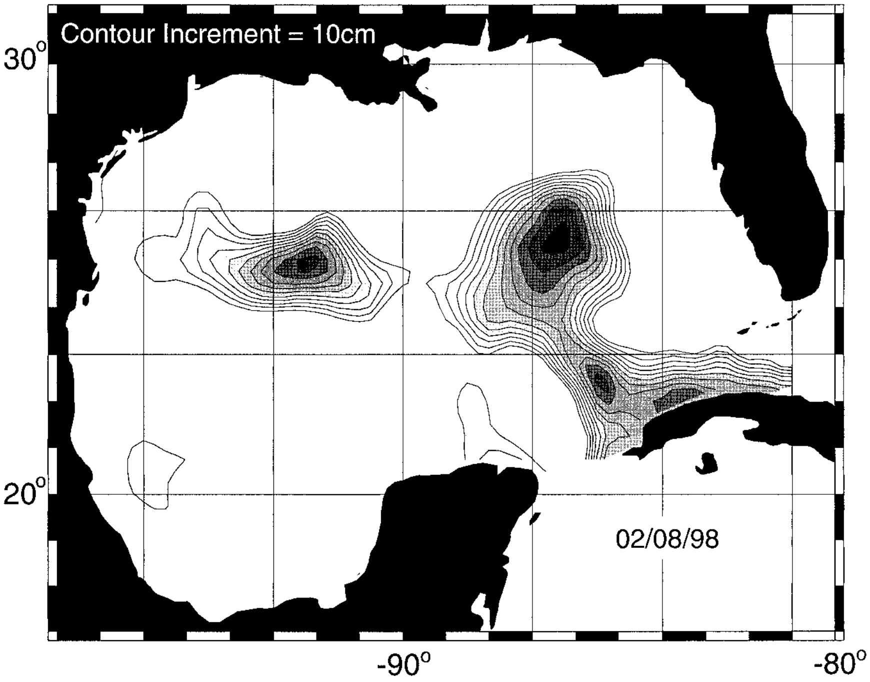

FIG. 1. A typical example of sea surface topography from satellite altimetric data; some small-scale features have been filtered out for clarity. A ring has separated and is drifting toward the west. This view is based on data for the ten days prior to 2 Feb 1998.

gradually being reduced to an uncertainty level of a few centimeters. The present level of accuracy suggests that, while there may be details of the surface height field that cannot be resolved exactly, large-scale features such as whether a ring has separated from the Loop Current can now be determined unambiguously.

Satellite altimeter data are now routinely available in both near-realtime (Lillibridge et al. 1997) and as archival data records. One of us (Leben) maintains a Web page on which daily maps of the Gulf of Mexico sea surface topography have been posted since 1996. Multisatellite sampling by the altimeters aboard the TOPEX/Poseidon and *ERS-1* and *ERS-2* satellites has been used to map the Gulf topography over the time period from April 1992 to the present. These maps have been useful, for example, for the study of Loop Current eddies in the western Gulf (Biggs et al. 1996).

Previously a dataset based on ring separations between 1973 and 1993 (Sturges 1994) suggested that the time intervals between ring shedding events had two modes, one at 8–9 months and the second at 13–14 months. These data were based heavily on satellite IR data. It is possible that some separations included on that list, particularly those in the spring or early summer, may not have separated. Since that analysis was completed, three changes have taken place. First, the earlier ‘‘community approved consensus’’ list, compiled by T. Berger (1993) has been subject to several further corrections. Second, the satellite altimetry data has made it possible to insure that summertime events are followed reliably. And third, several years elapsed during which more separation events have taken place. Consequently this new dataset contains over 50% more ring events than in the previous compilation. This new, expanded dataset is the focus of our paper.

2. New data and processing

We have reviewed maps of sea surface topography in the Gulf to estimate the times of ring separation events. These maps are based on geophysical data records from the TOPEX/Poseidon (T/P) and *ERS-1* and *ERS-2* satellite altimeters, processed in a manner consistent with the near real-time monitoring described by Lillibridge (1997).

TOPEX data were adjusted using standard corrections supplied on the JPL/PO.DAAC TOPEX GDRs,[1] including inverted barometer, electromagnetic bias, ionosphere and wet/dry tropospheric corrections, as recommended in the GDR handbook (Calahan 1993). Several additional corrections not found on the original GDRs were also applied to the TOPEX data. These corrections included orbits based on the JGM-3 gravity model and an empirical ocean tide model (Desai and Wahr 1995) based on TOPEX altimeter data computed

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[1] The Jet Propulsion Laboratory maintains a Physical Oceanography Data Archive Accession Center, PO.DAAC; it archives the geophysical data records (GDR).

using the JGM-3 orbits. The *ERS-1* and *ERS-2* Altimeter Ocean Products (ALTOPR) CD-ROMs were obtained from CERSAT. The ERS altimeter data were corrected using standard corrections supplied on the ALTOPR GDRs, including inverted barometer, electromagnetic bias, and ionosphere and wet/dry tropospheric corrections. The data were also corrected using JGM-3 orbits and the Desai and Wahr (1995) tide model to be consistent with the TOPEX processing. After extracting the data from the GDRs and applying corrections, the corrected sea surface from both satellites were referenced to an accurate high resolution mean sea surface based on altimeter data collected from the TOPEX/Poseidon, *ERS-1*, and GEOSAT Exact Repeat missions (Yi 1995).

These corrections allow data from both repeat and nonrepeat ground tracks to be combined by objective analysis, so that the nonrepeating ground tracks covered during Geodetic phase 1 and 2 of the *ERS-1* mission (10 April 1994–21 March 1995) can be used to augment T/P sampling for more accurate mesoscale mapping.

The final step in the along-track processing is to apply an empirical orbit error correction to the *ERS-1* and *ERS-2* along-track data to remove residual ERS orbit error. An empirical correction of the TOPEX orbits is not needed; however, to ''filter'' both datasets consistently, the empirical correction is also applied to the TOPEX data. This correction was based on an along-track ''loess'' filter, which removed a running least squares fit of a tilt plus bias within a sliding window from the along-track data. The filter window is approximately 15° of latitude (200 s along-track), passing the ocean mesoscale signals much shorter than this, while removing the longer wavelength orbit and environmental correction errors.

Daily maps of the Gulf of Mexico height anomaly relative to the mean sea surface were created using an objective analysis procedure (Cressman 1959). This method interpolates the along-track data to a ¼° grid over the Gulf. The method uses an iterative difference-correction scheme to update an ''initial guess'' field and then converges to a final gridded map. A multigrid procedure was used to provide the initial guess, as described in the appendix to Hendricks et al. (1996). Five Cressman iterations are used with radii of influences of 200, 175, 150, 125, and 100 km, while employing a 100-km spatial decorrelation length scale in the isotropic Cressman weighting function. Data were also weighted in time using a 12-day decorrelation time scale relative to the analysis date. The altimetry data are used here to determine only departures from the mean sea surface. To estimate the full sea surface height, or total dynamic topography, relative to a level surface, the mean surface from a 10-yr numerical ocean model (courtesy of L. Kantha and J. K. Choi), has been added to the height anomaly maps. To test the reliability of this surface for the purposes of this work, we found that the timing of ring-shedding events was insensitive to the mean used to produce the synthetic product, though the local structure of the Loop Current was affected by differences in the mean fields on the order 10 cm.

Altimetric mapping provides all-weather and all-season data. While it shows less horizontal detail than the IR data, the altimetric data used here are less likely to miss the shedding or reattachment of a ring. The primary advantages of the new list of sheddings, obviously, are that there are no data losses from clouds, or from the usual summertime uniformity of surface temperature in the Gulf.

3. Method

The method we have used is similar to that employed by Sturges (1994). By examining the maps as a time sequence, it is clear when a ring begins to separate. However, new rings often begin the separation process, only to reconnect with the Loop Current as much as a month or more later. In order to be able to tell for certain that a ring will separate, it is necessary to observe the nascent ring as it continues to form, pulling away clearly and drifting to the west as a separate feature. One advantage of this dataset, never obscured by summertime problems, is that the continued examination of the rings as they pull away allows us to be certain that the separation process goes to completion.

We evaluated all available frames of contoured data since the spring of 1992. The method is simply to examine each map to determine subjectively whether the ring appeared to be separating, and continue to track it as the separation process continued. A surprising feature of these results is that, even with a significantly improved dataset, the exact time of separation of a ring remains elusive. As has been reported earlier, based on numerical modeling results (e.g., Sturges et al. 1993) the separation process is not a single abrupt event, but a gradual pulling away, with parts of the flow connecting the main portion of the Loop Current to the separating ring for a significant part of its travel time to the west. When one examines the time sequence of maps, it is clear that this separation process takes many weeks. It is rarely possible, on the basis even of this new data set, to point to a particular time in the separation sequence and say, ''at this point the separation is complete.''

The most striking example of this ambiguity took place during 1996. It appeared that a ring was beginning to separate, and over the course of nearly a year the ''ring'' hovered in essentially the same general location. On the basis of many subjective viewings, we conclude that a ring did separate in September 1996, but the ambiguity is bothersome. Awareness of this phenomenon is certainly not new, as it has been observed to take place previously in the Gulf and for Gulf Stream rings as well.

To review briefly the method used earlier by Sturges (1994), the separation times shown in Table 1 are used to determine a histogram. To make the results more

TABLE 1. A compilation of ring-separation events; that is, times when data are available to show a ring separating reliably from the Loop Current.

Year	Month	Separation period (months)	Estimated uncertainty (weeks)
1973	Jul		
1974	Apr	9	
1975	Jan	9	
1975	Jul	6	
1976	Aug	13	
1977	Mar	7	
1978	Jun	15	
1979	Apr	10	
1980	Jan	9	
1981	Mar	14	
1981	Nov	8	
1982	May	6	
1983	Mar	10	
1984	Feb	11	
1984	Aug	6	
1985	Jul	11	
1986	Jan	6	
1986	Oct	9	
1987	Sep	11	
1988	May	8	
1989	May–Jun (?)	12.5	
1990	Aug	14.5	
1991	Aug–Sep	12.5	
1992	19 Jul	11.5	4
1993	22 Jun	11	4
1993	19 Sep	3	1
1994	22 Sep	12	4
1995	8 Apr	7	4
1995	18 Oct	6	4
1996	30 Apr	6	5
1996	Sep	5	4
1997	11 Oct	13	3
1998	14 Mar	5	2.5
1999	22 Aug	17	2

Entries through Oct 1986 are from Vukovich (1988); other entries prior to Jul 1992 are from Table 1 of Sturges (1994) using corrections based on Berger (1993). Data beginning 1992 are from satellite altimetry, this work.

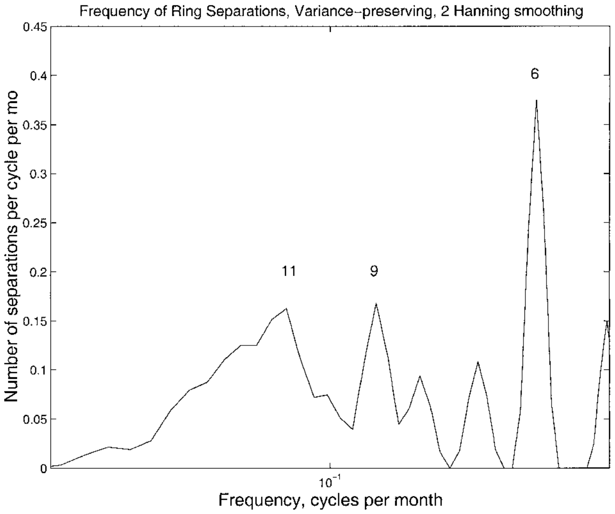

FIG. 2. Periodicity of ring separations from the Loop Current. This figure is actually a histogram, plotted to resemble a variance-preserving power spectrum. All known separations since Jul 1973 are included; see Table 1. The original distribution has been smoothed by two Hanning passes to retain high resolution. Values at intervals shorter than 5 months are off scale.

nearly in keeping with the usual analyses of time series data, however, the *inverse* of the separation interval is plotted—the resulting values are then smoothed with *n* Hanning passes to give the form of a power spectrum. The value of *n* is chosen, as in all spectral analysis, in an attempt to balance statistical confidence against resolution. Smoothing of a histogram is helpful because the size of the bins is clearly arbitrary, as is the starting point for their distribution. The basis for this procedure was described by Silverman (1986). Nevertheless, we emphasize that what is recorded in Table 1 is not a time series in the usual sense and Fig. 2 is not based on the usual spectral calculations.

4. Results

The complete list of ring separation times is shown in Table 1. Other ring separation events were recorded a decade or more earlier, but we show here only those for which we believe that *successive* separations are reliably known. There are 34 separation events in the 26-yr interval July 1973–August 1999. For the recent separations beginning in 1992 the apparent uncertainty interval is shown explicitly. The separation times listed are the midpoint of that interval.

Figure 2 shows the frequency distribution of ring separations in the form of a spectrum. The variance-preserving form is used because it shows, to the eye, the amount of power in each region. The results shown here provide conclusions that are somewhat more reliable than in the previous, similar calculation. For statistical reliability, we would prefer more smoothing than the two Hanning passes used for Fig. 2. However, the primary results are obvious at this level, and further smoothing obscures what may be an important detail.

The most noticeable regions of power are near 11 and 6 months, with another peak at 9 months. The peak in the lower-frequency mode, as could be determined from a histogram, is clearly at 11 months. Because the distribution is not symmetric about this peak, however, smoothing the distribution further would cause the peak to shift more and more toward 12 months, a value found in the early results of Maul and Vukovich (1993), using much less resolution than is now available. The resulting ‘‘annual mode’’ would then be an artifact of the smoothing, unsupported by the data of Table 1. We do not attach much significance, if any, to the precise value 11 months, as most of the separations are unknown to plus or minus at least a month. The 80% confidence limits, estimated by many iterations with a bootstrap method, extend to 1.7 times the power found in any peak. The mean value, for 33 separation intervals in 313 months, is near 9.5 months, yet there is little power at that value. The mode at 6 months contains slightly more events than the mode near 11, but this difference is probably not significant. The two modes have quite similar power levels.

5. Discussion

One difficulty with the data of Table 1 is that the uncertainties are perhaps large but unknown for the values based on the older data. Even with the satellite altimetry, the separation of September 1996 remains elusive. But by following the images carefully, we conclude that a ring did separate. Its motion was slow, and by the following late April or early May the ring appears almost to have been reabsorbed by the Loop Current. However, a ring emerges at about 93°W when this ring disappears, leading us to the conclusion that the ring actually separated.

What one does, when faced with such uncertainty, of course is to try the calculation both ways to see if it makes any significant difference. By computing the ‘‘spectrum’’ of Fig. 2 with and without the elusive ring, one finds that the differences are negligible. A small bump at ~30 months will appear, but the effect on the rest of the spectrum is hard to see by eye. The peak near 11 months would be broadened slightly, and the peaks at 6 and 9 months are unaffected.

It is well known that determining the true uncertainty of geophysical spectra is fraught with problems. We often deal more with hope than with confidence. The primary low-power peak here is near a year, so a 31-yr dataset might seem relatively ‘‘long’’ in some sense. However, a major uncertainty is that the wind system over the North Atlantic forces a decadal-scale variability in the flow (see, e.g., Hong et al. 2000; Sturges et al. 1998). The ‘‘typical’’ low-frequency variability in winds, sea level, and transport of the Gulf Stream seems to be at periods of the order of 100–200 months. We may thus suppose that, if the climate system has substantial variability at such long periods, the data of Table 1 may in fact now provide only two or three ‘‘looks’’ at the process, rather than 31. The error bars may thus be larger than we think.

The essential result is that the primary power lies near periods of 11 and 6 months, and there is almost no power at exactly 12.0 months. The lack of power at the annual period may be the most surprising conclusion.

When the wind forcing is averaged over many years it has a very clear annual cycle. It is surprising, therefore, that the low-frequency peak here is *near* one year, but quite distinctly *not* at 12.0 months. This finding remains unexplained. In the previous description of the ring-shedding frequency (Sturges 1994), this lack of power at 12 months was evident. The newer data, however, have shifted many of the details, due partly to the addition of many shorter events as well as to the division of two long-period separation events (in the previous Table 1 of Sturges 1994) into four shorter ones. The previous mode ‘‘near’’ annual, but at 13–14 months, is now found at 11 months, and the previous peak at 9 months is now much reduced. The fact that these peaks have shifted so much should give us a great deal of reluctance to put much credence in the details. The earlier ring separation results have unknown errors.

It is tempting to speculate that the lack of power at 12 months is caused by a beat-frequency effect, with the power at a lower frequency modulating the power at the annual period. The standard result is

$$f_1 \pm f_2 = f_3 \qquad (1)$$

where f_1 is annual, f_2 is the unknown, and f_3 is the observed 11-month peak. The unknown is easily found to be (approximately) 150 months. An uncertainty of ±0.2 months in the ‘‘observed’’ 11-month peak leads to an uncertainty of ~30 months in the low-frequency signal. Because an ‘‘annual’’ signal in weather emerges only in a long-term average, it is conceivable that a varying low-frequency component, together with an inherently variable annual signal, could lead to the observed near-11 month signal, but this is hardly more than speculation.

Acknowledgments. Estimated corrections to the earlier compilation were kindly provided by Dr. T. Berger, SAIC, Raleigh, North Carolina. We are grateful also to Prof. Robert O. Reid for pointing out errors in an earlier version of Table 1. Drs. L. Kantha and C. K. Choi most graciously provided the model mean sea surface result. We thank Chris DeHaan for calculating the Bootstrap error estimates. During the preparation of this manuscript, we have been supported by the U.S. Minerals Management Service (1435-01-96-CT-30825 and 14-35-0001-30787); Sturges thanks The National Science Foundation (OCE-9415642); Leben acknowledges Contract 958119 from the Jet Propulsion Laboratory. We greatly appreciate this support.

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