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# Observational evidence of seasonality in the timing of loop current eddy separation

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ABSTRACT

Observational datasets, reports and analyses over the time period from 1978 through 1992 are reviewed to derive pre-altimetry Loop Current (LC) eddy separation dates. The reanalysis identified 20 separation events in the 15-year record. Separation dates are estimated to be accurate to approximately ± 1.5 months and sufficient to detect statistically significant LC eddy separation seasonality, which was not the case for previously published records because of the misidentification of separation events and their timing. The reanalysis indicates that previously reported LC eddy separation dates, determined for the time period before the advent of continuous altimetric monitoring in the early 1990s, are inaccurate because of extensive reliance on satellite sea surface temperature (SST) imagery. Automated LC tracking techniques are used to derive LC eddy separation dates in three different altimetry-based sea surface height (SSH) datasets over the time period from 1993 through 2012. A total of 28–30 LC eddy separation events were identified in the 20-year record. Variations in the number and dates of eddy separation events are attributed to the different mean sea surfaces and objective-analysis smoothing procedures used to produce the SSH datasets. Significance tests on various altimetry and pre-altimetry/altimetry combined date lists consistently show that the seasonal distribution of separation events is not uniform at the 95% confidence level. Randomization tests further show that the seasonal peak in LC eddy separation events in August and September is highly unlikely to have occurred by chance. The other seasonal peak in February and March is less significant, but possibly indicates two seasons of enhanced probability of eddy separation centered near the spring and fall equinoxes. This is further quantified by objectively dividing the seasonal distribution into two seasons using circular statistical techniques and a k-means clustering algorithm. The estimated spring and fall centers are March 2nd and August 23rd, respectively, with season boundaries in May and December.



## 1. Introduction

Before the advent of satellite altimetry, a number of observational technologies were exploited for Loop Current (LC) monitoring. Studies of LC intrusion and eddy separation in the 1970s relied on a variety of data sources, including in-situ and satellite data to identify separation events, and were subject to periods of poor sampling. The earliest studies were based on upper-ocean temperature sections along shipboard survey cruise transects (Leipper 1970; Maul 1977; Behringer et al., 1977).

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Most of these observations were made during the spring, summer and fall. In those studies an annual cycle of LC intrusion was hypothesized based on earlier observations of an annual cycle in Yucatan Current inflow, with maximum currents in May and June and a minimum in October and November (Cochrane, 1965). Leipper (1970) proposed an annual cycle of LC intrusion in the spring followed by either a deeply intruded LC in the fall or a separated eddy and retreated LC. That study was based on in-situ data collected primarily during 1965 and 1966. Maul (1977) found a similar cycle in 1972 and 1973, and was able to track the frontal position of the LC over 14 months. Thus, by the mid-1970s the emerging consensus was that the LC exhibited a mean annual cycle, with significant deviations due to highly variable eddy-separation events. Separation periods had been observed to range from as short as eight months to as long as 17 months (Behringer et al., 1977). During an average annual cycle, the LC intruded northward into the Gulf in the spring, followed by maximum intrusion with probable eddy separation during summer and fall, and retreat to the south during winter, since the few winter observations over this time period did not show a LC intrusion north of 26°N.

In the mid-1970s, satellite radiometry imagery became available at sufficient resolution and precision to observe synoptic-scale and mesoscale fronts in the Gulf. Maul (1975) demonstrated that satellite imagery could be used to detect the western margin of the LC during winter. Legeckis (1976) reported the first wintertime deep intrusion and eddy separation determined from direct observations during the winter of 1974 and 1975. Later, Molinari et al. (1977) used both satellite and in-situ data to identify intrusions of the LC north of 26° N from 1974 through 1977, and LC eddy separation events in both winter and spring. They concluded that, since the earlier observational dataset was limited during the wintertime, it was not clear whether winter intrusions occurred before the mid-1970s. Their work provided the first evidence, however, that LC intrusion and eddy separation could occur in any season including winter.

By the late 1970s, "monthly" sea-surface temperature (SST) frontal analyses in the Gulf were being made from the very high-resolution radiometer (VHRR) instruments onboard polar orbiting NOAA satellites (Vukovich et al., 1979). These analyses were typically based only on a few clear-sky SST images and could not be made throughout the year. From June through October, the LC and LC eddy fronts could not be distinguished in the SST imagery when the warm seasonal surface mixed layer developed in the Gulf. In May, when the seasonal mixed layer was developing, intense image enhancement of some of the imagery was needed to identify the fronts. For this reason, there were times when the accuracy of some features in May frontal analyses were questioned and earlier analyses were used instead. In the time periods when LC and LC eddy SST thermal fronts were masked by the mixed layer, information on the LC and Loop Current eddies were also obtained from ship surveys in the Gulf. That information was supplemented with available Coastal Zone Color Scanner (CZCS) data to estimate the LC and LC eddy positions, the position of the northern boundary of the LC, the diameter of the ring, etc. Although frontal analyses could not be created from those data, they were entered into an unpublished database and used to identify LC eddy separation events (Vukovich 2012).

Infrared images from the Geostationary Operational Environmental Satellite (GOES) were also used for LC monitoring in the late 1970s. Imagery processed by the NOAA Miami Satellite Field Services Station was geo-registered using photographic techniques and animated in order to attempt to map daily locations of the LC front (Maul et al., 1978). The 24-h coverage provided by GOES geostationary sampling reduced data outages associated with cloud cover, and oceanic fronts in the Gulf Stream system could be mapped about half of the days (Maul et al., 1984).

Several significant technological advancements in satellite oceanography occurred in the mid to late 1970s that contributed to the development of operational satellite monitoring of the LC and LC eddies. These advancements included the first successful tests of satellite-tracked drifting buoys, satellite altimetry, and satellite ocean-color radiometry. Satellite-tracked drifting ocean buoys were developed using data collected by the NASA Nimbus-6 satellite, which carried a Tracking and Data Relay experiment that was used to determine drifting buoy positions using Doppler tracking (Kirwan et al., 1976). Nimbus-6 was launched on 12 June 1975 and operated until 29 March 1983. This research mission led to the development of the Advanced Research Global Observation Satellite (ARGOS) system, which collects, processes, and disseminates data from fixed and mobile platforms using polar orbiting NOAA satellites to the present day. Kirwan et al. (1984) documented the first use of satellite-based tracking of drifting buoys within a LC eddy. Three satellite-tracked drifting buoys were air deployed in November 1980 by the NOAA Data Buoy Center into a fall-separated LC eddy and permitted satellite tracking of the LC eddy into the western Gulf, well into spring 1981. The drifters were undrogued, but had 200-m thermistor cables attached. It is noteworthy that the only mention of a LC eddy separation event in the fall of 1980 reported in the peer-reviewed literature to date was in Kirwan et al. (1984). This event does not appear in any of the published LC eddy separation event censuses (Vukovich 1988; Sturges 1994; Sturges and Leben 2000; Leben 2005; Vukovich 2012). In the late 1970s, NASA flew the first ocean-altimetry and ocean-color satellite missions. Seasat, launched on 27 June 1978, carried the first satellite altimeter capable of measuring ocean-surface topography with the accuracy required to resolve ocean-mesoscale signals (Cheney et al., 1983). The first instrument devoted to the measurement of ocean color, the CZCS, was launched aboard the Nimbus-7 satellite on 24 October 1978. These were experimental missions and little of these data made it into the general user community for use in operational ocean monitoring or into the published LC eddy separation censuses. Later, Müller-Karger et al. (1991) demonstrated that the combined use of CZCS ocean-color and Advanced Very High Resolution Radiometer (AVHRR) SST images permits year-round monitoring of LC intrusion and eddy separation. The LC eddy separation event in the fall of 1980, mentioned above, can be seen clearly in the August and September ocean-color images shown in Plate 1 Plate 1b of that paper.

In the early 1980s, the hypothesis that the LC sheds eddies in response to annual variations in the inflow through the Yucatan Channel was challenged by a study of LC intrusion and eddy shedding using a numerical ocean model (Hurlbut and