Pergamon

Continental Shelf Research, Vol. 16, No. 8, pp. 1065–1085, 1996

0278–4343/96 $15.00 + 0.00

0278–4343(95)00056–9

Transport of anomalous low-salinity waters from the Mississippi River flood of 1993 to the Straits of Florida

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(*Received* 17 *September* 1994; *in revised form* 30 *May* 1995; *accepted* 13 *June* 1995)

Abstract—Recent field studies in the southern Straits of Florida revealed the existence of Mississippi River outflow embedded in the Florida Current and adjacent coastal waters. Surface thermosalinograph measurements for the period of 10–13 September 1993 indicated a band of low-salinity water measuring approximately 40 km wide and 30 m in depth extending from south of Key West to Miami, a distance of 260 km. Surface salinity values as low as 31 psu were found. The estimated volume of the band is approximately 33.3×10^{10} m^3 for the Key West to Miami region, thereby requiring roughly 1.2×10^{10} m^3 of fresh water to mix with oceanic waters to produce this low-salinity band. The only nearby, dynamically viable, source for such a large volume of fresh water is the Mississippi River during its flood stage in 1993. The proposed transport mechanism for the transport of flood waters from the shelf in the northeastern Gulf of Mexico to the Straits of Florida is via the Loop Current through entrainment. Salinity records from offshore C-MAN towers indicate that the low-salinity band persisted off the lower Florida Keys for approximately 3 months. The variability in the flow field in the southern Straits occurs in a 30–70 day band due to the meandering of the Florida Current and the subsequent formation, and propagation, of cyclonic gyres off the Dry Tortugas. This variability in the flow field had a clear affect on the evolution of the low-salinity band, as observed by the salinity records from the C-MAN towers. Because the band traveled as a lens in the upper 30 m of the water column and because its evolution was highly dependent on the variability within the Gulf Stream System, it was a good indicator of the mixing and exchange of offshore waters with shallow waters of the Florida reef tract and Florida Bay.

1. INTRODUCTION

A field study was initiated in September 1993 to examine the surface transport processes off the Florida Keys region in an effort to understand their influence on dispersal of ocean pollutants and reef fish and lobster larvae recruitment. The study was part of the combined efforts of the University of Miami South East Florida and Caribbean Recruitment (SEFCAR) and South Florida Oil Spill Research Center (SFOSRC) projects.

Simultaneous hydrographic and biological surveys of the coastal and offshore regions from Miami to Key West for the period 10–13 September 1993 revealed a large volume of low-salinity water embedded in the Florida Current and adjacent coastal waters. The

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volume of the observed low-salinity band, along with its biological and chemical characteristics, suggests the Mississippi River (MR) flood waters of 1993 as its only conceivable source (Ortner *et al.*, 1995).

Investigators have suspected that MR waters contribute to the fresh water input to the Florida Current and Gulf Stream systems. There have been previous reports of communication between the shelf waters in the northeastern Gulf of Mexico and the southeastern United States via entrainment of coastal water by the Loop Current (Murphy *et al.*, 1975; Parker *et al.*, 1979; Tolbert and Salsman, 1964; Schroeder *et al.*, 1987; Williams *et al.*, 1977). The Mississippi River was proposed as the source of a Gulf Stream freshening event, which was recorded in August 1973, when anomalously low salinities were observed from the Florida Keys as far north as the coast of Georgia (Atkinson and Wallace, 1975; Maul, 1975).

The large volume of low-salinity water observed in the Straits of Florida is a consequence of several independent processes. The meteorological conditions prior to the September 1993 survey period caused significant flooding. Persistent upwelling favorable winds over the Mississippi Delta encouraged the transport of plume waters southeast of the delta where they were entrained in the Loop Current and advected through the Straits of Florida. During the summer months, shelf waters are vertically stratified and mixing is inhibited thereby enhancing the signal downstream. Recent observations indicate that circulation patterns within the southern Straits of Florida and prevailing local winds promote onshore transport of surface water and this has been the focus of an ongoing regional study of the physics, chemistry and biology of the Florida Keys coastal waters (Lee *et al.*, 1992, 1995).

With the transport of relatively fresh river water from the Mississippi basin comes the possibility of significant changes within the ecological balance maintained in the Gulf of Mexico and Florida waters. It has been known for at least 20 years that the web of communities supported by the Florida coral reef system has experienced an ever increasing level of stress resulting in high mortality rates within the system (Hudson, 1981; Straughan, 1972; Stursa, 1974; Voss, 1973). This state could be intensified by extreme variations in environmental conditions such as temperature, salinity and oxygen concentration derived from local as well as distant sources. The dynamic link illustrated by previous reports and the observations presented here, warrants further investigation into the communication between distant inland contaminant sources and sensitive environments such as the coral reef communities of the Florida Keys National Marine Sanctuary.

This paper synthesizes observations illustrating the transport and evolution of the low-salinity band in the southern Straits of Florida. First, an introduction to surface transport processes in the Florida Keys is presented, followed by an explanation of sampling methods. Next, we present a first-order description of the observed characteristics of the low-salinity band. Comparisons with historic measurements in the southern Straits are presented with the goal of quantitatively defining the anomaly. Finally, possible sources and the evolution of the band will be explored with a discussion of its implications and probabilities for reoccurrence in the future.

2. SURFACE TRANSPORT PROCESSES IN THE FLORIDA KEYS

The oceanic circulation off the Florida Keys is governed by the variability of several currents which make up the Gulf Stream System. The Gulf of Mexico Loop Current (LC)

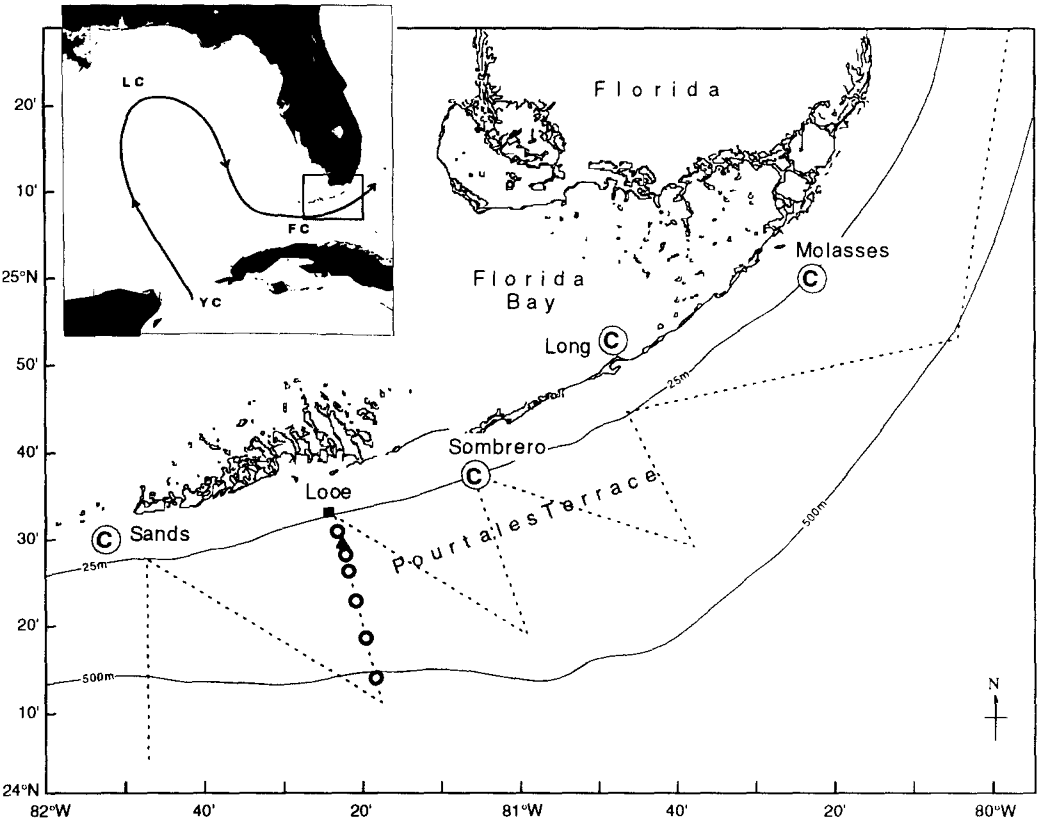


Fig. 1. September 1993 survey domain. The dashed line represents the cruise track with open circles for CTD stations, the solid square represents the moored current meter at Looe Reef, the triangle represents the location of a moored ADCP and Cs represent the C-MAN towers discussed in the text. The inset shows a schematic of the relevant current systems; Yucatan Current (YC), Loop Current (LC) and Florida Current (FC).

connects the Yucatan Current, flowing out of the Caribbean, to the Florida Current (FC) in the Straits of Florida (Fig. 1, inset). Flow variability within the southern Straits of Florida is markedly different than that of the northern Straits of Florida. Variability in both regions is dominated by the cross stream meandering of the FC which falls within a 3–10 day band in the northern Straits (Leaman *et al.*, 1987; Lee and Mayer, 1977; Brooks and Mooers, 1977a,b; Johns and Schott, 1987; Schott *et al.*, 1988) and a 30–70 day band in the southern Straits (Lee *et al.*, 1995). In the southern Straits of Florida the relatively long-period meanders of the FC are associated with the formation of large cyclonic gyres with dimensions of 100–200 km, which form off the Dry Tortugas (thus named Tortugas Gyres) and propagate through the region. Likewise, the dominant variability of the LC in the eastern Gulf of Mexico contrasts that of the southern Straits, with northward excursions into the eastern Gulf of Mexico and anticyclonic eddy shedding with a mean period of 8.5 months (Leipper, 1970; Maul, 1975; Sturges, 1992). Maul *et al.* (1975) found a strong correlation between the northward penetration of the LC and the position of the FC axis in the Straits of Florida, namely the farther north the LC penetrated into the Gulf of Mexico, the farther south the FC axis was found in the Straits.

The semi-permanent cyclonic gyres and prevailing downwelling favorable winds, provide mechanisms for the onshore transport of near-surface waters in the southern Straits of Florida. Therefore, water entrained in the FC may not be merely advected through the Straits as would be expected. Rather, entrained waters can be transported shoreward in the surface Ekman layer or retained within the recirculating flow of the coastal gyres. The evolution of the low-salinity band described below was highly dependent on the variability inherent in these coastal features and acted as a good indicator of the mixing and exchange of offshore waters with shallow waters of the Florida reef tract and Florida Bay.

3. METHODS

The sampling strategy used to observe the variable oceanographic features in the region of Looe Reef Sanctuary consisted of a mixture of moored measurements, shipboard surveys and satellite remote sensing. A moored current meter array deployed at the shelf edge (30 m isobath), and an upward looking 300 kHz Acoustic Doppler Current Profiler (ADCP) at the 150 m isobath monitored the current and temperature variability from 15 July through 28 October 1993 (Fig. 1). Three moorings were deployed at the 30 m depth equipped with three Niskin Winged Current Meters (NWCM) at depths of 7, 17 and 27 m. A single current meter was deployed at a depth of 5 m on the 13 m isobath shoreward of the reef tract. This paper will discuss observations made off Looe Reef by one of the NWCM moorings (30 m isobath) and the ADCP mooring (Fig. 1). Wind and salinity records were retrieved from offshore C-MAN towers located along the reef tract, for comparison with the evolving flow field (Fig. 1). A year long time series of Advanced Very High Resolution Radiometer (AVHRR) thermal imagery was begun in July 1993 to monitor FC frontal features and circulation patterns of the region. A Conductivity, Temperature and Depth instrument (CTD), expendable bathythermographs (XBT) and continuous near-surface thermosalinograph measurements were used to map the temperature and salinity fields along the cruise track shown in Fig. 1 for the 10–13 September survey.

4. OBSERVATIONS AND COMPARISONS

At the onset of the September 1993 shipboard survey, near surface thermosalinograph measurements revealed a band of anomalously low-salinity water extending from Key West to Miami (Fig. 2), a distance of approximately 260 km with an average offshore extent of approximately 40 km. A CTD section off Looe Reef shows the vertical structure of the low-salinity band, extending to approximately 20 m in depth where the lower limit of the maximum gradient in salinity occurs (Fig. 3a). Salinities within the band were as low as 31 psu, with lowest salinities observed shoreward at the surface. Prior to and during the cruise, AVHRR data provided a synoptic description of oceanographic features associated with surface temperature patterns. Analysis of AVHRR infrared imagery collected immediately prior to the 10–13 September shipboard survey revealed no evidence of recirculating eddy features in the southern Straits of Florida. Rather, the FC was close to shore and remained so for the duration of the cruise. This was confirmed by the downward sloping isotherms observed in the temperature sections composed of XBT and CTD data (data not shown).

To understand how anomalous this low-salinity event may be, a quantitative compari-

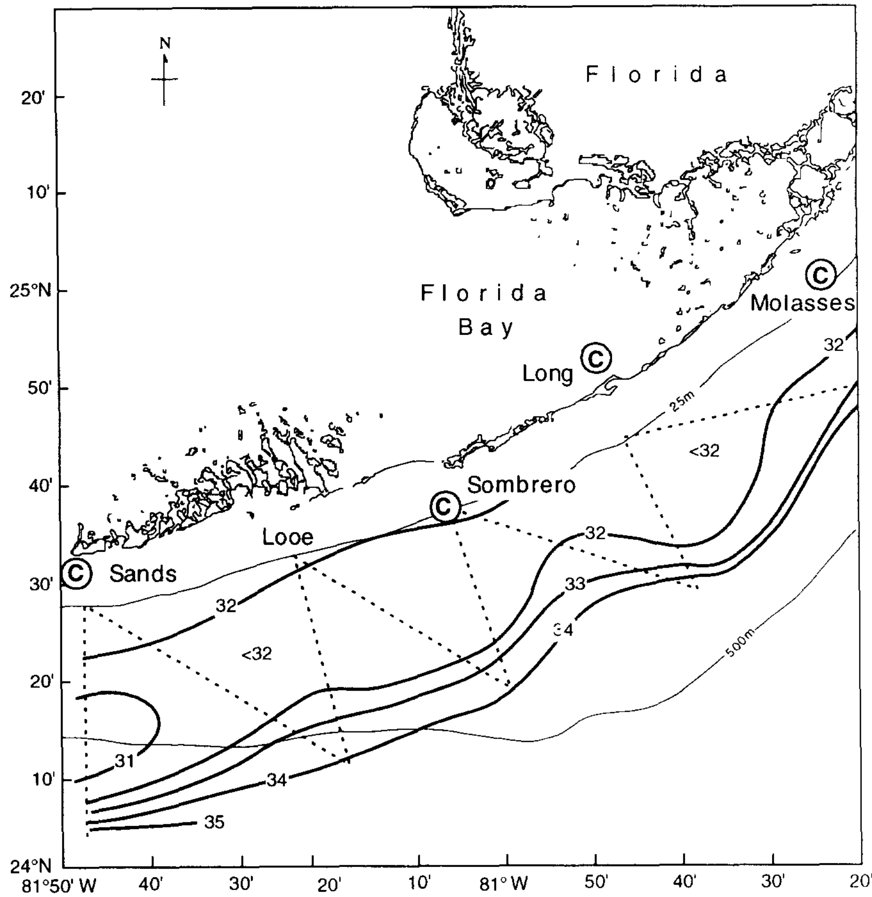


Fig. 2. Near surface salinity recorded by thermosalinograph sensors on the *R/V Columbus Iselin* during the 10–13 September 1993 survey. The Cs represent the C-MAN towers discussed in the text.

son was made between historical salinity data for the Looe Reef section and the 1993 observations. The Looe Reef transect (Figs 1 and 3) has been repeatedly sampled between 1989 and 1993 as part of the SEFCAR and SFOSRC programs. From these data, a mean salinity profile for the Looe Reef section was obtained and compared with the 1993 profile. Because there was no recirculating gyre present over the Looe Reef section during the 1993 survey, the comparison of mean profiles was made using only historical data from cruises which did not reveal the presence of such a feature. Survey dates which are included in the historical calculations include August and November 1989, May 1990, May and June 1991, and September 1993. The mean salinity profile for the "no gyre" cases was obtained by taking a horizontal (cross-shore) area-weighted average of the salinity at each depth from 4 to 200 m, in intervals of 2 m. Figure 4 shows the resultant mean profile with a 99% confidence envelope calculated using the t-distribution. This mean salinity envelope is considered to be typical for undiluted seawater off Looe Reef. Likewise, the mean salinity profile for the 1993 survey was calculated and is shown in Fig. 4. The low-salinity anomaly extends to a depth of approximately 25–30 m, where it lies outside the 99%

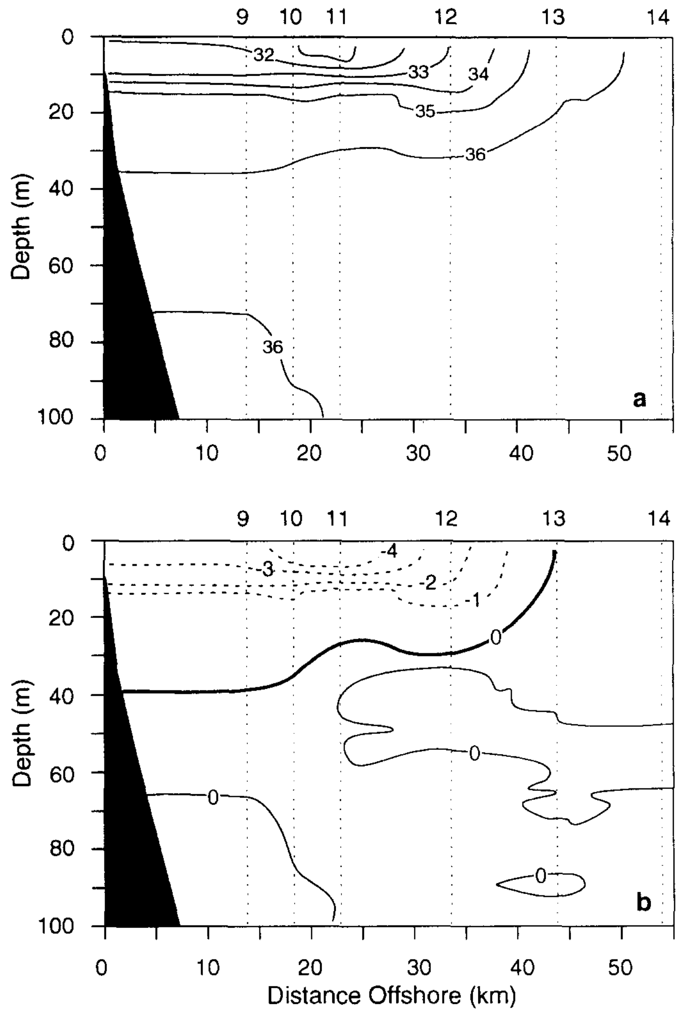


Fig. 3. Vertical (a) salinity (psu) section off Looe Reef for 12–13 September 1993 and (b) anomaly section off Looe Reef as determined by comparison with historical profile $S_b(z)$, see text for discussion of calculation. The vertical dashed lines represent the station locations across the section and are numbered accordingly at the top of each figure.

confidence envelope. Below 70 m, the 1993 profile also lies slightly outside the confidence envelope, however its curvature is close to that of the historical profile at these depths and appears to be merely offset by a constant value. This offset may be due to contamination of the historical profile due to the inclusion of transition periods prior to or immediately after the passage of a cyclonic gyre. Regardless, including this offset would not markedly change the depth over which the anomaly is identified. It must be noted that the 1993 mean profile is a conservative representation of the low-salinity event because the mean includes all stations across the Looe Reef section. This includes salinities within the edge of the FC which were much higher than the anomaly and closer to typical salinities of the region therefore offsetting the mean profile toward higher values.

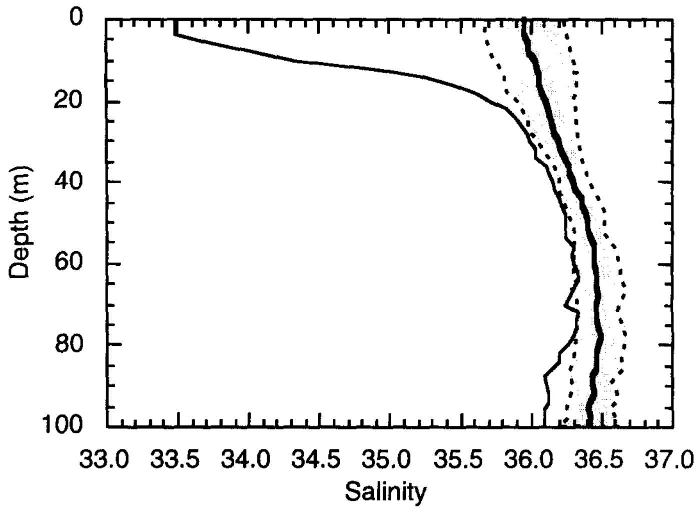


Fig. 4. Mean salinity (psu) profile for the Looe Reef CTD section. The heavy line is the historic profile derived from surveys with no gyre present over the Pourtales Terrace. The dashed curves form the 99% confidence limits for the historic mean profile and the light curve is the September 1993 mean salinity profile.

In order to compile a first-order description of the low salinity anomaly using the CTD observations off Looe Reef, some basic assumptions were required. As a conservative assumption, the lower 99% confidence limit calculated for the historic salinity profile was taken as the typical salinity profile for undiluted sea water at the Looe Reef transect, $S_b\,(z)$ hereafter. The Looe salinity section data from the 1993 CTD survey was interpolated to a 0.5 km by 2 m grid using a kriging technique. Salinities at grid points between the nearshore reef and the shoreward most CTD station were assumed constant and equal to the values at the shoreward station [#9 in Fig. 3(a)]. $S_b\,(z)$ was subtracted from the 1993 salinity value at each corresponding grid location in order to construct the salinity anomaly shown in Fig. 3(b). That is,

$$S'(x,z) = S_{93}(x,z) - S_b(z)$$

The zero contour in the anomaly plot defines the shape of the low salinity band off Looe Reef and all subsequent calculations were performed within this area [Fig. 3(b)]. The volume of the band calculated for a 1 km alongshore distance is $V_b = 1.28 \times 10^9\ \mathrm{m}^3$.

The amount of fresh water required to mix with oceanic waters to produce the observed low-salinity band was calculated as follows. The fresh water fraction of any sample may be written as

$$F(x,z) = \frac{S_b(z) - S(x,z)}{S_b(z)}$$

where $S_b(z)$ is the salinity of undiluted sea water, defined above, and $S(x,z)$ is the salinity of the sample considered, S_{93} in this case (Ketchum and Keen, 1955). The fraction of fresh water, $F(x,z)$, multiplied by the total volume of the low-salinity band, V_b, gives the volume of fresh water within the band, V_f. Likewise, $F(x,z)$ multiplied by the total area of the low-salinity band gives the area of freshwater within the band, A_f.

Following a technique similar to Dinnel and Wiseman's (1985), the Looe Reef section

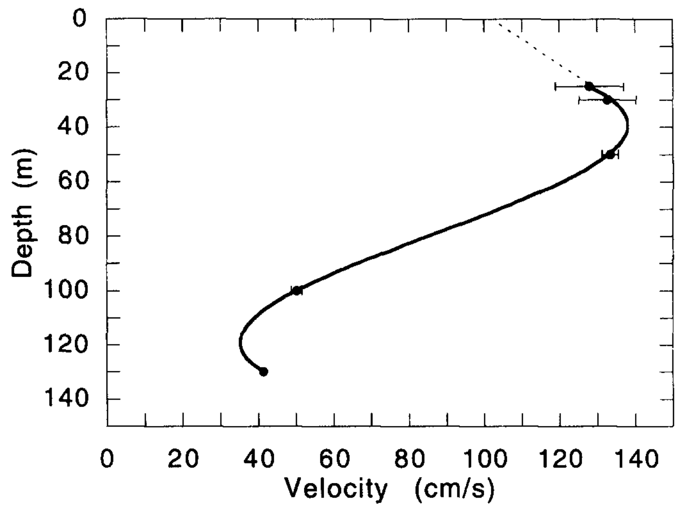


Fig. 5. Mean velocity profile over the upper 130 m as derived from the moored ADCP during the period 12–13 September 1993. The velocity profile above 30 m has been linearly interpolated upward from 30 m. Error bars are shown for the averaged velocities.

was divided into equal sub-volumes, each containing a hydrographic data point which defined the salinity value of the entire sub-volume. The fresh water fraction for each sub-volume was then calculated and averaged to obtain the mean fresh water fraction within the band; $\bar{F} = 0.037$. Finally, the fresh water volume calculated as

$$V_{\mathrm{f}} = \bar{F} \cdot \mathrm{V_b}$$

results in a value of $V_{\mathrm{f}} = 4.61 \times 10^7\ \mathrm{m}^3$ per 1 km distance alongshore. Likewise, the fresh water area, $A_{\mathrm{f}} = 4.61 \times 10^4\ \mathrm{m}^2$. For speculation purposes, if we assume that the shape and composition of the band is constant from Miami to Key West, a distance of 260 km where we do not have CTD observations, the total fresh water volume for this region may be calculated as $V_{\mathrm{f}}^{\mathrm{total}} = 1.20 \times 10^{10}\ \mathrm{m}^3$. This assumption may be justified by the fact that the surface width of the band, determined from the thermosalinograph measurements, was nearly constant between Looe Reef and Miami and the fact that there was no gyre present over the terrace at this time making vertical structure over the upper 50 m more uniform with alongstream distance. Further, measurements made roughly 6 weeks later covering the same Looe Reef transect and an additional cross-section off Fowey Rocks, Miami revealed similar cross-sectional structure in the band between the Looe Reef and Fowey Rocks sections (data not shown).

To define the rate at which the fresh water volume was advected through the Looe Reef section for a 1 m distance alongshore, the fresh water flux was calculated as

$$\phi = \nu \cdot A_{\mathrm{f}}$$

where ν is the alongshore velocity and A_{f} is the fresh water area off Looe Reef. The velocity record from the bottom mounted ADCP (location shown in Fig. 1) was used to estimate ν. The record was averaged for the period 10–14 September at depths of 130, 100, 50 and 30 m and a velocity profile was created (Fig. 5). The curve was linearly interpolated to the surface from a depth of 30 m and an average velocity was calculated for the upper

Table 1. Summary of the characteristics of the low-salinity band calculated using observations off Looe Reef sanctuary

Volume of band per 1 km alongshore (Looe)	$V_b = 1.28 \times 10^9\ m^3$
Fresh water volume per 1 km alongshore (Looe)	$V_f = 4.61 \times 10^7\ m^3$
Total volume of the band (Looe to Miami)	$V_b^{total} = 33.28 \times 10^{10}\ m^3$
Total fresh water volume of band (Looe to Miami)	$V_f^{total} = 1.20 \times 10^{10}\ m^3$
Fresh water flux	$\phi = (5.39 \pm 0.53) \times 10^4\ m^3\ s^{-1}$

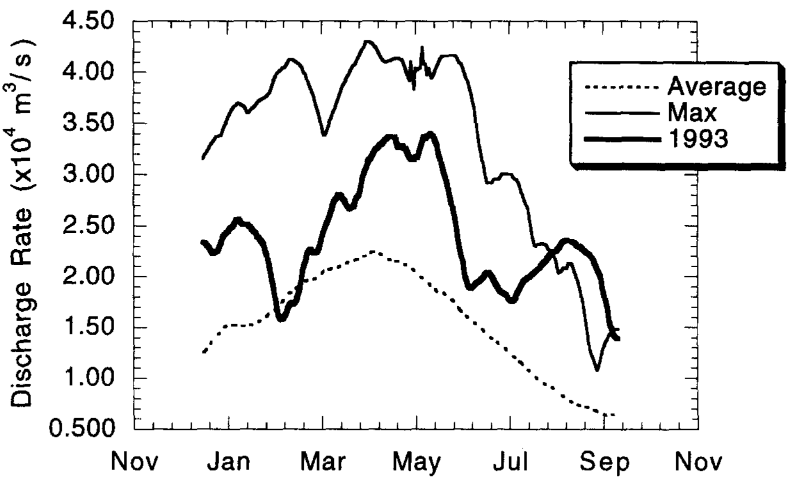


Fig. 6. Daily Mississippi River flows off Tarbert Landing for 1993 as recorded by US Army Corps of Engineers. The heavy solid curve is the daily 1993 discharge, the dashed curve is the average curve for 1931–1993 and the light solid curve is the average daily maximum for 1931–1993.

30 m (the approximate depth over which the anomaly extended). This velocity was calculated as $v = 117.2 \pm 15.3$ cm s^{-1}. Therefore, the fresh water flux through the Looe Reef section for a 1 m distance alongshore was $\phi = (5.39 \pm 0.70) \times 10^4$ m^3 s^{-1} with upper and lower limits determined by current variability. Table 1 summarizes the characteristic values of the low-salinity band calculated using the assumptions discussed above.

5. SOURCE OF LOW-SALINITY WATER

This section will examine (a) the possible sources for the low-salinity anomaly and (b) the mechanisms required for transport to the study region. The only reasonable source for such a large volume of freshwater in the lower Florida Keys region is the Mississippi River (MR). The dynamical constraints of the Straits of Florida, with a strong persistent flow to the north through a narrow channel, invalidate the southeast shelf as a possible low-salinity source. The only other possible low-salinity source would be from the fresh water discharge into the Gulf of Mexico from the major rivers east of the MR. The average annual fresh water discharge to the Gulf of Mexico from major rivers east of the MR along the west coast of Florida is roughly 4186 m^3 s^{-1} (NOAA, 1985). It would take approximately 33 days of discharge from these sources to produce a volume of fresh water of the magnitude found in the low-salinity band. Figure 6 presents daily Mississippi River flows at

Tarbert Landing, MS for 1993 as compared with 1930–1992 daily maximum and average flows. During the spring flood season the 1993 values did not exceed historical daily maximums. However, in August–September, typically a time of low flow, the 1993 discharge exceeded the historical daily maximums for 37 days, 5 August–10 September. The mean of the peak discharge calculated for this period was 2.1×10^4 m^3 s^{-1}. Therefore the total excess fresh water volume estimated for the Straits of Florida between Looe Reef and Miami, V_f^{total}, would correspond to roughly 6.6 days of discharge from the Mississippi River. This, of course, would be the case only if all of the peak discharge were to flow southeast from the northern Gulf towards the Straits of Florida. Nonetheless, these numbers provide a dramatic illustration of the magnitude of excess fresh water found in the Straits of Florida region in the September 1993 survey.

The MR discharge may be advected from the northern Gulf of Mexico to the Straits of Florida if the LC is fully formed and allowed to interact with the fresh water plume from the Mississippi Delta. This would require considerable offshore extension of the MR plume to at least the outer edge of the shelf. Evidence of a dynamic connection between MR outflow and the FC, namely the northward penetration of the LC into the Gulf of Mexico, is illustrated in a composite AVHRR image for the period 5–7 August 1993 [Fig. 7(a)]. The blue/green waters originating in the Yucatan channel define the boundaries of the LC front as it penetrates into the northern Gulf to within 170 km of the Mississippi Delta.

While normally the MR plume flows westward as it exits the delta, this image [Fig. 7(a)] shows the plume having a significant offshore and eastward extension, identified in the image as a tongue of warmer (red) water being entrained along the eastern edge of the LC (blue/green). Previous studies have shown that upwelling favorable winds and stratified shelf conditions both contribute to offshore extension of river plumes (Chao, 1988; Kourafalou, 1993). Wind data taken by the National Data Buoy Center buoy #42007 (located at 30.1°N, 88.9°W) indicate that the local winds near the delta had a significant eastward component from about 11 July to 9 August [Fig. 7b)] a time when the MR discharge exceeded its historical daily maximum, and the shelf waters would be vertically stratified.

A Minerals Management Service satellite-tracked, surface drifter (#20015) deployed off the Texas shelf [Fig. 7(a)] illustrates the connection between the MR plume and the Straits of Florida. The drifter was entrained in the warm (red) MR plume water around 19 August and entered our study region approximately 22 days later, during the September sampling period. From the drifter data, it is possible to assume the low-salinity event observed during the September survey corresponded to the peak of the summer 1993 MR discharge, which from Fig. 6 appears to be around 13 August. The drifter track indicates that the mean advection rate of the plume waters entrained by the LC was approximately 0.5 m s^{-1}. The drifter continued to be advected north out of the Straits of Florida, arriving off Cape Lookout, NC on 22 September. At this time, observations made by P. Tester and L. Atkinson in the region revealed the presence of anomalously low salinity water from the continental shelf edge into the Gulf Stream (Tester and Atkinson, 1994). They report that, in the region of their observations, the water was visibly more turbid than the Gulf Stream water which bounded it on either side. Tester and Atkinson (1994) estimate that 1.6×10^4 m^3 of fresh water were advected into their study region at a rate of 2.4×10^4 m^3 s^{-1}, too large an amount of fresh water for the rivers in the southeast U.S. to supply alone. The average annual fresh water discharge to the southeast U.S. shelf from Cape Canaveral,

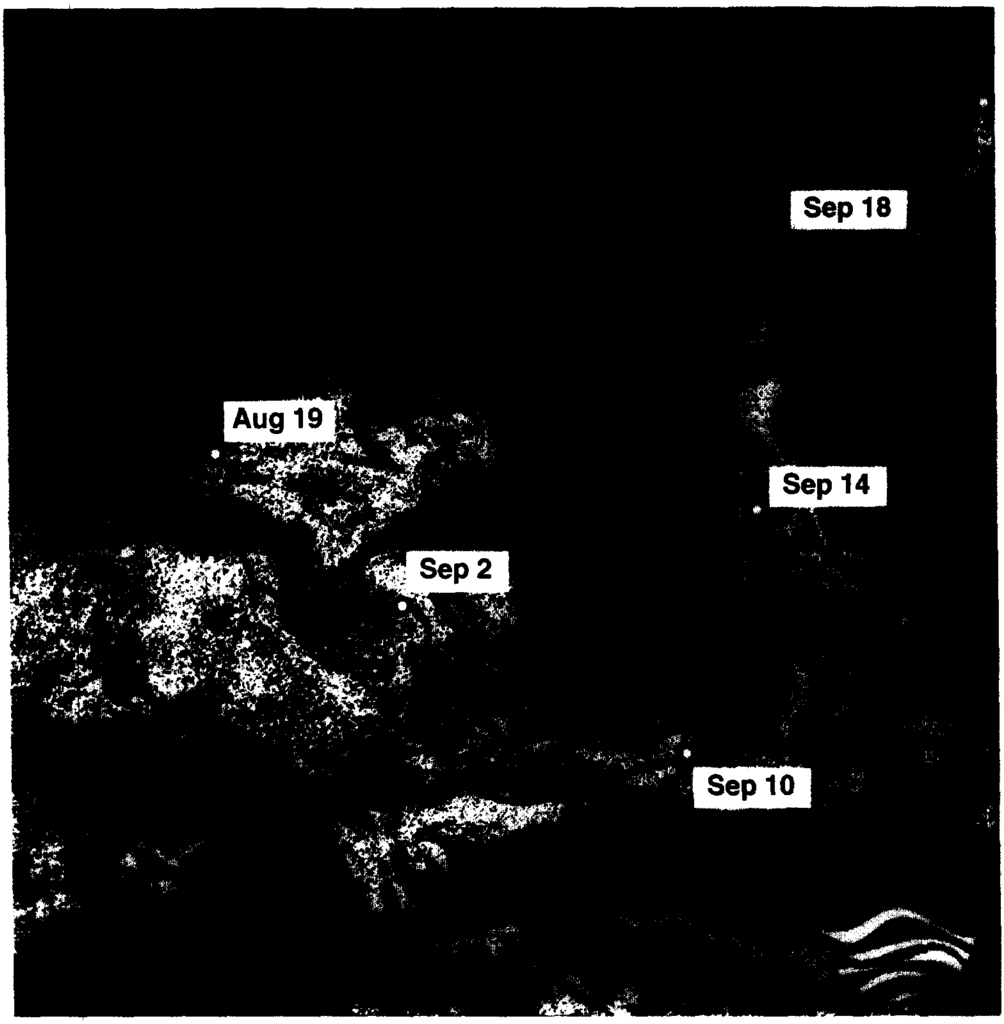
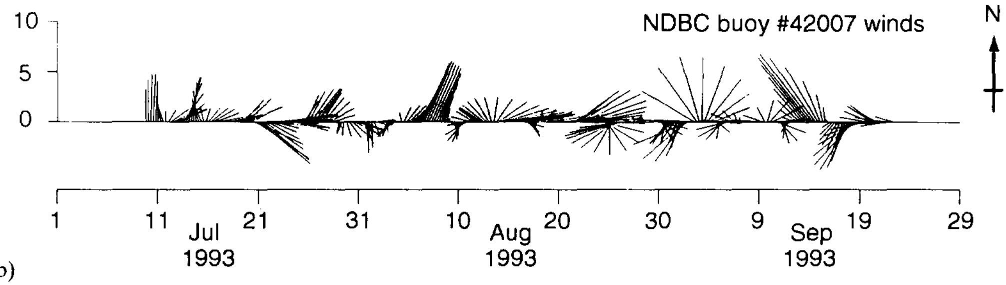


Fig. 7(a).



(b)

Fig. 7. (a) Composite satellite AVHRR infrared image depicting Sea Surface Temperature for the period 5 August–7 August 1993. The heavy black line indicates the track of MMS surface drifter #20015 as it was advected by the Loop Current through the eastern Gulf of Mexico and by the Gulf Stream around Florida's coast and north past Cape Lookout, NC. The gray patches in the image are clouds. The green portions indicate cooler SST while the red and yellow shades indicate warmer SST. (b) Winds taken from NDBC buoy #42007, located at 30.1°N, 88.9°W. The wind vectors have been rotated 180° to the oceanographic convention, filtered with a 40 h low-pass Lanzcos filter, and subsampled every 6 h.

Florida to Cape Hatteras, North Carolina is 2000 $m^3\ s^{-1}$ (Kourafalou, 1993). Minimum salinity values observed off Cape Lookout were 2–3 psu higher than those found off the Florida Keys with values as low as 34.9 psu (Tester and Atkinson, 1994).

6. TEMPORAL EVOLUTION OF THE LOW-SALINITY BAND

Low-salinity water was observed to persist in the Florida Keys coastal waters for a period of about three months, from mid August through late October (Ortner *et al.*, 1995). The variability in the flow field in the southern Straits of Florida occurs in a 30–70 day band due to the meandering of the FC and the subsequent formation and propagation of Tortugas Gyres (Lee *et al.*, 1995). It is likely that the evolution of the flow field played a significant role in the transport and distribution of the low-salinity band. Current records from the moored array shown in Fig. 1 and time series of AVHRR data will be used to provide a description of the flow field variability as related to the transport of the low-salinity band.

The moored current meter array deployed at the shelf edge and the upward looking ADCP deployed further offshore monitored the current and temperature variability from 15 July to 28 October. Figure 8 shows the currents observed at 17 m at the Looe Reef current meter mooring and by the ADCP at 30 and 50 m (Fig. 1 for locations). Winds for the same period were retrieved from a nearby offshore C-MAN tower located at Sombrero Reef (Fig. 1), and are also shown in Fig. 8. All current and wind records have been filtered with a 40 h low-pass Lanzcos filter, subsampled every 6 h and rotated 73° to align with local isobaths. The ADCP current record is dominated by the meandering of the FC across the mooring site, while the Looe Reef current meter record is a mixed response to wind and FC meandering. The Looe Reef current meter record shows a significant westward current reversal on 28 July which continued until approximately 27 August. Approximately 5 days later, a westward wind reversal occurred, which indicates that the initial current reversal was not wind related. For the same period, the ADCP record also shows a westward flow

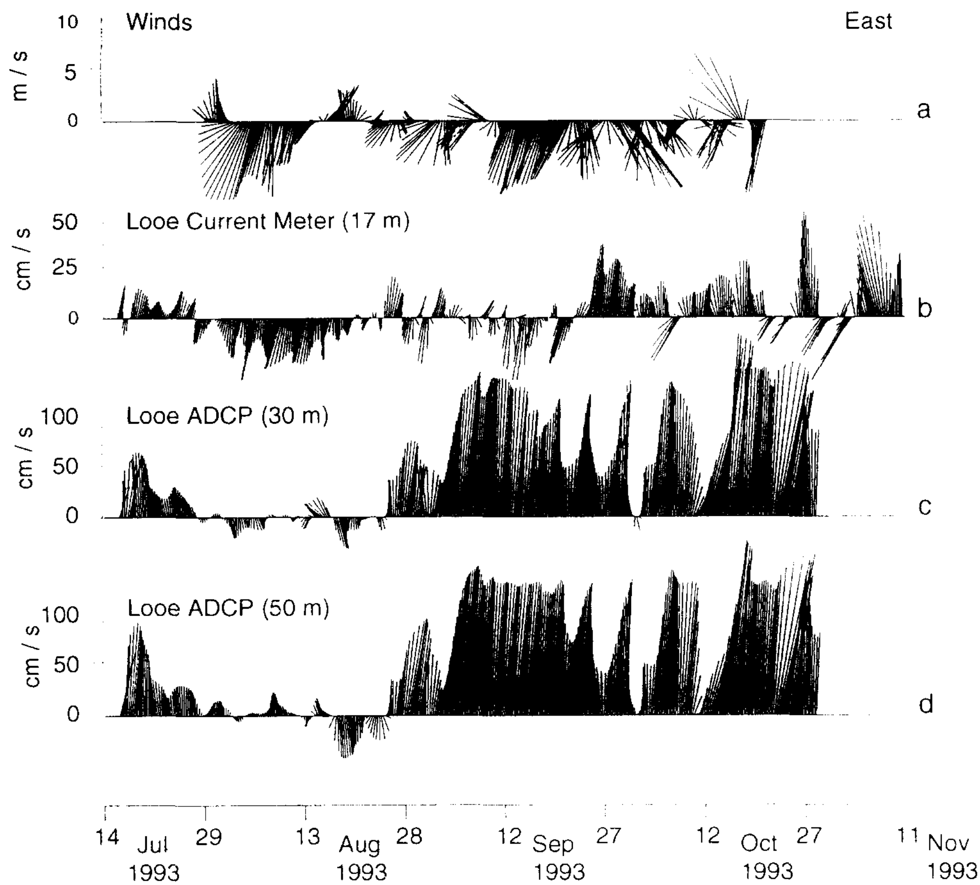
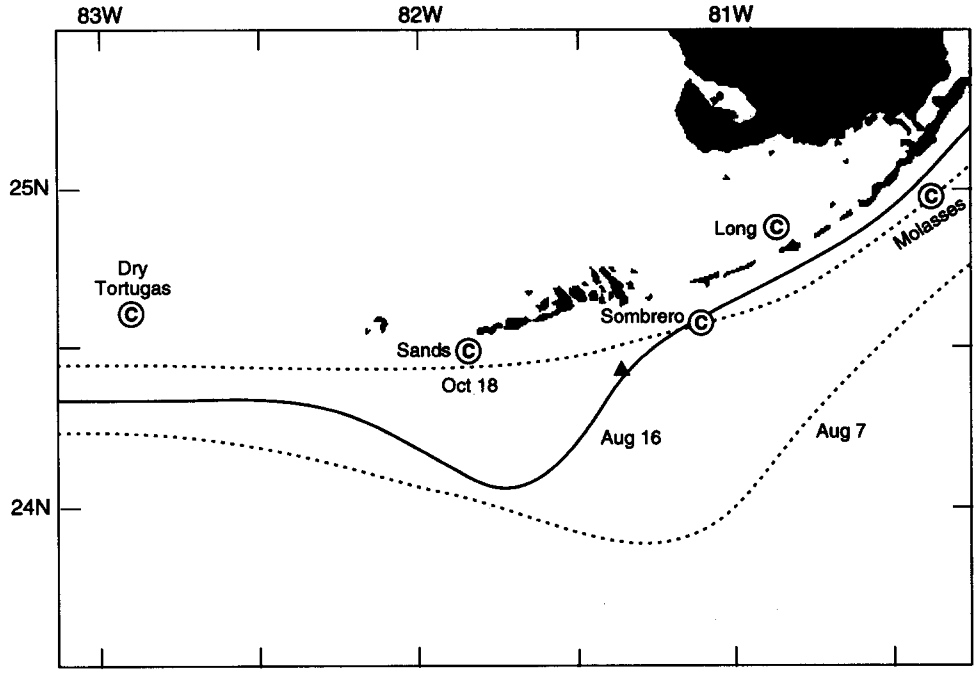


Fig. 8. (a) Wind vector time series from offshore C-MAN tower at Sombrero Reef for the period 29 July–21 October 1993. (b) Current vector time series as derived from Looe Reef current meter mooring at 17 m for the period 16 July–28 October. Current vector time series, for the period 16 July–28 October, as recorded by the bottom mounted ADCP at (c) 30 m and (d) 50 m.

in the upper layer that indicates that the FC had meandered offshore. This event appears to be due to the presence of a recirculating gyre feature over the Pourtales Terrace, such as that described by Lee *et al.* (1995). The return of the FC to an onshore position is clearly evident in late August in the ADCP record by the strong increase in eastward flow at all depths. There was a second increase in eastward flow at the ADCP site in the upper 50 m around 3 September. Eastward flow also occurred at the nearshore current meter mooring in late August, followed by frequent wind related reversals, then strong eastward flow in mid-September.

The time series of SST derived from AVHRR data provided further insight into the flow evolution in the study region. Figure 9 shows a sequence of frontal locations which have been traced from the SST fields. The tracings correspond to the shoreward edge of the FC located visually in the SST fields. The 30 m ADCP time series is displayed in the lower panel, with the velocity record corresponding to the image dates highlighted with vertical



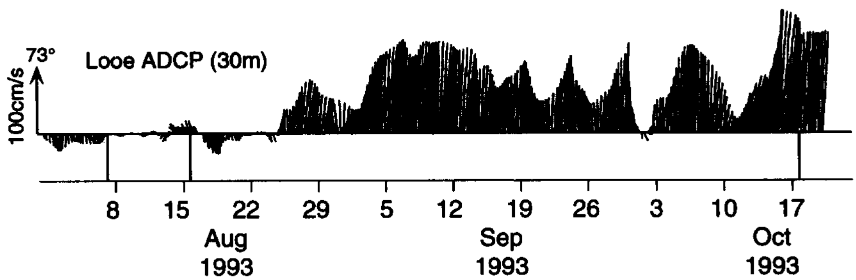


Fig. 9. A summary of the FC frontal positions traced from the AVHRR SST fields. The shoreward edge of the FC was identified by the significant horizontal gradients in the SST fields. The dotted curve is the shoreward edge of the FC on 7 August, the solid curve is for 16 August and the dashed curve is for 18 October. Also shown are rotated current vectors at 25 m from the ADCP off Looe Reef. Vertical event lines indicate the time of the FC front contour. Location of the ADCP is shown by the solid triangle and C-MAN tower locations are shown by the Cs.

event lines. On 7 August (Fig. 9), the surface thermal patterns indicate that the FC front was found offshore at all locations along the Keys. Recall that this is the same period during which a strong current reversal occurred in the current meter and ADCP records (Figs 8 and 9), thereby supporting the suggestion that a cyclonic gyre was present over the terrace at this time. With the hypothesis that the low-salinity water was entrained in the edge of the FC one would expect to find the low-salinity signal offshore, over the terrace at this time. The 16 August frontal tracing (Fig. 9) shows an onshore meander of the FC axis downstream of the Loor Reef section near Molasses Reef and Fowey Rocks and likewise one would expect that the low-salinity water has moved onshore with the FC near Molasses Reef at this time. Cloud coverage, water vapor contamination and lack of surface thermal contrast made the images difficult to interpret during the September survey period and immediately after. However the imagery indicated that, prior to the cruise period, the FC had meandered onshore, where it would remain for several months, which is in agreement with the strong eastward flows observed at the ADCP (Figs 8 and 9). The 18 October frontal tracing shows that the FC was still in an onshore position at all locations along the Keys which agrees with the conclusions drawn from the moored array records (Figs 8 and 9).

Salinity records from offshore C-MAN towers (locations are shown in Figs 1 and 9) shows the time history of the low-salinity water in the Keys, the ADCP recorded currents at 30 m are presented in the lower panel for reference (Fig. 10). All salinity observations have been preliminarily verified and scaled using CTD ground-truth measurements. The ADCP record has been filtered with a 40 h low-pass Lanzcos filter, subsampled at 6 h intervals and rotated 73° to align with local isobaths. If the FC had been onshore for the duration of the event, the low-salinity signal would have been observed by each tower in sequence from west to east, as the low-salinity waters were advected downstream by the FC. We suspect this was not the case based on the C-MAN data, together with data from the moored array and the analysis of the AVHRR data. C-MAN observations indicate that the low-salinity signal was observed at downstream locations first, at Molasses and Fowey around 16 August, followed by the upstream sensors (Sands Key and Dry Tortugas). The initial drop in salinity recorded at the Molasses and Fowey stations occurred simultaneously with the onshore meander of the FC downstream of Looe Reef at these locations on 16 August as observed by the imagery and instrument array (Figs 9 and 10). Recall that, at the upstream locations, the FC still remained offshore and, as a result, the Sand Key station recorded no significant drop in salinity until two weeks later. On 3 September, the FC meandered onshore over the moored ADCP, causing a sudden increase in eastward flow as discussed earlier, and simultaneously, the Sand Key, Molasses Reef and Fowey Rocks C-MAN stations recorded dramatic drops in salinity. This indicates that the FC meandered onshore in a near uniform manner over the alongshore distances and carried with it the low-salinity water. A vertical line has been drawn on Fig. 10 to identify this event. Finally, in mid-September, the remaining two stations at the Dry Tortugas and in Florida Bay (Long Key) recorded significant drops in salinity. It is postulated that these two stations in particular recorded the signal later because the water had to be transported via more complicated routes. Salinity measurements made by J. Wang (personal communication) in Florida Bay indicate that the low-salinity water reaching the Florida Bay station had to come from the FC, through advection and mixing by tidal currents in the passages between the Keys. The time delay of low-salinity water at the Florida Bay C-MAN site indicates that the exchange time-scale between FC waters and the southeastern part of Florida Bay was approximately 10 days. The delayed drop in salinity at the Dry Tortugas C-MAN station could be due to westward transport in a wind driven coastal current from the Looe Reef area as suggested by the westward flow at Looe during this time (Fig. 8); or due to an onshore meander of the FC front south of the Tortugas. It is evident that the evolution of the low-salinity band as observed in the Straits of Florida was dependent on the meander variability of the FC and was not merely advected through the region.

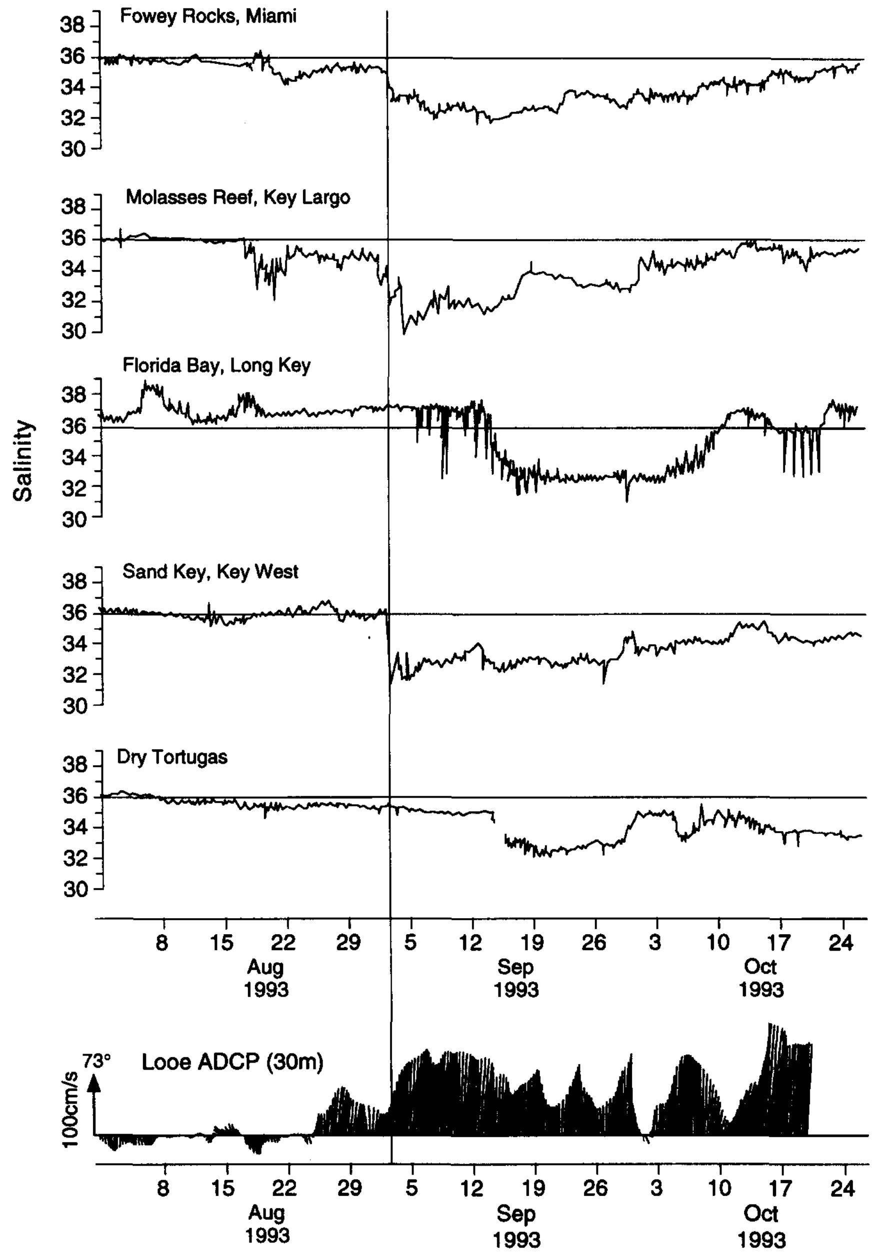


Fig. 10. Salinity (psu) records from offshore C-MAN towers for the period 1 August–26 October 1993. Salinity records have been verified through CTD casts. Shown in the lower panel is a time series from the bottom mounted ADCP off Looe Reef at a bin level of 30 m for the period 1 August–20 October 1993. The event line (vertical line) is drawn to identify the onshore meander of the FC front and the simultaneous drop in salinities at Molasses, Fowey Rocks and Sands Key C-MAN stations.

7. DISCUSSION

Based on hydrographic data taken for the period 10–13 September 1993, moored current measurements, AVHRR data, drifting buoy data and salinity measurements from offshore towers, a first-order description of a low-salinity anomaly off the Florida Keys has been presented. The anomaly persisted for approximately 3 months, a long enough period to be influenced by the meander variability within the FC. These observations, coupled with those made in 1973 by Atkinson and Wallace (1975), provide the basis for concern that a dynamic link can occur between the Mississippi River basin and the protected marine environment in the Florida Keys.

The evolution of the low-salinity band was highly dependent on the variability within the FC. Because the band traveled as a lens in the upper 30 m of the water column it was a good indicator of the mixing and exchange of offshore waters with shallow waters of the Florida reef tract and Florida Bay. Further, an event of this type can cause additional stress to the local coastal ecosystem both in its transport of pollutants from distant sources and its transport of those properties which cause extreme variations in the environmental conditions. Over the past 20 years, studies aimed at determining the health of Florida Reef communities have revealed increasing signs of deterioration resulting from numerous sources, both natural and man-made. For example, Hudson (1981) conducted a study obtaining data on past environmental conditions to determine if changes in coral growth rates over the past 50 years could be detected in a chosen species. Hudson reported on long histories of environmental stress and slowing growth rates in several locations off Key Largo coincident with a period of increased dredge and fill operations in the region. Several other studies have cited sewage, boat traffic, boat groundings and commercial coral collectors as contributors to mortality within the reef tract (Straughan, 1972; Voss, 1973; Stursa, 1974). Regardless of the causes, the web of communities supported by the Florida coral reef system appears to be experiencing increasing levels of stress which may only be intensified by harmful pollutants and extreme variations in environmental conditions such as temperature, salinity and oxygen concentration as derived from local as well as remote sources. The transport of such properties from distant locations, which have not been considered a threat to Florida's marine environment in the past, occurred in September of 1993 and was suspected to have occurred in 1973 by Atkinson and Wallace (1975).

The transport of relatively fresh river water from the Mississippi River basin appears to have caused significant changes within the ecosystems of the Gulf of Mexico and Florida coastal waters. Observers in the northern Gulf reported that there was a "major change in the size and structure of the phytoplankton community, which may have had major impact on productivity at higher trophic levels" on the Louisiana shelf in September, 1993 (Dortch, 1994). Further downstream, observers in the Straits of Florida report that there was a significant change in speciation of zooplankton across the low-salinity band (Ortner *et al.*, 1995). Elevated levels of the herbicide atrazine, primarily used in the agricultural region of MR Basin, were also observed in the Keys' coastal waters, and their effects on the marine communities enroute to and in the Florida Keys is yet unknown (Ortner *et al.*, 1995).

The connection between the MR and the southeast U.S. coastal waters is the LC in the eastern Gulf of Mexico. This link was demonstrated using AVHRR SST data and the track of a satellite tracked surface drifter. The large volume of low-salinity water observed in the

Straits of Florida was a consequence of several independent processes, both oceanographic and meteorological, occurring simultaneously at a critical time of the year. A hydrological analysis presented by Richards *et al.* (1994) emphasizes the rarity of the summer flood event and discusses several antecedent meteorological conditions which made flood conditions favorable in 1993. The random thunderstorms typical of midwestern summers are limited in their spatial and temporal extent and, for this reason, are not capable of exclusively causing the major river flooding witnessed in 1993 (Richards *et al.*, 1994). Therefore, the timing of this event was a critical factor in the determination of its impact on distant marine environments. Because the meteorological conditions caused flooding during the summer months, when the continental shelf was vertically stratified (Macnaughton, 1994), mixing with the ambient shelf waters was inhibited and the volume of fresh water observed off the U.S. east coast was enhanced. The stability of the water column on the continental shelf during the summer months, coupled with 1993s unusually high summertime MR outflow and the persistent upwelling favorable winds over the Mississippi Delta encouraged the transport of a large volume of low-salinity water southeast of the delta, where it was entrained by the LC and extended along the Gulf Stream front from the Florida Keys to Cape Lookout, North Carolina, and beyond.

The frequency of MR plume water events entering the Florida Keys region can not be determined with only two reported instances. It would seem that because there have not been more reported instances, these two (1973 and 1993) were truly anomalous. The observations presented here seem to indicate that several independent processes must take place simultaneously to produce the type of event we observed. However, the combination of eastward winds and a stratified shelf at the point of MR discharge, together with a northern position of the LC is not uncommon during summer and early fall seasons, which suggests the possibility of a more regular occurrence of entrainment to the Straits of Florida.

8. CONCLUSIONS

A band of anomalously low-salinity water was observed extending 40 km offshore of the Florida Keys from Key West to Miami Florida in September 1993. Salinities within the band were as low as 31 psu, which is about 5 psu below normal salinities of the region. The amount of fresh water in the band is estimated at 1.2×10^{10} m^3. Low salinity in the Straits of Florida persisted for about 3 months. The only conceivable source for such a large volume of fresh water is the Mississippi River during its flood stage in the summer of 1993. Several independent processes occurred simultaneously to account for the presence of the low-salinity band in the Straits of Florida. The unusually high discharge from the Mississippi Delta in the summer of 1993 occurred at a time when the Loop Current was fully extended into the northeastern Gulf of Mexico. Summer heating vertically stratified the shelf waters near the delta inhibiting mixing of the Mississippi River plume with ambient shelf waters. Persistent upwelling favorable winds transported the large volume of low-salinity water southeastward off the shelf where it was entrained in Loop Current front. The low-salinity water traveled as a shallow layer entrained in the shoreward edge of the Loop and Florida Currents through the Straits of Florida and was observed as far north as Cape Lookout, North Carolina as it emerged into the North Atlantic. Long-term measurements of conductivity at C-MAN towers located on the offshore reefs of the Florida Keys are essential to monitor these events in the future.

Acknowledgements—The authors would like to thank Joanie Splain for producing the SST fields from the AVHRR data. Thanks are also extended to David Forcucci from the Sustained Ecological Research Related to the Management of the Florida Keys Seascape (SEAKEYS) program for providing us with calibrated salinity records from the C-MAN towers. The data provided by Mr Forcucci were collected under a cooperative agreement with the Florida Institute of Oceanography and NOAA/NDBC as part of the SEAKEYS program. Mike Dowgiallo of NOAA Coastal Ocean Office provided the Mississippi River discharge values which were collected by the U.S. Army Corps of Engineers. We are grateful to W. Johnson of MMS for the surface trajectory data for a drifter originally deployed by P. Niiler on the Texas shelf—as part of the LATEX program. We thank M. Howard for his assistance in acquiring the NDBC wind data from the offices of the Texas–Louisiana Shelf Circulation Study. This work was funded in part by NOAA (SEFCAR and CIMAS NA85-WC-H-06134) and USCG (SFOSRC agreement #RD-93-02).

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