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Impacts of Winter Storms on Circulation and Sediment Transport: Atchafalaya-Vermilion Bay Region, Louisiana, U.S.A.

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ABSTRACT

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This study investigates the changes in circulation, sediment resuspension, sediment flux and salinity that accompany "winter storms" in the Atchafalaya Bay region, events that occur 20 to 30 times each year between October and April. NOAA-14 satellite reflectance imagery and time-series measurements of winds, water levels, current velocity and turbidity demonstrate that wind direction and speed are the major controlling factors for circulation, sediment transport and suspended sediment concentrations. East winds (occurring 62% of the time) induce a westward flow of sediment-laden Atchafalaya river water along the coast. West winds reverse the direction of plume movement and increase the size of the plume, partly as a result of Ekman processes. The strong north winds, characteristic of winter storms, cause rapid flushing from the shallow bays (30–50% of volume) and water level changes in excess of 1 meter. Seaward of these bays, a large sediment plume (180 km alongshore, 75 km offshore) is produced by the wind-wave resuspension of bottom sediments and the wind-forced seaward transport of bay and inner shelf waters. Water and sediment flux is primarily southeastward, temporarily disrupting the westward flow of river water along the coast. In the Vermilion-Cote Blanche Bay system, northwest winds maximize sediment resuspension and the seaward flux of sediment-laden river and bay water. The storm-related sediment resuspension and transport reduces the rapidity of delta development and deposition in these bays and re-distributes sediment along the inner shelf.

ADDITIONAL INDEX WORDS: *Coastal processes, sediment flux, resuspension, salinity flux, storm impacts, erosion, remote sensing.*

INTRODUCTION

The Atchafalaya-Vermilion Bay system is Louisiana's largest estuary, encompassing about 1500 km^2 (Figure 1). This bay complex is comprised of five contiguous bays, including (from east to west) Fourleague Bay, Atchafalaya Bay, East Cote Blanche Bay, West Cote Blanche Bay and Vermilion Bay (Figure 1). Water depths within these bays range from 1 to 4 meters. The Atchafalaya River, the main distributary of the Mississippi River, discharges into the northern Gulf of Mexico, primarily through Atchafalaya Bay. The combined water and sediment discharges of the Mississippi and Atchafalaya Rivers are 18,400 m^3 s^{-1} and 210 $\times$ 10^6 tons/year (MILLIMAN and MEADE, 1983). The Atchafalaya River carries about 30% of the Mississippi River flow (an amount regulated by the Old River Control Structure) and 40 to 50% of the sediment load (MOSSA and ROBERTS, 1990). The Atchafalaya River is joined by the Red River, which contributes an additional 5% to its discharge (MOSSA, 1990).

This is a microtidal coastal region (tides < 0.5m) where the diurnal tide dominates. East Cote Blanche Bay and Atchafalaya Bay are open to the Gulf of Mexico, whereas Marsh Island separates the two westernmost bays from the Gulf of Mexico. Southwest Pass, a narrow and unusually deep (>25 m in places) channel, connects Vermilion Bay to the Gulf. Oyster Bayou connects Fourleague Bay to the Gulf.

The Atchafalaya complex was an abandoned delta of the Mississippi River until about 1950 when a new episode of delta building began its subaqueous phase (SHLEMON, 1975; ROBERTS *et al.,* 1980). Two sizeable deltas have developed since the 1970's (ROBERTS *et al.,* 1980; ROBERTS *et al.,* 1997). Atchafalaya River water enters the coastal ocean primarily through the Atchafalaya River and the Wax Lake Outlet (Figure 1). In addition, the Gulf Intracoastal Waterway (GIWW) carries water east and west of the main river outlets where it enters this estuarine system through smaller channels such as the "Jaws" (Figure 1).

This shallow, nutrient-rich environment serves as a nursery ground for shrimp and fish species (JUNEAU, 1975), many of which are commercially harvested and sought after by sports fishermen. Considerable controversy has arisen re-

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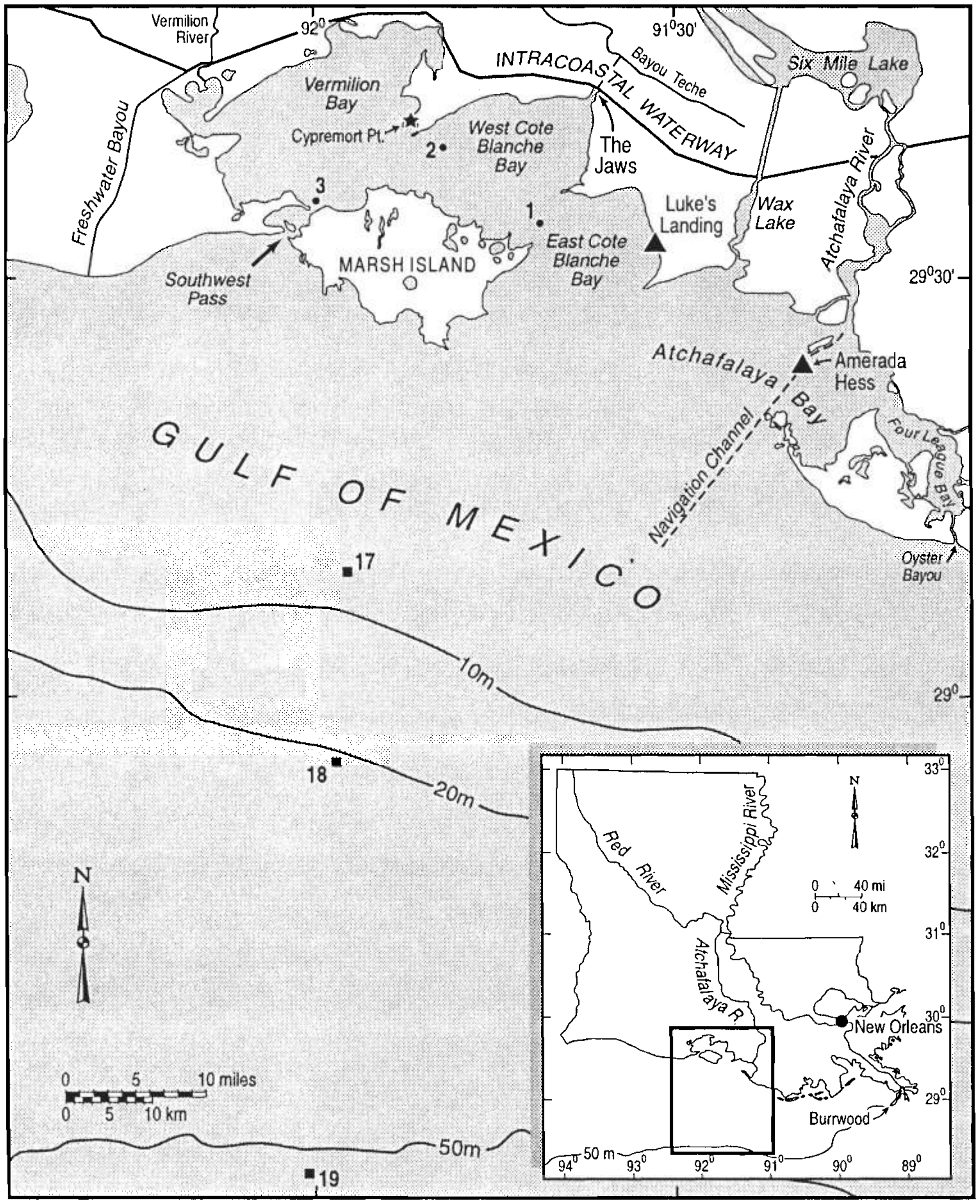

Figure 1. A regional view of the Atchafalaya-Vermilion Bay system and the adjacent shelf of the northern Gulf of Mexico. Time-series measurement stations 1, 2, and 3 are indicated with solid dots. The wind station is indicated with a star. The water level stations are shown with solid triangles. The shelf mooring stations (17, 18 and 19) are indicated with squares.

cently concerning management of the incoming freshwater and sediment resources. Historically, the Corps of Engineers has managed the system for flood control and navigation. However, pressure is mounting from commercial shrimpers and sports fisherman, land owners, and others to consider additional environmental aspects when making management decisions. The need for making well-grounded decisions has sparked interest in understanding the impacts of Atchafalaya River water and wind forcing on the distributions and fluctuations of salinity, sediments, nutrients and productivity in the bays and the coastal ocean.

Much of the geophysical research efforts in this coastal region has concentrated on understanding the growth of the Atchafalaya and Wax Lake deltas (ROUSE *et al.*, 1978; ROBERTS *et al.*, 1980; VAN HEERDEN and ROBERTS, 1980; WELLS and KEMP, 1981) as well as downstream depositional effects in the Chenier Plain (ROBERTS *et al.*, 1989; HUH *et al.*, 1991). Using the Multispectral Atmospheric Mapping Sensor (MAMS), MOELLER *et al.* (1993) showed that the Atchafalaya sediment plume responds quickly to changes in wind direction. Using MAMS, HUH *et al.* (1996) were able to map various water types within the Atchafalaya Bay system. Fourleague Bay has been the focus of several ecological studies including DENES (1983), CAFFREY and DAY (1986); MADDEN (1986) and RANDALL and DAY (1987). The Vermilion-Cote Blanche Bay system, located west of Atchafalaya Bay has received little research attention despite its considerable economic importance to the coastal fishery.

The main goal of this study was to improve the understanding of circulation, sediment transport, and salinity changes associated with winter storms in this shallow estuarine system and on the adjacent shelf. Understanding the physical processes and the fluxes in and out of this system are essential for the development of effective management strategies. In addition, this information is needed to validate models being used to assess the potential impacts of future modifications to the existing hydrological system.

This study uses NOAA AVHRR satellite reflectance measurements to investigate the regional impacts of wind forcing and river discharges on circulation, sediment distribution, resuspension and transport. Time-series field measurements of currents, turbidity, salinity, temperature, water level and winds are used to quantify the fluxes of water, sediment and salt associated with the cold-front type storm that is experienced 20 to 30 times each year from October through April.

METHODOLOGY

Satellite Data and "Surface Truth" Measurements

Satellite-acquired visible band data can provide valuable information on the distribution of river water and sediments in estuaries and on the continental shelf as well as on circulation processes affecting the fate of riverborne sediments (ROUSE and COLEMAN, 1976; DINNEL *et al.,* 1990; WALKER *et al.,* 1992; STUMPF *et al.,* 1993; MOELLER *et al.,* 1993; HUH *et al.,* 1996; WALKER, 1996). For this study, the visible (0.58–0.68 μm) and near infrared (0.7–1.1 μm) channels of the NOAA-14 AVHRR afternoon passes were used to derive water reflectances. These digital satellite data were downlinked in real-time and processed at the Earth Scan Laboratory of the Coastal Studies Institute. The spatial resolution of 1.1 km^2 (at nadir) and the daily coverage provided regional synoptic information on the surface distribution of total suspended solids (or seston) in this turbid coastal region.

Atmospheric correction of the data were performed using a technique developed by STUMPF (1992). This technique corrects for changes in solar irradiance, aerosols, Rayleigh scattering, and sunglint. The correction procedure has three main steps. First, corrections are performed to channels 1 and 2 to compensate for changes in downwelling solar irradiance and transmission changes based on the Rayleigh optical depth and the gaseous absorption optical depth. Subsequently, channel 2 reflectances are subtracted from channel 1 reflectances. The purpose of this step is to remove contamination from aerosols and sunglint. Last, a clear-water pixel is identified in the area of interest and the reflectance value of this pixel is subtracted from the entire scene. This last step removes contamination due to Rayleigh scattering. This technique has been used previously in studies of Mobile Bay and Delaware Bay (STUMPF, 1992) and the Mississippi plume region (WALKER, 1996). This technique required modifications for the Atchafalaya region, since erroneous values and patterns resulted when channel 2 reflectances were subtracted from channel 1 reflectances. This result is attributable to the very high suspended sediment loads encountered. The original technique assumes that water reflectance in channel 2 is 0, an assumption that is not valid in this region because of the very high sediment concentrations that caused non-zero reflectance in channel 2. A solution for this problem was obtained by modifying the bias correction technique for use with channel 1 alone. Basically, step 2 was omitted from the above procedure. This technique was successful in retaining the turbidity patterns within the area of interest. However, images containing excessive spatial variability in sunglint or aerosols within the region of interest could not be processed using this technique. The reader is referred to STUMPF (1992) or WALKER (1996) for additional details on the technique described above.

Estimates of the concentration of total suspended solids ($mg\ l^{-1}$) were obtained for the image data by developing an algorithm relating "surface truth" measurements of suspended solids to satellite reflectance values (Figure 2). To accomplish this, water samples were collected by helicopter simultaneously with the acquisition of clear-sky satellite data on April 26, 1996 and June 21, 1996 (WALKER *et al.,* 1997). The inorganic and organic sediment concentrations were determined using the glass fiber filter method (U.S.G.S., 1987) and GF/F filters. In these datasets, the inorganic sediment fraction contributed 80% or more to the total suspended solid weight when total solids exceeded 10 $mg\ l^{-1}$. At lower concentrations, the organic fraction of each water sample increased to 50%, primarily as a result of phytoplankton biomass. Both "surface truth" collection trips were made during conditions of weak winds. In the text that follows, the term 'suspended sediments' will be used in place of suspended solids since the inorganic component is the main contributor to satellite reflectance and turbidity in this river-dominated region.

The Newton method of non-linear curve-fitting was used to solve the equations below using the satellite reflectance values (R_d) and the corresponding field measurements of total suspended solids (n).

For turbid water, reflectance can be approximated by the equation:

$$R_d = (y \cdot F)/(1 + G/n),$$

where 'n' is the total suspended solids in $mg\ l^{-1}$, y is 0.178 and

$$F = b^*/(b^* + a^*), \qquad G = a_x/(b^* + a^*)$$

where b^* is the specific backscatter coefficient for sediment and a^* is the absorption coefficient for sediment and a_x is the absorption coefficient for non-sediment constituents (from STUMPF, 1992).

Figure 2 depicts the data points used to establish values for 'F' and 'G' in this study, the best-fit line and the 95% confidence limits. The RMS reflectance error was 0.00783. In this study, 'F' was large compared with previous studies indicating that sediment-related backscattering contributes more (about double) to the reflectance. The Red River (Figure

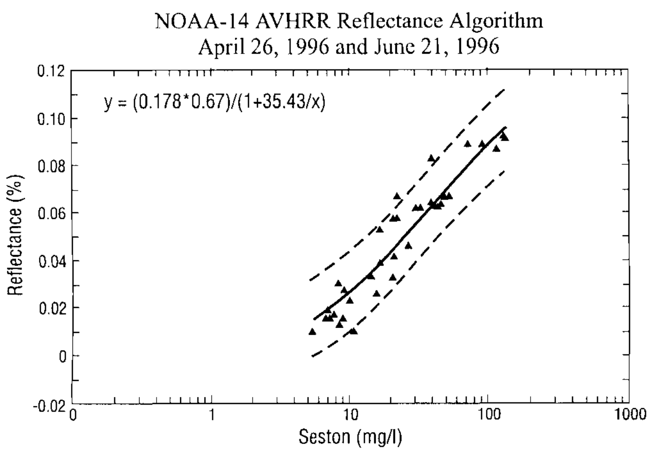

Figure 2. A scatterplot showing the relationship between seston (mg l^{-1}) measurements and satellite reflectance (%) measurements ($\times 10^{-2}$) obtained on April 26, 1996 and June 21, 1996. The non-linear equation describing the relationship is shown. The 95% confidence limits are depicted with dashed lines.

1) sediments may, in part, account for the difference in 'F' between the Atchafalaya and Mississippi. 'G', a measure of absorption by non-sediment components, was similar to that of the Mississippi plume (WALKER, 1996).

Field Measurements

In August 1997, time-series measurements were initiated in Vermilion Bay, East and West Cote Blanche Bays at the three sites shown in Figure 1. Current speed and direction were obtained with Marsh-McBirney electro-magnetic current meters. Conductivity, temperature, turbidity and oxygen measurements were obtained with YSI 6000 instruments. Measurements were made at mid-depth in the water column every 30 minutes. These measurements are considered representative of the water column, as previous measurements in winter showed minimal vertical stratification (WALKER, unpublished data). Water samples were obtained every six hours during several four day periods with ISCO automatic water samples for the determination of surface suspended sediments (inorganic and organic components). These data were used to calibrate the continuous digital turbidity measurements. Linear regression was used to establish relationships between the digital turbidity measurements and the *in-situ* water samples of suspended solids (resulting $R^2 = 0.97$).

Meteorological measurements were obtained at Cypremort Point on the east side of Vermilion Bay. A climatological wind data analysis (10 years) was performed using the Burrwood C-Man station, approximately 130 km east of Atchafalaya Bay (Location, Figure 1). This station was chosen as it is considered to be the most representative coastal station with a long-term record.

Tide Gauge and River Discharge Data

Water level data in digital format were obtained from the U.S. Army Corps of Engineers (New Orleans District) for Amerada Hess (Atchafalaya Bay) and Luke's Landing (East Cote Blanche Bay) (Locations, Figure 1). Only the Amerada Hess station was of sufficient quality for statistical processing. After interpolation for missing values, the Amerada Hess data was low-pass filtered using a Butterworth 40-hour low pass filter to remove the tidal component of the water level signal. Daily estimates of Atchafalaya River discharge (at Simmesport) were obtained from the U.S. Army Corps of Engineers (New Orleans District).

Table 1. *Seasonal and yearly frequency of occurrence (%) of wind directions from the northeast, southeast, southwest, and northwest quadrants at Burrwood, LA for the 1985–1994 time period.*

Wind Direction	Spring	Summer	Autumn	Winter	Year
NE	23.9	14	41.6	43.7	30.8
SE	42.8	29.9	33.9	24.6	32.8
SW	20.1	36.3	12.2	14.2	20.7
NW	12.3	18.2	12.2	17.3	15.0

RESULTS

Seasonal Wind Climatology

Previous studies have shown that wind direction is a major controlling factor for coastal water levels, sediment transport and circulation in Louisiana estuaries and the coastal ocean (MURRAY, 1975; KEMP *et al.*, 1980; CHUANG and WISEMAN, 1983; COCHRANE and KELLY, 1986; MOELLER *et al.*, 1993). Seasonal wind roses compiled from Burrwood measurements reveal that coastal wind direction changes significantly throughout the year (Figure 3). In spring, east and southeast winds are most prevalent, occurring about 43% of the time (Table 1). In summer, high pressure intensifies over the Gulf of Mexico and a greater frequency of south and southwest winds is experienced. As a consequence, southeast wind frequency decreases to 30% and southwest wind frequency increases to 36%. In autumn, northeast and north winds are most frequent as cold-front passages (and the high pressure systems behind them) begin to move southeastward across the study region (Figure 3). Northeast winds occur 42% of the time in autumn (Table 1). During winter, winds are stronger and the north and northwest wind frequency increases (Figure 3). If we average wind frequencies at Burrwood over the entire year, southeast winds are the most prevalent at 33%. Northeast winds occur with a frequency of 31%. Southwest and northwest winds occur with frequencies of 21% and 15%, respectively. Although the frequency of occurrence of northwest winds is lowest overall during the year, winds from this quadrant are often relatively strong.

Wind Forcing of Water Level Changes

The most energetic wind events in this region are winter storms and hurricanes. The winter cold-front propagates from northwest to southeast with a recurrence interval of 4 to 7 days in winter (ANGELOVIC, 1976). Although these storms are usually most intense in winter, they affect the region from October through April. They introduce a rotary

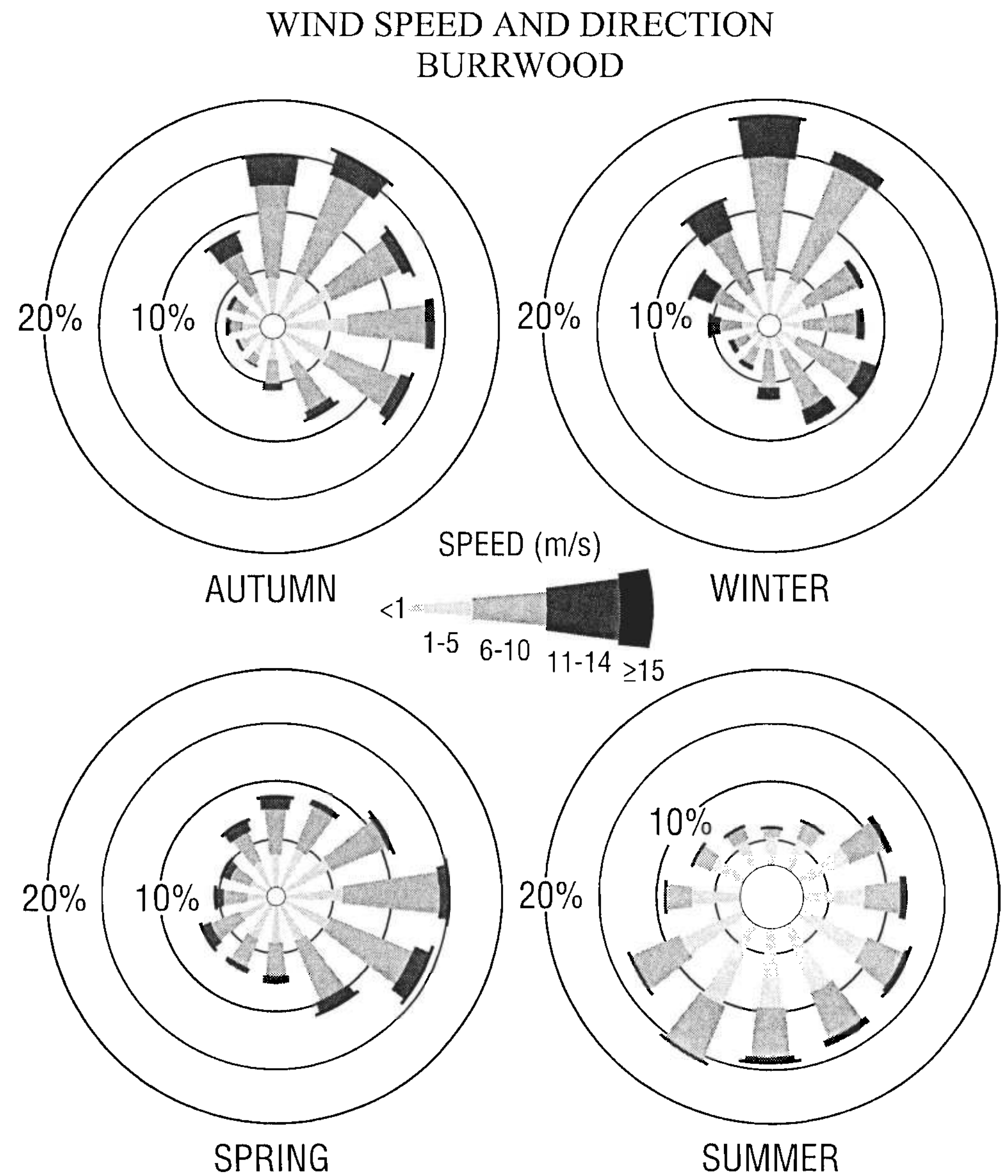

Figure 3. Seasonal wind roses compiled from Burrwood wind data from 1986–1995 (Courtesy of Jay Grymes, LA Office of Climatology). Percent frequencies are shown for each 30 degree wind delineation. Percent calms are shown in the center of each circle. The speed scale is shown in m s $^{-1}$.

wind field in which the onshore-offshore modes dominate (CHUANG and WISEMAN, 1983). Since winter storms occur 20 to 30 times each year, they have a large cumulative impact on coastal processes (ROBERTS *et al.*, 1987; MOELLER *et al.*, 1993).

Tide gauge data from Amerada Hess and Luke's Landing were used to investigate the magnitude and causes of water level changes in the Atchafalaya-Vermilion Bay system. Previous research in the Atchafalaya Bay region has demonstrated that wind-forced water level changes can exceed 1 meter (KEMP *et al.*, 1980). Although the Luke's Landing data were not quite as complete as the Amerada Hess data, they were considered more representative of the western bays, since the Amerada Hess site is directly influenced by river flow. Water level events from January 1992 to April 1996 were identified in the Luke's Landing data by visual inspection of the graphs. Large and rapid changes in water levels, from a high water stand to a low water stand were identified in the records. The magnitude of the water level changes and the time difference between high and low water were determined for major water level events from the digital records.

Over the 3 ½ year period, 64 events were selected for analysis based on data availability and the quality of records. At Luke's Landing, the average water level change for these events was 0.99 m (s = 0.2 m). The Amerada Hess average for these same events was 0.67 m (s = 0.14 m) (Table 2). The

Table 2. *Statistics on magnitude and time responses of water level changes at Amerada Hess and Luke's Landing from January 1992 through April 1996.*

	Amerada Hess	Luke's Landing
Average water level change (m)	0.67	0.99
Standard Deviation (m)	0.14	0.20
Time from high to low water (hr)	19	19
Standard Deviation (hr)	8	8

Table 3. *Top ten cold-front related water level events with Luke's Landing water level changes and associated wind directions and speeds from January 1992 through April 1996.*

Rank	Date	Water Level Change (m)	Wind Direction (°)	Wind Speed (ms^{-1})
1	Jan 18, 1996	1.38	NW	10–15
2	Dec 19, 1995	1.37	WNW	10
3	Apr 11, 1995	1.36	NNW	>10
4	Jan 19, 1995	1.35	NW	10
5	Jan 27, 1996	1.33	NNW/NNE	10
6	May 19, 1995	1.30	NNW	10
7	Mar 18, 1996	1.29	NW	10–15
8	Nov 11, 1995	1.22	NNW	10–15
9	Feb 1, 1996	1.20	N	10–15
10	Jan 14, 1995	1.19	NW	10

average time from extreme high to extreme low water level varied from 9 to 43 hours, with an average of 19 hours (s = 8 hours). The water level responses were maximized when the wind effects were in phase with the astronomical tidal effects, particularly during spring tides.

In an attempt to better understand cold front forcing of water level change in the region, the ten largest water level events were isolated for more detailed inspection (Table 3). It is interesting to note that all 10 events occurred in 1995 and 1996, evidence of inter-annual variability in water level changes. At Luke's Landing, maximum water level changes ranged from 1.19 to 1.38 m over time periods of 9 to 38 hours. In all cases, the rapidly falling water levels were associated with strong (10–15 m/s) northwest and north winds, which were usually preceded by relatively strong south winds. In nine out of these ten extreme cases, northwest winds were the causal agent. The northwest wind forcing provides an efficient driving mechanism over the western bay region as it blows down its long axis, thus maximizing fetch and wave height. Changes in coastal water levels prior to the onset of northwest winds probably enhance the direct wind effects. Previous research has shown that coastal water levels along the Louisiana/Texas coastline respond most strongly to variations in the east-west wind components (COCHRANE and KELLY, 1986). Since the wind rotation with cold front passages is clockwise, coastal water levels would start dropping because of Ekman processes before the arrival of northwest winds with the frontal passage. This sequence of events provides a priming mechanism that could increase the rate of water level exchange between the bays and the inner shelf with the arrival of northwest winds.

Wind Impacts on Regional Suspended Sediment Distribution

NOAA-14 satellite image data were used to obtain a regional picture of surface suspended sediment distributions and plume morphology for various wind regimes. Clear-sky imagery, from January 1995 through May 1997, were selected as input to a compositing analysis. Compositing of the images entailed computing arithmetic means of suspended sediment concentrations for each of the four major wind quadrants (northwest, northeast, southeast, southwest) during high and low river discharge periods. A discharge at Simmesport of 5666 m^3 s^{-1} (200,000 cfs^{-1}) was used as the cutoff criterion to separate the high and low discharge categories. Four images were used to produce each composite image (Figures 4, 5).

During high river discharge conditions, the size and surface suspended sediment concentrations of the Atchafalaya sediment plume were maximized by northwest winds (Figure 4a). Plume size averaged 4400 km^2 and surface suspended sediment concentrations exceeded 200 mg l^{-1}. The composite plume extended beyond the 10 m isobath onto the inner shelf, seaward of the bays. Plume measurements were based on a concentration of 10 mg l^{-1} and did not include the interior bay region. The second to largest plume resulted from southwest winds (Figure 4c) with an average area of 1925 km^2. Based on plume orientation, net transport during west wind events was to the east and southeast. In contrast, plume orientation during east wind periods was towards the west. During northeast and southeast wind periods, sediment plumes were smaller and confined to a near-coastal region. Average plume sizes for northeast and southeast winds were similar (1060 km^2 and 1134 km^2, respectively). In all wind cases under high river discharge conditions, the highest concentrations of suspended sediment were observed in close proximity to Atchafalaya Bay where the largest volumes of water and sediment enter the bay system through the Atchafalaya and Wax Lake Deltas. In addition, sediment concentrations were consistently high in the northeast corner of West Cote Blanche Bay where river water enters the western bay from the Gulf Intercoastal Waterway (GIWW) through the "Jaws" (Location, Figure 1). Here a secondary sediment "plume" was detected in the northwest, southwest and southeast composite images.

During periods of low river discharge, the largest plumes were again associated with northwest wind conditions (Figure 5). The surface sediment plumes during northeast, southeast and southwest winds were about four times smaller than the northwest plume composite. With the reduction in river discharge, surface sediment concentrations decreased, and the locations of maximum sediment concentration were more dependant on wind direction. During low river stage, the highest sediment concentrations were probably caused by wind-wave resuspension in shallow areas, and winds from different directions would move the region of maximum resuspension.

Winter Storm Impacts on Circulation and Sediment Transport

In this section, the impacts of several winter storms in December 1997/January 1998 are discussed using satellite and

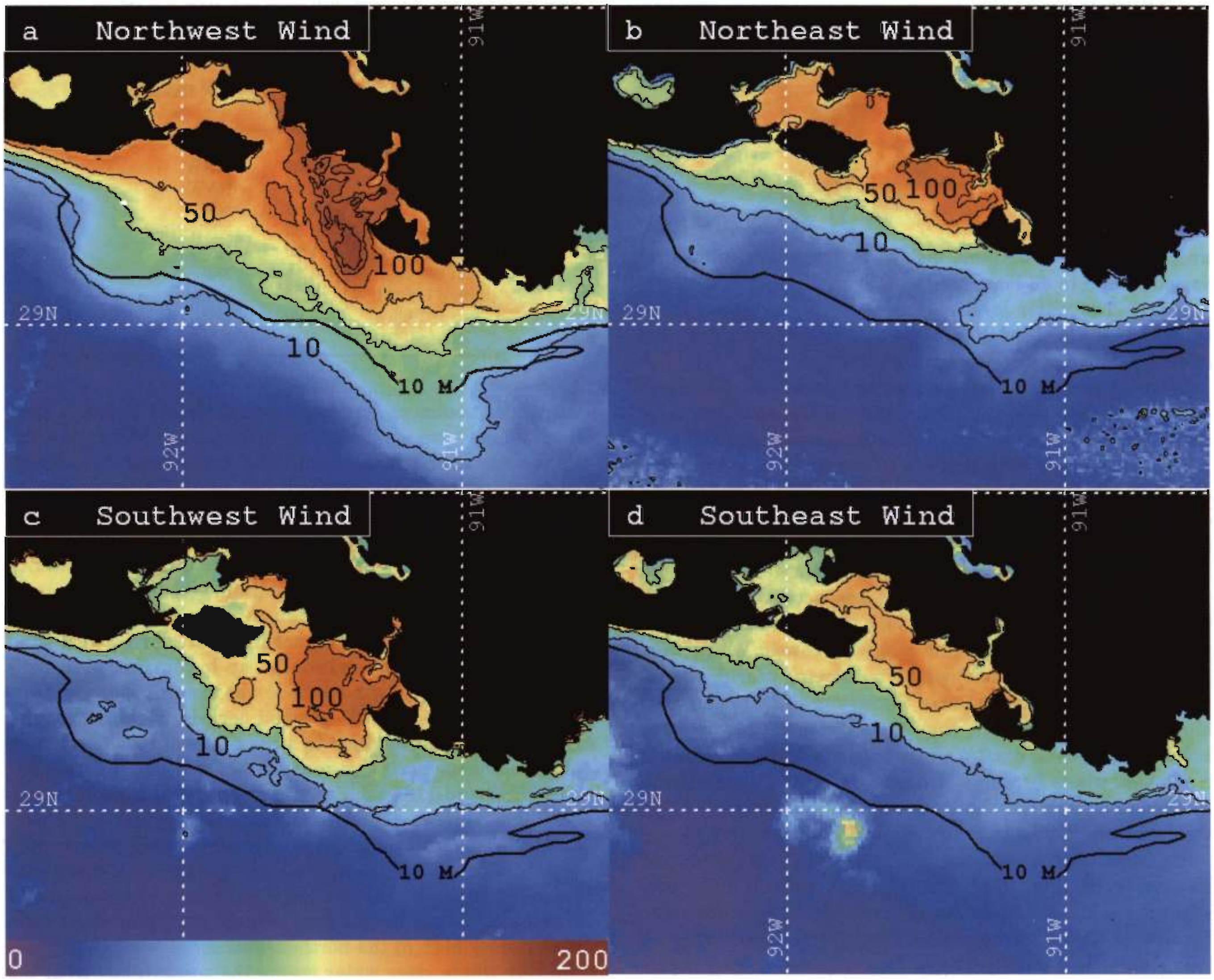

Figure 4. Satellite image composites of surface suspended sediment concentrations during moderate-high river discharge for the four main wind quadrants: (a) northwest, (b) northeast, (c) southwest and (d) southeast. Contours of total suspended solids (10, 25, 50, 100, 150 and 200 mg l^{-1}) are shown. A color scale in mg l^{-1} is also shown. Each composite represents the average of four images.

field measurements. Three clear-sky NOAA-14 images are used to illustrate the regional impacts of these storm events on surface turbidity patterns (Figure 6). The time-series field measurements obtained at Sites 1 and 3 (Figure 1) are used to investigate circulation, sediment re-suspension, sediment flux and salinity changes during these events.

Several winter storm systems impacted southern Louisiana between December 23, 1997 and January 12, 1998. The two main episodes that will be discussed have been highlighted in Figures 7 and 8. The first episode, December 26 through 30, involved two storm systems. The clear-sky image obtained on December 25 (Figure 6a) illustrates suspended sediment distribution patterns before arrival of either storm. During this pre-frontal period, weak northeasterly winds prevailed. On the afternoon of December 25, the highest concentration of suspended sediments were within Atchafalaya Bay; however, in general values were very low. A large region of turbid water was observed in the northeast corner of West Cote Blanche Bay where river water entered from the GIWW. The next clear-sky image was obtained on December 29 (Figure 6b) after the passage of two winter storms, the first of which was accompanied by strong north winds and the second with strong northwest winds. The contrast between the pre-frontal and post-frontal satellite images is striking. The areal extent of turbid waters in the Atchafalaya region was maximized by the strong offshore winds. Large increases in turbidity were observed within the bays and on the inner shelf seaward of them. Before these storms, the Atchafalaya plume (seaward of the bays) measured 1621 km^2. Subsequent to them, the plume measured 11,405 km^2. These measurements were con-

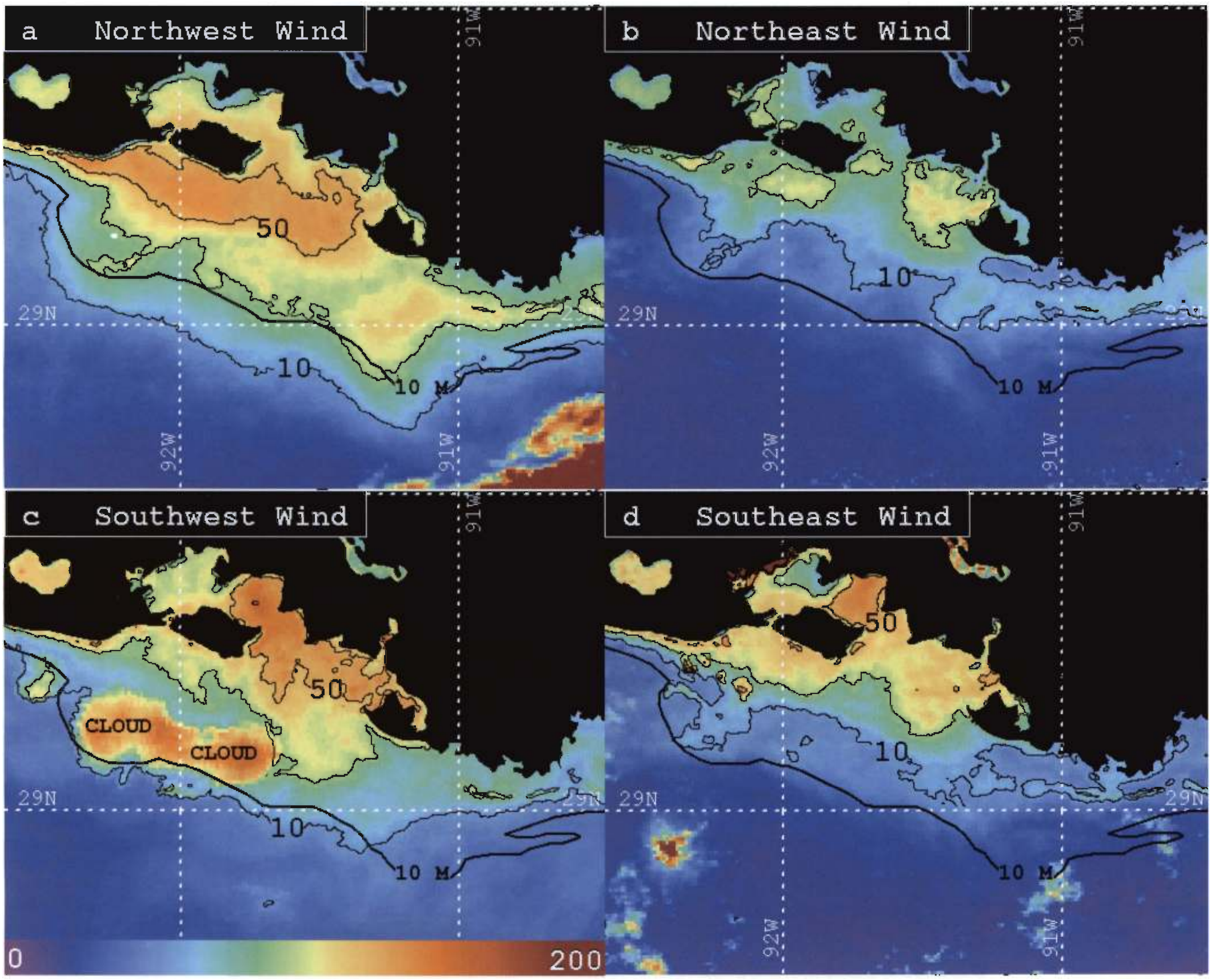

Figure 5. Satellite image composites of surface suspended sediment concentrations during low river discharge for the four main wind quadrants: (a) northwest, (b) northeast, (c) southwest and (d) southeast. Contours of total suspended solids (10, 25, 50 mg l^{-1}) are shown. A color scale in mg l^{-1} is also shown. Each composite represents an average of four images.

fined to the shelf and were based on a reflectance of 5% (about 25 mg l^{-1}). The turbid water region on the inner shelf seaward of Atchafalaya Bay had dimensions in excess of 180 km (length) and 75 km (width). The December 29 image (Figure 6b), revealed a two-lobed structure that was similar in morphology to the 10 m isobath (heavy solid line, Figure 6). This lobed structure reveals shallow regions where resuspension of bottom sediments was maximized and brought to the surface by intense vertical mixing. The eastern portion of the plume extended more than 100 km towards the southeast in the direction of wind flow. The highest suspended sediment concentrations were detected within Atchafalaya Bay. A tongue of very turbid water exited Atchafalaya Bay and extended intact for about 40 km along the coast to the east. This feature suggests the existence of an eastward flowing near-coastal current generated by the northwest wind event. In comparison with other bay regions, satellite-observed reflectances were relatively low in the northern portions of Vermilion and West Cote Blanche Bay, around Cypremort Point. This observation may reflect a change in the type of sediment in suspension. In this region, relatively high concentrations of organic matter from eroding marshes have been observed in water samples. This material would result in a less reflective water mass compared with waters high in inorganic silt and clay components.

Time-series data including wind, water level, turbidity, and sediment flux at sites 1 and 3 are shown for the period December 23 to January 12 (Figures 7, 8). The strong (12–14 m s^{-1}) north winds characteristic of each storm caused water levels to drop 1.3 m (Figures 7b, 8b). The digital turbidity

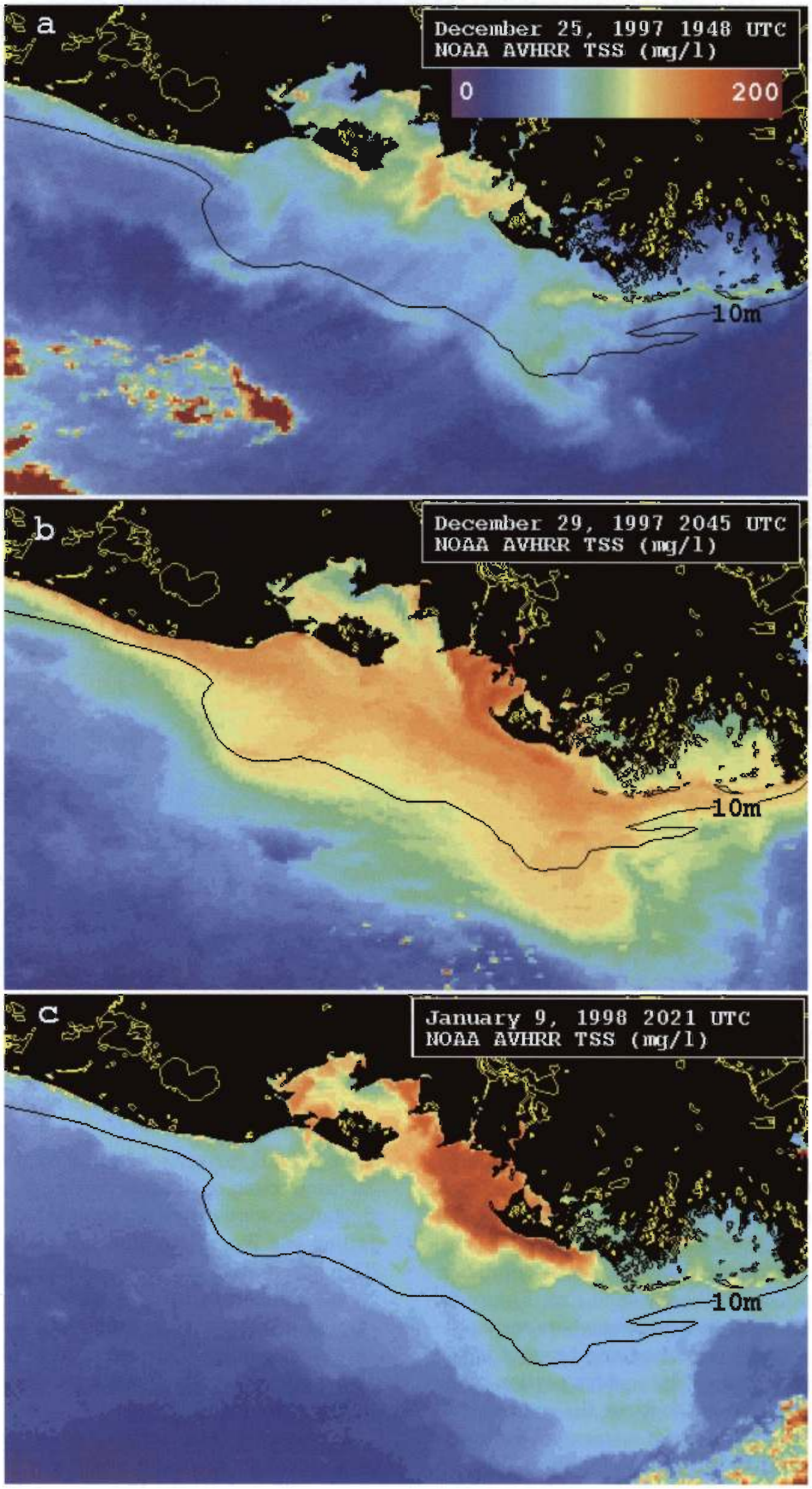

Figure 6. NOAA-14 reflectance images acquired on (a) December 25, 1997, (b) December 29, 1997 and (c) January 9, 1998. A scale relating image colors to total suspended solids in mg l^{-1} is shown. The 10 meter isobath is depicted.

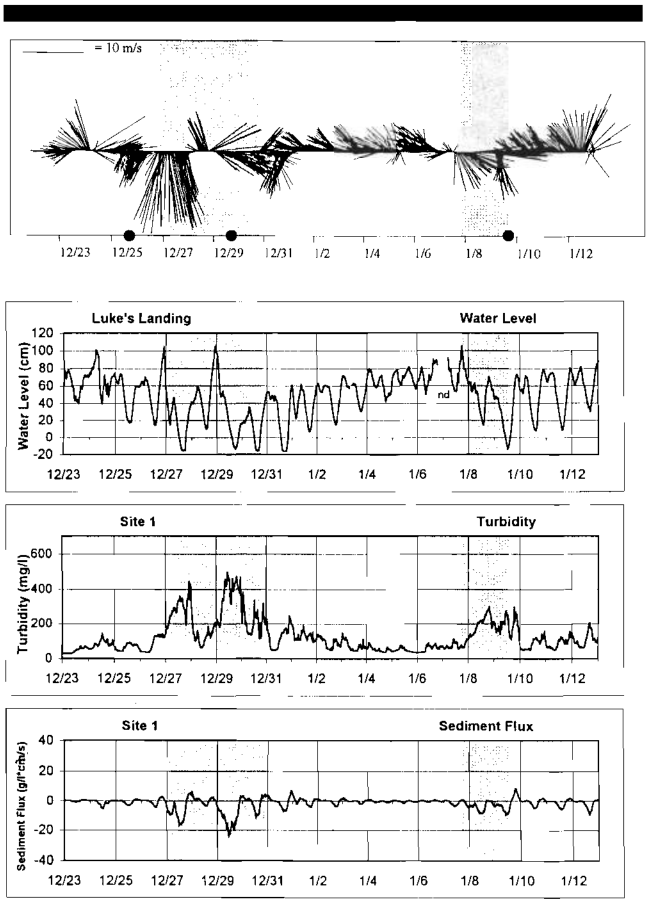

Figure 7. Time-series measurements during the winter storm period from December 23, 1997 through January 12, 1998 of (a) wind speed/direction at Cypremort Point (stick vectors extend in the downwind direction); (b) water level at Luke's Landing, East Cote Blanche Bay; (c) turbidity (mg l^{-1}) at Site 1 and (d) sediment flux (g $^{-1}$·cm $^{-1}$) at Site 1. Two cold front episodes are shaded. The filled circles indicate the times of satellite image acquisition. Times are in UTC (Universal Time Coordinated) to correspond with satellite imagery.

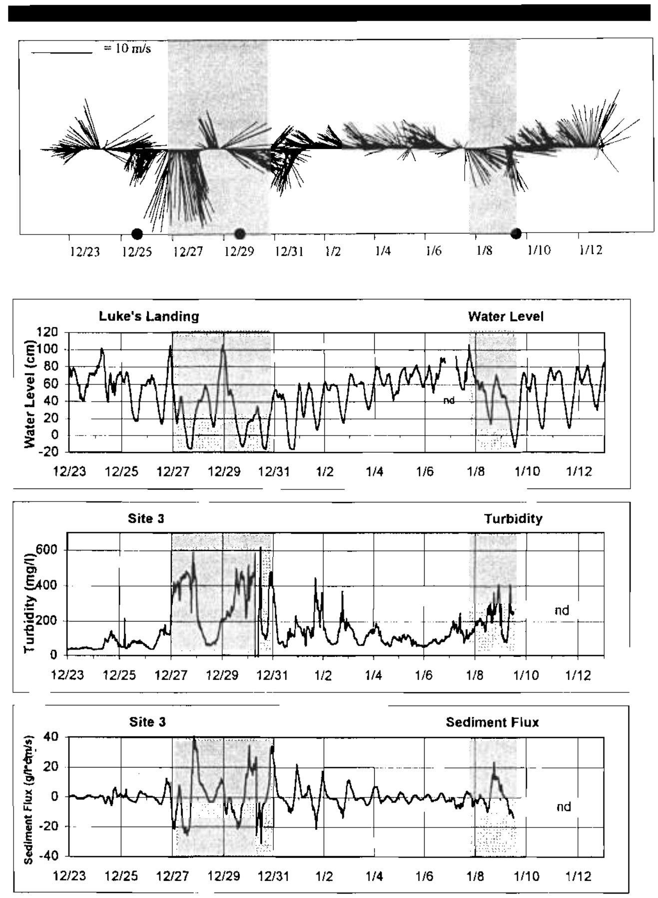

Figure 8. Time-series measurements during the winter storm period from December 23, 1997 through January 12, 1998 of (a) wind speed/direction at Cypremort Point (stick vectors extend in the downwind direction); (b) water level at Luke's Landing, East Cote Blanche Bay; (c) turbidity (mg l^{-1}) at Site 3 and (d) sediment flux (g^{-1}·cm^{-1}) at Site 3. Two cold front episodes are shaded. The filled circles indicate the times of satellite image acquisition. Times are in UTC (Universal Time Coordinated) to correspond with satellite imagery.

records (calibrated to mg l^{-1}) show two large peaks in suspended sediments, each corresponding to a period of strong offshore winds and lowered water levels (Figures 7c, 8c). At both sites, sediment concentrations (at mid-depth) increased from <100 mg l^{-1} before frontal passage to 400 mg l^{-1} after frontal passages. Turbidity levels were a little higher during the second event when winds blew from the northwest (rather than north). Turbidity returned to prevent levels as winds weakened and water levels increased. The time-series records reveal a close correlation between turbidity measurements (Figures 7c, 8c) and local wind speeds (Figures 9b, 10b).

Sediment fluxes (Figures 7d, 8d) were computed using the primary component of the currents at each site (Figures 9c, 10c) and the calibrated turbidity measurements (Figures 7c, 8c). The primary axis of the currents at Site 1 was 140/320 degrees and at Site 3 was 30/210 degrees. Sediment fluxes were found to be distinctly different at the two sites, primarily as a result of differences in the flow regime. At site 1, sediment transport was mainly to the southeast out of the bay as a consequence of the dominance of out-flow over inflow during both storms (Figure 9c). Outgoing current speeds were similar during both cold fronts of episode 1 and exceeded 40 cm s^{-1}. Episode 1 corresponded in time with a spring tide period that increased the tidal prism. Maximum sediment transport occurred in concert with the peak turbidity values and outgoing currents (Figure 7d). The net sediment flux at site 1 was towards the southeast. The sub-tidal component of the currents reveals an almost continuous net outflow at this site and currents of 20 to 30 cm s^{-1} during frontal passages. The dominance of outflow over inflow is at least partially attributable to inflow of river water through "the Jaws."

At site 3, currents were observed to be stronger than at Site 1, and the outgoing and ingoing currents were more similar in magnitude (Figure 10c). Outgoing current speeds exceeded 60 cm s^{-1} during strong north wind periods. After frontal passages, as the wind speed decreased slightly, currents at site 3 reversed direction and strong inflows occurred.

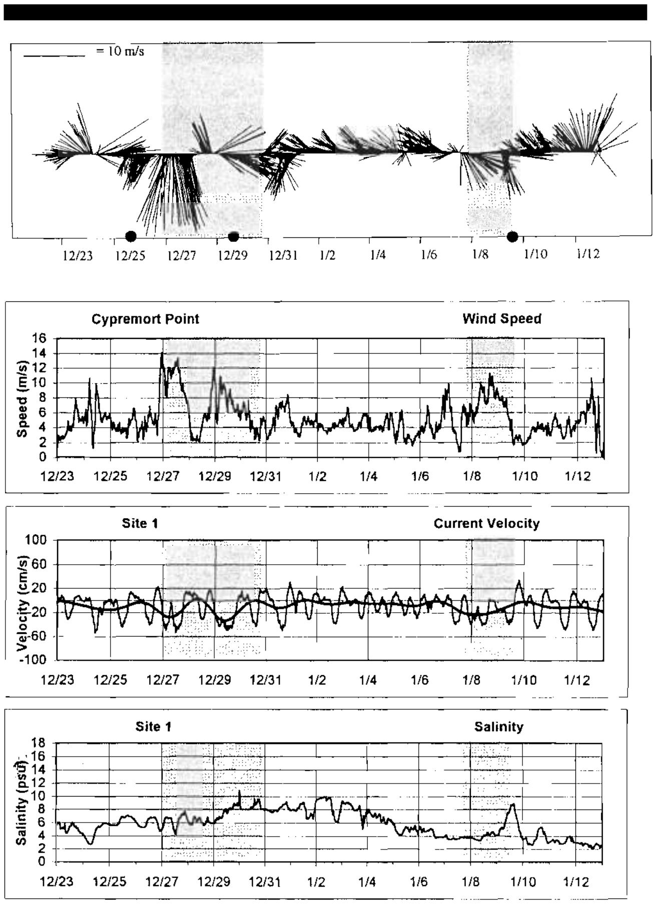

Figure 9. Time-series measurements during the winter storm period from December 23, 1997 through January 12, 1998 of (a) wind speed/direction at Cypremort Point (stick vectors extend in the downwind direction); (b) wind speed at Cypremort Point (m s^{-1}); (c) primary axis current speeds (cm s^{-1}) at Site 1 and (d) salinity (psu) at Site 1. Two cold front episodes are shaded. The filled circles indicate the times of satellite image acquisition. Times are in UTC (Universal Time Coordinated) to correspond with satellite imagery.

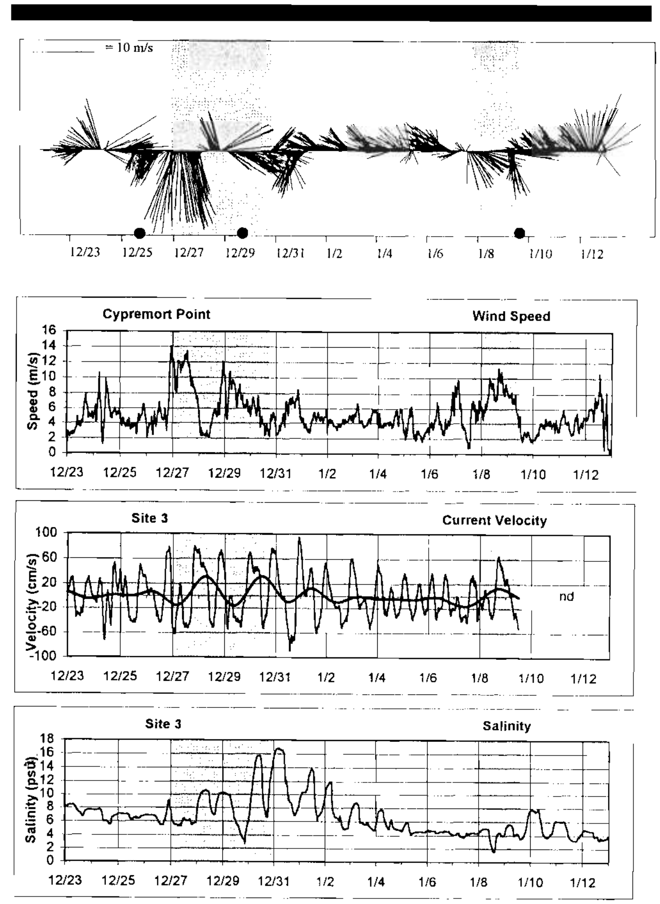

Figure 10. Time-series measurements during the winter storm period from December 23, 1997 through January 12, 1998 of (a) wind speed/direction at Cypremort Point (stick vectors extend in the downwind direction); (b) wind speed at Cypremort Point (m s^{-1}); (c) primary axis current speeds (cm s^{-1}) at Site 3 and (d) salinity (psu) at Site 3. Two cold front episodes are shaded. The filled circles indicate the times of satellite image acquisition. Times are in UTC (Universal Time Coordinated) to correspond with satellite imagery.

Ingoing currents reached 75 cm s^{-1} (Figure 10c). Similar current patterns were experienced during both storms at Site 3. Overall, the ingoing currents at Site 3 were stronger than the outgoing currents, and as a consequence, more sediment entered Vermilion Bay than left it during the first cold front episode. The maximum currents at Site 3 were measured on December 31 in concert with a strong north-northeast wind event. This wind direction induced a set-up of water levels in the southwest corner of Vermilion Bay thus explaining the relatively strong outflows. Compared with northwest and north winds, northeast winds are less effective at flushing the Cote Blanche Bays.

The time-series measurements have demonstrated an important aspect of circulation in the western bays. During northwest and north wind events, much of the water in the western bays is driven out of the system towards the southeast through the wide opening to the inner shelf provided by East Cote Blanche Bay. In the rebound phase after frontal passage, Southwest Pass appears to be a more important conduit for restoring water levels into the western bays. From January 1 to 6, southeast wind conditions were experienced as the continental high pressure system (in the wake of the cold fronts) moved eastward. During this period, turbidity values were relatively low. The second cold front episode to be discussed was characterized by a single, more moderate winter storm. The time-series measurements demonstrate a similar pattern to the previous cold-front passages with increased turbidities at both sites corresponding with the increase in wind speed and reduction in water levels. A clear-sky satellite image was obtained on January 9, while north winds still prevailed (Figure 6c). Although the extended plume on the inner shelf was smaller (4660 km^2 compared with 11,405 km^2 on December 29), the suspended sediment concentrations within the bays were higher than on December 29. This observation is partially attributable to an anomalous rainfall event on January 7, caused by a Gulf of Mexico low and upper level disturbance over southwest Louisiana (NATIONAL WEATHER SERVICE, 1998). Local rivers, such as the Vermilion River and Bayou Teche (Figure 1), were in flood as a result of this rainfall event. In addition, Atchafalaya River discharge surged from 3598 to 6713 $m^3\ s^{-1}$ between December 23 and January 9. The satellite image of January 9 revealed the regional impacts of the river runoff into the bays and coastal ocean. In the coastal regions most directly impacted by river inputs, concentrations of suspended solids were estimated from the imagery at 150 to 200 mg l^{-1}. Very turbid waters were observed in the northeast corner of West and East Cote Blanche Bays. In addition, the western side of Vermilion Bay was extremely turbid primarily as a result of discharge from the Vermilion River through Little Vermilion Bay (just west of the big bay). A distinct plume of sediment-laden water was detected south of Southwest Pass, extending 50 km seaward into the Gulf of Mexico (Figure 6c). The current speeds and sediment fluxes at both sites were lower during episode 2 because of the weaker winds.

Salinity fluctuations associated with the series of storms were larger at site 3 than at site 1. During the period of study, salinities ranged from 2 to 11 psu at site 1 (Figure 9d) and from 2 to 17 psu at site 3 (Figure 10d). Salinity values were lower during the north wind events and higher during the southeast wind periods after frontal passages. At site 3, a large and rapid salinity change of 13 psu (3–16) occurred over 12 hours on December 29/30, during the inflow period after the second cold front passage of episode 1 (Figure 10d). Subsequent to this peak salinity, values above 10 psu occurred with the ingoing tidal currents for 4 consecutive days. The lowest salinity values (2–4 psu) occurred during episode 2 when offshore winds occurred in tandem with the high rainfall event, local flooding and increasing river discharge. At site 1, an unexpected salinity peak (>8 psu) was observed on January 9, in tandem with a relatively strong inflow during the rebound period after the north wind abated.

DISCUSSION

The in-situ measurements and satellite imagery have demonstrated that sediment resuspension and transport are maximized by the sequence of events associated with the passage of winter storms in this region. Additional analyses of satellite imagery and field measurements indicate that the case studies presented are fairly typical of winter storm events. The turbidity records demonstrate that the amount of sediment in suspension is increased substantially by these offshore wind events. Although wave measurements were not available, it can be inferred from the close correlation between wind speed and turbidity that resuspension processes are maximized by these strong winds, a process that is enhanced by the falling water levels. The rapid and substantial (>1 m) decrease in water levels that occurs with northwest and north wind events dramatically increases the resuspension potential of the wind-waves as, in some places, pre-storm water levels are not much more than 2 m. The boundary layer turbulence created by the intrusion of cold air over warmer water may also enhance wind-wave generation processes.

Although current meter data were not available on the inner shelf during the period presented in this paper, current meter measurements have been made on the inner shelf seaward of Atchafalaya Bay during the MMS-sponsored Louisiana-Texas Shelf Physical Oceangraphy Study (DIMARCO *et al.*, 1997). Data collected at three stations (17, 18, 19) seaward of Atchafalaya Bay in December 1993 are shown in Figure 11 (Locations, Figure 1). These data (Figure 11b–d) in combination with the wind data from Burrwood (Figure 11a) demonstrate that strong northwest wind events cause rapid reversals in current direction across the shelf, at least as far as the 50 m isobath. Southeastward currents ranging in speed from 30 to 60 cm s^{-1} were measured at stations 17 (3 m depth), 18 (12 m depth), and 19 (3 m depth) during a winter storm event on December 14, 1993.

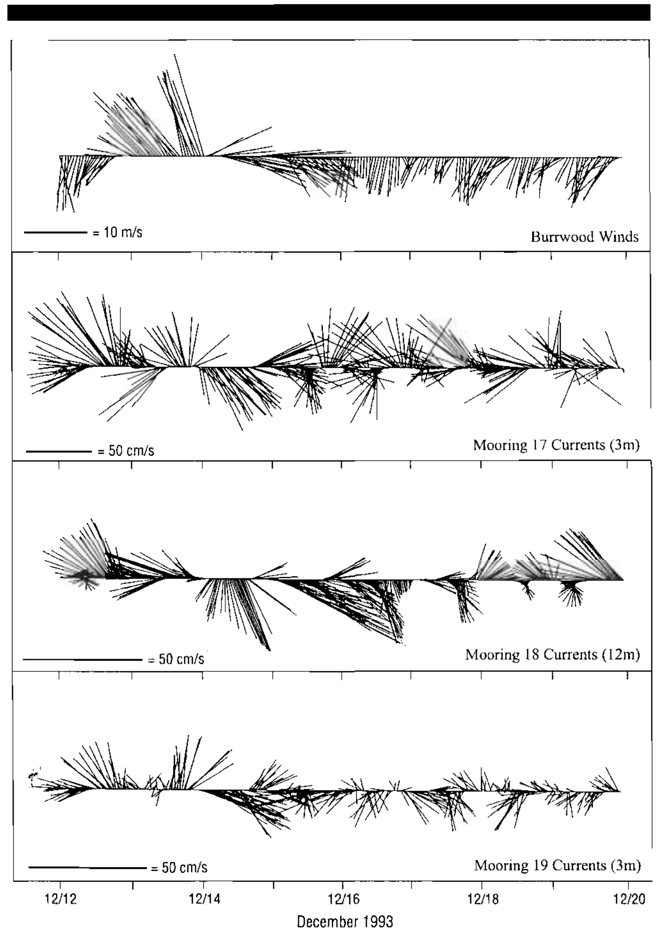

Figure 11. Time-series of wind vectors from Burrwood, LA and current vectors measured seaward of Atchafalaya Bay from December 12–20, 1993. The locations of moorings 17, 18 and 19 are shown in Figure 1. Water depths of these moorings were 7, 22, 51 meters. Instrument depths were 3, 12 and 3 meters. A winter storm episode is shaded. Stick vectors are plotted in downwind and downcurrent direction.

One of the key questions arising from the satellite data concerns the source of the sediments in the plume. How much of the plume originates in the bays and how much results from resuspension on the inner shelf? If one assumes an average surface current of 50 cm s^{-1} for 19 hours (typical of winter storms), turbid bay water would be transported 34 km from the bay mouth. The sediment plume, as observed on

December 29, extended 75 km offshore and 180 km east and west of the Atchafalaya Bay mouth. The fact that the surface sediment plume aligns itself with the bottom contours suggests that resuspension is a major contributor to the extensive sediment plume seaward of the bay. In addition, the plume on December 29 (and other case study events) was very symmetrical on the shelf. If it were comprised primarily of material transported onto the shelf, it would be asymmetrical extending towards the southeast. From the evidence presented, we estimate that 20 to 25% of the sediment plume observed in satellite imagery is flushed onto the shelf and the remaining 75 to 80% results from the resuspension and seaward transport of inner shelf bottom sediments.

An estimation can be made of sediment leaving the bay system during a cold front event. If we assume an average sediment concentration of 200 mg^{-1} (surface to bottom), approximately 400,000 metric tons of sediment are transported onto the shelf during an average winter storm. Over the year, approximately 25 cold-front events are experienced, yielding an exchange with the inner shelf of 10 million tons. This value is about 12% of the yearly average sediment discharge of the Atchafalaya River over the 20 year period, between 1974 and 1993.

The cold-front related erosion of sediments is a process that reduces the rapidity of delta development (VAN HEERDEN and ROBERTS, 1980). This process would also slow the rate of infilling in the shallow bays to the east and west of Atchafalaya Bay. This process could be important in maintaining a reasonable depth for fisheries habitat. Considerable shoreline erosion has been observed on the northeast point of Marsh Island near site 1 of this study (EDWARD MOUTON, *personal communication*), a fact that may result from the generation of wind-waves and strong currents during these strong north wind events. A bathymetric change analysis performed for the western bay region (CUNNINGHAM and GRYMES, 1997; WALKER *et al.*, 1997) has revealed that Vermilion Bay has experienced shoaling over the past 20 years, whereas the southern portions of East and West Cote Blanche Bays have experienced scour. In contrast, the large influx of sediments through the "Jaws" has resulted in a subaqueous delta in the northeast corner of West Cote Blanche Bay. The removal by dredging of the East Cote Blanche Bay oyster reefs, between 1950 and 1980, may have increased winter storm impacts by increasing current velocities and sediment transport onto the shelf through East Cote Blanche Bay. If the post-frontal influx of water and sediments through Southwest Pass increased in response to the increased flushing, then the shoaling in southern Vermilion Bay may also be indirectly attributable to these dredging activities.

Seaward of the bays on the inner shelf, ecological impacts would be expected from the large volumes of river and bay water discharged onto the inner shelf during winter storms. It has been shown that biological productivity is increased by the discharge of nutrient rich waters onto the shelf. Chlorophyll *a* concentrations in excess of 20 to 30 $\mu g\ l^{-1}$ have been measured in the shelf extension of the Atchafalaya plume after passage of a cold front (RABALAIS and TURNER, 1997; WALKER *et al.*, 1997). The frequency, intensity and timing of these flushing events may be an important factor affecting Louisiana's coastal fisheries and perhaps the distribution of low oxygen waters the following summer.

CONCLUSIONS

The "winter storms" that are experienced in the Atchafalaya-Vermilion Bay region from October through April have major impacts on circulation, sediment resuspension, sediment transport, water level and salinity changes. Coastal and bay water levels usually rise before frontal passage because of a strengthening of the pre-frontal southerly winds. Bay water levels then drop 1 m on average in East Cote Blanche Bay during the offshore wind period of winter storms. Northwest winds (rather than north or northeast) cause the largest water level changes in the Vermilion-Cote Blanche Bays during these events. Sediment resuspension and water column turbidity increase 5 times or more by the strong north winds under conditions of decreasing water levels. The flux of sediment onto the inner shelf is maximized by the wind-driven flushing of the turbid bay waters. It is estimated that 400×10^3 metric tons of sediment is flushed from the bays during an average event, amounting to 10 million tons over a typical year. This process and resuspension processes on the inner shelf produce a large turbid plume that can extend 180 km alongshore and 75 km offshore. A sequence of NOAA AVHRR satellite reflectance imagery vividly demonstrates the rapid regional changes in sediment resuspension and transport that result from winter storms in these shallow coastal systems. An analysis of multi-year satellite imagery confirms that the size and orientation of sediment plumes is directly related to wind forcing. The largest sediment plumes result from northwest wind events caused by flushing of the bays, the regional resuspension of bottom sediments and Ekman processes enhancing offshore surface layer transport of turbid waters. The winter storms temporarily reverse the prevailing westward flow of river water along the coast.

Time series measurements obtained during the winter of 1997/98 revealed consistent patterns of circulation, sediment transport and salinity change during three winter storm events. At Site 1 in East Cote Blanche Bay, water flowed to the southeast at 40 to 50 cm s^{-1} for about 20 hours during winter storm events. In Vermilion Bay, water flowed south out of Southwest Pass at 50 to 60 cm s^{-1}. Sediment flux at Site 1 was primarily southeastward towards Atchafalaya Bay as the outflow greatly exceeded the post-frontal inflow of water and sediments. Through Southwest Pass, strong outflow was followed by strong inflow, and thus, sediment flux was in both directions. The net sediment flux through Southwest Pass was into Vermilion Bay as a result of stronger inflow than outflow. The strong inflow of water after frontal passage through Southwest Pass produced large and rapid increases in salinity. After one of the winter storms, salinity increased from 3 to 16 psu over 12 hours. A similar salinity change was not noted at site 1. In general, salinities drop during the offshore wind period when river drainage is enhanced by the extremely low coastal water levels. Salinities rise after winter storm events, particularly in southern Vermilion Bay where inflow through Southwest Pass is strong and there is a source of higher salinity water away from the large opening into Atchafalaya Bay. Further quantification of sediment fluxes would benefit from the collection of continuous current measurements using ADCPs across the channels linking these bays to the coastal ocean.

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