SHORT-TERM EVOLUTION OF A MARSH ISLAND SYSTEM AND THE IMPORTANCE OF COLD FRONT FORCING, TERREBONNE BAY, LOUISIANA

A Thesis

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By
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ABSTRACT

Short-term, wave induced erosion along bay beaches in the northern Gulf of Mexico has been linked to the postfrontal phase of cold front passages. Not until recently has consideration been given to the importance of wave erosion on marshes fringing large bays during the entire cold front event. Two WAVCIS (Wave-Current-Surge-Information System) stations were established on the north and south flank of a small marsh island in Terrebonne Bay, Louisiana, to measure and elucidate the hydrodynamic response to these events. Data from WAVCIS stations, which includes wind speed and direction, air temperature, significant wave height and water level, were collected between June 1999 and January 2002. These data were coupled to measured shoreline change data obtained from a series of north/south repetitious profiles along the length of the island. Four high-resolution topographic surveys were conducted between April and June 1999 and a fifth in December 1999. These surveys were complimented by annual surveys conducted in spring from 2000 on with an additional survey in October 2003.

Data obtained from this effort allows the conclusion that low-energy fringing marshes undergo substantial geomorphological change from locally generated high-frequency waves developed by strong winds (12.99-14.14 m/s maximum wind speed) associated with cold fronts. On marsh islands, 80% to 90% percent of erosion occurs during the winter causing the island to thin in space 2.5 m/yr. Erosional patterns observed on the marsh edge include 1) neck and cleft formation, 2) neck cut off and 3) undercutting and marsh toppling. When compared to tropical storms, erosion associated with a season of cold fronts is equal to erosion from one tropical storm. This work underscores the significance of locally generated waves in marsh loss of coastal Louisiana over short time scales (years).

CHAPTER 1

INTRODUCTION

Catastrophic weather systems are known for the important role they play in the short-term evolution of coastal systems (STONE *et al.*, 1996; STONE *et al.*, 1997; STONE *et al.*, 1999). Recent evidence suggests geomorphological change associated with cold fronts exceeds that of hurricanes and tropical storms because of their frequency of occurrence (ROBERTS *et al*., 1987). Research that supports this includes progradation of the Chenier Plain (KEMP *et al*., 1980; KEMP, 1986; ROBERTS *et al*., 1987; ROBERTS *et al*., 1989; MOELLER *et al*., 1993), and shoreline change along barrier islands (BOYD and PENLAND, 1981; PENLAND and BOYD, 1981; PENLAND and SUTER, 1984; RITCHIE and PENLAND, 1988; DINGLER and REISS, 1990; ARMBRUSTER *et al.*, 1995; CHANEY and STONE, 1996; ARMBRUSTER, 1997). Studies on change due to cold fronts have largely focused on high-energy, sandy coastlines (PSUTY, 1965, 1967; FOX and DAVIS, 1976; NORDSTROM, 1980; BOYD and PENLAND, 1981; MORTON, 1988; RITCHIE and PENLAND, 1988). With the exception of the Chenier plain in the Gulf of Mexico, only a few studies have concentrated on low-energy shores (ARMBRUSTER *et al.,* 1995; CHANEY and STONE, 1996; ARMBRUSTER, 1997) with emphasis on sediment redistribution (REED, 1989; MOSSA and ROBERTS; 1990; MURRAY *et al*., 1993, STONE et al, 2004a).

Coasts in southeast Louisiana are comprised of fine-grained fluvial sediments built up over time by the formation of multiple deltas as the Mississippi River changed course (KOLB and VAN LOPIK, 1966; FRAZIER, 1967). With each delta-switching event, the inactive delta begins to dewater, compact, and subside, forming multiple shallow bays, lakes and isolated sections of marsh (MORGAN, 1979). As the water bodies grow larger, the surrounding marsh islands are sheltered from waves propagating across the Gulf of Mexico by barrier islands but remain subject to local wave erosion, except where waves enter the bays through tidal inlets (STONE and MCBRIDE, 1998). With the deterioration of the barrier islands, it is predicted that fair-weather wave energy will increase in the bays by 700% transforming the bays and surrounding marsh from low to high-energy environments on timescales of 10-100 years (STONE and MCBRIDE, 1998).

Marsh edge response to waves has not been studied extensively. One study in Maryland suggests that 80% of the marsh is eroded around the perimeter of bays by wave action but also concludes that sea level rise, over longer time scales, is an important factor (DOWNS *et al.*, 1994). Work by FINKELSTEIN and HARDAWAY (1988) along the York River attributes sea level rise as the main cause of marsh edge erosion and occurrence of high-energy storm waves as a secondary cause. PHILLIPS (1986) lists subsidence, sea level rise and dissection of the marsh surface as the main reasons for wetland loss in Delaware Bay. Wave effects were not included in that study. ZABAWA and OSTROM (1980) found that storm waves in Maryland caused greater marsh erosion compared to wind waves and boat wake. Using GIS analysis, PENLAND *et al*, (1998) estimated 43% of land loss in the Mississippi River Delta Plain was due to submergence and 36% was caused by wave erosion.

Waves produced by cold fronts are known to be capable of resuspending sediment in the bays of Louisiana (MOSSA and ROBERTS, 1990; MURRAY *et al.*, 1993; WALKER and HAMMACK, 2000; WALKER, 2001; WALKER *et al.*, 2002; FITZGERALD and KNIGHT, in press). Little is known, however, about how much erosion they cause along low energy marsh shorelines.

Objectives

As studies focus on cold fronts as a mechanism of geomorphologic change, research on the impact of cold fronts on marshes is virtually nonexistent. The objective of this work is to quantify marsh erosion attributable to cold fronts by coupling shoreline change data to measured wave data and to study the effect of waves on low energy coastlines. The general east to west orientation of the coastline in south-central Louisiana makes it an ideal location for such a study. Both shorelines of the island are directly impacted by the frontal system as it moves south over the northern Gulf of Mexico. Hydrodynamic conditions are compared and contrasted on the north and south shores of a marsh island during three different weather types, summer, winter and tropical storms. A site specific model is created to relate marsh edge response to changes in the wave regime.

The Cold Front Cycle

Cold fronts, along with Nor'easters, are part of a larger class of storms termed extratropical storms. An extratropical storm is a cyclonic weather system, which develops in non-tropical regions (CHANEY, 1998). Two types of extratropical storms identified in North America are mid-latitude cyclones and Gulf cyclones. Mid-latitude cyclones are most common and extend across the entire United States. Warm air is transferred north along the frontal boundary, while cold air is pushed south. Gulf cyclones form over the eastern Texas/ western Gulf of Mexico region and propagate eastward on a southerly track, bypassing the north central Gulf of Mexico (CHANEY, 1998).

The northern Gulf of Mexico experiences 30-40 cold fronts a year, with weekly occurrences primarily during the months of October through April (DIMEGO *et al*., 1976; ROBERTS *et al*, 1987). The ability of a cold front to cause long term cumulative change lies in the intensity of the pressure system, speed of frontal movement, higher frequency of occurrence and a distinct cycle of meteorological conditions including a uniform direction of approach, changes in wind patterns, barometric pressures, temperature, and humidity (ROBERTS *et al.*, 1987). The work of ROBERTS *et al.* (1987) resulted in recognition of this pattern and he separated cold fronts into three phases: prefrontal, frontal, and postfrontal. The prefrontal phase is defined as weather conditions that exist prior to the frontal passage. Winds blow from the south, barometric pressure decreases, and humidity and temperatures rise. The frontal phase describes conditions during the time of passage, ascending winds, a sudden drop in barometric pressure, and squall lines. After the front passes, postfrontal conditions are characterized by northerly winds, rising barometric pressure, decreasing temperatures and humidity (HUH *et al.*, 1984, ROBERTS *et al.*, 1987; ROBERTS *et al.*, 1989). During all three phases, systematic increases in wave energy occurs in addition to changes in water level

PEPPER (2000) determined that exratropical storms have a major influence on the hydrodynamics of the Gulf. He found that each storm passage is accompanied by elevated, long-period waves from a southerly direction, weak to moderate currents (>10 cm/s), and an increase in shear velocity and sediment transport during the pre-frontal phase. As the front passes, waves, currents and shear velocity decrease. During the postfrontal phase, increased wave heights propagate from the north along with strong currents and very high sediment transport (PEPPER and STONE, 2002; PEPPER and STONE, 2004; STONE *et al.*, 2004b).

Study Site

The study site is a saltmarsh island located in Terrebonne Bay, along the Louisiana Gulf Coast (Figure 1). The bay is approximately 1761 km^2, has an average depth of 2 m, and a salinity of 18 ppt (USEPA, 1999). Tides in Terrebonne Bay are diurnal with a semi-diurnal

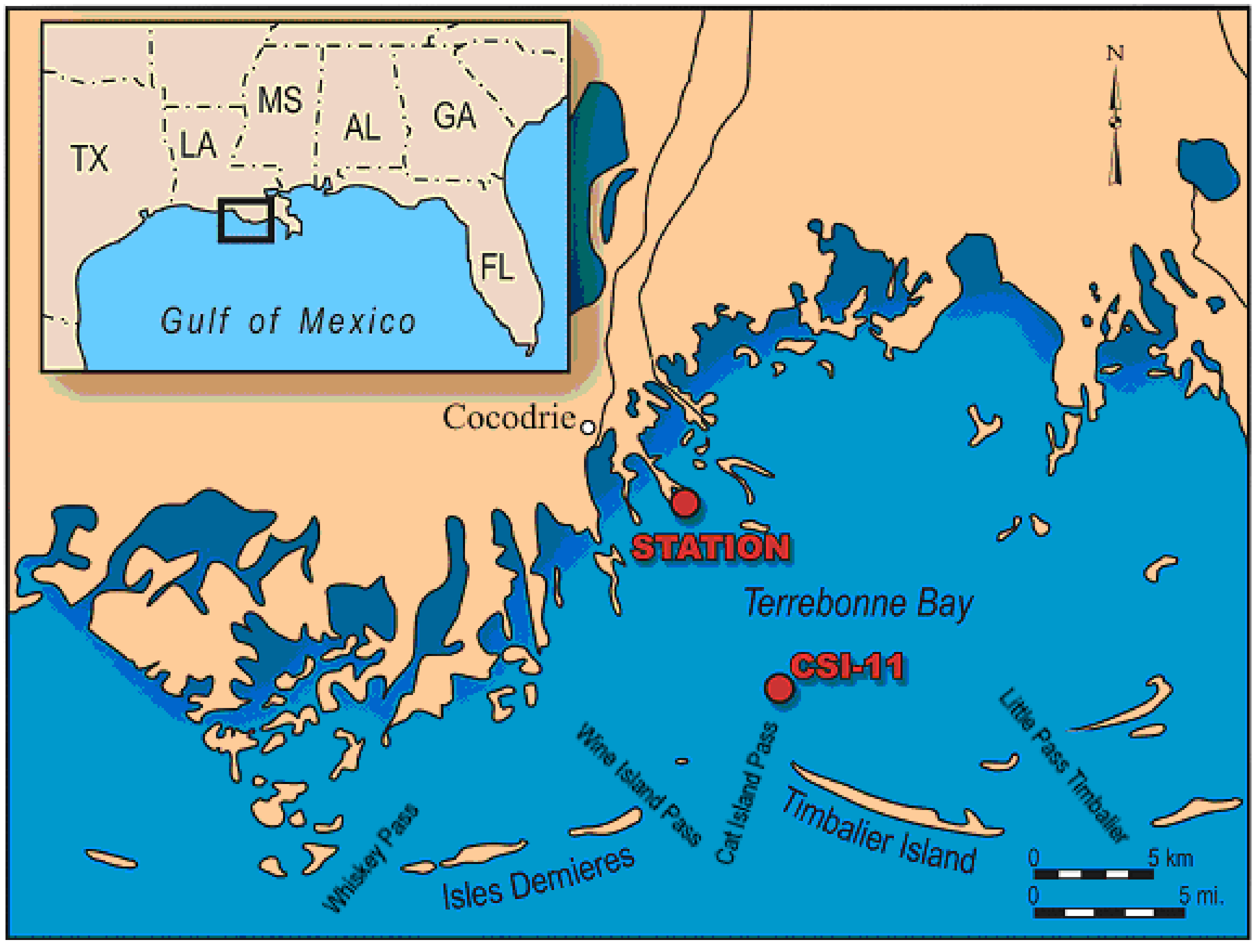

Figure 1: Study Site located in Terrebonne Bay, along the Louisiana Gulf Coast

component. The tidal range is approximately 20 cm for an equatorial tide and 80 cm for tropic tides (INOUE and WISEMAN, 2000). Circulation in the bay is impacted by winds due to shallow depths but strong tidal currents can form where the depth increases near tidal inlets (INOUE and WISEMAN, 2000). Terrebonne Bay is separated from the Gulf of Mexico by two barrier island chains, Timbalier Islands and Isles Derniers and is connected by four tidal passes, Whiskey Pass, Little Pass Timbalier, Cat Island Pass and Wine Island Pass. The main pass is Cat Island Pass which has depths of 5-6 m (INOUE and WISEMAN, 2000).

The present study area is part of the Teche delta complex, created by the Mississippi River over 2,800 years B.P. and was reoccupied by the Lafourche delta 1000-300 years B.P. (KOLB and VAN LOPIK, 1966; MORGAN, 1979). After the river changed course the sediment supply was no longer sufficient to sustain marsh growth. As soils compacted, land subsided until it could no longer remain above sea-level and became open water. Relative sea-level rise for Terrebonne Bay is estimated to be 1.09 cm per year, with 76% attributed to subsidence (RAMSEY and PENLAND, 1989). Over time, shallow bays and lakes formed, isolating small sections of marsh. These marsh islands are subject to wave erosion. The east-west orientation of the island makes it an ideal feature to study the effects of cold fronts on marsh edge systems; as the front passes, effects of the prefrontal and postfrontal conditions can be determined.

The marsh island used in this study is 174 m long and 20 m wide and is located in the northern part of Terrebonne Bay. The southern shoreline is exposed to waves propagating from the Gulf of Mexico into the bay through Cat Island Pass, while the northern shoreline is fetch limited. The soil is predominantly clay with less than 5% organic content which was deposited while the Mississippi River occupied the Bayou Teche and Bayou Lafourche channels. Overlaying the clay layer is organic rich soil composed of living and dead root material (ARE *et al.*, 2002).

CHAPTER 2

METHODOLOGY

The study was divided into two components, topographic surveys which were used to monitor the amount of shoreline change on the island and two WAVCIS stations which measured hydrodynamic and meteorological data. Shoreline data were obtained using topographic surveys with a Topcon electronic total station for seventeen north/south survey lines. Figure 2 shows the location of the profile lines across the island while Figure 3 shows the equipment used for the surveys. Four surveys were conducted in the spring/early summer of 1999 and another in December. In subsequent years a survey was conducted every spring with an additional survey in October 2003 for a total of 11 surveys; survey dates are presented in Table 1. Nearshore bathymetry surveys were conducted in July 2004 on profiles C2, C4, C6, C9 and C12 to determine differences in water level along the shoreline.

Since there is no official elevation for the island, all measurements are relative to a benchmark placed in the ground by the survey team. With the exception of two profiles, C1 and C3, the survey lines extend along the entire width of the island from the north to the south shore. The difference between distances of an erosional scarp, which is a distinctive feature on the profiles, was used to calculate the amount of erosion or deposition between surveys. Accuracy for the survey instrumentation is 0.3-0.5 mm in both the horizontal and vertical directions (TOPCON ELECTRONIC TOTAL STATION INSTRUCTION MANUAL).

Profiles from April 8, 1999 to July 17, 1999 are used to represent the summer season. Profiles from December 2, 1999 to March 25, 2001 and October 31, 2003 to March 17, 2004 are used to represent the winter season. The assumption is made that during the winter, profile

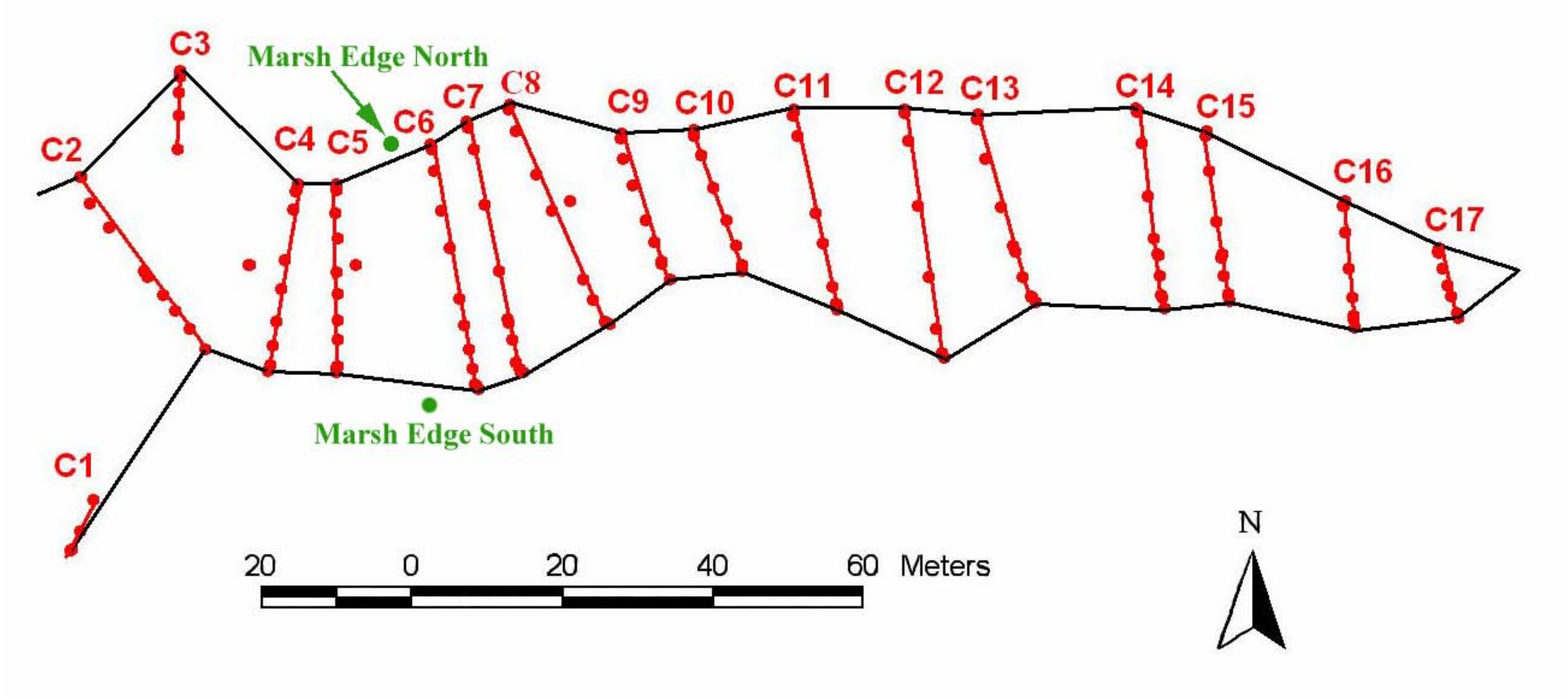

Figure 2: Location of seventeen north/south profile lines across the study area.

Figure 3: Topcon electronic total station and equipment used for the surveys, instrumentation in collects meteorological data.

Table 1: Dates of Topographic Surveys

April 8, 1999
April 26, 1999
May 24, 1999
July 17, 1999
December 2, 1999
June 15, 2000
March 25, 2001
March 14, 2002
April 4, 2003
October 31, 2003
March 17, 2004

erosion was caused primarily by cold fronts since no tropical storms occurred. From March 25, 2001 to October 31, 2003, four tropical cyclones passed near Terrebonne Bay: Tropical Storm Allison in June 2001, Tropical Storm Isidore and Hurricane Lili in September and October 2002, and Tropical Storm Bill in 2003 (www.nhc.noaa.gov). Erosion from these storms is included in the combined tropical storm and winter change data, because no surveys were conducted between the storm and the winter season.

Hydrodynamic and meteorological data were collected using WAVCIS stations. Scientists in the Coastal Studies Institute at Louisiana State University developed the WAVCIS program to provide real time conditions for the Louisiana Gulf Coast via the internet (STONE, 2001; ZHANG, 2003). Parameters recorded include significant wave height and period, water level, barometric pressure, air temperature, water temperature, wind direction, and wind speed. Each hour a station collects 2048 readings by having a sampling frequency of one burst of 8.5 minutes every hour at 4 Hz (ZHANG, 2003). The data are sent by satellite to the WAVCIS Processing Lab at Louisiana State University where they are post-processed and made available on the WAVCIS website (www.wavcis.lsu.edu).

Three WAVCIS stations were utilized during this study. Two temporary Marsh Edge stations, (Marsh Edge North and Marsh Edge South), were built on the north and south flanks of the island (Figure 2), respectively, while meteorological instrumentation was placed in the middle of the island between the two stations as seen in Figures 4-6. Stations were in operation from June 1999 to September 2002, until Tropical Storm Isidore and Hurricane Lili, destroyed the platform which held the instruments in place.

Data were downloaded from a third station, CSI-11, and used for comparison with the Marsh Edge stations. The station, Figure 7, is located at -90^{o}35’ W 29^{o}10’ N in Terrebonne Bay,

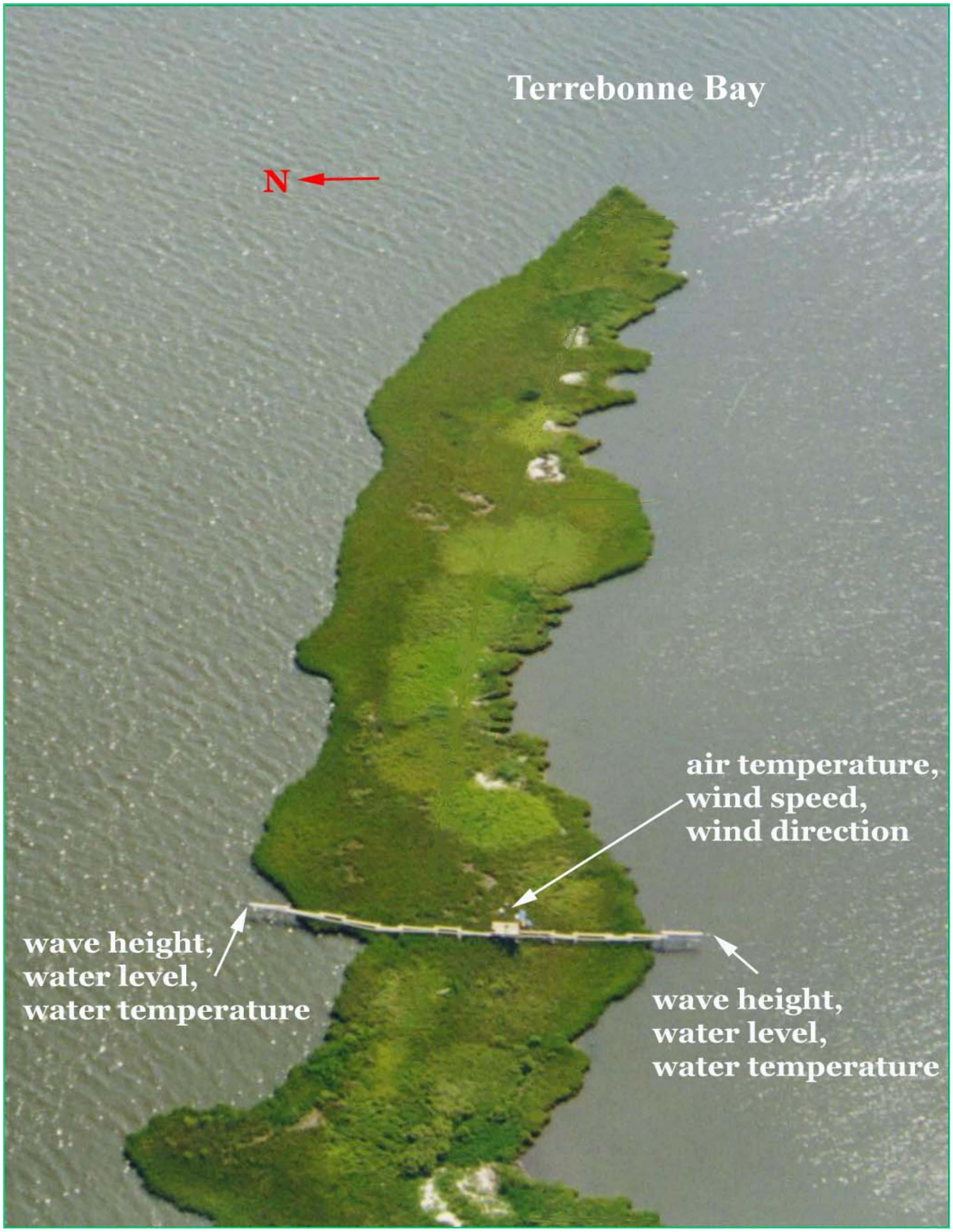

Figure 4: Wave data were collected on the north and south shores of the island, meteorological data were collected in the middle.

Figure 5: Hydrodynamic data were collected by submerged sensors placed at the end of the platforms on the north and south shorelines.

Figure 6: Meteorological instrumentation collected data from a platform constructed in the middle of the marsh island.

Figure 7: WAVCIS Station CSI-11 located in Terrebonne Bay (www.wavcis.lsu.edu).

and came online November 1, 1999; CSI-11 remained in operation until June 2004. The hourly data for all three WAVCIS stations were processed using Microsoft Excel and MatLab.

CHAPTER 3

RESULTS

Survey Data

Results from the surveys are divided into three parts, summer change, winter change and a combination of tropical storm and winter change. Summer change includes shoreline change from April 8, 1999 to July 17, 1999. Surveys taken between December 2, 1999 to March 25, 2001 and October 31, 2003 to March 17, 2004 comprise the winter change. Shoreline change from March 25, 2001 to October 31, 2003 is attributed to a combination of tropical storms and cold fronts. A map of the island showing the location of profile lines can be seen in Figure 2 and a detailed description of each profile is presented in the Appendix. Table 2 shows shoreline change during summer, winter and the combination of tropical storms and change measured over the winter for all 17 profiles.

Seasonal analysis of the data show that on the southern shoreline during the summer months of 1999 (Figure 8), 13 of the profiles experienced erosion while 3 profiles showed minor accretion. The degree of erosion ranged from 0.05 to 0.44 meters per month and accretion ranged from 0.01 m to 0.06 meters per month. The average erosion during the summer on the southern shore was 0.12 meters per month. Along the northern shore (Figure 9), 9 profile lines eroded and 6 accreted. Erosion ranged from 0.01 to 0.30 meters per month and accretion ranged from 0.01 to 0.11 meters per month. The average shoreline change for the northern shore during the summer was -0.03 meters per month. Overall the southern shore experienced 73% more erosion during the summer months than the northern shore.

During the winter surveys, erosion was measured on all profile lines for both shorelines. On the southern shore erosion ranged from 0.01 to 0.19 meters per month and had an average of

0.11 meters per month. Erosion on the northern shoreline ranged from 0.08 to 0.21 meters per year with an average of 0.13 meters per year. When erosion on the north shore is compared with erosion on the south shore as in Figure 10, 65% of the profiles experienced more erosion on the north shore than on the south shore.

For the years of combined tropical storm change and winter change all profile lines eroded (Figure 11). Average erosion on the southern shore was 0.07 m per month with a range of 0.01 to 0.13 meters per month. On the northern shoreline average erosion was 0.11 meters per month with a range of 0.04 to 0.22 meters per month. Seventy-five percent of the profiles experienced more erosion on the north shore than along the south shore.

Total shoreline change for the entire study are listed for each profile in Table 3. The average amount of marsh eroded was 5.03 m on the southern coast with the highest value of 8.95 m on profile C8 and the lowest 0.28 m on profile C16. Average erosion along the northern shoreline was 7.35 m with 13.34 m being the largest on profile C14 and the smallest amount 2.14 m on profile C17. Overall, the north shoreline experienced 60% more erosion than the southern shoreline. Eighty percent of the profiles showed higher erosion on the northern shoreline with an average of 2.37 m more erosion than the southern shoreline.

A typical shoreline response can be seen in profile C4 (Figure 12). For this example, 0.38 m eroded from the southern coastline during the summer and 0.11 m eroded from the northern coastline. Change representing winter was 1.38 m of erosion on the south shore and 4.01 m along the north shore. The three years of combined tropical storm and winter change resulted in 3.74 m being eroded from the south shore and 4.10 m eroded form the north shore. The total amount eroded was 5.82 m from the south shore and 8.70 m from the north shore. During the five-year study, 65% of the profile eroded

Table 2: Shoreline change per month during summer and winter seasons

	Summer (April 1999-July 1999)		**Winter** (December 1999-March 2001 and October 2003-March 2004)		**Tropical Storm and Winter** (March 2001 - April 2003)	
Profiles	Southern shoreline	Northern shoreline	Southern shoreline	Northern shoreline	Southern shoreline	Northern shoreline
C1	-0.12	-	-	-		
C2	-0.07	0.11	-0.11	-0.15	-0.08	-0.06
C3	-	-0.04	-	-0.09	-	-0.04
C4	-0.09	-0.03	-0.07	-0.21	-0.09	-0.1
C5	-0.10	0.03	-0.04	-0.10	-0.04	-0.08
C6	-0.18	0.01	-0.19	-0.09	-0.06	-0.08
C7	0.01	-0.07	-0.18	-0.13	-0.06	-0.09
C8	-0.05	0.03	-0.16	-0.10	-0.13	-0.1
C9	-0.29	0.11	-0.15	-0.14	-0.04	-0.15
C10	-0.33	-0.01	-0.12	-0.19	-0.01	-0.1
C11	-0.14	-0.04	-0.19	-0.11	-0.08	-0.19
C12	0.03	0.00	-0.10	-0.14	-0.1	-0.15
C13	0.06	-0.20	-0.13	-0.13	-0.07	-0.07
C14	-0.13	-0.04	-0.11	-0.17	-0.03	-0.22
C15	-0.10	-0.08	-0.03	-0.13	-0.09	-0.07
C16	-0.05	-0.30	-0.01	-0.08	-	-
C17	-0.44	0.01	-0.10	-0.11	-	-
Average	**-0.12**	**-0.03**	**-0.11**	**-0.13**	**-0.07**	**-0.11**

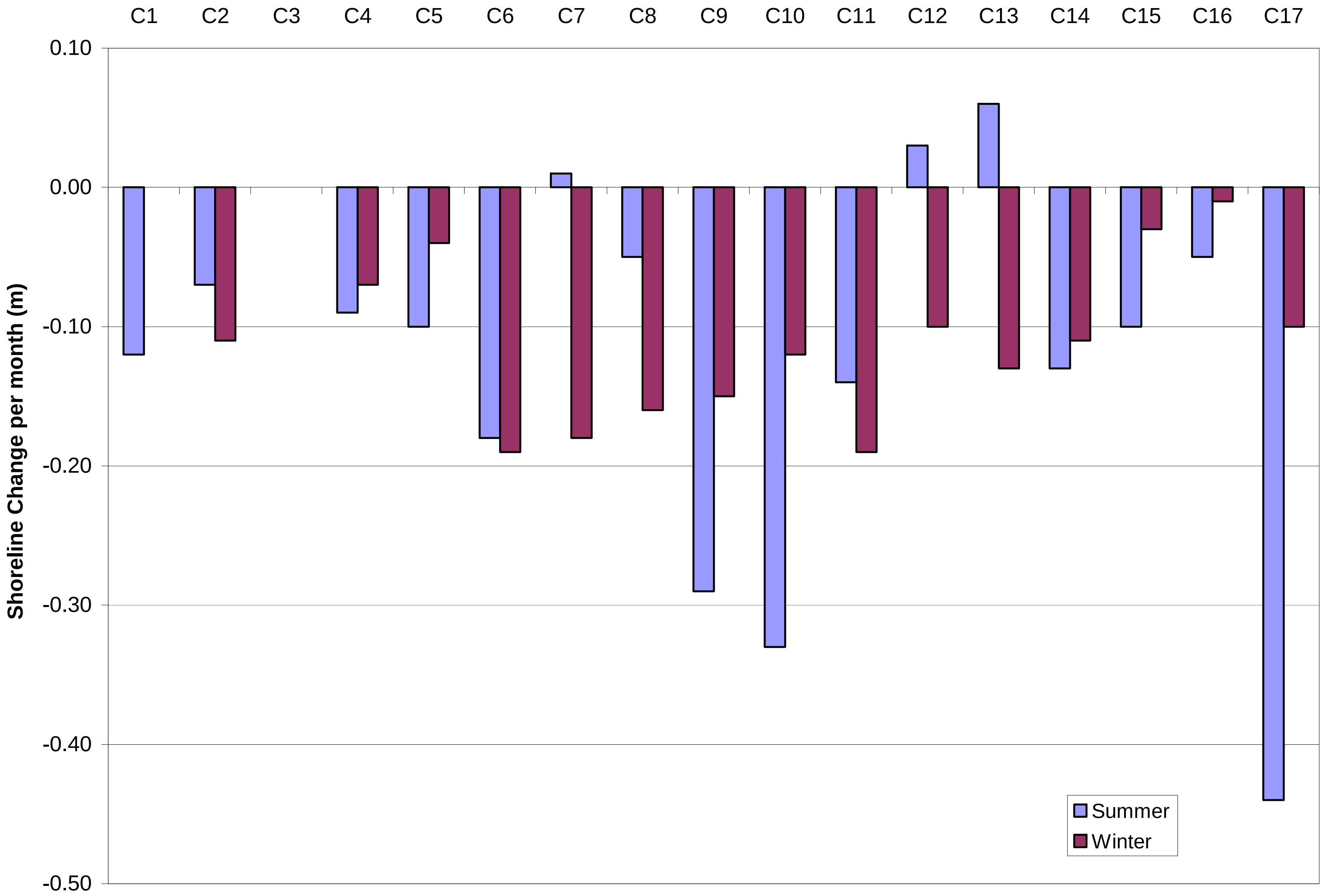

Figure 8: Seasonal shoreline change on the south flank of the island.

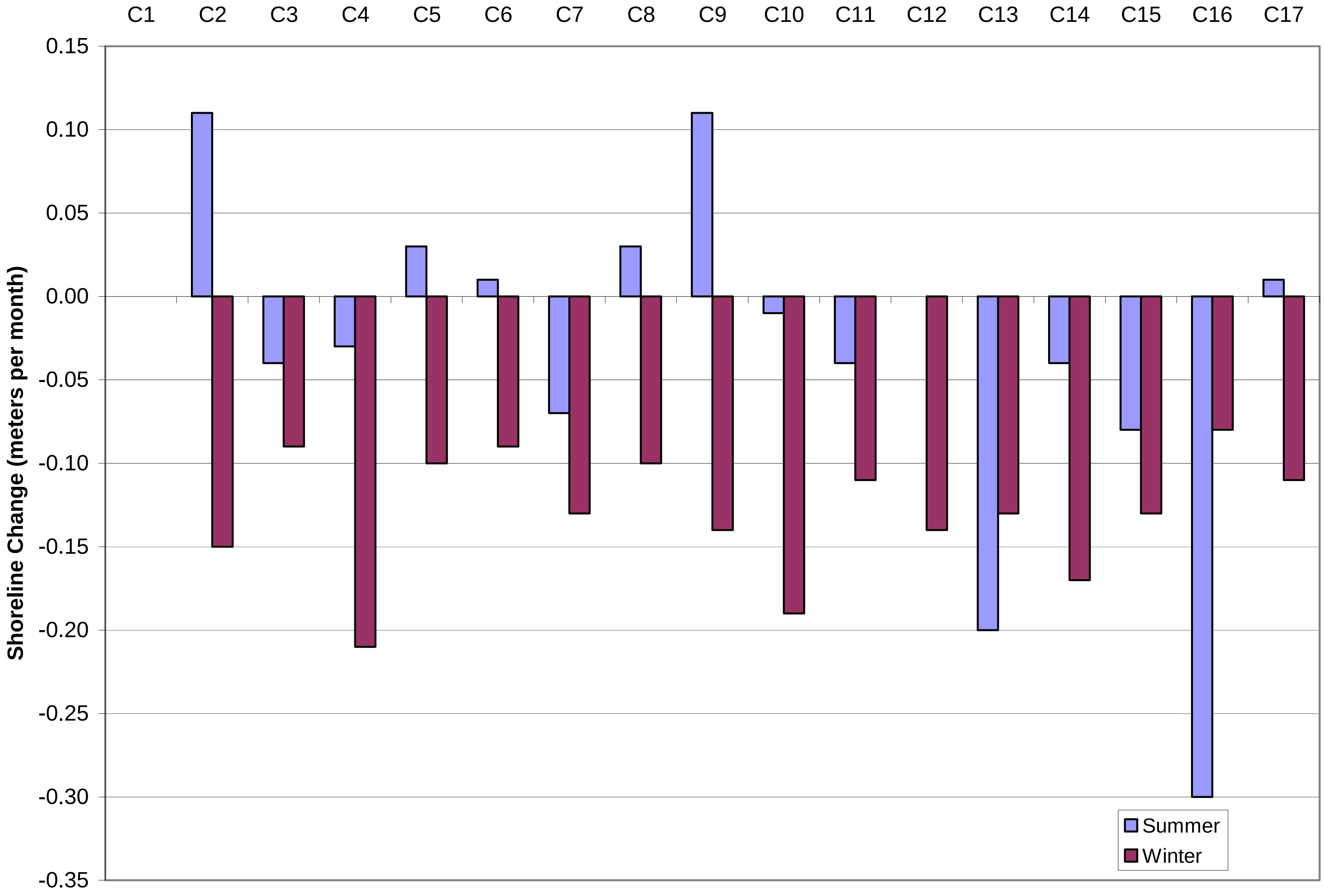

Figure 9: Seasonal shoreline change on the north flank of the island.

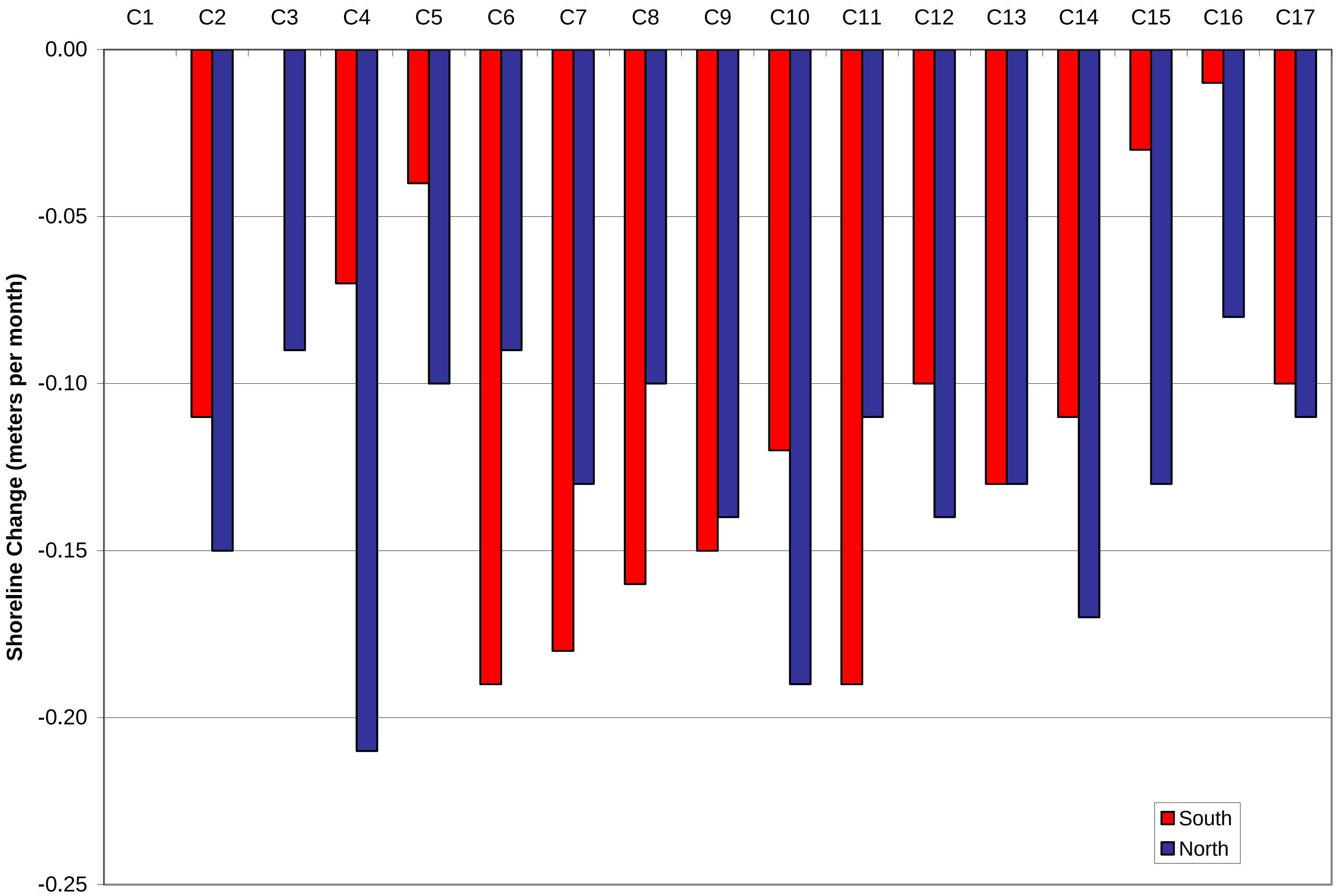

Figure 10: Winter change on the southern and northern shorelines

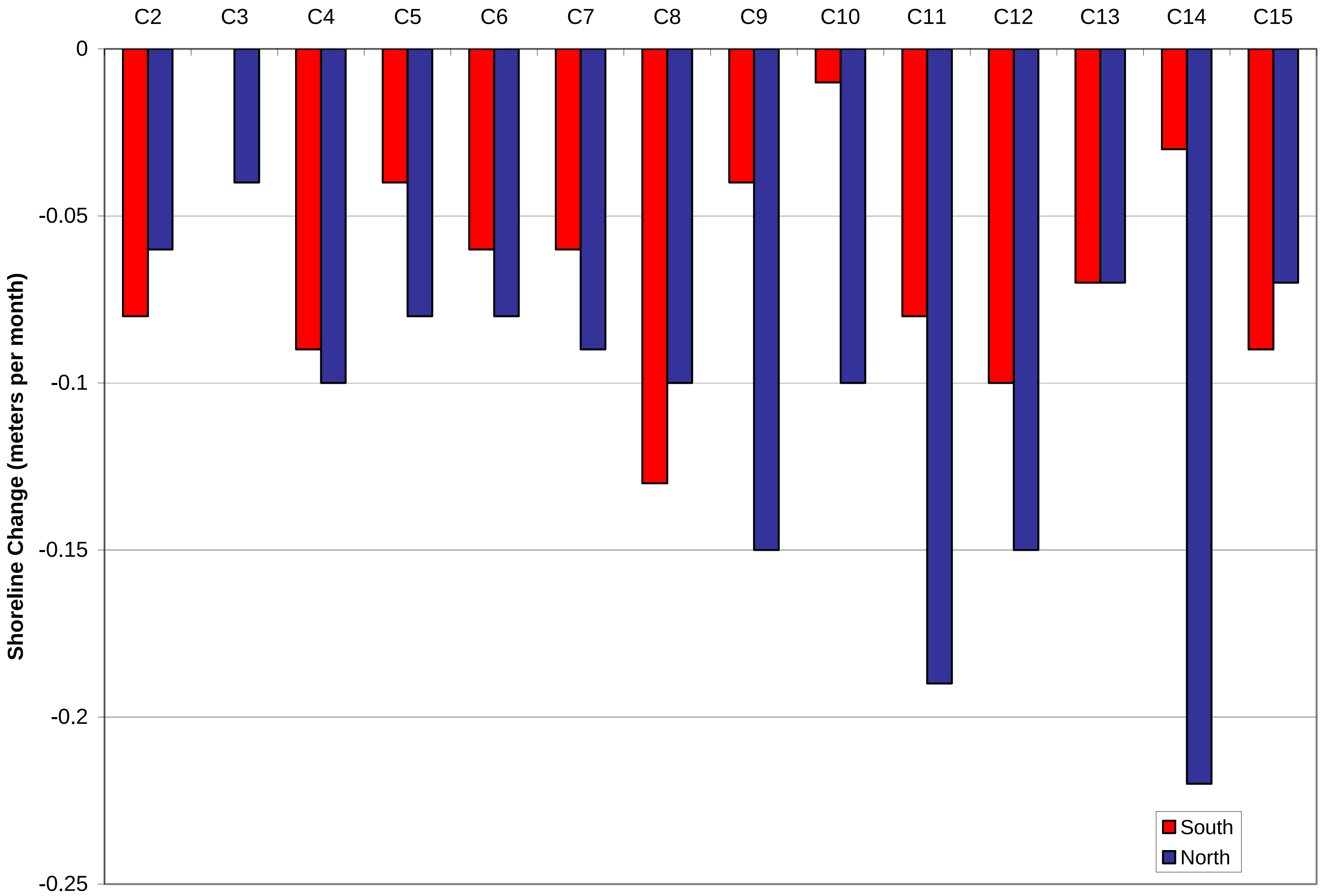

Figure 11: Tropical storm plus winter change on the southern and northern shoreline.

Table 3: Total shoreline change between April 8, 1999 and October 31, 2003

Total Change (m)		
Profiles	**Southern shoreline**	**Northern shoreline**
C1	-0.71	
C2	-4.98	-5.98
C3		-3.89
C4	-5.82	-8.70
C5	-3.37	-5.68
C6	-6.99	-5.73
C7	-6.44	-7.08
C8	-8.95	-7.59
C9	-6.05	-9.43
C10	-3.02	-9.39
C11	-8.55	-10.83
C12	-6.44	-9.67
C13	-5.67	-7.38
C14	-3.97	-13.34
C15	-4.97	-6.50
C16	-0.28	-4.31
C17	-4.20	-2.14
Average	**-5.03**	**-7.35**

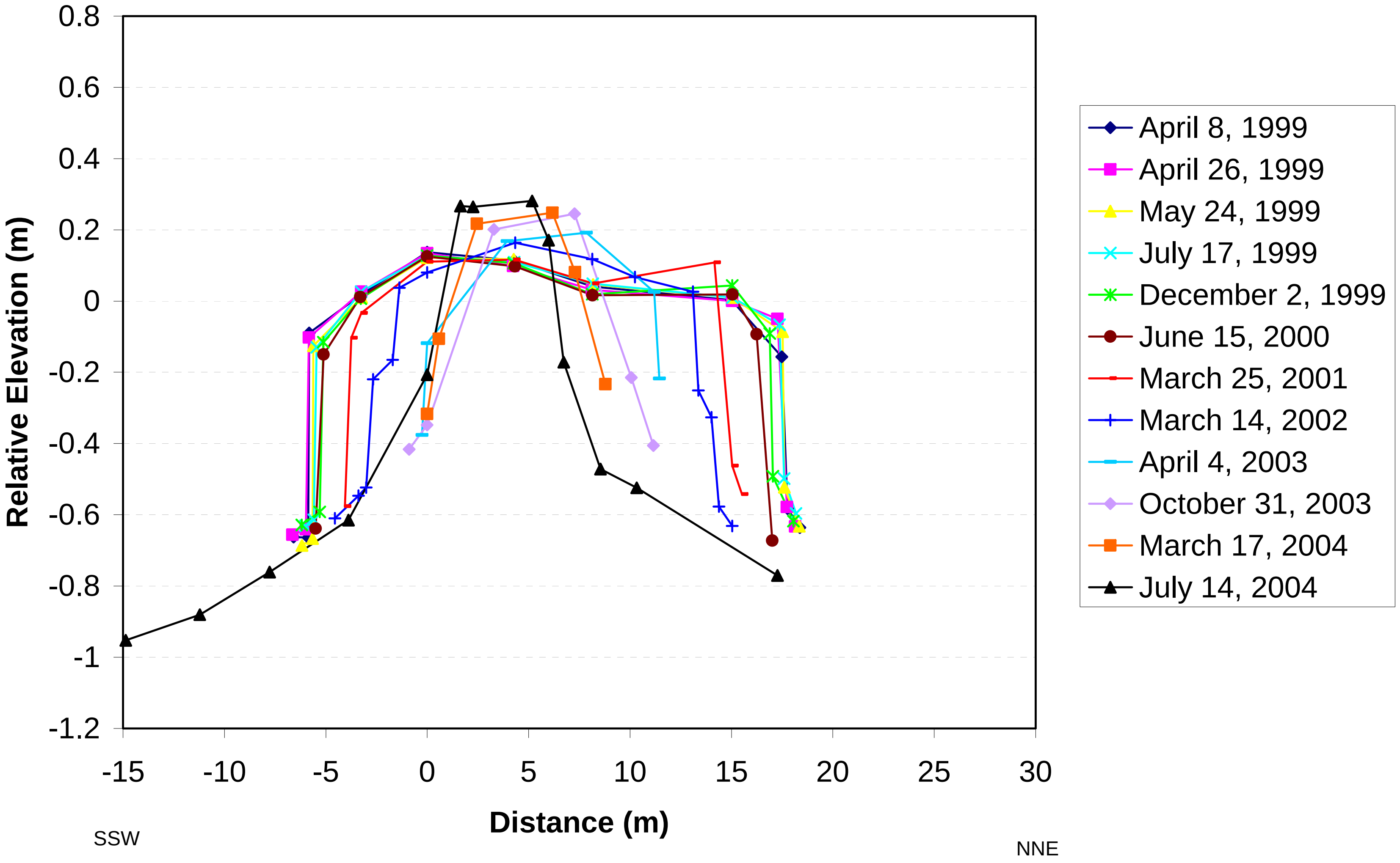

Figure 12: Profile C4 shows erosion of the marsh edge on both shorelines through time.

WAVCIS Data

Seventy four cold fronts passed over the study site between December 2, 1999 and March 25, 2001. The passage of a cold front is identified in the data by a 180 degree shift in wind direction, from southerly to northerly, and a drop in air temperature and barometric pressure. Figure 13 shows that when these parameters are presented together, their usefulness in delineating the front becomes apparent. As an example, during the prefrontal phase (Table 4), winds blew from the south at an average speed of 4.48 m/s and a maximum of 12.99 m/s producing average wave heights of 0.08-0.09 m on both the southern and northern coast with the maximum wave height ranging between 0.10-0.11 m. Wave periods ranged from 2.28-2.34 s with peak wave periods measuring 3.09 s on the south shore and 2.89 s on the north shore. Water level on the south shore was 0.45 m and 0.68 m on the north shore.

The postfrontal phase was characterized by winds from the north with an average speed of 5.26 m/s and a maximum of 14.14 m/s. Significant and maximum wave heights of 0.04 m, average wave periods of 2.64 s and water levels of 0.37 m occurred on the southern shoreline while on the northern shoreline significant wave heights measured 0.08 m and the maximum wave height was 0.10 m. Average wave period was 1.94 s, and water levels measured 0.61 m.

During the summer, average wind speed measured 4.48 m/s and blew from the south. Average significant wave heights were 0.07-0.08 m on both shores with maximum wave heights of 0.09-0.11 m. Wave periods of 2.69 s were measured on the south shore and 2.12 s on the north shore. Water level was 0.48 m on the south shore and 0.74 m on the north shore. Figures 14 and 15 are time series from June through August 1999 and the December 2000 through February 2001. Data plotted include wind direction and speed, air temperature, significant wave height and wave period.

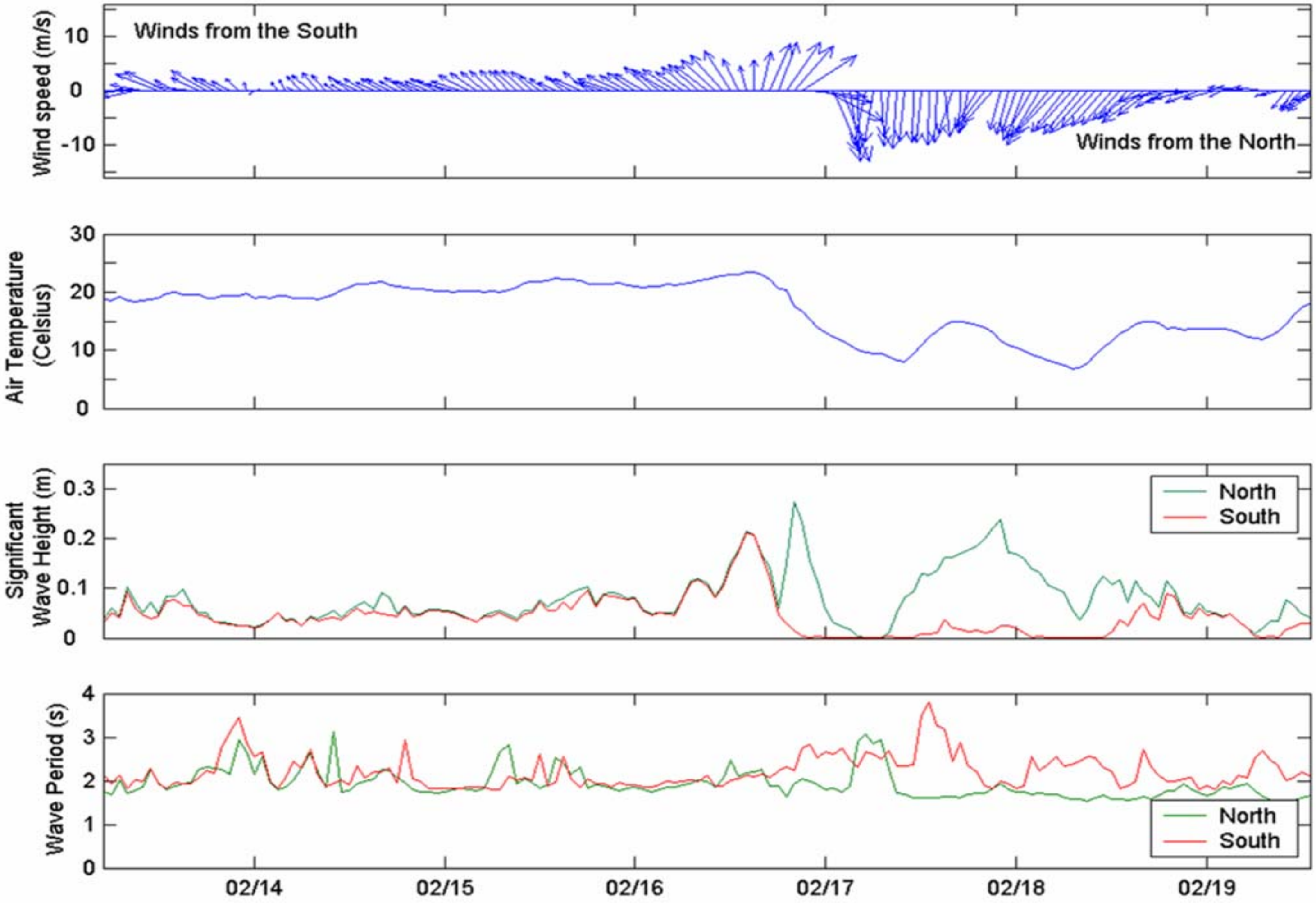

Figure 13: Time series wave and meteorological data during a cold front on February 13-19, 2001. Data recorded from the Marsh Edge stations includes wind speed (m/s), air temperature (^{o}C), significant wave height (m) and wave period (seconds).

Table 4: Summary of average wave conditions during the prefrontal and postfrontal phases and during the summer from Marsh Edge South and Marsh Edge North.

		Significant Wave Height (m)	Maximum Wave Height (m)	Wave Period (sec)	Peak Wave Period (sec)	Water Level (m)
South Shoreline	Prefrontal	0.08	0.10	2.34	3.09	0.45
	Postfrontal	0.04	0.04	2.64	3.98	0.37
	Summer	0.07	0.09	2.24	2.69	0.48
North Shoreline	Prefrontal	0.09	0.11	2.28	2.89	0.68
	Postfrontal	0.08	0.10	1.94	2.18	0.61
	Summer	0.08	0.11	2.12	2.3	0.74

Six statistical comparisons were made on the significant wave heights using a two tailed Student's T-test with an α equal to 0.05. On the southern shoreline comparisons of prefrontal and postfrontal were carried out, in addition to winter and summer comparisons. The same comparisons were made for the northern shoreline. Prefrontal significant wave heights were tested for significance along the northern versus southern shorelines. The test was repeated for the postfrontal significant wave heights. The T-test showed there was no significant difference in any of the comparisons made returning critical values close to zero for all tests.

WAVCIS station CSI-11, which is located in the southern region of Terrebonne Bay, recorded data similar to that at the study site (Table 5). Prefrontal significant wave heights were 0.17 m and had an average period of 2.55 s and a peak wave period of 3.13. Postfrontal wave heights measured 0.22 m with an average wave period of 2.32 s and a peak wave period of 2.70s. Water level did not change during the two cold front phases and remained at 3.46 m. Summer wave heights, at CSI 11, were equal to the postfrontal wave heights, but had a lower average wave period of 2.23 and peak wave period 2.46 s. Figure 16 shows the correlation between wind

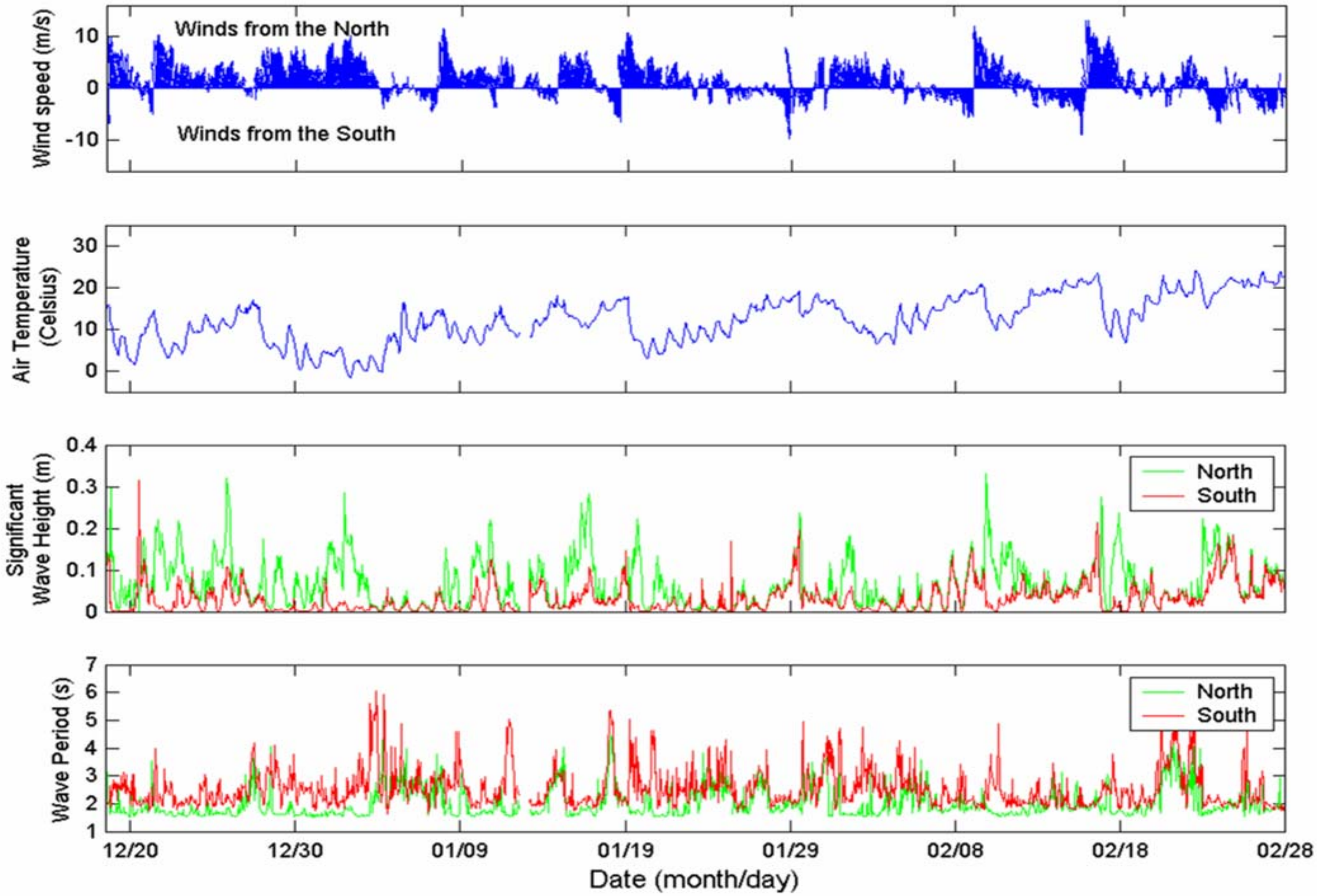

Figure 14: Times series from December 2001 to February 2002 showing wind speed (m/s), air temperature (^{o}C), significant wave height (m) and wave period (seconds) on the north and south shores.

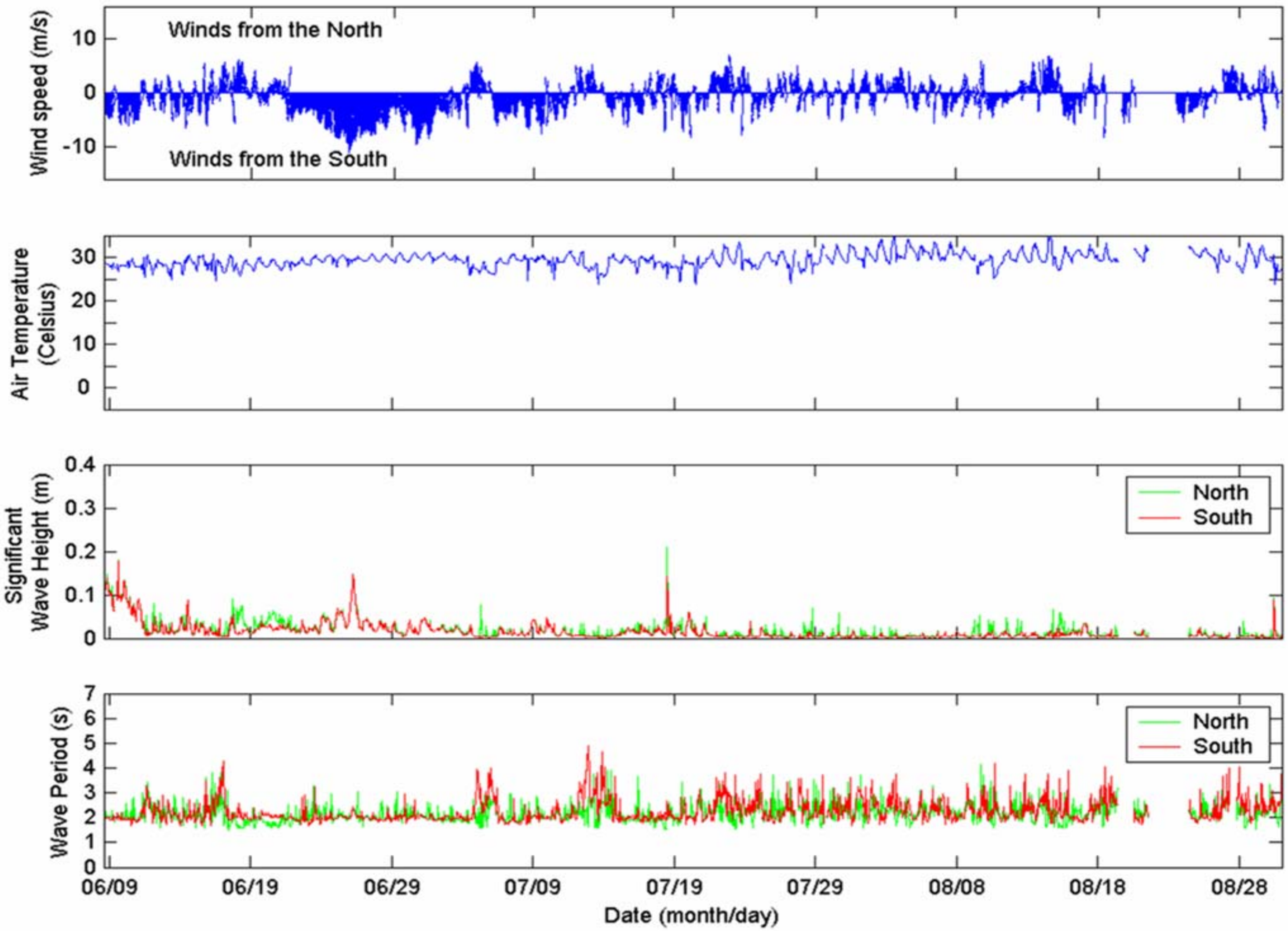

Figure 15: Time series data from June 1999 to August 1999, 2002 showing wind speed (m/s), air temperature (^{o}C), significant wave height (m) and wave period (seconds) on the north and south *shores*.

direction and wave direction at CSI-11 during the same cold front featured in Figure 12. Dominant wind direction is from the northwest with over 40 observations and speeds around 5 m/s. Wave direction is coherent with wind direction and the northwest is the dominant direction from which waves propagate.

Table 5: Summary of average wave conditions during the prefrontal and postfrontal phases and during the summer from CSI-11.

	Significant Wave Height (m)	Wave Period (sec)	Peak Wave Period (sec)	Water Level (m)
Postfrontal	0.22	2.32	2.70	3.46
Prefrontal	0.17	2.55	3.13	3.47
Summer	0.17	2.23	2.46	3.50

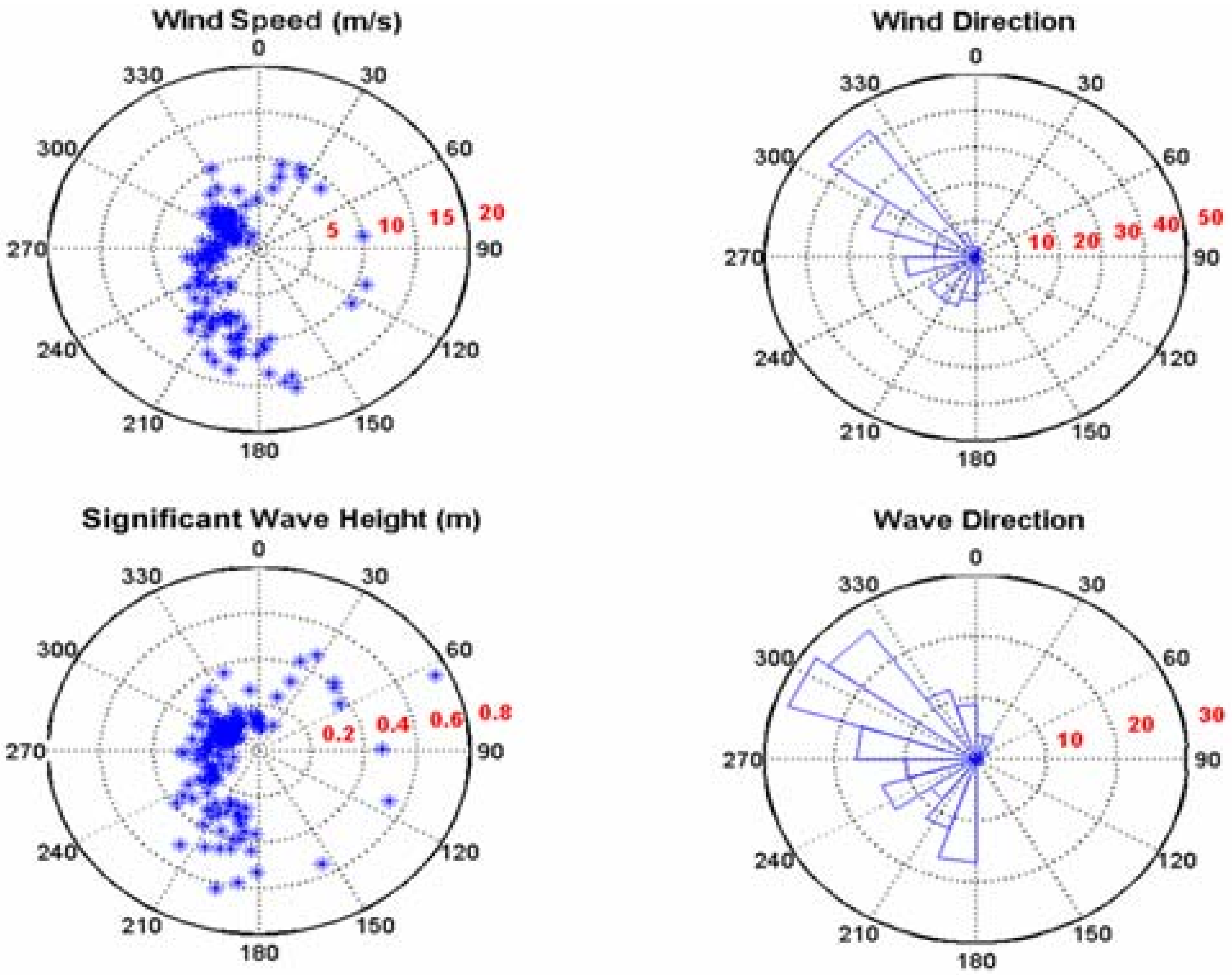

Figure 16: Wind speed (m/s) and wind direction (% occurrence from the north) with significant wave height (m) and wave direction (% occurrence from the north) for a cold front event on February 13-19, 2001, from CSI 11.

CHAPTER 4

DISCUSSION

As stated in the introduction, Louisiana's marsh is protected from Gulf of Mexico waves by barrier islands. Cold fronts, which occur on a weekly basis in the winter, and tropical storms produce locally generated waves in the bays. Elucidating how waves impact these low energy marsh shorelines is the objective of this study. A site-specific model is presented to help illustrate a sequence of events and mechanisms pertaining to the observed change.

On many sandy, well-sorted beaches, profiles gently slope from a flat berm to the low-water line in the foreshore and then levels off. During a storm or higher wave energy conditions, beaches often respond by losing sand from the foreshore, flattening the profile and deposition of that sand occurs offshore in longshore bars. Bars dissipate wave energy before it reaches the shore preventing further erosion. After the storm, beaches often recover as waves move sand stored in the bars back onshore, increasing the slope (SHEPARD and LAFOND, 1940; SHEPARD, 1950; BASCOM, 1953). On a marsh edge, a gently sloping profile is not observed and the profile is distinctly different than a sandy beach. A small drop-off of 60-80 cm into the bay typically occurs at the study site (Figure 17). There are two major differences between sandy beaches and the marsh shorelines, which cause the difference in profiles. Coarser grained, sandy beaches subject to higher wave energy most of the year, do not have vegetation growth extending to the water line. Fine grained, marsh shorelines are sheltered from high-energy waves and are only subject to erosional forces during the cold front season or severe storms. This wave regime allows thick vegetation to grow to the water line. Parameters such as grain size, vegetation and elevation are different and cause different responses when subject to higher wave energy.

Figure 17: Erosional scarp at the edge of the marsh, heights ranged from 60 cm to 80 cm measured from the bayfloor. Picture was taken on March 14, 2002

A model used for low energy sandy beaches is described by ARMBRUSTER (1997) based on work conducted on back barrier beaches in Florida. On the north side of Santa Rosa Island, as a cold front approaches, southerly winds characteristic of the prefrontal phase elevate water level allowing waves to erode the foreshore and deposit material on the nearshore platform. The beach profiles show four different responses seen in Figure 18; foreshore flattening or steepening, and parallel retreat or advance. As the frontal system passes and wind direction shifts from the north, water level dropped, however, wave heights increased. Waves broke along the nearshore platform and caused sediment redistribution along the nearshore.

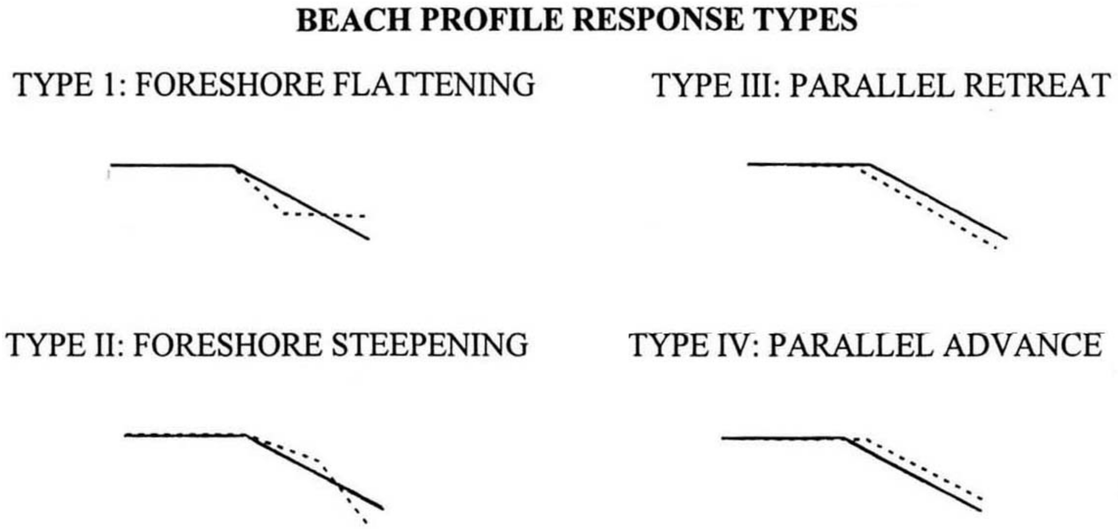

Figure 18: Beach profile response on low energy sandy beaches (ARMBRUSTER, 1997)

A marsh model was developed by SCHWIMMER (2001) to describe annual erosion of a Delaware marsh due to waves. Three different types of marsh response occurred; 1) cleft and neck formation; 2) neck cut off and 3) undercutting with root mat toppling. Cleft and neck formation occurs when a straight shoreline has areas more susceptible to erosion than others. These areas will erode faster creating a cleft. The neck is that potion between two clefts which extends bayward and is more resistant to erosion. After significant erosion occurs the shoreline evolves from a straight line to a series of crenulations. When the base of a neck erodes faster than its tip, the neck will eventually become separated from the base creating a marsh stack. This process is referred to as neck cutoff. The third process observed by Schwimmer is undercutting and marsh toppling. As waves break upon the scarp, the underlying clay is eroded faster than the overlying plant and root material. The plant layer is no longer supported by the clay and hangs over the bay, only to be supported by the root system. Eventually, a threshold is reached where the overhang becomes larger than the root system can support resulting in failure (SCHWIMMER, 2001).

These three types of erosion were observed at the Terrebonne Bay study site. Both the north and south shores were crenulate as seen in Figure 19A, and a marshstack was also evident (Figure 19B). However, the Terrebonne Bay study site is a marsh island, and erosion is occurring on both sides decreasing its width. Eventually, as more material is removed, clefts forming on both shores will converge, the island breaches and becomes more fragmented as seen in Figure 19A.

Differences in plant root structure, sediment properties, or presence of oyster shells on the marsh surface may attribute to erodability of the marsh edge and form the crenulations observed along marsh islands. Although sediment properties were not measured, the sediments along the marsh edge appeared to be homogeneous. Plant species and amount of coverage varied along the length of the island. The northern shore had an abundance of oysters seen at C4 and C8. Along the southern shore, vegetation cover varied from sparse on profiles C2 and C8-C10 to abundant on the remaining profiles. Oysters were observed at all the profiles except for C2, C5 and C8. Oyster shells are thought to armor the shoreline and impede further erosion. Studies in Terrebonne Bay and in North Carolina suggest that the placement of oyster shells along fringing marsh helps to stabilize the shoreline by absorbing wave energy from wind generated waves and boat wakes (MEYER *et al.*, 1997; PIAZZA *et al.*, unpublished data).

The marsh edge at the study site eroded at an average rate of 2.5 m per year. The average winter erosion per year (0.77 m) is twice as much as erosion during the summer (0.31 m). The difference in erosion rates can be explained by the seasonal change in weather patterns

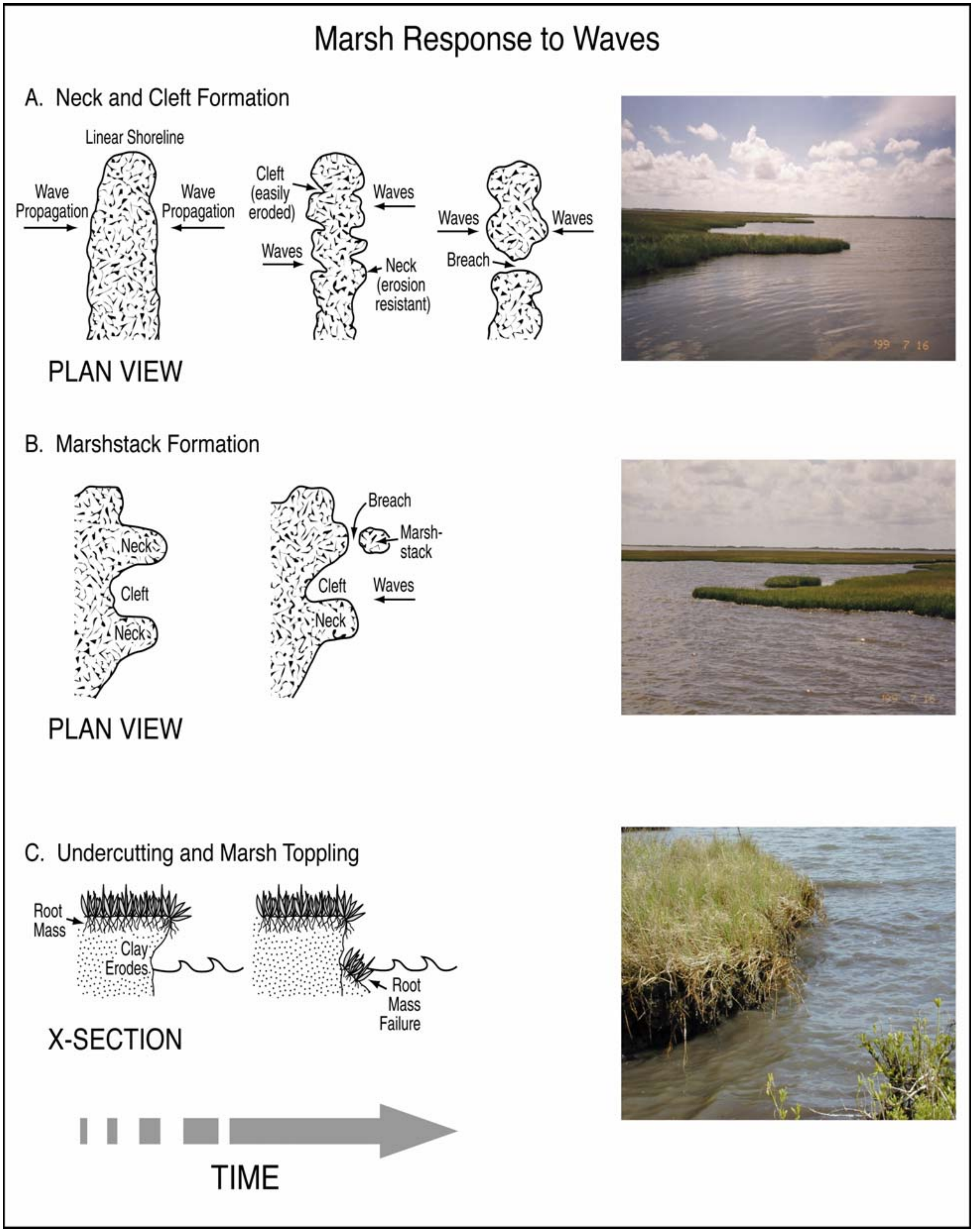

Figure 19: Three types of marsh response to waves. A: Neck and Cleft formation, B: Marshstack formation and C: Undercutting and marsh toppling. Modified from SCHWIMMER, 2001.

and is illustrated in Figure 20. During the summer months as waves created by prevailing southerly winds propagate though the tidal inlets and into the coastal bays, the southern shore of the marsh edge islands will experience higher erosion than the northern shoreline. During the winter months, cold fronts occur on a weekly basis bringing strong winds with the ability to produce high-energy waves. As the cold front approaches the coast, the southeasterly winds push water landward and into the coastal bays where it is trapped against the coastline causing water levels to rise e.g. 0.08 m. Water level setup is accompanied by an increase in wave heights on both sides of the island.

After the front passes over the island, the wind direction changes to the north/northwest causing waves to propagate from the north. The wind pushes water in the bay south towards the Gulf, causing water level setdown around the island. As the wind changes direction so to does the direction of wave propagation. Previously, waves propagated north because of the southerly winds but during the postfrontal phase waves travel southward and impact the north shore of the island. The island protects the south shore from postfrontal waves leading to wave-damping along the south shoreline. The fetch on the northern end of the island is much smaller than the southern end but the stronger postfrontal winds and steeper offshore bathymetry leads to less wave dissipation and allows waves with increased wave heights to impact the north shore. These postfrontal waves continue to erode the north shore until frontal winds subside a few days later.

During the three years when tropical storms passed near the area, 70% more erosion occurred. The average erosion rate per year was 2.45 m, one meter greater than the average winter erosion when there were no tropical storms. Although this area has experienced four tropical storms in the last three years, the average rate of occurrence is at least one tropical storm every other year (STONE *et al*, 1997), leading to higher than normal tropical storm erosion estimates. The average erosion per tropical storm is equal to one year of cold front associated erosion. During an average ten year period with 1.09 cm of relative sea level rise per year (RAMSEY and PENLAND, 1989), 15 m of land could be eroded from the marsh edge because of a combination of tropical storms and cold fronts with approximately 50% of the marsh eroded due to the effects of cold fronts only. The amount of marsh loss over ten years due to subsidence, 10.9 cm, is small compared to land loss from wave erosion over annual to decadal time scales.

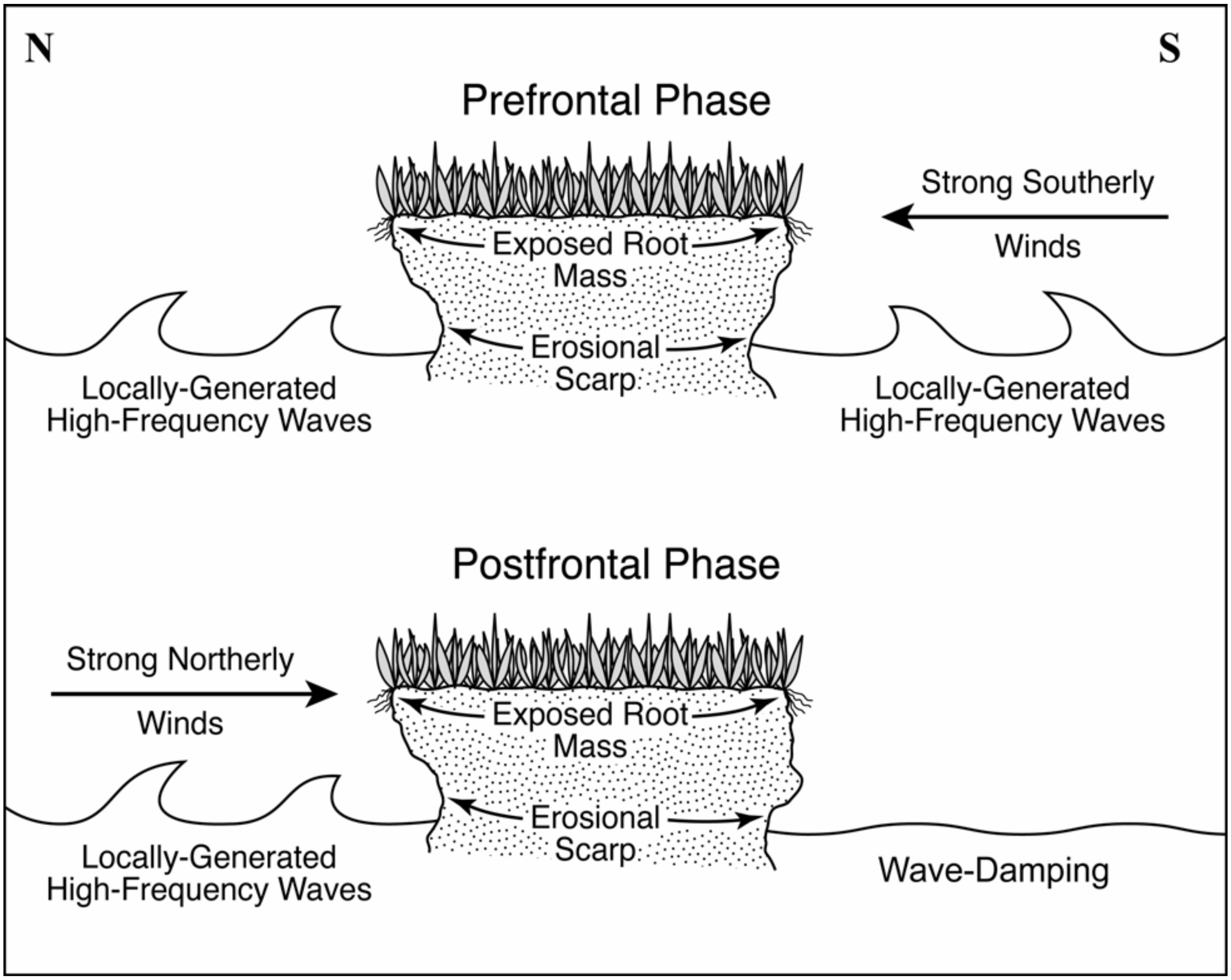

Figure 20: Schematic representation of a marsh island and active processes during the pre and post frontal phases of a cold front.

CHAPTER 5

CONCLUSIONS

The results from this study have led to a number of conclusions allowing a more concise understanding of marsh response to waves. The primary conclusions from this study are:

- Low energy fringing marshes surrounding coastal bays are susceptible to erosion from locally generated, high frequency waves developed from strong winds (12.99 – 14.14 m/s maximum wind speed) associated with cold fronts over short time scales (years).

- Eighty to ninety percent of the erosion takes place during winter months when cold fronts occur on a weekly basis causing along island narrowing due to a combined total of 2.5 m/yr of erosion from both sides.

- Contrary to preconceived notions, the south shore is affected by cold fronts and is undergoing significant geomorphological change similar to the north shore, resulting in erosion of both shores with the north shore having higher erosion rates.

- The marsh edge does not erode at a consistent rate, neck and cleft formation, marshstack formation, and undercutting and marsh toppling create the crenulations observed along the shorelines. However, the study site erodes on both sides and eventually will be breached as waves reduce the island width.

- Cold fronts are an equally important process of shoreline change when compared to tropical storms. The survey profiles show that a winter of cold fronts causes just as much erosion on both shorelines as a single tropical storm.

Currently Louisiana’s coastal bays are only exposed to higher energy waves during the winter season or a severe storm, but as wave energy increases in the bays due to the deterioration of the barrier islands and shift from a low to high energy environment, the fringing marsh will erode more rapidly. By understanding the processes affecting the present marsh, managers will be better prepared to protect marshes in the future. It is apparent that cold fronts play a large role in geomorphological change of the coast, requiring the need for continued studies on these storms, whether the environment is a sandy barrier island, the Louisiana Chenier plain, or a fringing marsh.

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APPENDIX

TOPOGRAPHIC / BATHYMETRIC PROFILES AND INTERPRETATION

Profile C1 is located on the southern shore of the island and is the furthest west of all the profiles. Originally, the profile extended 7.35 m onto the shore. Throughout the surveys taken in the summer 1999, profile C1 eroded a total of 0.47 m. No profiles could be taken after 1999 due to a loss of the stakes marking the profile.

East of profile C1 is profile C2 which spans the entire width of the island. The first survey measured the distance from the north to the south shore as being 28.26 m. Throughout the summer surveys, 0.30 m eroded from the southern coast while 0.46 m eroded on the northern coast. During the winter surveys, 2.08 m of erosion was measured on the southern shoreline and 2.87 m of erosion on the northern shoreline. For the three surveys which include tropical storm and cold front change, 3.53 m was eroded along the south shore and 2.44 m was eroded along the north shore. Total net change of the south shore was -4.98 m and 5.98 m eroded from the north shore. Presently, the island at profile C2 measures 14.17 m, 50% of its original length.

Profile C3 encompasses only the north shore of the island. The length of the profile began at 10.04 m. Summer change was -0.17 m and winter change was -1.62 m. Cold front and tropical storm change was -1.73 m. Total net change for the profile was -3.89 m. The last survey was taken in March 2003 due to missing profile markers, at that time the profile length measured 6.29 m.

Profile C4 spans the entire width of the island. The beginning length in 1999 measured 24.97 and was 8.78 m at the end of the study. A total of 5.82 m eroded from the south shore while 8.70 m eroded from the north shore or 65% of the original profile length. The summer surveys of 1999 reported 0.38 m of erosion on the south shore and 0.11 m of erosion on the north shore. The winter surveys resulted in 1.38 m eroded from the southern coast and 4.01 m from the northern coast. In the three years of combined tropical storm and cold front change, 3.74 m eroded from the south shore and 4.10 m eroded on the north shore.

At the start of the study the island at C5 was 24.84 m wide and at the end it was 14.78 m. A total of 3.37 m were eroded from the south shore and 5.68 m from the north shore. Summer change shows -0.39 m on the south shore and 0.11 m on the north shore. Winter change measures -0.80 m on the south shore and -1.83 m on the north shore. Combined tropical storm and cold front change was -1.93 m on the south and -3.35 m on the north shore.

Profile C6 is located just to the right of the WAVCIS stations. It measured 33.13 m in length at the beginning of the study. A total of 6.99 m were eroded from the south shore while 5.73 m eroded from the north shore. During the summer surveys, 0.73 m were eroded from the south shore and 0.02 m accreted from the north shore. The winter surveys show 3.63 m of erosion on the south shore and 1.78 m on the north shore. The combined tropical storm and cold front data show 2.53 m eroded from the south shore and 3.64 m from the north shore. At the end of the study, the profile measured 20.41 m.

Profile C7 was 34.09 m long at the beginning of the study and at the end was 19.51 m long. Total net change on the southern coast was -6.44 m and 7.08 m total eroded from the northern coast. The summer surveys show 0.05 m of change on the south shore and -0.26 m on the north shore. The winter change was -3.50 m on the south shore and -2.52 m on the north shore. Tropical storm and cold front combined change was -2.75 m on the south shore and -3.85 m on the north shore.

Profile C8 was 32.09 m in length when the study began and at the end measured 54% of its original length at 17.23 m. Total net change on the southern shore measured -8.95 m and -7.59 m on the north shore. Summer change was -0.19 m on the south shore and 0.12 m on the north shore. Winter change was -3.01 m on the south shore and -1.92 m on the north shore. Change from tropical storms and cold fronts were -5.72 m on the south shore and -4.39 m on the north shore.

The island at profile C9 was 20.45 m wide at the beginning of the survey and measured 7.14 m at the end of the study. Only 35% of the original profile remains. Total net change was -6.05 m on the south shore and -9.43 m on the north shore. Summer change accounts for -1.14 m on the south shore and 0.42 m on the north shore. Winter change was -2.88 m on the south shore and -2.63 m on the north shore. Change from tropical storms and cold fronts was -1.57 m on the south shore and -6.53 m on the north shore

At the beginning of the study, profile C10 was 19.71 m long. Summer change was measured to be -1.34 m on the southern coast and -0.05 m on the northern coast. Winter change on the southern coast measured -2.21 m and -3.70 m on the northern coast. Combined tropical storm and cold front change was -0.42 m on the southern coast and -4.43 m on the northern coast. Total change for the southern coast equaled -3.02 m and for the northern coast -9.39 m. The length of the profile at the end of the study was 7.84, a decrease in length of 60%.

Profile C11 is located in the middle of the island, is the longest profile and has the highest rate of change. The profile length began at 34.51 m, 77% of it eroded leaving a length of 7.87 m. Total net change on the south shore measured -8.55 m while 10.83 m were eroded from the north shore. Summer change was measured as -0.56 m on the south shore and -0.17 m on the north shore. Winter change was -3.70 m on the south shore and -2.09 m on the north shore. Change due to tropical storms and cold fronts were -0.42 m of change on the south shore and -4.43 m on the north shore.

Profile C12 experienced 40% of change. The profile began at 33.36 m in length and ended at 19.97 m. Total net change from the south was -6.44 m while 9.67 m was eroded from the north. Summer change was 0.12 m on the south shore and on the north shore there was no change. Winter change measured -1.91 m on the south shore and -2.68 m on the north shore. Tropical storm and cold front change was -4.37 m on the south shore and -6.66 m on the north shore.

Profile C13 was 26.09 m at the beginning of the study, after the five year study, 50% of the profile eroded away and the length was 12.83 m as of the last survey. Total net change along the southern shoreline equaled -5.67 m and -7.38 m from the north. Summer change was 0.26 m on the southern shoreline and 0.80 m on the northern shoreline. Winter change was about equal for both coasts, -2.42 m on the south and -2.52 m on the north. Tropical storm and cold front change was also equal, -3.00 m on the southern coast and -3.05 m on the northern coast.

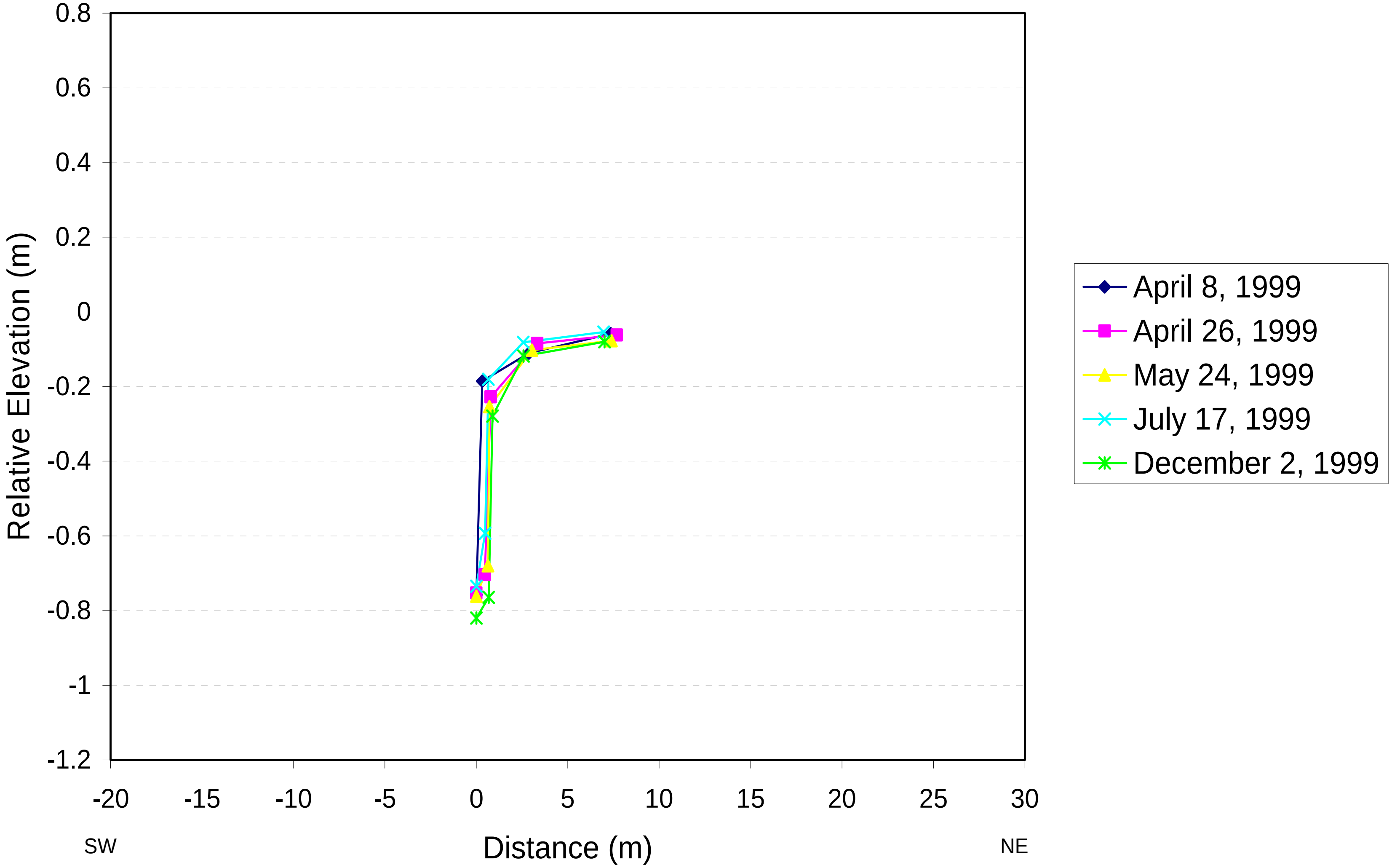
Profile C14, at the beginning of the study, was 26.91 m in length. A total of 3.97 m eroded from the south shore compared with 13.34 m eroded from the north shore. Of that total only 0.52 m eroded from the south shore during the summer and 0.16 m from the north shore. During the winter, -2.12 m of change was measured on the south shore and 3.32 m eroded from the north shore. Most of the change is from the combined effect of tropical storms and cold fronts. On the south shore 1.38 m eroded while 9.46 m eroded from the north shore. The profile is presently 9.07 m long with only 34% of the original profile length left.

Profile C15 was 19.28 m long at the beginning of the study. By the end, 50% had eroded and at the last survey it was 10.11 m long. Total net change of the south shore was -4.97 m with 0.39 m eroded during the summer, 0.65 m eroded during the winter and 3.73 m eroded from a combination of tropical storms and cold fronts. Total net change on the north shore was -6.50 m with 0.32 m eroded during the summer, 2.40 m eroded during the winter and 3.01 m eroded by tropical storms and cold fronts.

The island at profile C16 was 16.74 m wide at the start of the study. The last survey of this profile was taken on March 25, 2001, after that the pipes marking the profile could not be found. At that time the profile measured 10.72 and 64% had been eroded. Total change on the south side was -0.28 m and -4.31 m on the north shore. Summer change measured -1.78 m on the south side and 0.03 m on the north. During the winter surveys, 0.11 m eroded from the south and 1.49 m eroded from the north. The profile pipes were lost before the combined tropical storm and cold front surveys took place.

The last profile on the island was C17. Like profile C16, the last survey was taken on March 25, 2001. The profile was the shortest in length at 9.61 m. At the last survey the profile was 4.33 m, a decrease of 45%. The total change on the south side was -4.20 m and -2.14 m on the north side. Summer change was -1.78 m on the south side and 0.03 m on the north side. Winter change was -1.83 m on the south side and -2.00 m on the north. Tropical storm and cold front erosion could not be determined.

Profile C1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-0.4
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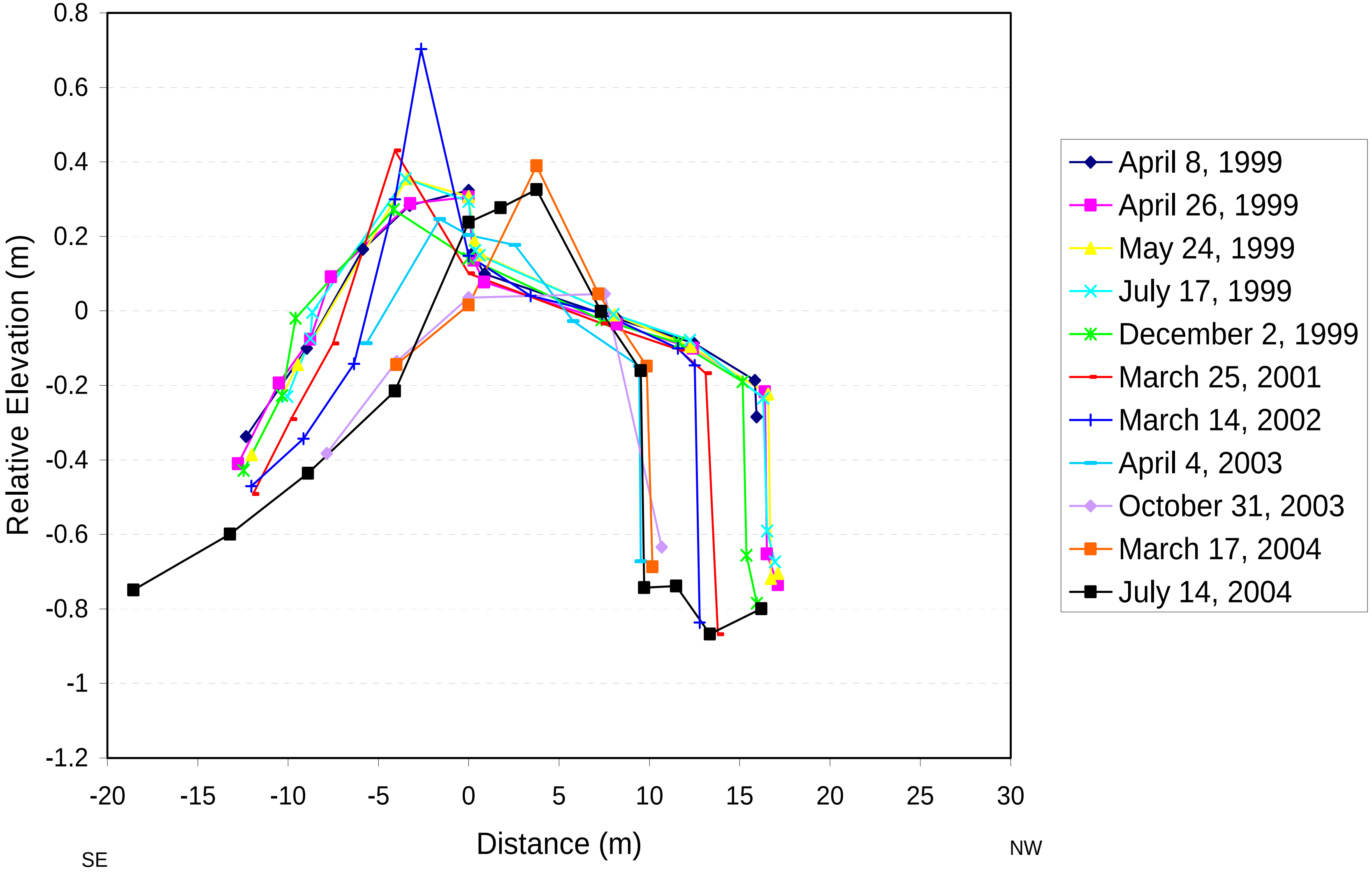
-0.8
-1
-1.2
Relative Elevation (m)
-20
-15
-10
-5
0
5
10
15
20
25
30
SW
Distance (m)
NE
April 8, 1999
April 26, 1999
May 24, 1999
July 17, 1999
December 2, 1999

Profile C2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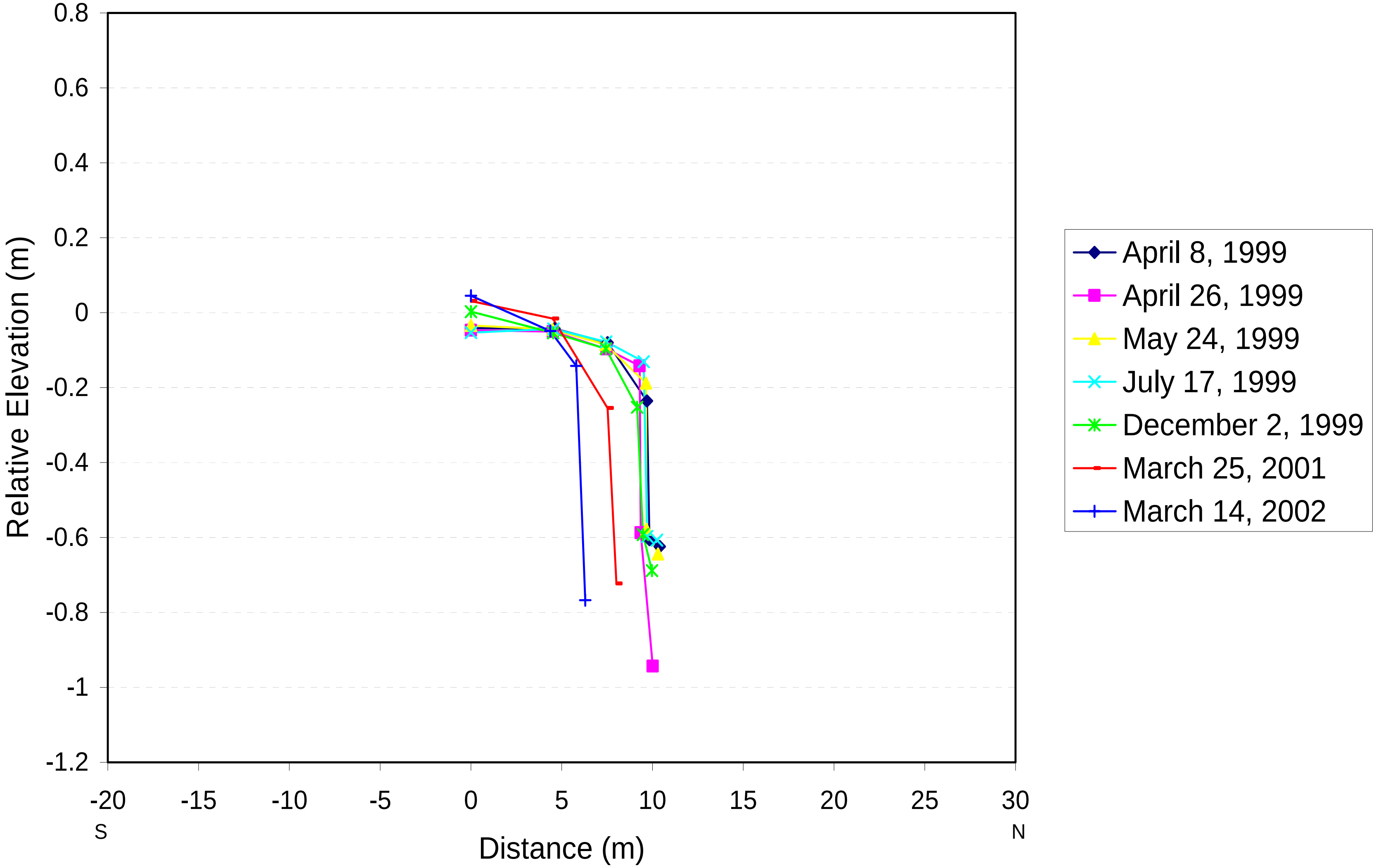
-1.2
-20
-15
-10
-5
0
5
10
15
20
25
30
Distance (m)
SE
NW
April 8, 1999
April 26, 1999
May 24, 1999
July 17, 1999
December 2, 1999
March 25, 2001
March 14, 2002
April 4, 2003
October 31, 2003
March 17, 2004
July 14, 2004

Profile C3



Relative Elevation (m)
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-0.4
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-1
-1.2
-20
S
-15
-10
-5
0
5
10
15
20
25
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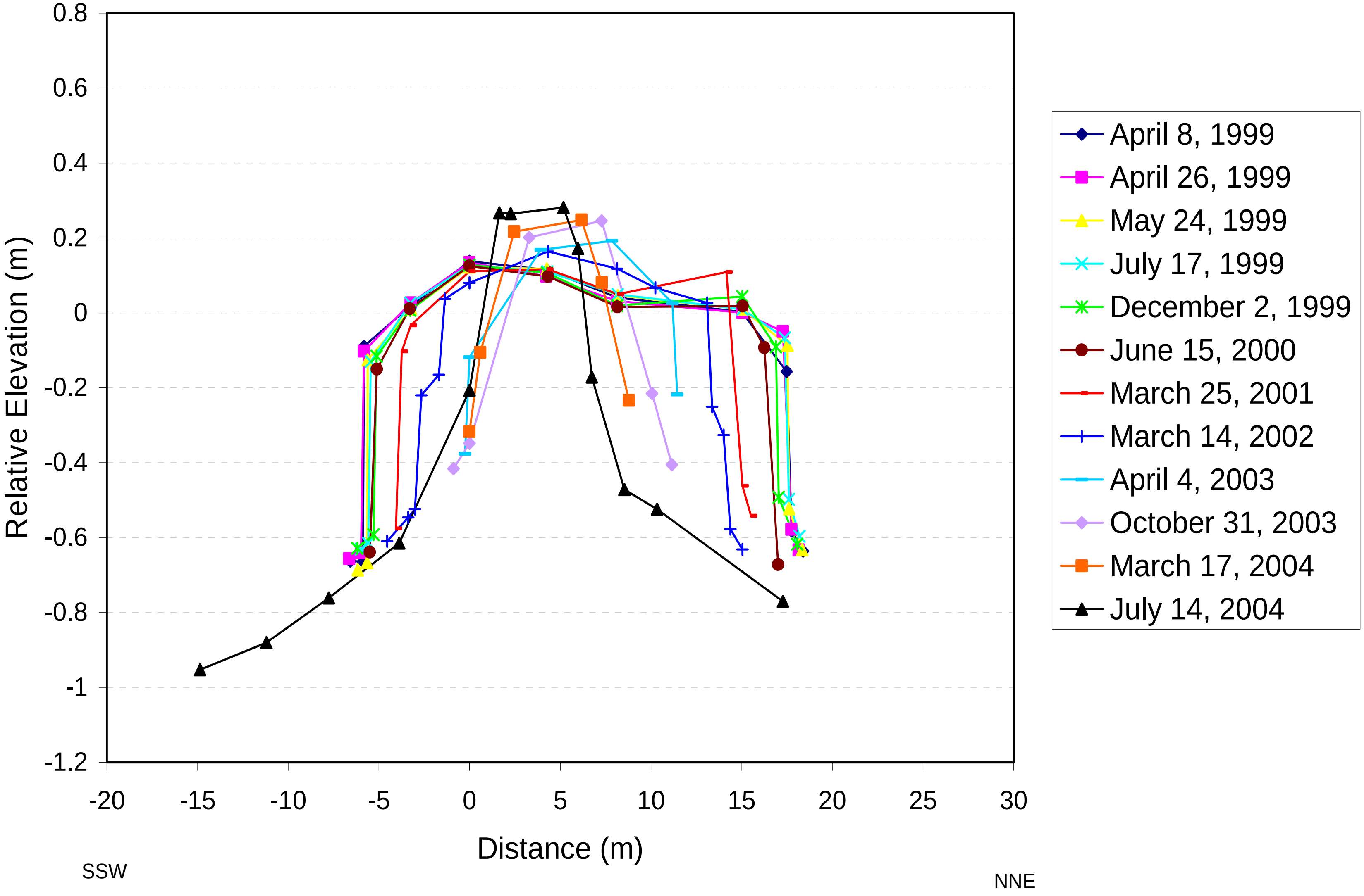
N
Distance (m)
April 8, 1999
April 26, 1999
May 24, 1999
July 17, 1999
December 2, 1999
March 25, 2001
March 14, 2002

Profile C4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-1.2
Relative Elevation (m)
-20
-15
-10
-5
0
5
10
15
20
25
30
Distance (m)
SSW
NNE
April 8, 1999
April 26, 1999
May 24, 1999
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March 25, 2001
March 14, 2002
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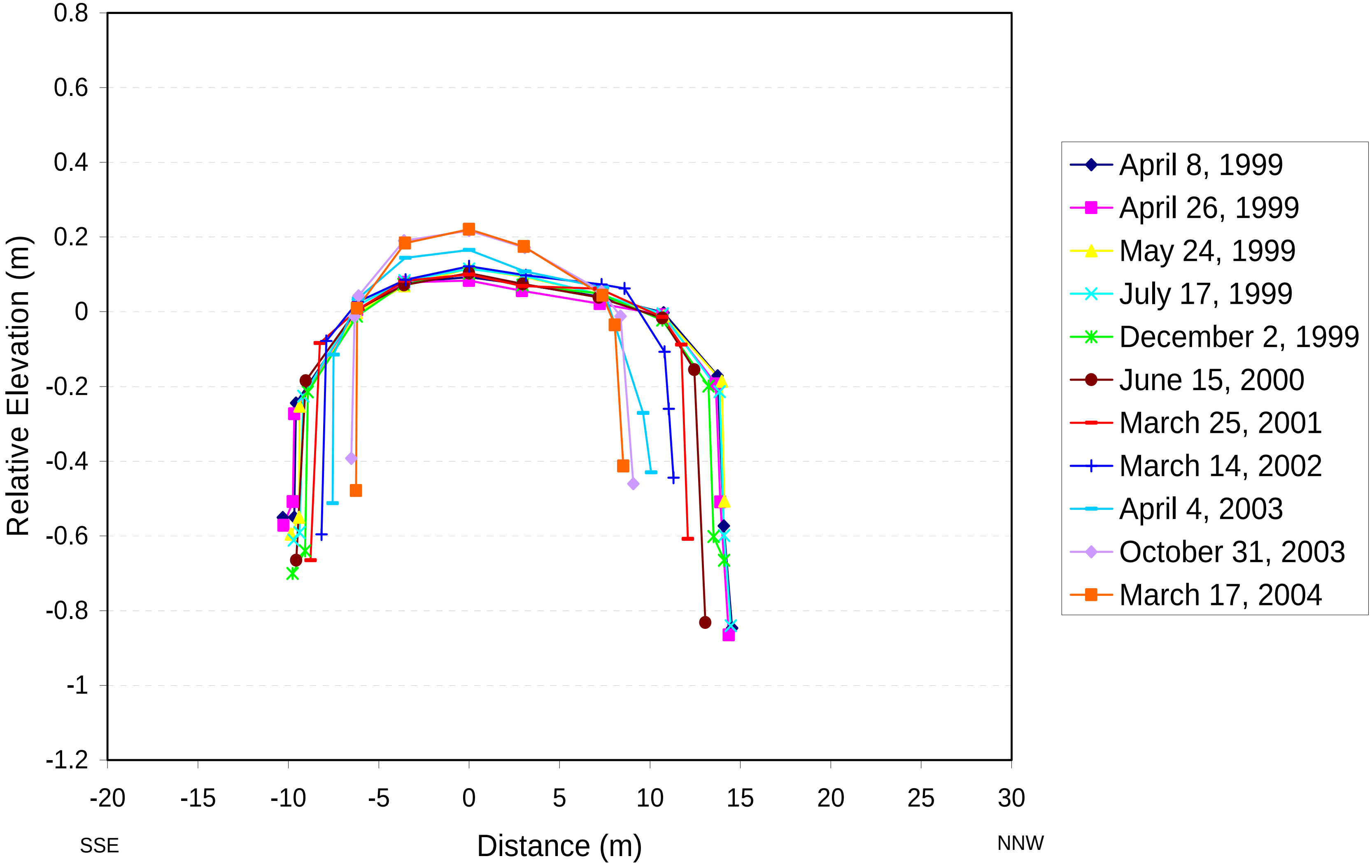
March 17, 2004
July 14, 2004

Profile C5



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-20
-15
-10
-5
0
5
10
15
20
25
30
SSE
Distance (m)
NNW
April 8, 1999
April 26, 1999
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June 15, 2000
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April 4, 2003
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March 17, 2004

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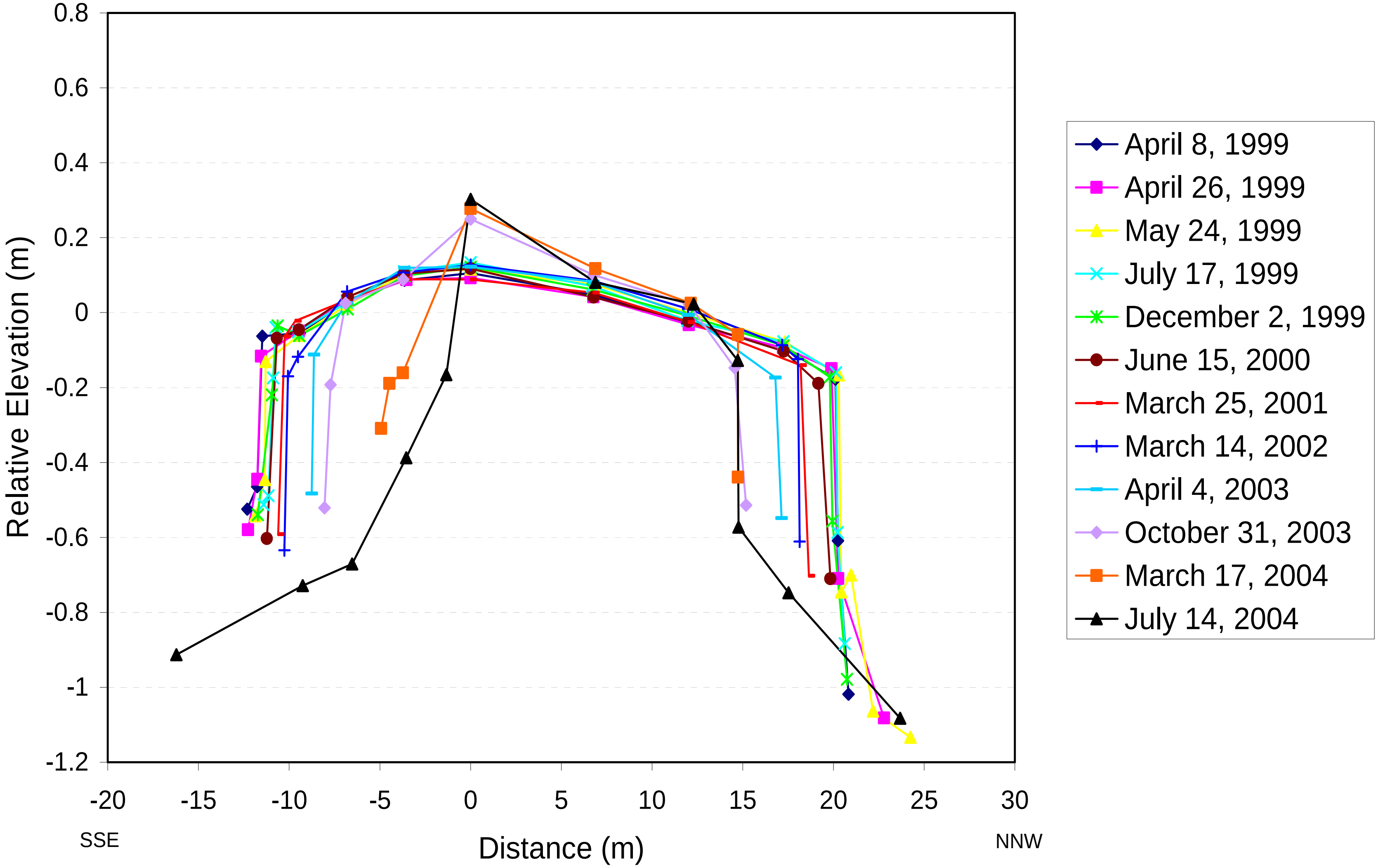

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-1.2
-20
-15
-10
-5
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5
10
15
20
25
30
SSE
Distance (m)
NNW
April 8, 1999
April 26, 1999
May 24, 1999
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June 15, 2000
March 25, 2001
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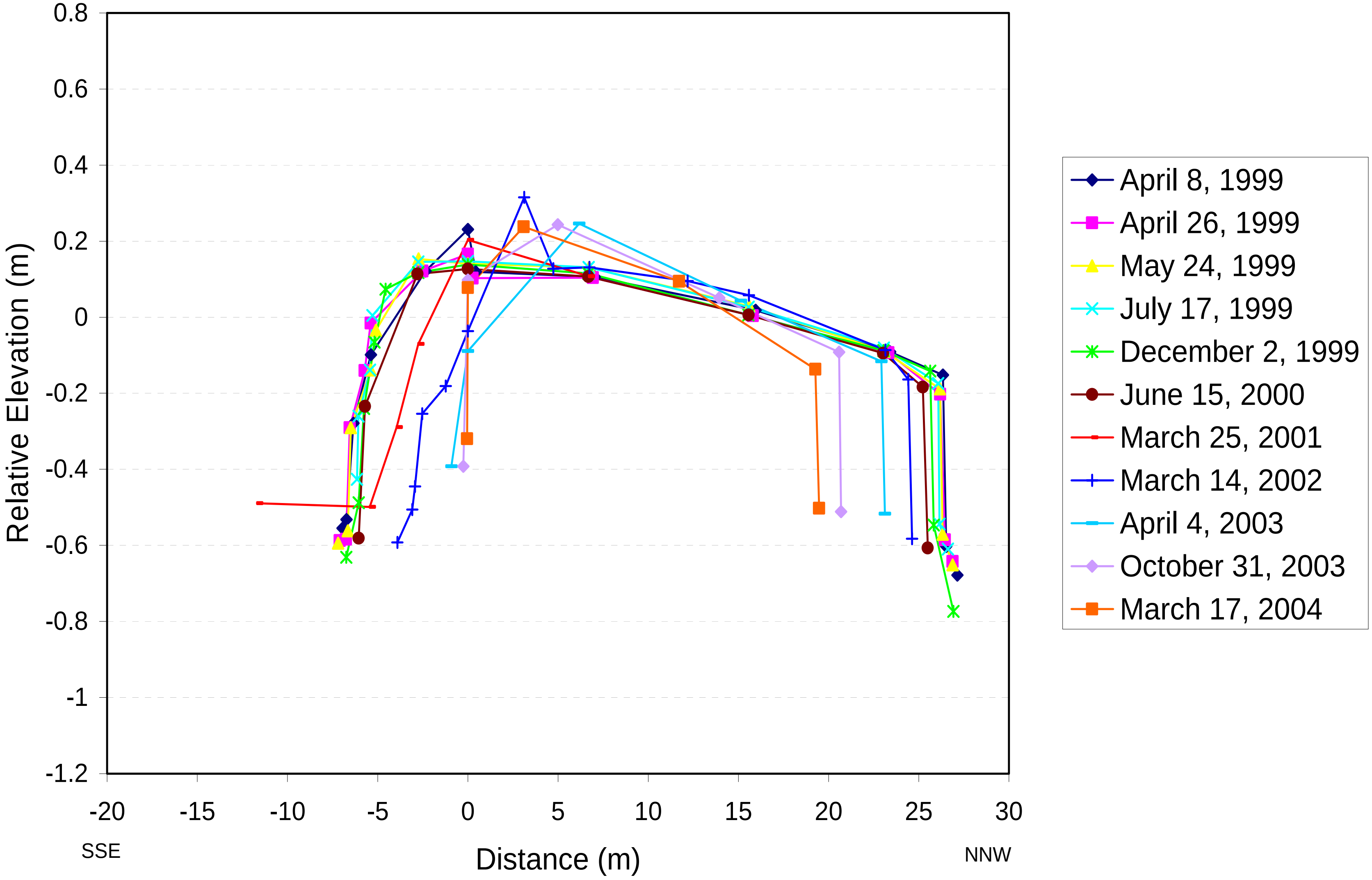
October 31, 2003
March 17, 2004
July 14, 2004

Profile C7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-0.4
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-1
-1.2
Relative Elevation (m)
-20
-15
-10
-5
0
5
10
15
20
25
30
SSE
Distance (m)
NNW
April 8, 1999
April 26, 1999
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June 15, 2000
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April 4, 2003
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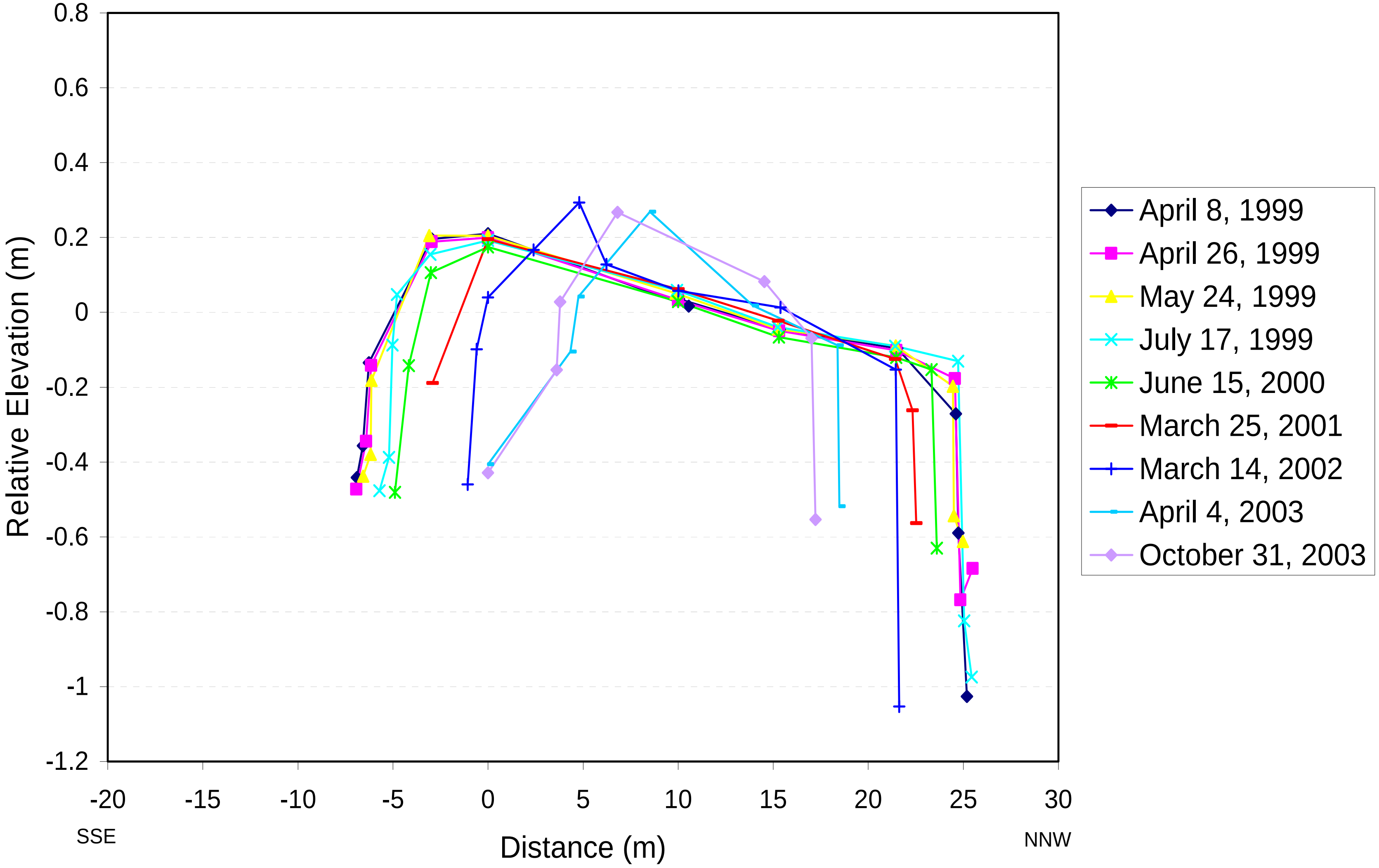
March 17, 2004

Profile C8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-1.2
Relative Elevation (m)
-20
-15
-10
-5
0
5
10
15
20
25
30
SSE
Distance (m)
NNW
April 8, 1999
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May 24, 1999
July 17, 1999
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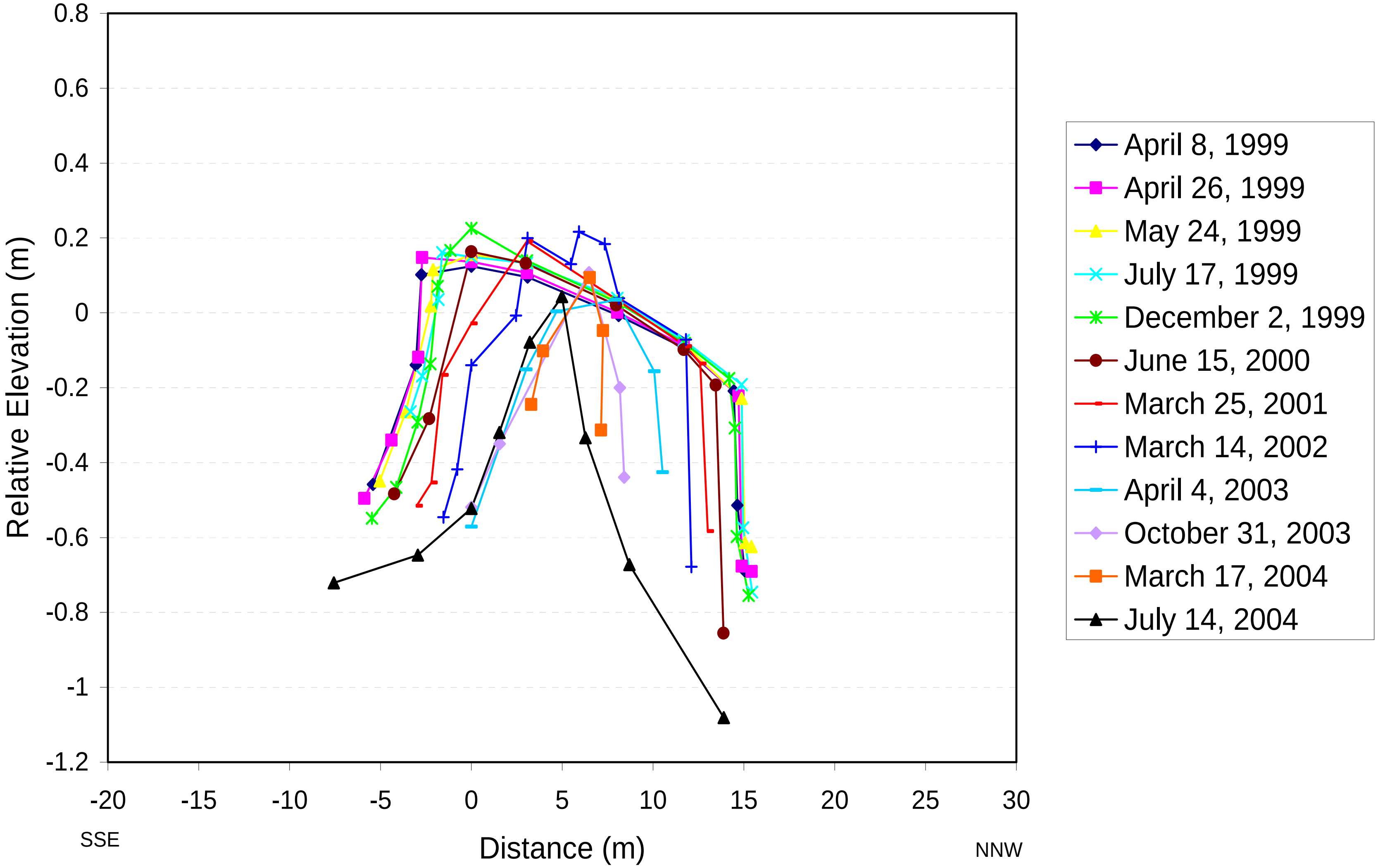
March 14, 2002
April 4, 2003
October 31, 2003

Profile C9



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-1
-1.2
Relative Elevation (m)
-20
-15
-10
-5
0
5
10
15
20
25
30
SSE
Distance (m)
NNW
April 8, 1999
April 26, 1999
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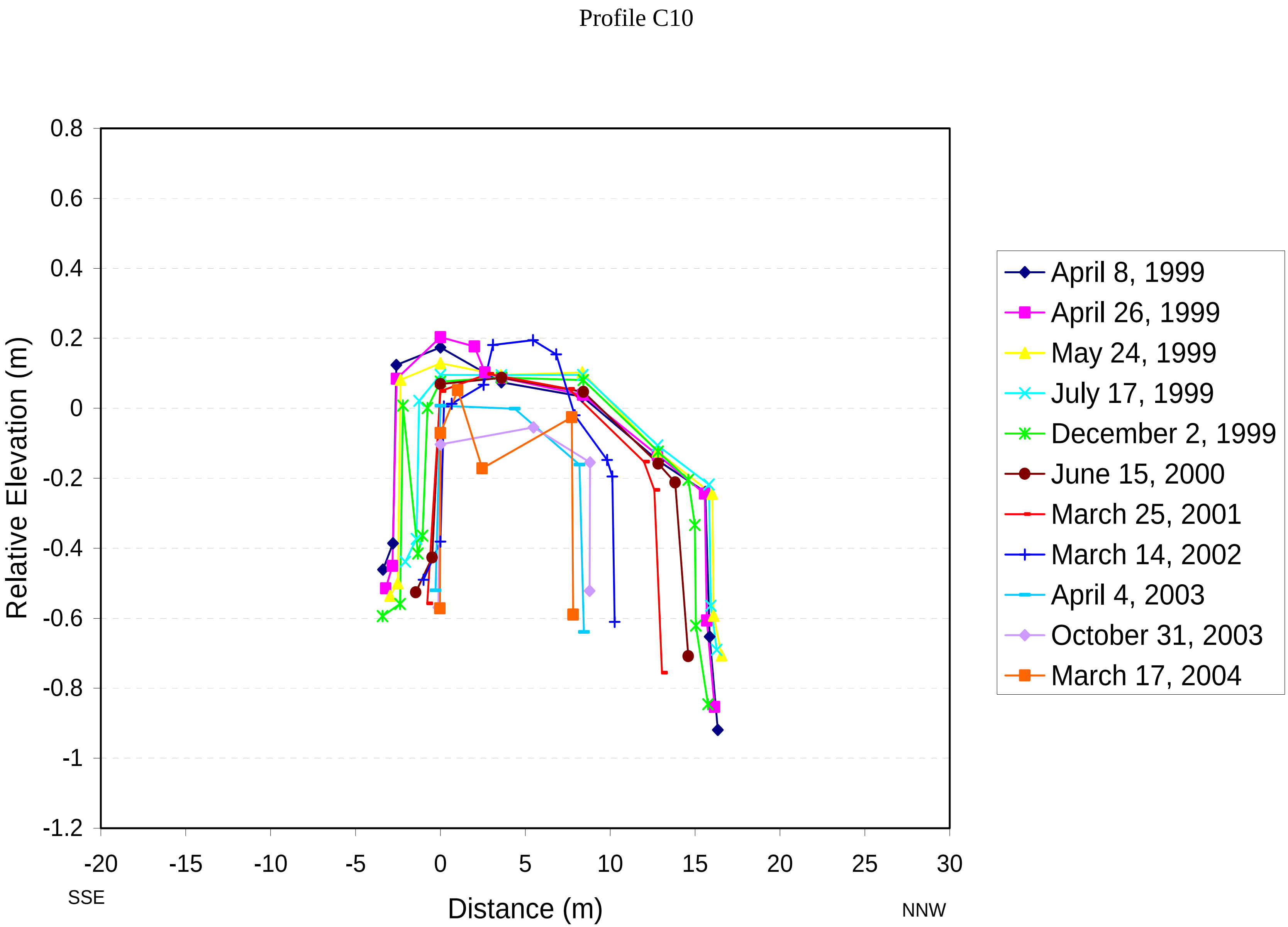
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15
20
25
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SSE
Distance (m)
NNW
April 8, 1999
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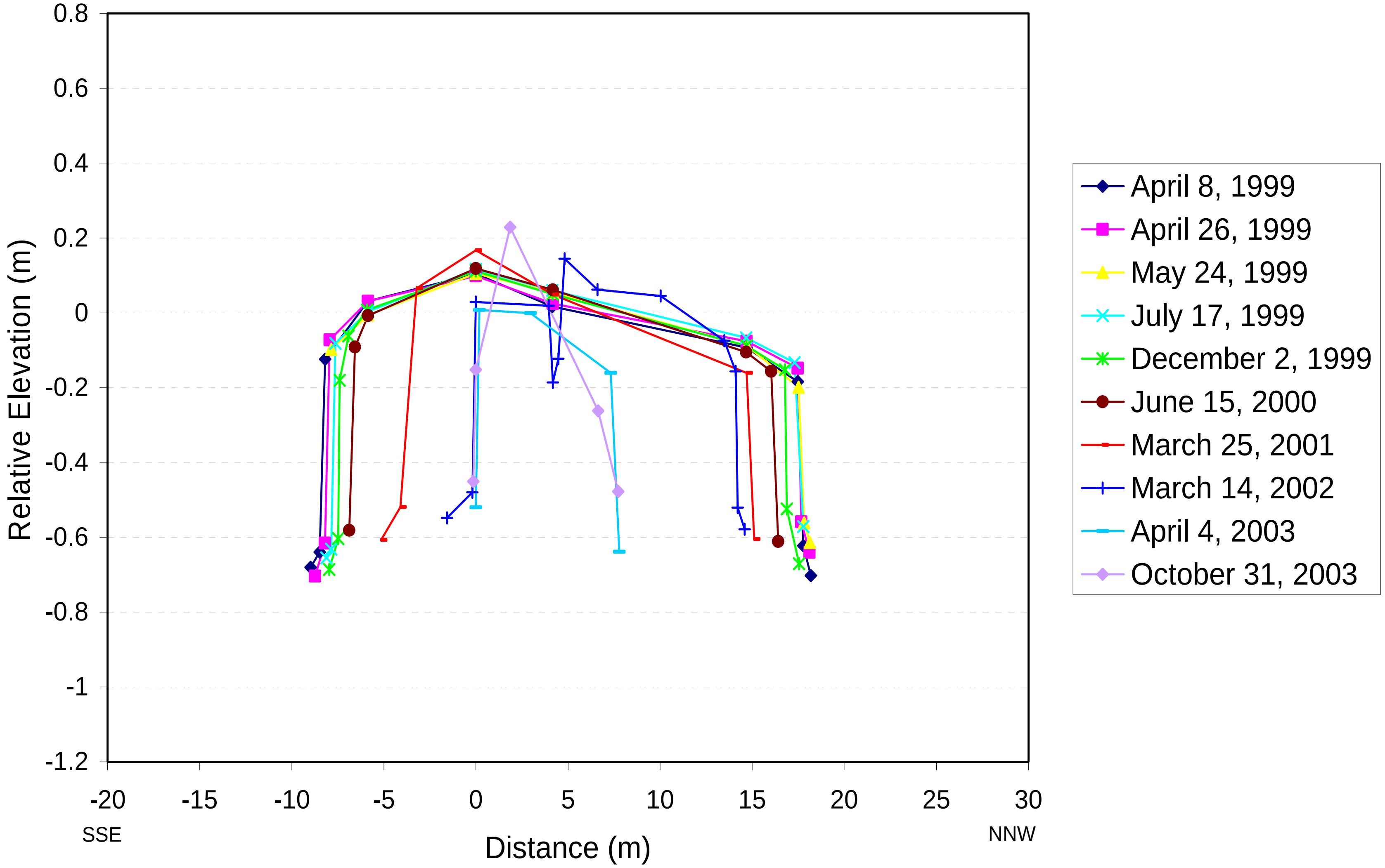
Profile C11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-1.2
Relative Elevation (m)
-20
-15
-10
-5
0
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10
15
20
25
30
SSE
NNW
Distance (m)
April 8, 1999
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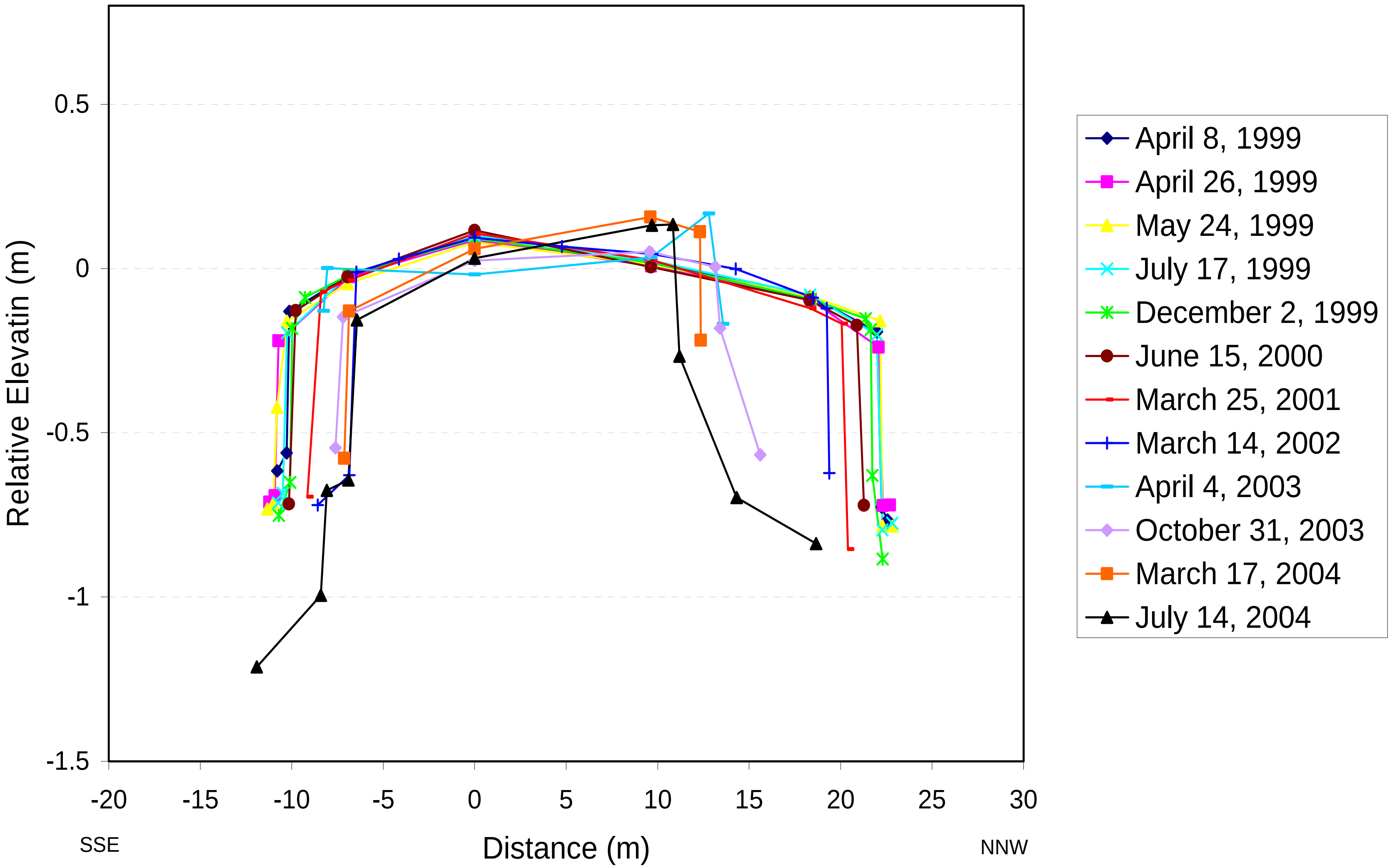
Profile C12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SSE
Distance (m)
NNW
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April 26, 1999
May 24, 1999
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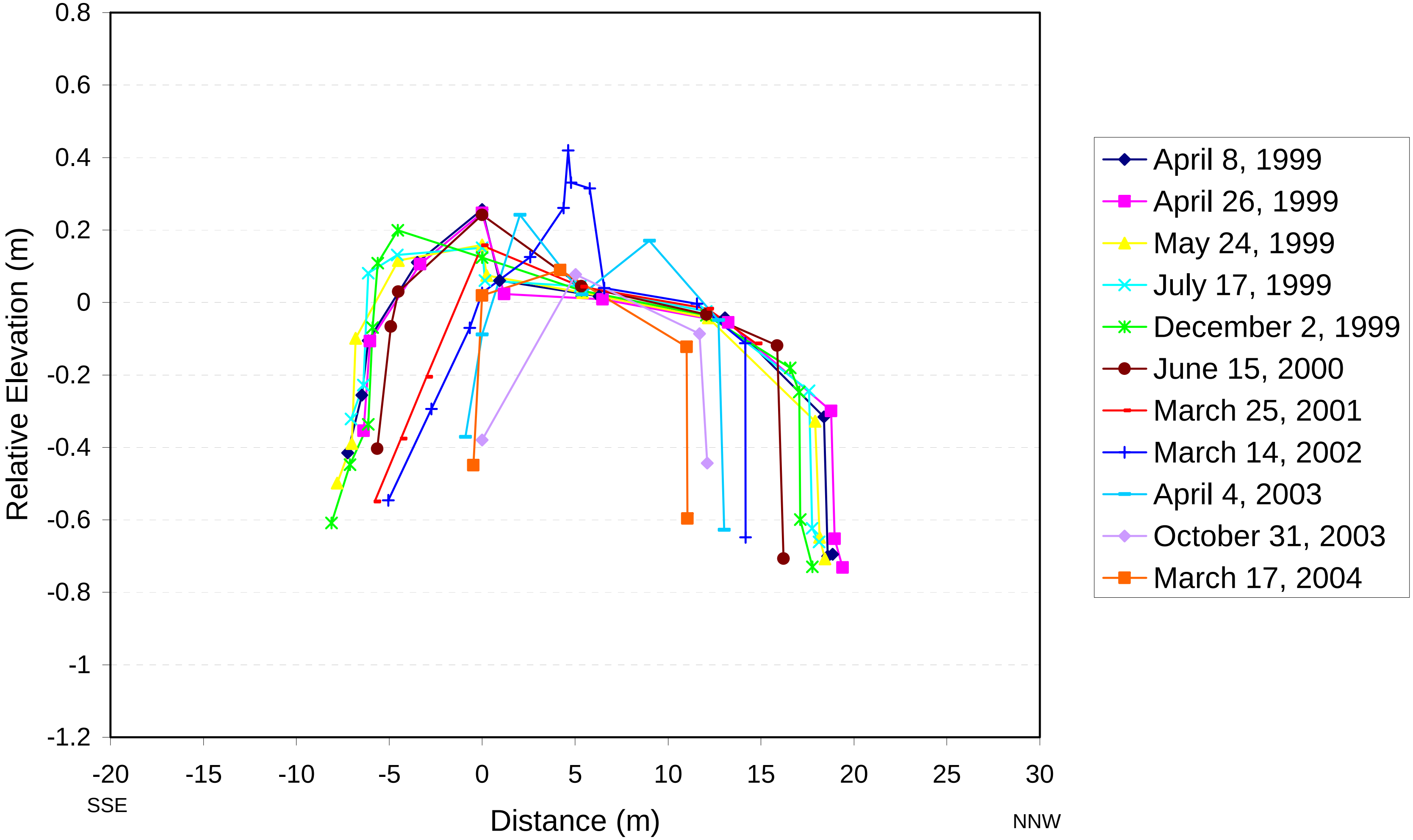
July 14, 2004

Profile C13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SSE
Distance (m)
NNW
April 8, 1999
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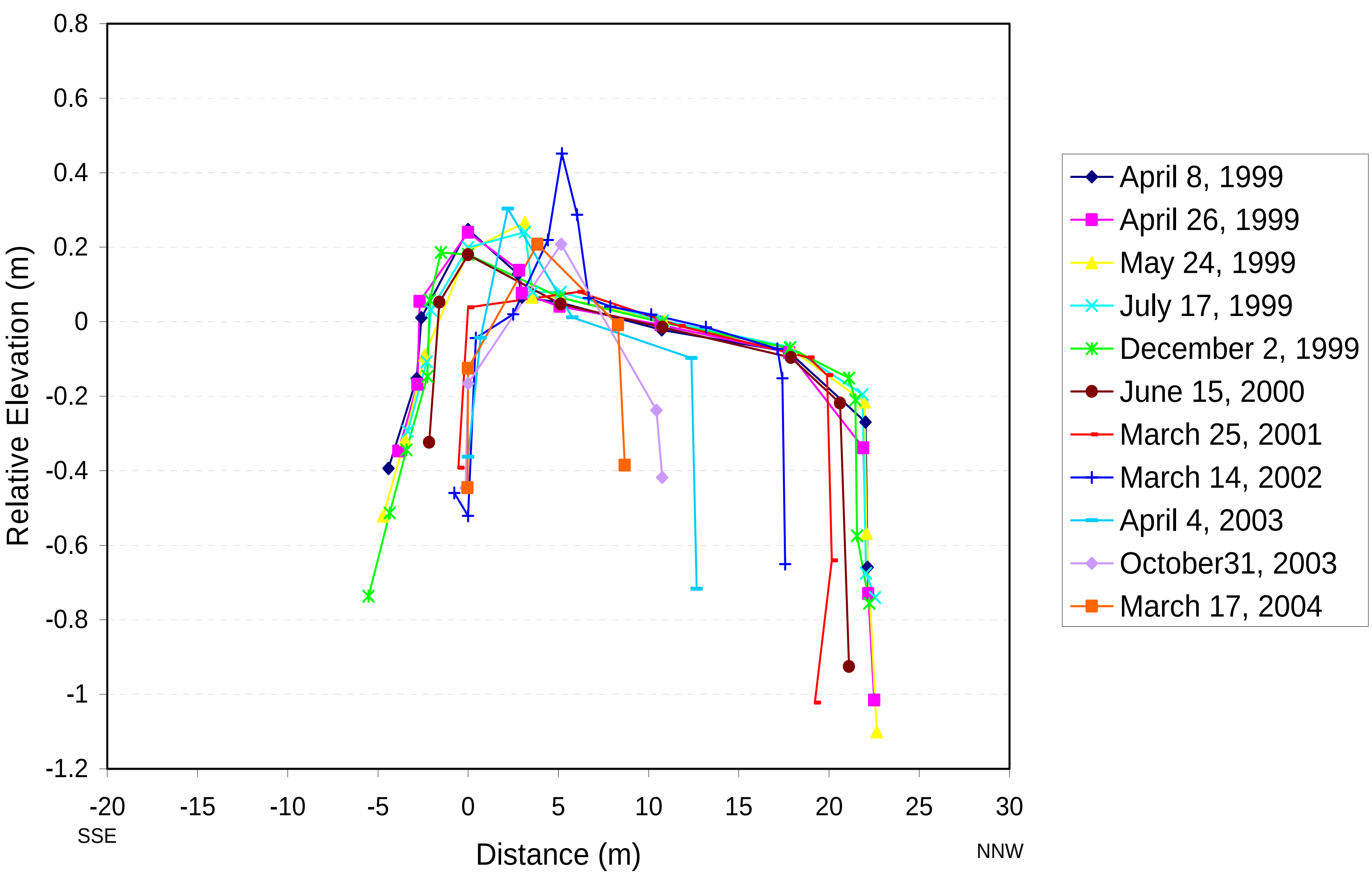
Profile C14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Relative Elevation (m)
-20
-15
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10
15
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25
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SSE
Distance (m)
NNW
April 8, 1999
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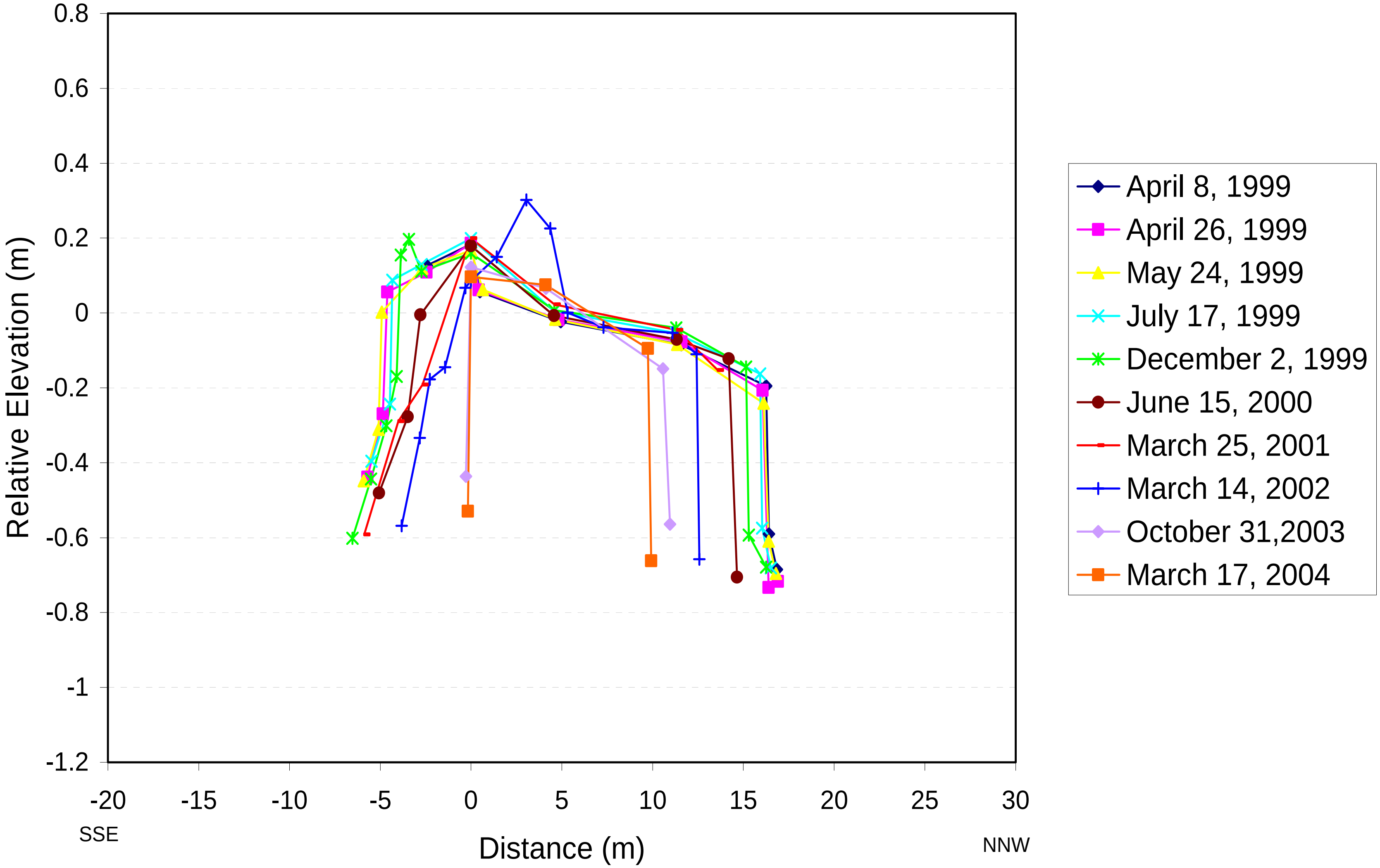
Profile C15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Relative Elevation (m)
-20
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-5
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15
20
25
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SSE
Distance (m)
NNW
April 8, 1999
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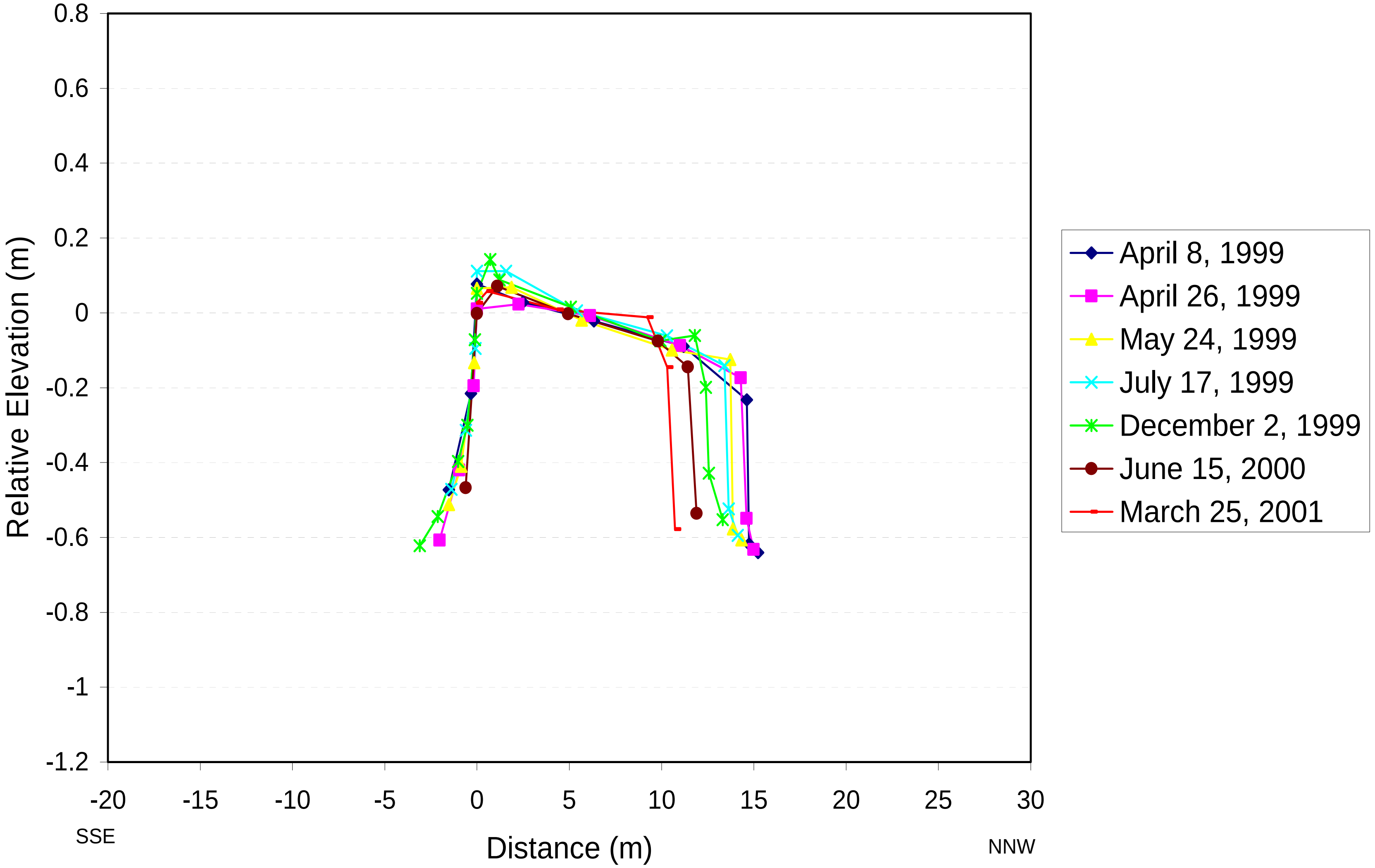
March 17, 2004

Profile C16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Relative Elevation (m)
-20
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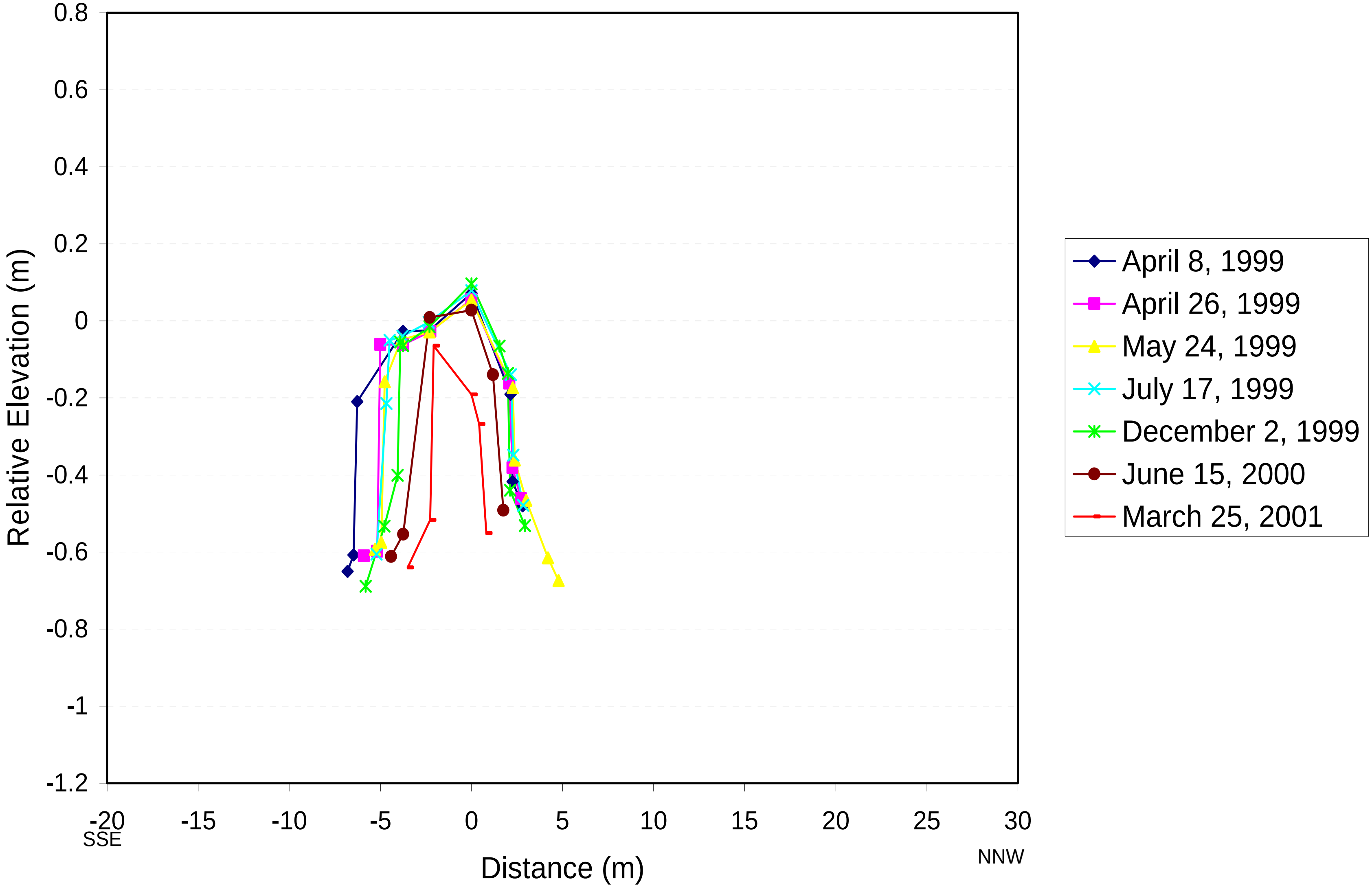
5
10
15
20
25
30
SSE
Distance (m)
NNW
April 8, 1999
April 26, 1999
May 24, 1999
July 17, 1999
December 2, 1999
June 15, 2000
March 25, 2001

Profile C17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Relative Elevation (m)
-20
SSE
-15
-10
-5
0
5
10
15
20
25
30
NNW
Distance (m)
April 8, 1999
April 26, 1999
May 24, 1999
July 17, 1999
December 2, 1999
June 15, 2000
March 25, 2001

VITA

Dana Ann Watzke was born on July 24, 1979, in Kenner, Louisiana, the daughter of Edward and Faye Watzke. She graduated from St. Lawrence the Mater elementary school in 1993 and Archbishop Chapelle High School in 1997. She obtained her Bachelor of Science degree in geology and geophysics from the University of New Orleans in May 2002 specializing in coastal geology. Dana accepted an offer from the Department of Oceanography and Coastal Science to pursue her Master of Science Degree and will graduate in December 2004.