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Morphological Barrier Island Changes and Recovery of Dunes after Hurricane Dennis, St. George Island, Florida

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MORPHOLOGICAL BARRIER ISLAND CHANGES AND RECOVERY OF DUNES AFTER HURRICANE DENNIS, ST. GEORGE ISLAND, FLORIDA

By

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I dedicate this manuscript to my family and friends, the people who I cherish most, who stand by my side, and who continually encourage me to stay the course.
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ABSTRACT

A robust dune system is one of the principal factors in the protection of recreational and residential property within barrier islands. Storm surge from significantly large storm events may remove some or all of the dunes during overwash processes and deposit sediment as washover fans or terraces in the back-barrier. During the summer of 2005, Hurricane Dennis greatly overwashed much of the northwest barrier island chain along the Florida panhandle.

The post-storm recovery of dunes and morphological changes occurring after Hurricane Dennis within St. George Island State Park is investigated, in addition to the application of numerical methods as a supplemental tool in determining the post-storm “recovery state” of the barrier and envision morphologic trends. Dune recovery rates are estimated by calculating sediment volume changes of profiles through time. One-dimensional, spatial-series Fourier analysis of individual profiles are used to quantify the recovery and morphologic nature of secondary dunes. Two-dimensional Fourier analysis of elevation data were attempted to be used as a tool to discriminate geomorphic trends in the barrier. Digital elevation models are used to describe post-storm morphologic changes, and the future recovery state of the barrier may be supplemented by analyzing the distributions of curvature and gradients calculated numerically from LIDAR data.

Results show that secondary dunes recovered at an average rate of ~3-4 cm per month, and sediment volume changes across transects varied between $-1.5 \text{ m}^3/\text{m}$ to $1.2 \text{ m}^3/\text{m}$ depending on the presence of vegetation, storm-debris pavement, and proximity to washover deposits. Despite some transects having a net sediment volume loss, all dunes in the presence of vegetation had increased in height. Vegetation did not propagate where storm-debris pavement existed during the one-year duration of the study. The presence of vegetation inhibited dune migration thus favoring dune growth or decreasing the effect of erosion from strong wind events.

Fourier analysis of profiles captured changes in dune height at specific wavelengths. The highest energies from the spectra were usually at 30 to 40 meter wavelengths for each profile in time, which reflects the immobility of the dunes and may also reflect the controls of vegetation on dune spacing. The results of two-dimensional Fourier analysis on terrain data were difficult to interpret, but may prove a potential use in terrain analysis.
Overwash was prevalent throughout the barrier. For the studied area, St. George Island had experienced inundation overwash with an estimated 100,000 ft$^3$/ft net loss of sediment following the hurricane. Nearly the entire foredune complex was removed, save a few remnants. Storm surge had likely penetrated first in areas where foredunes were either low or discontinuous; in these areas, beach widening was less prevalent. In contrast, the beach widening (~30ft) occurred in areas where the foredunes were higher and more continuous.
INTRODUCTION

Less than one year after Hurricane Ivan, Hurricane Dennis made landfall as a Category 3 hurricane on July 10, 2005. Landfall occurred east of Pensacola, FL with the strongest reported wind speeds of 115-120 mph occurring east-northeast of the eye. Areas within the northwest barrier island chain between Navarre Beach and Wakulla County were severely affected by storm surge. In particular, St. George Island State Park was subjected to 10 to 12 feet of storm tide during the storm despite relatively low reported wind speeds (45 mph). The high storm surge resulted in major erosion by overwash, thus completely removing most of the foredune and leveling the smaller secondary dunes behind it (BBCS 2005).

Washover deposits resulted in the translation of large quantities of sediment to the back-barrier and St. George Sound/Apalachicola Bay. Aside from the removal of most of the secondary dunes, the impact of this event was apparent, as trees were inundated by sediment, the back-barrier was denuded of vegetation, and segments of the roadway were destroyed and displaced from their original position by as much as 30 m.

In this manuscript, the growth and stability of secondary dunes is qualitatively linked to vegetation and “pavement” (storm detritus). A qualitative and quantitative analysis of the recovery, stability and/or migration of dunes is also completed via transect elevation surveying and one-dimensional Fourier analysis of the collected data. Likewise, the geomorphic trend, or preferred orientation, of pre-storm secondary dunes of the back-barrier is also investigated utilizing a two-dimensional FFT. In this way, it is possible to observe, and quantify, any possible trend in geomorphic features that might not otherwise be noticeable visually, especially during post-storm recovery. Representative wind data for the area might then be linked to long-term aeolian processes responsible for dune orientations.

The redistribution of sediment is mapped and described by subtracting the pre- from post-storm LIDAR (Light Detection And Ranging) digital elevation models. Sediment volume changes for sections of the barrier are then calculated to determine whether or not the system had conserved mass after overwash, as purported by some authors in the literature (Stone 2004).

Finally, quantifying the future “state of recovery” of the dune complex may be possible by investigating the gradient and curvature distributions of topographic data using post-storm LIDAR data as they become available, and comparing those to pre-storm distributions; the application of this method is shown by example via this study.
CHAPTER 1

BARRIER ISLAND OVERVIEW

**Barrier islands**

Barrier islands are formed from the accumulation of sediment by wave and wind processes, and are reworked by these same processes along with currents, tides, sea-level change, and sediment supply. They are typically low elevation, shore-parallel features that are separated from the mainland by a lagoon, bay, sound, or other body of water. The sediment size and composition which comprise a barrier island are varied depending on the geologic setting and sourcing. For example, shell fragments comprise the majority of sand-sized grains in lower latitudes of the Florida peninsula, while quartz sand dominates the Florida panhandle. Beaches in the tropical Pacific Ocean are composed mostly of basalt sands, while those in New England are glacially derived and contain a variety of grain sizes and compositions (Davis 2004). It is generally accepted that barriers formed about 3000-7000 years ago after the last glacial highstand (18000 YR BP) (Komar 1976) owing to a decrease in sea-level rise during that time (Komar 1976; Blum et. al, 2002). Barrier islands tend to develop near rivers with high sediment discharge and along low-gradient littoral zones. Hence, many well-developed barriers can be found along the Gulf and Atlantic coastlines, among other geographic locations. The landward sides of barriers, termed the back-barrier, usually consist of tidal flats and/or salt marsh but can also have a beach (Stone 2004). A generalized cross-section of a barrier is provided in Figure 1.

Figure 1. Generalized cross-section of a barrier island indicating typical physical environments. Behind the foredune complex there may exist secondary dunes, a ridge and swale complex or both. Backbarrier dunes can be higher than the foredunes (as the case with SGI) or may not be present at all. Likewise, the berm may not always be present. Adapted image from coastal.beg.utexas.edu.
Barriers are aptly named in that they play an integral role in protecting the mainland by acting as a buffer to dissipate wave energy from large storm events and related storm surge. They are the sites of heavy residential and resort industry development, and have therefore become commodities for many cities. Barrier islands are also areas of unique habitats and serve as nesting sites for protected migratory birds. For these reasons, considerable efforts are made within academic, coastal engineering, and governing communities in understanding, quantifying, and linking the processes that influence the barrier island system. A large part of this protection is directly related to a barrier’s dune system.

**Dune formation and mechanics**

Dunes form from the accumulation of sand-sized sediment and can vary greatly in terms of their size and morphology, depending on the grain-size distribution, wind regime, surface roughness, and sediment supply (Davidson-Arnott 1990; Hesp 2002). The primary mechanism of sediment mobility is through saltation, first coined by Gilbert (1914). The process of saltation occurs when a wind speed exceeds a certain threshold to the extent that the shear stress induced on the sand is sufficient to overcome the shear strength of the sand grains. Once exceeded, the forces imparted on the grains are such that they are capable of being lifted into the wind stream and thus transported some distance in a series of leaps. Bagnold (1941) further attributes the transfer of momentum between impacting grains in aiding in the saltation process. For grain sizes between 0.25 and 0.75 mm, he estimated the threshold velocity for aeolian transport at 5 to 10 m/s (11 to 23 mph) when wind velocities were measured at a height of 2 meters; this threshold can vary depending on surface roughness and grain size.

**Foredunes**

The foremost dune along a barrier is termed the foredune. A foredune typically marks the beginning of the beach area and are sometimes termed incipient dunes, frontal dunes, retention ridges, beach ridges, parallel dunes, or transverse dunes (Hesp 2002). These shore-parallel features may be one to several meters in height depending on factors as mentioned above, as well as the wind approach angle with respect to the foredune (Arens 1996). Foredunes are usually heavily vegetated, especially on the landward side, or they may be scarped on the shore-facing side from storm activity. One way in which foredunes may develop is from offshore bars that can migrate onshore and become welded onto the beach especially near tidal inlets (Davis 2004) presumably because of the large amounts of sediment stored in the ebb and flood deltas of the inlet. The welded bars supply sediment to the beach area which can then be
transported by wind to a vegetation front in the backbeach. Once vegetation can take hold the
dune becomes more stable, and where sediment supply is abundant, a series of foredune ridges
and low lying swales may develop, indicative of a prograding environment (Davis 2004).

The formation of dunes principally requires abundant sediment supply, and wind to
transport the sediment. Wind processes cannot transport wet sediment easily; therefore most
dunes are formed at or behind the backshore area. For given sediment size and supply, wind
speed, and surface roughness, the amount of sediment in and out of a given area should be
conserved unless conditions change. However, any obstacle in the path of wind flow can
accumulate sediment behind the obstacle. These features, shown in Figure 2, are known as sand
shadows and are observed to form on the lee, or down-wind, sides of shells or debris and
vegetation.

![Figure 2. Large sand shadows outlined against the road illustrate the effectiveness
of vegetation at trapping sediment. The shadows point in the direction of wind
flow.](image)

Vegetation is very efficient at trapping sand. One species of vegetation that is
particularly well-suited at trapping and piling sediment is *Uniola paniculata*, or common sea oat.
Davies (1980) and Hesp (1983) reported that higher plant species produced higher, more-
hummocky (mound-like) dunes and lower, rhizomatous plants produced lower less-hummocky
dunes. Other plants, like the beach morning glory, are also effective at stabilizing the substrate.
Once the dune is no longer dynamic, other species of vegetation (like woody plants) can take
hold, further stabilizing the dune. Presence of woody vegetation should therefore give some indication of the age, or at least stability, of the dune as also reported in Hesp (2002).

Dune development depends on plant density and cover, distribution, rates of sediment transport, and wind velocity (Hesp 2002). Models show that as plant height increases, dune height increases and dune length decreases (Buckley 1987; Aylor et al. 1993, Raupach 1992; Van Dijk et al. 1999; Hesp 1989). The migration of dunes by aeolian processes is usually correlated with a lack of vegetation, as was observed in the present study.

**Sediment transport within vegetated dunes**

There are three types of dune-plant species that are delineated by how they respond to sediment mobility: dune builders and burial-tolerant stabilizers (both having vertical growth capacity to keep pace with sediment accumulation), and burial-intolerant stabilizers (those that cannot keep pace with high rates sediment accumulation) (Hosier 1973; Woodhouse 1982; Ehrenfeld 1990). Common dune building plants, such as high growing *Uniola paniculata* (sea oats), are effective in trapping sediment and accelerating dune growth, while *Ipomoea imperati* (beach morning glory) are considered burial-tolerant stabilizers given that they grow very close to the ground as a series of rhizomatic runners and therefore do not promote vertical dune growth, but rather help to stabilize the substrate (Stallins 2001).

For a given flow regime across a horizontal surface, the velocity of flow is reduced near the bottom boundary layer as a result of increased drag from surface roughness. Thus, the presence of vegetation dramatically increases surface roughness thereby further decreasing wind velocities on the downwind side. Furthermore, a positive feedback exists between vegetation growth (of the dune building type) and dune growth; the deposition of sediment within vegetation encourages plant growth (to keep pace with sediment accumulation) which then further increases surface roughness and sediment deposition (Hesp 1989, cited in Arens 1996). This is the basic mechanism by which dunes develop in the presence of vegetation.

The effect of vegetation on sediment transport was first measured by Buckley (1987) in wind-tunnel experiments. For a random distribution of stemmed vegetation measuring 10 cm high and 12 cm across, and an initial wind velocity of 10 m/s measured at 0.5 m height, he found that sediment flux decreased by 35 and 84 percent for a 5 and 17 percent vegetation cover (of 1 m$^2$), respectively. This is in agreement with field measurements by Hesp (2005) at Prince Edward Island. Hesp reports that the wind velocity above the vegetation canopy across a foredune *increases* from the toe to the crest of the dune due to a pressure gradient from dune-
normal winds. However, concurrent measurements below the canopy (within 10 cm of the surface) resulted in a linear decrease in wind velocity of 8.6 % per meter across the foredune (with an R-squared value of 0.876).

**Overwash**

Early work on overwash came from Johnson (1919), who photographed what he called “wave deltas” in accounting for one of many contributions of sediment-infilling to explain how the lagoon behind barrier islands might be transformed to land.

The dune complex, while protective, is quite vulnerable to storm surge, which increases the landward distance over which wave energy is spread. If storm-tide and/or wave run-up exceeds the height of the foredune, or berm if a foredune does not exist, then the consequence is a partial or complete removal of the dune complex by inundation of seawater (Donnelly 2006). Such activity is known as overwash, and the deposited sediment is termed a washover deposit.

Quite often, tropical storms and hurricanes are responsible for overwash events on barrier islands; however, a strong nor’easter can also produce significant overwash, as was the case for Assateague Island in the years after jetties were built in 1935 (Davis, 2004), and the Ash Wednesday storm of 1962 in which seventy-eight percent of the coastline between New Jersey and North Carolina were overwashed (Morton et al. 2003). Material removed from the foredune is deposited as a washover fan, or apron (if extensive), often reaching the back-barrier bay or nearby coastal lakes—coarse-grained sediment layers contained within the otherwise organic-rich mud of coastal lakes are often used as a proxy for large storm events; i.e., paleotempestology (see Liu 1993, 2000; Donnelly, 2001, 2007). The overwash process may result in an overall conservation of mass of the barrier island (Stone 2004) (although Donnelly (2006) noted that from a coastal management perspective washover sediment is accounted for as a sink term in the littoral sediment budget). An analogue of a simple washover fan and its morphology is illustrated in Figure 3.

The breaching or lowering of the foredune increases the risk of overwash causing damage to infrastructure and habitat by flooding, scouring, and wave attack. Previous washover deposits are easily recognizable in aerial photographs of barrier islands, which explain the undulating morphology of the back-barrier. Such deposits may develop into new tidal flats and salt marshes as salt-resistant plants take hold. Hence, the process of barrier-island rollover may occur, which is partially responsible (along with sea-level rise) for the migration of barrier islands toward the mainland, recognized by peat deposits and/or relict tree roots along the beach.
A storm’s ability to overwash a barrier depends on storm-surge height, wave height, foredune height, and storm duration (C. Donnelly 2006), as well as storm-wave set up and swash run-up (Wang 2006). Overwash can even occur in cases where storm-tide is lower than foredune height due to wave run-up and dune scarping (Morton and Sallenger 2003). Additionally, the potential for overwash is likely amplified during Spring tides which would increase storm surge elevation. Wang et al. (2006) report that storm-layer deposits generally decrease in thickness landward; this may not be the case when considering washover lobes (this study).

Initial post-storm recovery (i.e., re-establishment of vegetation, dune growth, or other accumulation of sediment) occurs on the order of a few months along the beach and backshore environments (Wang et al. 2006). This study finds that significant growth of the secondary dune complex may occur within one year providing sediment is supplied in the presence of vegetation, but complete recovery may take longer, especially if the recovery process is interrupted by subsequent storms. Likewise, foredune recovery may take years and require human intervention (Davis 2004), especially if the coast is already affected by long-term erosion processes.

**Study area**

*Locality and characteristics*

St. George Island (SGI) is part of the northwest Florida barrier chain located in Franklin County, Florida, about 112 km (70 miles) southwest of Tallahassee. SGI is a northeast-southwest trending barrier roughly 45 km (28 mi) in length and about 410 m (450 yd) in width, and is separated about 7.2 km (4.5 miles) from the mainland by Apalachicola Bay and St. George Sound (Figure 4). The eastern and western ends of the island are characterized by recurved spits.
and ridge and swale topography. Previous to Hurricane Dennis, the back-beach was marked by a 3-3.5 m (10-12 ft) high continuous-to-discontinuous vegetated foredune. Wind direction frequencies measured between the months from June to December were nearly evenly distributed (as discussed later in the results). The strongest winds, however, were between the north, east, and south directions, with dominant directions occurring from the east and north. This is in good agreement with a Department of Environmental Protection report written by the Beaches and Shores Resource Center at Florida State University (2007). The island is wave-dominated and micro-tidal, with a tidal range usually not exceeding 60 cm (2 ft) above mean lower low water (MLLW).

The study sites, shown in Figures 4-6, are located within St. George Island State Park, which occupies the eastern 14 km (11 mi) of the island. The location of the study area was chosen because it closely models a pristine system due to lack of infrastructure and minimal human intervention, and for ease of access. The sediment composition is mainly fine to medium quartz sand with some shell detritus, although there is now considerable asphalt and shell debris as a result of Hurricane Dennis which formed a pavement in many areas.
Figure 4. Regional map of Franklin County illustrating the regional setting (top) and study area (St. George Island State Park, bottom). Modified from BBCS, 2005.
Figure 5. Aerial photo image of study site 1 with the approximate locations of transects 4-6 as marked by GPS. The trends of the profiles are approximately North-Northwest and span about 100 meters. The shoreline trends approximately NE-SW.

Figure 6. Aerial photo image of study site 2 with the approximate locations of transect-8 and anemometer (triangle) as marked by GPS. The trend of transect-8 is approximately East-West and spans about 125 meters. The shoreline trends approximately NE-SW.
Vegetation

Abundant sea oats and beach morning glory typify the coastal dunes of the study area, while cord grasses (genus *Spartina*) are typical in the tidal-flat back-barrier, although various species of vegetation are present throughout the island. Older relict dunes, of considerable height, are bounded by slash pine trees near the back-barrier.

Sea oats are remarkably robust. They are tolerant to many physical stresses such as winds and storms, but are also resistant to salt spray. Snyder and Boss (2002) noted that sea oats recovered very rapidly, from the remnants of dispersed colonies after storm surge from hurricanes Erin and Opal scoured and denuded many areas of Santa Rosa Island, Florida, (approximately 200 km west of SGI) in 1995. Sea oats were observed to nearly double their height, reaching as high as 2 meters during the summer months.
CHAPTER 2

EFFECTS OF HURRICANE DENNIS AND METEOROLOGICAL CHARACTERISTICS

Meteorological aspects

Hurricane Dennis made landfall as a category 3 hurricane on Santa Rosa Island two miles east of Pensacola, Florida on July 10, 2005, 2:25 pm CDT (Figure 7). The maximum wind velocity was recorded on Navarre Beach at 121 mph. The pressure recorded from a Florida Coastal Management Program (FCMP) tower located on Navarre Beach was 965.2 mb at 1909 UTC. Wave heights reached 35 ft recorded by NOAA buoy station 42039 125 miles southeast of Pensacola.

Effects of Dennis on the Northwest Florida barrier chain

Most of the Northwest Florida barrier chain was severely eroded and/or overwashed. The Bureau of Beaches and Coasts, Florida Department of Environmental Protection damage assessment report (2005) provides a more detailed description of site damage for multiple locations; however, these are summarized in Table 1. A comparative analysis of damage caused by hurricane Dennis to that of past hurricanes affecting the same region can be found in a study by Clark and LaGrone (2006).
Figure 7. Location map showing the tracks and landfalls of hurricanes Elena (1985), Opal (1995), Ivan (2004), and Dennis (2005). These hurricanes were all Category 3 hurricanes at the time of landfall, yet only Dennis severely affected St. George Island and surrounding areas.
Figure 8. Erosion classes defined by Clark (1981, BBCS) from condition I (minor), to condition IV (major), based on post-storm beach and dune changes.
Table 1. Summary table of storm conditions and sustained erosion for parts of the northwest Florida barrier chain. A list of abbreviations is provided below. Dashes indicate no data.

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance to eyewall (mi)</th>
<th>Sustain/Max wind (mph)</th>
<th>Source*</th>
<th>Storm surge/tide† (ft)</th>
<th>Erosion class**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pensacola Beach</td>
<td>10, E</td>
<td>82/93</td>
<td>FCMP</td>
<td>4.16†</td>
<td>I (minor)</td>
</tr>
<tr>
<td>Navarre Beach</td>
<td>7.5, W</td>
<td>99/121</td>
<td>FCMP</td>
<td>10-12‡</td>
<td>IV (major)</td>
</tr>
<tr>
<td>Ft. Walton Beach</td>
<td>23, W</td>
<td>/102</td>
<td>FLDEP† report</td>
<td>8-10†</td>
<td>III-IV (major)</td>
</tr>
<tr>
<td>Destin</td>
<td>32, W</td>
<td>56/74</td>
<td>KDTS</td>
<td>8-10†</td>
<td>IV (major)</td>
</tr>
<tr>
<td>Walton Co.</td>
<td>38 – 62, W</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>IV (major)</td>
</tr>
<tr>
<td>Panama City beaches (R1-R37)</td>
<td>62 – 67, W</td>
<td>59/73</td>
<td>NOAA— Buoy PCBF†</td>
<td>5.72†</td>
<td>IV (major)</td>
</tr>
<tr>
<td>Panama City beaches (R37-R77)</td>
<td>67 – 75, W</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>II-III (moderate)</td>
</tr>
<tr>
<td>Panama City beaches (R77-R93)</td>
<td>75 – 80, W</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>III (moderate)</td>
</tr>
<tr>
<td>St. Andrews St. Park</td>
<td>80, W</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>II (minor)</td>
</tr>
<tr>
<td>Mexico Beach</td>
<td>100, W</td>
<td>--</td>
<td>--</td>
<td>6-8†</td>
<td>II (minor)</td>
</tr>
<tr>
<td>St. Joe Peninsula</td>
<td>103, W</td>
<td>--</td>
<td>--</td>
<td>5.5+</td>
<td>IV (major)</td>
</tr>
<tr>
<td>St. Vincent Island</td>
<td>123, W</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>IV (major)</td>
</tr>
<tr>
<td>St. George Island State Park*</td>
<td>173-182, W</td>
<td>40/63</td>
<td>NOS Apfl</td>
<td>7.2†</td>
<td>IV (major)</td>
</tr>
<tr>
<td>Dog Island</td>
<td>184-190, W</td>
<td>--</td>
<td>--</td>
<td>10-12‡</td>
<td>IV (major)</td>
</tr>
<tr>
<td>Alligator point</td>
<td>&gt;200, W</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>IV (major)</td>
</tr>
</tbody>
</table>

* NOS= National Ocean Service station; FCMP=FL Coastal Management Program tower; FL Dept of Environmental Protection report; NOAA=National Oceanic and Atmospheric Science buoy; KDTS=Destin-Fort Walton Beach Airport Designation
** From Bureau of Beaches and Coasts (2005)
† Water level above predicted tide
‡ Water level above the National Geodetic Vertical Datum of 1929 (NGVD 29)
+ Water level above the North American Vertical Datum of 1988 (NAVD 88)

Effects of Dennis on St. George Island State Park

St. George Island is located about 180 miles east of Dennis’ landfall. Wind speed measured at Apalachicola was about 40 mph with a maximum recording of 63 mph. Although the park was located at a considerable distance from the eye-wall and experienced only moderate tropical storm force winds, the area had still sustained condition IV beach and dune erosion (Figure 8). All of the dunes were leveled between markers R105 and R128 seaward of the road. Washover deposits were abundant; trees were inundated with sand and the road was displaced in many locations and/or covered with sand. Much of the park was denuded of dune vegetation. The eastern four miles of the park experienced inundation overwash (i.e., Gulf waters connected with St. George Sound), though there are scattered remnants of the foredune. Abundant asphalt and shell debris formed a lag deposit over much of the island. Many of the boardwalks and park facilities were destroyed.
CHAPTER 3

METHODS

Collection of dune height profiles

Five shore-normal transects were taken using a standard surveying total station (Figures 5-6). For each transect, a graduated line was extended between two control points; each graduation on the line measured approximately 0.5 m. Four of the transects, located near marker R-115, are approximately 100 meters in length and extend from the road to the bay (Figure 5). The fifth transect, approximately 170 meters in length, is located near marker R-115 and extends from the road to the beach (Figure 6) (see Figure 4 for marker locations). The four transects located near marker R-115 were chosen because they would not be disturbed by post-storm construction efforts and for their initial morphologic character and topographic expression. To expound, transects 4 and 7 had varying amounts of vegetation and topographies; transect 6 had a scarped remnant dune (i.e., survived the storm), while transect 5 was devoid of vegetation and nearly featureless when surveying began. The final transect near R-135 was chosen when the original study area near R-115 was no longer accessible due to nesting birds.


For each transect, the profiles are plotted relative to the first control point and are not tied to any datum. The top of the sediment surface was marked on each of the control point stakes to track erosion or deposition to allow for corrections to the data set; as it were, no net erosion or deposition occurred to any significant degree at the control point for each transect.

Time-series plots of the profiles were created using EXCEL, whereby each profile is successively plotted relative to the first profile. Sediment volume changes between time intervals were estimated using the trapezoidal method of numerical integration,

\[ \int f(x)dx = \sum (x_2 - x_1) \frac{f(x_1)+f(x_2)}{2} \]  

\[ (1) \]
where \( x_1 \) and \( x_2 \) are points between each measurement and \( f(x_1) \) and \( f(x_2) \) are the corresponding values of dune height.

**Fast Fourier Transform**

The purpose of the Fourier Transform, in a practical perspective, is to identify periodic components from a seemingly random, sinusoidal-varying signal, regardless of whether that signal is deterministic or stochastic (Emory and Thompson 2004). This is achieved by a transform function in which a signal from a time-domain can be transformed to a frequency-domain. The “Fast” Fourier Transform (FFT) is a computationally efficient algorithm of this procedure first formulated by Cooley and Tukey (1965). With regard to transect data, the FFT attempts to quantify changes in dominant wavelength, and amplitude, of dunes through each successive profile measurement.

The following discussion on the discrete FFT is intended to give a basic conceptual framework of the methods involved with the FFT algorithm and its use in signal analysis. A rigorous mathematical description is beyond the scope of this manuscript; instead, an example is used to illustrate the technique involved and to interpret the meaning of the results. This basic example will hopefully orient the reader in understanding the more complicated signals involved in the data set. First, an example on 1-dimensional FFT is illustrated, then an example on 2-dimensional FFT. Many of the equations describing the Fourier transforms are taken from Peters (2006), Vanderbilt Department of Electrical Engineering and Computer Science.

*The Fourier series*

In Fourier analysis, a continuous periodic signal can be represented by a sum of sinusoids. For example, a square wave can be represented as the integral sum of \( n \)-sinusoids of odd-numbered harmonics; i.e., the sum of sinusoids containing odd-numbered frequencies. This can be expressed by the function for odd-numbered \((2n + 1)\) harmonics for a sine wave (Peters 2006):

\[
F(x) = \sum_{n=-\infty}^{\infty} \frac{1}{2n+1} \sin \left( \frac{2\pi}{x} (2n + 1)x \right)
\]  

(2)
Thus, as shown in Figure 9, for all $n$, the sum of the series becomes exactly a square wave. The sine function of equation (2) is called the basis function, which represents different vibration frequencies, and the coefficient is the Fourier multiplier, also called the Fourier coefficient (Peters 2006). The coefficients can be thought of as amplitudes of the signal.

Now, consider a 1-dimensional time-varying sine wave of the form

$$y(t) = A \sin \left( \frac{2\pi}{\lambda} t - \theta \right)$$

(3)
where \( A = \) amplitude, \( \lambda = \) period, \( t = \) time increment, \( \theta = \) phase shift, and the expression \( \frac{2\pi}{\lambda} \) is the angular frequency in radians/second. In Figure 10a and b, we see a sine wave with a frequency of 2 Hz (cycles per second) and 4 Hz, respectively, with \( A = 8, \theta = 0 \) and time \( t \) from 0 to 1 in 0.01 time steps.

\[
\sum_{n=1}^{\infty} \left( a_n \cos \frac{n\pi}{\lambda} t + b_n \sin \frac{n\pi}{\lambda} t \right)
\]

where \( a_n = \frac{2}{\lambda} \int_{-\frac{\lambda}{2}}^{\frac{\lambda}{2}} f(t) \left[ \cos \left( \frac{2\pi}{\lambda} t - \theta \right) \right] dt, n \geq 0 \)
\[ b_n = \frac{2}{\lambda} \int_{-\frac{\lambda}{2}}^{\frac{\lambda}{2}} f(t) \left[ \sin \left( \frac{2\pi}{\lambda} t - \theta \right) \right] dt , \quad n \geq 0 \quad (6) \]

and are usually written in terms of complex exponentials

\[ f(t) = C_ne^{i\frac{2\pi nt}{\lambda}} , \quad \text{where } C_n = |C_n|e^{i\phi_n} \quad (7) \]

Here, \( C_n \) represents the amplitude and phase of the original signal (where \( A = |C_n| \)). However, this assumes that the function is a continuous periodic function. For discrete data (as in our case), the signal \( h_k \) of length \( N \), can be represented as the weighted sum of \( N \) sinusoids by

\[ h_k = \sum_{n=0}^{N-1} H_n e^{-i\frac{2\pi kn}{N}} \quad (8) \]

where \( H_n \) are the Fourier coefficients and are defined as the projection onto sinusoid, \( n \), by

\[ H_n = \frac{1}{N} \sum_{k=0}^{N-1} h_k e^{i\frac{2\pi kn}{N}} \quad (9) \]

In MATLAB, we perform a FFT on the signal shown in Figure 10c above to obtain the Fourier coefficients (the FFT is a fast algorithm in computing the discrete Fourier transform, or DFT). The coefficients of the Fourier series are complex numbers, the real part of which represents the amplitude, and the complex part represents the amplitude and phase of the signal. Some values of the FFT are shown in Table 3.

| Time (t) | F(t)  | FFT(F(t))       | | FFT | Frequency (Hz) | Period (s) |
|----------|-------|-----------------|--------|-------------|-------------|
| 0        | 0     | 0 + 0i          | 0      | 1           | 1           |
| 0.01     | 2.99  | 0.23 - 7.34i    | 2      | 1           | 0.5         |
| 0.02     | 5.84  | 25.30 - 406.15i | 3      | 0.33        |
| 0.03     | 8.42  | 0.31 - 3.32i    | 4      | 0.25        |
| 0.04     | 10.60 | 49.08 - 392.42i | 5      | 0.20        |
| 0.05     | 12.31 | -3.48 + 22.20i  | 6      | 0.17        |
| 0.06     | 13.46 | -2.05+9.25i     | 7      | 0.15        |

Table 2. Calculated values of the Fourier coefficients, power, frequency, and period in MATLAB.
The first value of power in Table 3 is the sum of all the coefficients, which represents the average value of the function; in this case, the average value of the function is zero. Normally this data point is deleted after taking the transform. The modulus squared of the transform coefficients is termed the power, and this value can be thought of as representing the deviation from the average value that is explained at a certain frequency component; the units of power here are m²/m. Plotting the power versus frequency gives a power spectral density (PSD), or periodogram, as shown in Figures 11a and b.

Figure 11. (a) Power spectral density in showing symmetrical power peaks resulting from the calculation of the FFT. One peak is slightly less than the other due to bin leakage. (b) The redundant latter half of points removed from (a). The two power peaks correspond with frequencies of 2 Hz and 4 Hz.
In Figure 11a the plot is vertically symmetric, accounting for N/2 real frequency and N/2 imaginary frequency components of the transformed signal. As such, a series consisting of N signals in the time domain are transformed to N/2 signals in the frequency domain. Once the absolute value of the transformed series is calculated, all the information needed to describe the frequency domain is contained in the first half of the PSD, and the latter half can then be deleted. In Figure 11b we see two strong peaks corresponding to the two dominant frequencies at 2 and 4 Hz contained within the summed signal, which is what we expected. It is often convenient to express the spectrum in terms of period. Therefore, we take the inverse of the frequency and plot as a stem plot along with the summed wave for comparison (Figure 12b).

Figure 12 shows the powers corresponding to a period of 0.25 s and 0.5 s are nearly equal. This is because both functions started with an amplitude of $A = 8$. Let us suppose the 4 Hz sine wave had only an amplitude of $A = 4$, then the power related to the period at 0.25 s would be approximately $\frac{1}{4}$ that at 0.5 s since power is a squared value.
Fourier analysis applied to topographic profiles

A plot of transect data is similar to any other varying ‘signal’ and can be represented in a frequency-domain and such a domain can be obtained and analyzed using FFT. This is because the Fourier transform can represent periodic functions, as well as aperiodic functions, as the sum of sinusoids. Signal processing in this manner will quantify changes in dominant wavelengths and amplitudes occurring with dune recovery by plotting the distribution of dominant frequencies and compared those to other successive transects taken at different times.

To achieve this, data from a surveying total station are loaded into MATLAB and plotted to check for outliers or discrepancies. We then remove any linear trend in the data thereby forcing the mean to be zero, allowing for more accurate comparisons of power distributions. We then perform the FFT and plot the results as a stem plot against the period (as explained above). Since not every profile has the same length, due to sampling errors or loss of control points, profiles of longer transects are shortened to match that of the shortest transect so that amplitudes of specific frequencies may be compared.

Two-dimensional fast-Fourier transforms

A double Fourier analysis is applied to a digital elevation model (DEM) for the purpose of terrain analysis. The following discussion explains the procedure by example applied to an idealized simulated terrain.

In the case of a 1-d FFT, the coefficients were calculated for each row-value in a column vector. For the 2-d case, the FFT algorithm performs the calculations for each row and column vector in a matrix data set, but the concept is the same—surface undulations on a two-dimensional surface can be represented by a double sum of sinusoids, represented by the Fourier coefficients from the FFT of 2-d sinusoids. A 2-d sinusoid has the form (Peters, 2006)

$$F(r, c) = \frac{A}{2} \left\{ \cos \left[ \frac{2\pi}{\lambda} (r \cdot \sin \theta + c \cos \theta) + \phi \right] + 1 \right\}$$

where $r$ and $c$ are row and column values, respectively, $\theta$ is the angle with respect to the column axis (see Figure 13), and $\lambda$ is the wavelength. Equation (9) thus fully describes the amplitude, period, orientation, and phase of the wave.

The transform is given by
\[ F(r, c) = \sum_{r=0}^{R-1} \sum_{c=0}^{C-1} G(v, u) e^{+i2\pi \left(\frac{vr}{R} + \frac{uc}{C}\right)} \] (11)

where

\[ G(v, u) = \sum_{r=0}^{R-1} \sum_{c=0}^{C-1} F(r, c) e^{-i2\pi \left(\frac{vr}{R} + \frac{uc}{C}\right)} \] (12)

are the Fourier coefficients, and the exponential terms are the 2-d sinusoids. \( R \) is the number of rows, \( C \) the number of columns at the point \((v, u)\) in matrix space. In this scenario, it is important to note that the values of \( v \)-rows increases down, and the value of \( u \)-columns increases to the right, which plays a significant role in deciphering the direction of the wave fronts within the frequency domain of the Fourier transform.

Suppose that \( R = C = N \). Then the 2-d sinusoids at points \((v, u)\) are represented by the expression:

\[ e^{+/i2\pi \left(\frac{vr}{R} + \frac{uc}{C}\right)} = e^{+/i2\pi \left(\frac{vr+uc}{N}\right)} = e^{+/-\frac{2\pi\omega}{N}(r \cdot \sin \theta + c \cdot \cos \theta)} \] (13)

where

\[ v = \omega \cdot \sin \theta, \quad u = \omega \cdot \cos \theta, \quad \omega = \sqrt{v^2 + u^2}, \quad \theta = \tan^{-1} \frac{v}{u} \]

And \( v, u \) are the angular projections of the point \((v, u)\), \( \omega \) = distance to the point, and \( \theta \) = angle WRT the horizontal (u) axis

Figure 13. Schematic diagram showing how \( \omega, \theta \), and the direction of the wave front are related to a right-handed coordinate system.
The wavelength of the sinusoid is then \[ \lambda = \frac{N}{\omega} \] (14)

where \( N \) is the number of rows and columns.

For each point \((v,u)\), the power is the squared absolute value of the amplitude, given by the Fourier coefficients

\[ Power = |G(v,u)|^2 \] (15)

Figure 14, which shows a 2-d sine wave with an amplitude of unit 1 and \( R = C = 100 \) illustrates the technique. The domains of the image are divided into 10-degree sectors as shown schematically in Figure 15. The left-hand side of the figure accounts for information described by positive geomorphic trends in the data (with respect to a right-handed coordinate system; see Figure 12 above), and the symmetrical right-hand side accounts for information described by negative trends.

**Figure 14. 2-d artificial sine wave at 45 degrees with respect to the origin created in MATLAB**

Positive trends are those between 0 and 90 degrees with respect to the origin. Negative trends are 0 to -90 degrees, which is the same as 90 to 180 degrees. In MATLAB, once the 2d-FFT is performed and the power collected, the data are ‘flipped’ about the vertical axis and the
The process is repeated. The power spectra from both are then combined to give a complete power *distribution* between 0 and 180 degrees. In this way, all positive and negative trends are captured. Figures 16 and 17 show hypothetical waves and their front directions as well as corresponding plan-view power peaks in Fourier space. The positions of the peaks depend on the angles and wavelengths of the wave-fronts. The 2d-sine wave above is shown schematically in Figure 16b.

![Figure 15](image15.png)

*Figure 15. Schematic diagram showing how a domain of information is divided for 2-d FFT analysis. The left side will account for positive trends while the right side accounts for negative trends.*

![Figure 16](image16.png)

*Figure 16. Hypothetical wave-fronts and their directions—a) and b) are 45 degrees; c) and d) are 135 degrees. To the right of the wave-fronts are schematically diagramed power peaks in Fourier space—a) and c) represent low frequencies, b) and d) represent high frequencies. Notice how the peaks shift with these differences.*
Figure 17. Hypothetical wave-fronts and their directions—a) and b) are 0 degrees; c) and d) are 90 degrees. To the right of the wave-fronts are schematically diagramed power peaks in Fourier space—a) and c) represent low frequencies, b) and d) represent high frequencies. Notice how the peaks shift with these differences.

Figure 18. Mesh diagram of power spectrum from the 2-d FFT of the wave in Figure 13. Since the transform is symmetric, only information captured in the lower two quadrants need be analyzed. Information in the lower right, or ‘NEG’, quadrant was not visible previously since it is many times order of magnitude smaller. Theoretically, all the information should be contained within the ‘POS’ quadrant for this example.

Figure 18 shows two distinct peaks. The peak that occurs in the positive quadrant reflects the fact that the wave-front direction makes a positive angle with respect to the horizontal axis as shown in Figure 14. The other peak results from the Fourier transform being symmetric. Because of this symmetry, we are only interested in those quadrants labeled “POS” and “NEG” above, while the other two are removed.
Figure 18b-c shows the removed positive (18b) and negative (18c) quadrants re-plotted separately. The power that exists in the negative quadrant is an artifact of the transform probably due to either observational error or the wave not being \textit{exactly} an integer number of cycles. The negative power was not visible previously since the power contained in the positive quadrant is three orders of magnitude larger. The data are then binned according to what angled sector they located given by the inverse tangent of the row/column ratio (see Figure 13). Figure 19 shows the distribution of power as a function of angle WRT the x-axis, and we see that most of the power is contained at 45 degrees.

\textit{Wind data collection and processing}

Wind data were collected by use of a wind-cup anemometer attached to a data-logging device. The instrument is attached to a 4 m anchored tripod and is deployed near marker R-135 about 200 m landward of the shoreline. The sampling frequency is 1 Hz, and the maximum and average wind speeds along with average wind direction are logged every 10 minutes. The
direction of the instrument sensor was oriented with a brunton compass, adjusted for magnetic
declination of the area. Data collection occurred between June 18 to Dec 03, 2006.

HOBOware® software from the Onset Computer Corporation allows for rapid
visualization of the data as it plots the wind direction and speed on a dual axis. This format is
useful to analyze details of wind regime, although it is difficult to interpret the prominent wind
direction over a given time period. Analysis of wind direction frequencies was performed using
Georient™, a freeware package that can easily plot wind direction frequencies using a polar rose
diagram. The wind roses are classified by mean wind speed, and each ring in a sector represents
a percentage of the data (see Figures 34-38). The arrow on the plot indicates the resultant mean
direction and includes the 95% confidence interval (shown by the arc). Wind direction is always
reported in the direction the wind is coming from.

LIDAR data analysis and DEM’s

Pre- and post-Dennis topography and can be investigated using digital elevation models
(DEM’s), which are user defined grid data representing terrain elevations. The data come from
Light Detection and Ranging, or LIDAR, which measures the time it takes for a laser beam to
reach the surface and back to a source with a known differential GPS location. The pre-Dennis
LIDAR was collected from the University of Florida in 2004, while post-Dennis LIDAR data
was attained between July 08 and July 31, 2005 by the Joint Airborne Lidar Bathymetry Center
of Expertise (JALBTCX). For the raw data, vertical resolution is 1cm and horizontal resolution
is 0.00000001 degrees of longitude and latitude. Both data sets are in State Plane Coordinates
(SPC) with x,y,z, in feet (Gary Cook, pers comm.).

The data are loaded into the software package Transform®, in a 3-column x,y,z format,
then transformed to create a data matrix. The Transform software has an easy to use graphical
user interface and allows the user to choose the desired interval for gridding the data. In this
case, the data matrix was gridded to 5 ft in the northing and easting directions. The data are then
uploaded into MATLAB and plotted as a DEM.

A program was written in MATLAB to calculate elevation gradient using a forward finite
difference scheme and curvature by calculating the 4th derivative using a five-point stencil
scheme from DEM data matrix. Gradients are calculated across the north-south, east-west,
northeast-southwest, and northwest-southeast directions. The distribution was then be plotted as
a color relief map and also a frequency distribution. Frequency distributions were compared before and after Hurricane Dennis.

Pre- and post-storm matrices can be subtracted from one another to give changes in sediment redistribution for a given area. A column-wise (north-south) integration of the matrices allowed for quantification and determination of sediment mass balance.
CHAPTER 4

RESULTS

Transect data

The first figure for each transect shows the time-series profiles for that location. At the top of the plot area, significant vegetation, sand, and shell/debris pavement are summarized graphically. Vegetation is not quantified in this study. Subsequent graphs illustrate the profile changes occurring between measurement times; corresponding integrated volume changes are indicated as a positive or negative value in the upper left corner of the plot area. Axis-values on all plots are in meters. The heights represented in the figures are relative, and are not tied to any datum. Careful consideration is given when interpreting profile changes since translations in the dunes may plot as large changes in profile height and is not necessarily related to dune accretion. Therefore, volume changes may only be significant across the entire profile and not for any particular point. Volume change calculations were truncated with respect to the lowest number of data points for any given transect. The total profile change was calculated by integrating the difference between the first and last profiles for a given transect, again truncated to account for differences in transect length. Data collection for transects 4-7 were inhibited for a six month duration (Apr 06 – Sept 06) due to protected nesting birds.

Transect 4

Four profiles were acquired over a one year period (Oct 05, Jan 06, Mar 06, Oct 06). This transect was selected at this location since some vegetation already existed and because of its close proximity to a washover fan. The maximum relative dune height in October 2005 was about 30 cm, and that of October 2006 was about 66 cm. There are various extents of vegetation at the positions of each dune along transect 4 with an exception occurring between 65 – 70 meters, whereby the topographic expression in this region is not controlled by vegetation, and is a result of a sand shadow from a neighboring area that cuts across transect 4. Vegetation has partial control over the profile morphology of the dunes. For example, the width of the dunes roughly corresponds with the lateral extent of vegetation; the small extent of vegetation at the last dune correlates well with the dune’s narrow morphology (dune 4 in the Figure 20a). By examining profile change plots, it becomes apparent that the extent of erosion and translation is minimal near vegetation compared to the rest of the transect (Figure 20d-e).
The stability of the dunes appears to be inhibited with decreased vegetation; for instance the second dune, between about 40 – 55 meters (Figure 20a), is more susceptible to translations since the amount of vegetation is sparser, thus dune total vertical accretion is less. The last dune experiences lateral accretion as opposed to vertical accretion. Here, the vegetation is dense yet laterally narrow. Therefore, vegetation that is too dense may not allow for efficient dune accretion in the presence of abundant sediment supply. Where there is no vegetation, dune accretion or erosion is erratic as shown with the third dune between 65 and 70 meters.

Transect 4 accumulated +7.4 m$^3$/m of sediment between October 2005 and January 2006 over an 85 meter length. This value does not include the profile change in the last 10–15 meters for that time period since the initial transect length did not extend as far as subsequent measurements. Between January 2006 and March 2006, transect 4 accumulated +4.4 m$^3$/m of sediment over a 95 meter length. Again accumulation is predominant in vegetated areas.

The six months between March 2006 and October 2006 (Figure 20d) experienced sediment loss of -14 m$^3$/m over a 95 meter length. Although much of the erosion occurred in the first and last 20 meters of the profile, as well as near 45 meters, those areas in the vicinity of vegetation were eroded to a lesser extent. It is not possible to differentiate which months contributed most significantly to the loss though it is recognized that appreciable amounts of sediment were accumulated during the previous winter months.

The last plot in this series shows the total profile change from October 2005 to October 2006. The net erosion between October 2005 and October 2006 was -2.3 m$^3$/m across 85 meters of length, and would be much greater if erosion of the terminus of the washover deposit were considered. While most of transect 4 was subjected to a net loss of sediment, there was approximately 40 cm of sediment accumulation in the vicinity of the first dune where vegetation was extensive, whereas most of the erosion occurred where there was little to no vegetation. Overall, this area eroded at an average rate of -0.2 m$^3$/m per month. Most of the erosion is accounted for between March and October. Despite this, the region corresponding to the first well-vegetated dune (15-30 meters) accumulated an average of 0.3 m$^3$/m per month of sediment.
Figure 20. Transect 4 profiles (a), and volume changes (b-d) between successive measurements from Oct. 2005 to Oct. 2006.
There was an overall loss of sediment due to a storm event, except where prevented by vegetation between 15 and 35 meters.

**Transect-5**

Four profiles were acquired over a one year period (Oct 05, Jan 06, Mar 06, Oct 06). Transect-5 is located along a washover throat and fan about 10-15 meters east of transect-4. This location was chosen since it was devoid of vegetation compared to transect-4. The maximum relative profile height in October 2005 was about 0.22 meters and the minimum about -0.81 meters, while the October 2006 maximum height was 0.12 meters and the minimum -1.35 meters. The maximum height for the year, 0.32 meters, occurred in January 2006.

Most of transect-5 occurs along the throat of the washover deposit and is therefore nearly featureless. In fact, many of the dune-like features captured in the profile were due to the northwesterly accumulation of sediment behind vegetation about 10 meters to the eastward of transect-5. A notable exception was a dune that developed between March and October, 2006 (transect-5c between 77.5 and 82.5 meters). Here, a sharply-sloped dune had developed where a narrow patch of vegetation had taken hold.

Transect-5 lost 17.9 m$^3$/m of sediment over the one year period, much of which occurred from erosion of the washover fan that had penetrated the sound. Sediment loss was -5.2 m$^3$/m from October 2005 to January 2006, -5.9 m$^3$/m from January to March, 2006, and -6.9 m$^3$/m from March to October, 2006 over 95 meters of length. Across this area, sediment loss or accumulation was entirely random owing to the lack of vegetation where sand grains are free to move about. The least amount of change occurred in the first 20-25 meters since that area was covered by debris pavement. Because of the lack of vegetation in the area, and also the erosion of the washover fan, this area eroded at an average rate of -1.5 m$^3$/m per month. If the erosion of the washover fan is not included, then the average erosion rate is about -1.2 m$^3$/m per month.
Figure 21. Transect 5 profiles (a), and volume changes (b-d) between successive measurements from Oct. 2005 to Oct. 2006. The plots show continuous loss of sediment month-to-month due to lack of vegetation.
Figure 21 (cont.) Total volume change given in (e) indicates large net sediment loss. Transect 5 is located on a washover deposit devoid of vegetation.

**Transect-6**

Five profiles were acquired between October, 2005 and February, 2006 (Oct. '05, Jan. '06, Mar. '06, Dec. '06, Feb. '07). Transect-6 is located about 65 meters eastward of transect-5 and extends nearly 95 meters. There were two prominent dunes at this location, at the beginning and end of the transect, the latter of which (dune 2) changed very little. The dune 2 is remnant from overwash during the hurricane, evident by the steeply cut face with exposed root systems on the gulf-facing side and dense vegetation on the sound-facing side. It remained about 1.5 meters in relative height; the dunes again coincide with vegetation.

In contrast, the first dune formed during recovery after hurricane Dennis once vegetation took hold. The maximum height for this dune in October 2005 was 0.5 meters, while the maximum in February 2007 was 0.88 meters. The first dune nearly conserved its mass, starting low and broad, then ending taller but narrower. This conservation is visible in the total profile change plot where the graph coinciding with the first dune has a sinusoidal curve as the dune translated seaward.

Sediment volume change for the duration of measurements was about +12 m$^3$/m over a 95 meter length resulting in an average sediment accumulation rate to 1.0 m$^3$/m per month. Between October 2005 and January 2006, the profile increased sediment by +2.3 m$^3$/m, January to March 2006, +15.7 m$^3$/m, March to December 2006, -8.6 m$^3$/m and December 2006 to February 2007, -2.2 m$^3$/m. Most of the accumulation occurred shoreward of the scarped dune between January and March 2006, which was expected as the scarped dune face began to infill with sediment. The dune was able to retain the steep slope due to a dense network of vegetation roots that binds the sand.
Figure 22. Transect 6 profiles (a), and volume changes (b-d) between successive measurements from Oct. 2005 to Feb. 2007. Most of the sediment accumulation occurred between Jan. and Mar. 2006.
Transect-7

Four profiles were taken over a one year period between January, 2006 and February, 2007 (Jan. '06, Mar. '06, Dec. '06, Feb, '07). Located about 30 meters westward of transect-4, transect-7 also extends from the park road to the sound about 95 meters. There are two prominent dunes, both with vegetation to some extent. The maximum height of the dunes in January, 2006 was 45 cm and 69 cm; by February, 2007, they had grown to heights of 110 cm and 85 cm, respectively. While the second dune remained more or less stationary, the first dune shifted about 5 meters shoreward between March and December, 2006. This same shift occurred in transect-6 at the first dune during this time period.

Each profile and subsequent sediment volume calculation shows consistent vertical accretion of dunes between measurements. Most of the accumulation occurred between March and December, 2006 with a profile change of 12.0 m$^3$/m; the net accumulation for the year was 16.4 m$^3$/m. Between the two dunes was a significant amount of debris pavement without vegetation accounting for the lack of accumulation or erosion in that area. The growth may attributed to strong and consistent wins during the month of September, 2006, which had wind events in excess of 20 mph from the ENE and high frequency winds from SE to SW in excess of
10 mph, capable of moving fine-grained sand; the shifting of the dune 1 may be explained by the high frequency northerly winds greater than 15 mph during the month of November, 2006. The average sediment accumulation rate for this area was approximately $1.4 \, \text{m}^3/\text{m}$ per month.

Figure 23. Transect 7 profiles (a), and volume changes (b-c) between successive measurements from Oct. 2005 to Oct. 2007.
Figure 23. Profile change (d) and total volume change (e) for transect 7. Transect 7 experienced continuous dune growth in the vicinity of vegetation (5-25 m and 65-75 m) and no net change where lag deposit is present (35-60 m).

Transect-8

Seven profiles were acquired along transect-8 between May and December, 2006. This series of profiles began when study site 1 was temporarily inaccessible because of protected nesting birds. Transect-8 is located about 65 meters eastward of the easternmost parking lot and about 4 kilometers eastward of study site 1. The transect begins in a hummocky, secondary dune environment, previously eroded by overwash, and traverses shoreward 125 meters into the backshore. The trend is approximately east-west and is therefore not shore normal. There are four distinct physical settings in which transect-8 traverses: 1) 0 – 25 m, featureless sand and pavement; 2) 25 – 60 m, prominent secondary dunes; 3) 60 – 100 m, anthropogenically-vegetated backshore (nv on the plot indicates newly vegetated); 4) > 100 m, backshore and beach. The shoreline, mean sea-level, mean high-water and mean low water are not known explicitly. Individual profiles of transect-8 are plotted separately in Figure 25 to better highlight some of the changes.

The profiles along Transect-8 showed relatively little change during the eight months between May and February; most of the measured change occurred beyond 85 meters. Sediment transport in these areas is very dynamic due to lack of dense vegetation. There was a net
accretion of sediment between each month except June-July (-5.1 m$^3$/m) and October-December (-2.2 m$^3$/m). The loss of sediment between June and July can be explained by the local wind regime during that time. This period was relatively quiescent with an average wind speed of about 7 mph. Upon analyzing the wind data in more detail, it was noted that there were short intervals (60-230 min) of greater than 15 mph winds, and that these winds were usually from the NNW, or offshore, direction. Sediment loss may only occur locally, being redistributed and trapped by vegetation elsewhere, rather than being lost to the system (offshore).

The greatest accumulation occurred between September and October. Three strong wind events occurred during the month of October. Average winds speeds exceeded 20 mph for three days from October 16-19, with gusts around 26 mph. Wind directions during this time began from the NE, or shore parallel direction then shifted ESE, which is nearly shore-perpendicular. This strong wind event most likely supplied sediment from the beach to the backshore and subsequent dune field. Moreover, the October storm is responsible for the berm face (115 meters) and ridge and runnel system (135-155 meters), both visible in the profile (Figure 24a). The piling of sediment that created the berm is responsible for much of the net accumulation seen in the profile change graph between September and October; however, it is clear that 5-10 cm of sediment had accumulated in most of the transect.

The loss of sediment from October to December can also be explained by very large, northerly wind events occurring in early- and mid-November. It should be pointed out, however, that the top of the first dune still managed to accumulate 5-8 cm of sediment. Overall, this area accumulated a net of 10.8 m$^3$/m of sediment resulting in an average sediment accumulation rate of 1.2 m$^3$/m per month.

Excluding the beach and backshore (100-150 meters), all the accumulation occurred within vegetated areas. The area between 60 and 100 meters began as a non-vegetated sand and debris mix. Sea oats seedlings were planted uniformly in this region (60-100 meters) as part of a dune restoration project by park service personnel. Starting around mid June, 2007, they were about 10 cm in height and by February had grown 30 cm. It was observed that even this small density of vegetation has a marked effect on sediment accumulation (dune 4). As the sea oats continue to grow, it is expected that a new foredune will develop in time at the shoreward vegetation boundary, provided the region is not affected by tropical cyclones for some time.
Figure 24. Transect 8 profiles (a), and volume changes (b-d) between successive measurements from May 2006 to Aug. 2006. Volume changes are not considered beyond 120 m (the shortest transect).
Figure 24 (cont) Transect 8 volume changes (e-h) between successive measurements from Aug 2006 to Feb. 2007. Total volume change is given in (i). The high values between 85-120 m are due to newly planted sea-oats.
Figure 25. Plots of individual profiles of transect-8 (a–h) to show subtle differences that are difficult to see in the combined plot above. For each plot, no vegetation from 0-50m, mature sea-oats from 50-120m, immature vegetation from 120-200m. The beach begins at ~200m and extends toward the right. The immature vegetation was planted in June; by December, there is a noticeable step at the vegetation boundary (at 200m) where it is trapping wind-blown sand from the beach environment.
1-dimensional Fourier analysis of profile data

The purpose of performing Fourier analyses on profile data was to determine if this method could capture and quantify information pertaining to variations in dune height and their characteristic frequencies. This information alone, however, cannot shed light on any of the underlying processes governing such changes, and is not intended to do so. The intent is to demonstrate the technique and its applicability to rapid analyzation of remotely sensed data and how this might be useful in a coastal management perspective.

The following is a discussion on the results of the FFT on individual transects. Figures 26-30 show the results of the FFT on individual transects through time as a series of periodograms. In each, there is usually a dominant period, denoted by the maximum power, which tends to remain the dominant period through time. This can be explained by the simple reasoning that dunes, formed in the vicinity of vegetation, are inhibited from translations. The FFT analysis of all profiles were performed with respect to the shortest profile for a given transect. This was necessary to be able to accurately compare each profile of a particular transect, and only a small amount of information is lost.

Periodograms plot the distributions of harmonics (i.e., frequencies) that best describe the original functions (in this case, relative profile height). The minimum frequency that can be captured by this type of analysis is $\frac{1}{2 \cdot dx}$ where $dx$ is the sampling interval, and is often referred to as the Nyquist frequency (after Harry Nyquist). Meeting this criterion ensures that the harmonics used to reconstruct the original signal do not overlap, which would produce erroneous contributions to power plotted in the periodograms.

Recall that the power represented in a periodogram is equal to the squared absolute value of the FFT. Thus, higher power refers to greater deviation from the average value of zero (the average value of zero is obtained once any linear trend is removed from the transect.)
Figure 26. Periodogram stem plots of transect-4 from October, 2005 to October, 2006 resulting from FFT of 1-d topographic data. Most of the power is contained at ~30 m wavelength and increases through time as dunes accrete at that wavelength.
Figure 27. Periodogram stem plots of transect-5 from October, 2005 to October, 2006 resulting from FFT of 1-d topographic data. The low dune heights of transect-5 are represented well by the low values of power in the stem plots. A near featureless profile plots like that shown in d).
Figure 28. Periodogram stem plots of transect-6 from October, 2005 to February, 2006 resulting from FFT of 1-d topographic data. Although there are subtle changes in the power distribution, none are significantly remarkable.
Figure 29. Periodogram stem plots of transect-7 from January, 2006 to February, 2007 resulting from FFT of 1-d topographic data. Most of the power is dominated by a wavelength of ~32 m and is shown to increase through time (nearly doubling overall), along with the 25 m wavelength.
Figure 30. Periodogram stem plots of transect-8 from May, 2006 to February, 2007 resulting from FFT of 1-d topographic data. Changes to the power distribution vary significantly through time. Most of the changes are a result from changes occurring to the profile in the last 40 meters. Individual transects were analyzed with respect to the shortest transect in the series, therefore not all information for some profiles were captured.
Transect 4, (figures 26a-d)

The periodograms exhibit a characteristic wavelength of ~30 meters over the course of one year; this is qualitatively verifiable by examining the corresponding profile plot in Figure ___. For each periodogram in 19 a–d), the power at the 28m wavelength increases significantly from about 100 to nearly 300 corresponding to consistent increases in dune height through time. Another notable result is the apparent smoothing of the profile between October and January, 2005 (Figures 19 a and b). This is seen in the high frequency/low wavelength end of the spectrum where the power near 10 meters in October is reduced to near-zero values in January. This smoothing is accompanied by an increase of power at 17 and 30 meter wavelengths (whether or not these events are related is unknown). The smoothing appears to be a real effect, and not that caused random noise, again verifiable by inspection of the profile. It must be pointed out, however, that some peaks in periodograms themselves could be represented by noise, and the probability of this being true would have to be tested by one of a number of test statistics via Shuster’s test, Walker’s test, Fisher’s test, or others (Priestley 1997). It may therefore be prudent to examine only those peaks of power significantly far from zero unless such statistical testing is performed.

Transect 5, (figures 27a–d)

The dominant wavelength occurs at ~40 meters. Since transect 5 remained nearly featureless, the representative power is much lower for each profile versus the other transects. Changes in power are also quite variable through time, accounting for the instability of this part of the dune system, and is related to the lack of vegetation throughout this transect. The removal of sediment during a notable October storm in 2005 explains the marked reduction in power shown in figure 20d.

Transect 6, (figures 28a–e)

There is significant power at ~30 meters wavelength for transect 6, which remained fairly constant. There are some power shifts in the lower wavelengths that are also variable and are accounted for heavily shifting sands between the two stable dunes in the transect, which is, like transect 5, devoid of vegetation. The constancy of power at 30 meters reveals the relative static nature of the two dunes in this transect. Also noted is the lack of change in the periodogram between March and December, 2006 (figures 21c and d) whereby a large storm in October was
insufficient to lower the dunes in this transect (although significant seaward translation had occurred in the first dune).

**Transect 7, (figures 29a-d)**

Again the dominant power occurs near the 30-meter wavelength corresponding to the only two dunes in this transect. A marked increase in dune height is captured with a significant increase in power at this wavelength between March and December, 2006. The increases in power, however, is a result of increases in the height of the first dune in the transect, while the second dune had remained relatively constant. Considering that changes in a single dune can greatly affect the power obtained from the periodogram at multiple frequency bins, then periodograms cannot be specific about changes in height to individual dunes.

**Transect 8, (figures 30a-h)**

Of all the periodograms, those represented in transect 8 are the most variable. This is not trivial since, as discussed for transect 7, changes in single dunes can greatly affect the power. It is noted in this case, however, that height increases in smaller dunes near the end of the profile affected the power at different wavelengths, even in the presence of larger, stable dunes. For the most part, two dominant wavelengths are captured at 25 and 40 meters, and the dominance of one over the other varies through time. All of the shifts in power at one particular wavelength over the other are the result of changes in dune height in the last 40 meters of the profile. The previous 80 meters of the profile are well-vegetated and change very little in the duration of the study. In contrast, the last 40 meters include the then newly vegetated back-beach area, which is prone to the most growth (or erosion) being closest to the most energetic part of the beach.

To summarize, periodograms of profile data captured changes in relative dune height as well as changes in wavelengths by examining changes in power (or variance from the average value of zero) at specific wavelengths. However, such changes cannot be teased out to relate to any particular dune or any topographic expression within the profile, nor can morphologic details (relative sizes, shapes, etc.) relating to underlying processes. A sustained power at a particular wavelength over time may be interpreted as showing stability, or no net deposition or erosion. In the present study the dominant wavelength, in the presence of vegetation, is always around 30 meters (with the exceptions of transects 5 and 8). The dominant wavelength may also be an indicator of the distribution of vegetation since dunes in a back-barrier setting exist only in the
presence of vegetation and are inhibited from translation. This implies that if the dominant wavelength changes, and is sustained, then new vegetation may have taken hold.

2-dimensional Fast-Fourier Analysis on LIDAR data

A 2-D FFT was performed on LIDAR data to determine if geomorphic trends in topography could be captured and quantified. The results of the analysis are for a section of Pre-Dennis LIDAR data identified as having linear and successive topographic features; the same section of post-Dennis LIDAR was not analyzed since it is nearly topographically featureless. The main goal of this type of analysis was to compare average wind direction frequencies to the results of the 2-D FFT. Doing so may shed light on processes governing these features, or otherwise explore the notion of objectively capturing and quantifying trends not readily apparent in the DEM.

A section of pre-Dennis LIDAR data showing geomorphic lineation was selected for this analysis. Figure 31a shows the DEM selection without interpolation where the data density becomes apparent. Figure 31b shows the same selection filled with a linear interpolation and rotated 30 degrees via trigonometric transformation so that the shoreline (at bottom) is roughly parallel to the matrix boundary. A mesh plot emphasizes the topography as shown in Figure 31c; here, the DEM shows two discontinuous, shore-parallel foredunes at the bottom of the figure and smaller north-trending dunes (indicated by the arrow) near the top of Figure 31c. The wave-front angle is then perpendicular to this.
Figure 31. Pre-Dennis DEM selection for 2-D FFT analysis without interpolation (A), with linear interpolation and rotated 30 degrees clockwise (B), and with topography emphasized (C). Elevation in feet indicated by the color map in (A).
At this point in the discussion, it is critical to point out the difference in which Matlab chooses to plot data, depending on the command function used, and where the origin of the data is located. In the Methods section above, the example 2d-sine wave was plotted using the Matlab command `mesh`; in this plot, the origin is located in the lower left corner (see Figure 14). To view the DEM for the selected pre-storm LIDAR data, the command `imagesc` is used; in this graphic, the origin is located in the upper left corner. The consequence of this origin rotation results in a rotation of the overall domain of the DEM and the direction of the partitioning angles with respect to the origin, which has an effect on interpreting the 2D-FFT, which captures the angle of the assumed wavefront (not trend) of topographic features. Thus, for Figure 31c, it is expected that the wavefront angle is between 30 and 45 degrees with respect to the upper left corner of the domain, now represented in the schematic diagram shown in Figure 32; compare this to Figure 15 in the Methods section above.

The results from the 2D-FFT are represented as a stem plot in Figures 33a-c showing the power distribution as a function of angle with respect to the origin. The most outstanding feature of the plot is the peak at 90 degrees, which represents nearly 80 percent of the total power (Figure 33b). This peak power is representative of the two parallel foredunes, both of which are at much higher elevations than the surrounding dunes. Also noticeable are the overall higher percentages in power for positive angles (0-90 deg) than for negative angles (90-180 deg) implying that the linear back-barrier dunes, whose wave-front angles are about 30 degrees. The signal 90 degrees is removed in Figure 33c to emphasize the contributions of power from angles less than 90 degrees. Overall, most of the power is represented by features with wave-front angles being 90 degrees (which is the same as 180 degrees) or positive angles. This is visually comparable in the DEM. However, it is difficult to see any features with negative wave-front angles, yet they are clearly represented in the power distribution (albeit much smaller than the positive angles).

The difficulty with this type of analysis is the sensitivity by which geomorphic features can be captured. A major concern is that of bin leakage during the FFT. This is a natural consequence of the computation whereby some of the power at given frequency can ‘leak’ into an adjacent frequency which can be somewhat of a false positive. This may explain the significant amounts of power associated with the negative wave-front angles from above.

There are techniques to increase the sensitivity and decrease the error of the FFT analysis. These include detrending the data along the rows and columns of the DEM matrix,
using windowing functions (a way of smoothing via moving average), and analyzing signals with length that is a power of two to reduce leakage and end effects (Emory and Thompson 2004).

In summary, the results of the 2D-FFT analysis are ambiguous; the overall technique appears to work but is not refined enough to tease out much information. Although this type of data processing may be used to identify geomorphic trends, it does not appear to be useful unless supplemented by more sophisticated correction techniques such as windowing. Conceptually, a program could be written to automatically identify geomorphic trends from LiDAR data using 2D-FFT, and these results could then potentially be cross-correlated with meteorological data to measure the similarity between the two data sets. This is a venture that will be more rigorously explored in the future.

Figure 32. Schematic diagram representing the appropriate partitioning scheme for 2D-FFT analysis of DEM data, shown in Figure 31c.
Figure 33. Power distributions as a function of shore-parallel angle (A), normalized to total power (B), and without 90 degree harmonic (C), of pre-Dennis DEM data from Figure 24 above.
Wind data collection and processing

Presented below are rose diagrams (Figures 34-38) which illustrate the distributions of wind directions and speeds. There are two data sets, one collected by the land-based NOAA weather station *APCF1* in Apalachicola, Florida, which was retrieved using the National Data Buoy Center’s website and spans from July 01, 2004 to July 01, 2005. The other data set was collected *in situ* at SGI using a cup anemometer and spans from June 18, 2006 to December 03, 2006. The NOAA data were averaged per hour, while the in situ measurements were averaged every ten minutes. The diagonal black line on the rose diagrams represents the approximate orientation of the SGI shoreline, approximately NE-SW.

**NOAA wind data**

The mean wind speed of the NOAA data set was 3.3 m/s (7.4 mph) with a standard deviation of 2.3 m/s (5.1 mph). The maximum one-hour averaged wind speed was 17.5 m/s (39 mph), blowing from the east (84 degrees), which occurred near the beginning of October, 2004. Time-averaged wind speeds of greater than 5 m/s (11 mph) made up nearly 20 percent of the data, while speeds greater than 10 m/s (23 mph) made up only 2 percent of the data. Since the data are time-averaged, they represent the *minimum* amount of time the area experienced such wind speeds. Winds that exceeded 10 m/s were mostly from the ENE as shown in Figure 34a. In contrast, Figure 34b illustrates that moderate winds between 5 and 10 m/s tend to be more northerly.

Wind directions are variable but show seasonal trends. Warmer months (March-August) tend to have large southerly wind components while the cooler months tend to have more northerly components (Figure 27). The distribution within a single month can either be concentrated in a single direction (such as Dec. 04, Jan. 05, Jun. 05; Figures 35f, l, and g) or be highly variable (such as Mar-Apr-May 05, Figures 35i, j, and k). Moreover, the strongest winds are not always prominent; for example, the prominent wind direction in August, 2004 was from the southwest, yet the strongest winds were from northeast.

Of the twelve months, eight had significant wind directions from the north. This is also illustrated in Figure 36, as wind direction is distributed evenly except for north. The approximate orientation of SGI is roughly NE-SW. Winds that are shore perpendicular (especially from east and south directions) are important in supplying the backbarrier with sediment from the beach. Northerly winds are likely to be just as important in terms of dune
building processes; seeing as the trapping efficiency of vegetation is high, any sediment not bound by vegetation can be redistributed to areas with vegetation. However, the backbarrier acts only as a local sediment source implying that areas without vegetation may actually decrease in elevation while adjacent vegetated dunes would increase in height unless new sediment is supplied from the beach. This would likely be an annual, cyclic process whereby sediment is introduced from the beach to the backbarrier by summer E-SE-S winds, and is then redistributed by winter NW-N-NE winds. We can speculate that without vegetation, strong northerly winds—frequent throughout much of the year—would remove sediment from the barrier and deposit it offshore at rates higher than what may occur at present with vegetation.

Figure 34. One-year distribution of wind directions and corresponding speeds exceeding 10 m/s (a) and those between 5 and 10 m/s (b) of Apalachicola wind data, July 01, 2004 - 2005. Winds exceeding 10 m/s are mostly from the ENE and occurred at least 2 percent of the specified time, while more moderate winds (but still capable of moving sediment) occurred at least 20 percent of the time and are more northerly. Note the differences in the color scale.
Figure 35. Apalachicola monthly wind direction and strength from July 2004 to June 2005. Warmer colors indicate stronger wind (dark blue > 10 m/s). The seasonality of wind direction is evident; during warmer months the wind is from the south (onshore), while in cooler months winds from the north (offshore) tend to dominate. The solid black line indicates the approximate orientation of SGI. Data obtained from NOAA’s National Data Buoy Center.
Figure 36. Rose diagram of one-year wind directions and speeds at Apalachicola spanning July 2004 to July 2005. Overall, a higher percentage of the wind direction is between NNW and NNE; higher wind speeds are also more common in these directions. Data obtained from NOAA’s National Data Buoy Center.

**St. George Island wind data**

The St. George Island data show similar trends in wind direction as with the NOAA data (Figures 37a-d); During June 2005 (NOAA) and 2006 (SGI) winds were from the southeast, from the southwest during July-August and from the north during the winter months of both years. October was especially energetic, with an average wind speed of 3.8 m/s, maximum sustained (10 min) speed of 10.8 m/s, and gusts up to 19 m/s; winds that exceeded 5 m/s were consistently from the north. In contrast, wind speeds exceeding 10 m/s were from the southeast, but shorter lived. Table 2 lists descriptive statistics of the data for the time periods specified which shows higher mean and max wind speeds from summer to winter. Rose diagrams for the time periods corresponding with the time between transect measurements are shown in Figure 37, and those corresponding to Table 3 are shown in Figure 38.
Table 3. Descriptive statistics of SGI wind data. \textit{maxDir} is the direction the Max wind is coming from. There is an increase of mean and max wind speeds from summer to winter months.

<table>
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<th>Period</th>
<th>Mean (m/s)</th>
<th>Stdev (m/s)</th>
<th>Max (m/s)</th>
<th>maxDir (deg)</th>
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<td>1.7</td>
<td>10.0</td>
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<td>2.0</td>
<td>10.9</td>
<td>35</td>
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</tbody>
</table>

Figure 37. Wind directions and speeds on SGI from June 2006 to December 2006. Data collected from \textit{in situ} anemometer. The data are binned to correspond to the time between transect measurements. Dark blue > 5 m/s. The solid black line indicates the approximate orientation of SGI.
Figure 38. Rose diagrams for SGI wind data from June 14 – December 03, 2006, classified by wind speed in m/s.
Topographic, morphologic, and volumetric changes of St. George Island

Topographic and morphologic changes

St. George Island was drastically affected by storm surge and subsequent overwash from Hurricane Dennis. Figure 39 shows the pre-storm DEM created from 2004 LIDAR data. Here, the foredune complex, reaching elevations between 8–14 ft, is not wholly continuous but instead has many breaches and low elevations points along its front (Figure 40). The foredune complex consists of a two sub-parallel frontal dunes; the landward dune is likely a previous foredune. The areas of low elevation labeled in Figure 40 are most vulnerable to storm surge and likely act as conduits for the water to travel to the backbarrier via overwash throats (Figures 42 and 43).

Figure 42 shows the post-storm DEM from LIDAR taken shortly after Hurricane Dennis. The topographic changes are quite remarkable. Nearly the entire foredune complex in this part of the barrier was removed as a result of storm surge. Sediments comprising the dunes were displaced landward as a series of washover fans separated by overwash throats. The overwash throats appear to have a characteristic spacing which may very well correspond with the potential breach points shown in Figure 40. It is unclear, based on the DEM only, if sediments were deposited in St. George Sound for this section of the barrier (although it is noted that this indeed occurred in other, more narrow parts of the barrier near study site 1). It is also noted that the eastern end of this section (Figure 43b) had significantly fewer overwash throats than western end. This may be explained two ways: 1) the foredune complex is, on average, ~2 ft higher in elevation thus providing more sediment to be redistributed as a washover fan/apron, and 2) there are fewer breach points along this portion of the foredune which impedes the development of overwash throats since it is less likely that water energy becomes concentrated and flow channelized.

The post-storm DEM was subtracted from the pre-storm DEM to provide and elevation change map (ECM) shown as Figure 44. Any non-overlapping data points were removed prior to the subtraction. The ECM not only emphasizes the removal of the foredunes, but also highlights a general widening of the beach not recognizable between the pre- and post-storm DEM’s. Washover deposits are also more highlighted. Beach widening is evident in most locations along the shoreline. Areas highlighted in warm colors indicate deposition of sediment; therefore, a significant volume of sediment did not remain offshore during overwash.

Pre- and post-storm profiles were extracted from the DEM’s across transects indicated by the white and black lines in Figure 46c, and are presented in Figure 47a-f and Figure 48a-b.
In addition to the beach widening, a post-storm ridge and runnel system has developed, which is
typical, and evident in each profile. Each profile shows the removal of the foredune complex
and the deposition of a washover deposit. The washover deposits tend abruptly terminate
landward, seen by the sharper gradient, suggesting that washover penetration may not have
reached the sound. It is interesting to note that despite the removal of the foredune, some
sections of the profile in Figure 47e maintained its original morphology between the original
foredune and the washover deposit. Perhaps more sediment was moved offshore, or laterally.
The large scour marks in each of the profiles denotes the road surface, most of which was
washed away. There was 1-2 ft of erosion at the road surface boundary which is highlighted as a
‘trench’ in the mesh plot of Figure 49b.

Figure 46c shows the profiles taken across the black lines to compare the cross-sectional
morphologies of an overwash throat (47a) and fan (47b). There are some distinct differences
with these profiles from the previous profiles. Across the throat, the profile is relatively flat,
with a lack of any significant washover deposit. Likewise, there is also a lack of beach widening
at this point. Perhaps the same holds true for other overwash throats. In both profiles, there
seems to be a lack of scouring seen in previous profiles.

While all of the aforementioned profiles display the removal of the foredunes, there is
one notable exception. Figure 35b shows a single remnant dune that survived the storm surge.
Upon taking before and after profiles, it was discovered that the post-storm profile had actually
increased in height (Figure 41c). The mechanism by which this happens is unknown, but is it
possible that sediment is deposited during wave run-up? There is a possibility that the data
lacked sufficient post processing and is therefore capturing vegetation that might have survived.

Volume changes

The net change in elevations can be integrated to obtain a volume changes which serve as
a proxy for net erosion or deposition occurring across the barrier. The volume change was
estimated by numerically integrating the shore-normal column values of the ECM; positive
values indicate net deposition while negative values indicate erosion. The results are plotted in
Figure 45b. Approximately 80 percent of this section of the barrier underwent a net volume
change implying net erosion. This estimate is complicated, however, by the fact that it does not
include the non-overlapping portions of the DEM’s. Further distorting the true value is the effect
of existing vegetation represented in some parts of the post-storm DEM, which give anomalously
high values making some parts of the ECM summation to appear as net deposition. The average volume change was for a given shore-normal transect was \(-89 \text{ ft}^3/\text{ft}\) with a standard deviation of \(136 \text{ft}^3/\text{ft}\). A smaller section of the DEM data set (white boxes in Figure 46a and b) was also integrated to obtain volume changes for comparison. Here, there was an average net loss of \(-47 \text{ ft}^3/\text{ft}\) with a standard deviation of \(134 \text{ ft}^3/\text{ft}\) for any given shore-normal transect. The integration is plotted in Figure 46d. The total volume lost represented in Figure 45 was estimated at \(-100,000 \text{ ft}^3/\text{ft}\), while the loss represented in Figure 46 was about \(-14,000 \text{ ft}^3/\text{ft}\).
Figure 39. Pre-Dennis DEM, 2004. The most noticeable feature is the shore-parallel foredune complex, which is not always continuous, but instead has many breaks and low elevation points.
Figure 40. Close-up view of boxed area in Figure 31. The overwash potential becomes amplified by weak areas in the foredune complex.
Figure 41. Post-Dennis DEM, 2005 immediately after Dennis made landfall. The entire foredune complex, save one small area, was overwashed. Washover fans and aprons, and overwash throats are ubiquitous. Sections were the road used to be is also visible by the lower elevation centered in the DEM. More overwash throats occur at the western end of the barrier because of the lower elevations of the foredune complex and increased number of breach points.
Figure 42. Magnified view of the boxed area in Figure 33. Here, the morphology is characterized by a series of alternating washover fans and overwash throats.
Figure 43. Magnified views of the eastern end of the barrier for pre-storm (A) and post-storm (B) DEM’s. Overwash throats are less common, and much of the low lying areas in (A) are now filled with sediment.
Figure 44. Elevation change map resulting from the subtraction of the post- and pre-storm DEM’s. Warm colors indicate deposition while cool colors indicate erosion. Here, erosion of the foredune complex is clearly visible. A general widening of the beach and washover deposits are also easy to see in this way.
Figure 45. Elevation change map with corresponding volume changes. Approximately 80 percent of the corresponding length resulted in a net loss of sediment. Net sediment loss is amplified (negative values) at narrow parts of the barrier, at overwash throat locations and at locations without any beach widening. Total volume change represented here is estimated at -100,000 ft$^3$/ft.
Figure 46. Pre- and post-storm DEM’s (A) and (B) respectively with magnified area (C) for profile and corresponding volume change analysis (D). Profiles extracted at the white and black line transects. Total volume change for (C) was estimated at -14,000ft³/ft, but includes only data within the control boxes of (A) and (B). Significant losses occurred where the barrier was narrow or where an overwash throat was present.
Figure 47. Extracted profiles from (white lines) from Figure 38c. Extraordinarily, the profile in (E) had retained its original morphology (between 100-120) despite the removal of 6 feet of foredune material.
Figure 48. Profiles across an overwash throat (A) and washover fan (B) (black lines in Figure 38c). In (A), the post-storm profile is quite flat, lacks a significant washover deposit, and lacks significant widening of the beach. The original beach morphology in (A) is also retained post-storm. In (B), the termination of the washover fan is apparent. There is very little scouring near the road at these locations (compare to above).

Figure 49. Mesh plots of the boxed sections in Figure 38 a. and b. This illustrates the major morphological changes to the barrier and the penetration and distribution of overwash sediments. Scouring near the road is severe (1-2 ft).
Figure 50. A bizarre circumstance; (A) and (B) are mesh plots of the small area surrounding a surviving portion of a foredune (see Figure 35 b). The profiles in (C) reveal that not only did this retain much of its original morphology, but there is also an increase in elevation of the remnant dune by as much as 2 feet.
Gradient and curvature analysis

The goal of this analysis is to estimate the recovery of barriers after large storm events with the understanding that flatter topography should have a gradient and curvature distribution more closely centered on zero. Skewness, \(S\), (asymmetry) and kurtosis, \(K\), (peakendess) are calculated to quantify pre- and post-storm changes to the distributions (Table 3), where

\[
S = \frac{\sum_{i=1}^{N} (X_i - \bar{X})^3}{(N - 1)\sigma^3} \quad (16)
\]

\[
K = \frac{\sum_{i=1}^{N} (X_i - \bar{X})^4}{(N - 1)\sigma^4} \quad (17)
\]

and \(N\) is the number of samples, \(X_i\) is sample value, \(\bar{X}\) is the mean, and \(\sigma\) is the standard deviation.

The gradients, \(G\), for the x-, y-, left oblique and right oblique directions were numerically calculated using a central difference scheme for pre- and post-storm DEM data. Curvature, \(C\), was calculated using a 5-point stencil for second derivatives (Figure 51) using the numerical formulae,

\[
G_{R,C} = \frac{\partial f}{\partial x} = \sum \frac{(f_{R,C+1} - f_{R,C-1})}{2\Delta x} \quad (18)
\]

\[
C_{R,C} = \frac{\partial^2 f}{\partial x^2} = \sum \frac{(f_{R+1,C} + f_{R-1,C} + f_{R,C+1} + f_{R,C-1} - 4f_{R,C})}{4\Delta x^2} \quad (19)
\]

where \(R\) and \(C\) are row and column values, respectively, \(\Delta x\) is the cell width (here 5ft), \(f\) is the value of the elevation for a given \(R,C\).

The maximum gradient was selected for each point in every direction which can then be used to build pre- and post-storm maximum slope maps as shown in Figures 52-55. The distributions are then normalized, binned, plotted and compared against each other.

In Figures 52-53 the highest pre-storm gradients (for any given direction) are distributed among the foredunes and along the shoreline. In Figures 54-55 the highest post-storm gradients are distributed primarily among the road surface boundary where it was scoured, and along the terminating boundaries of washover deposits. To plot the distributions, the data were binned between -1 and 1 with a bin spacing of
0.01 to give 200 bins; proper bin spacing is important in capturing the correct shape of the distribution curve (Figure 45). Greater than 95 percent of the data fall between -0.2 and 0.2 and are plotted as such.

Figure 47 shows the distributions for the pre- and post-storm N-S (vertical, or ‘y-gradient’), E-W (horizontal, or ‘x-gradient’), NW-SE (left oblique), and NE-SW (right oblique) gradient directions. In Figures 57a and b, the pre-storm x and y distributions have broad shoulders that have an inflection point as the curves go from convex to concave then peak sharply about a zero gradient. The post-storm distributions do not inflect their curves and have increased peakedness. The trends are similar for the curves in the oblique directions, curvature, and maximum gradient except the pre-storm curves also do not inflect. Also, skewness values increase from pre- to post-storm, implying a greater distribution of positive gradients. This can be visually confirmed by looking at the slope maps whereby the pre-storm slope maps have more negative slopes (blue) than in post-storm slope maps. Of greater importance however, is that in general, all the distributions have in increase in kurtosis except in the y-direction (Table 4); this numerically verifies a flattening of topography. With a controlled methodology, this technique could supply useful information about the recovery state of barriers on the whole, since it is difficult to assess the status of smaller, hummocky secondary dunes. Future distributions that approach pre-storm distributions would imply that dunes are reaching their pre-storm state; this should be used in conjunction with other monitoring techniques, however.

Figure 51. Stencil representing cells in a DEM used for gradient and curvature calculations (equations 17 and 18).
Figure 52. Map of the maximum calculated gradient between the x-, y-, left and right oblique directions. The shoreline (highlighted in blue) has mostly a negative gradient for any given direction, while the dune complexes are mixed. The area seaward of the shoreline is not land, but signals returned from LIDAR collection and of the water surface that had not been post-processed fully. The gradients are higher and more concentrated near the east end of the island compared to the west end. North is edge vertical.
Figure 53. Magnified view of the lower left corner of Figure 43. Visible are the shoreline, road surface, foredune complex, and secondary dunes.
Figure 54. Overview of the maximum gradient map from the post-storm DEM. The highest gradient are now more closely distributed around the terminus of washover deposits, and also near the road surface.
Figure 55. Magnified view of the lower left corner from Figure 45. The darker circles, anomalously high, are vegetation, while a boardwalk (used to access the beach without trampling the dunes) is visible in the lower left.
Figure 56. Comparison of distributions using a bin spacing of 0.05 (A) and 0.01 (B). The geometry of the curves in (B) is much more accurate of the true distribution, and that a lower percentage of gradients are distributed around zero.
Figure 57. Resultant gradient distributions calculated in various directions. Overall, skewness and kurtosis increase pre- vs post-storm implying a shift toward more positive gradients and flattening of topography, respectively, for a given direction.
Figure 58. The distribution of curvature (A) and maximum gradient (B). Here the results are the same, a positive shift in skewness and increase in peakedness. The maximum gradient is the maximum chosen gradient for each point in the data matrix between the four directions given.
Table 4. Skewness (a measure of asymmetry) and kurtosis (a measure of peakedness) for the pre- and post-storm distributions of gradient and curvature. Aspect refers to the following: gradient in the x- (X), y- (Y), left oblique (L), and right oblique (R) directions, the curvature (C), and maximum (M) of all gradient directions. Also given is the percent change of pre- to post-storm values for each aspect. A positive skewness is skewed to the right and negative to the left; a skewness of zero means the distribution is symmetric. Higher values of kurtosis implies more peakedness to the distribution. Here, we see that the distributions consistently become more right-skewed and more peaked from pre- to post-storm (with the exception of kurtosis in Y). Increases in peakedness verify a flattening of topography.

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CHAPTER 5

DISCUSSION AND CONCLUSION

This thesis examined the short term recovery rates of secondary dunes on St. George Island and their relationship to vegetation and wind, and also characterized some of the morphological and volumetric changes to the barrier before and after Hurricane Dennis using available LIDAR data. Additionally, it also examined the viability of using numerical methods to help characterize such changes and also the potential state of recovery of a barrier system via Fourier analysis and gradient analysis.

Transect measurements were initiated about 3 months after Dennis made landfall. Recovery rates from that time to about one year afterward varied from -1.5 m$^3$/m per month to about 1.2 m$^3$/m per month across the transect. However, it can be said that individual dune recovery rates were nearly always positive despite overall erosion for some transects. These rates tended to be around +0.5-1.0 meters for the year and are a direct result of the trapping efficiency of vegetation. In this environment, dunes form in the presence of vegetation and as such, the spatial extent of the dunes matches that of the vegetation. Since vegetation traps sediment by increasing surface roughness, dunes tend to be inhibited from any significant translations; therefore, dune morphology may be directly related to vegetation distributions and also explains the somewhat random appearance of secondary hummocky dunes.

The availability of sediment to supply a dune may also be inhibited by vegetation. For example, onshore winds, which would normally provide sediment during the summer months, become trapped at the vegetated boundary of a newly developing foredune. This effectively retards sediment mobility to secondary dunes landward of the foredune vegetation boundary. If the barrier contains pockets of vegetation (as is our case), then it is likely that those areas without vegetation act as a local sediment source to the dunes from any prominent wind direction and strength sufficient to mobilize the sand; the vegetation is efficient at trapping sand from any direction. As such, after a large storm has deposited sediment to the backbarrier, then the recovery of the secondary dunes depends primarily on the presence of vegetation and the ability of wind to redistribute the sediment throughout the year. Indeed if the recovery rates are high in the initial few months after overwash events and slow after some time, then perhaps it is due to
the new colonization of plants (randomly?) which rapidly propagate, thus attenuating sediment flux across the barrier through time.

A pavement consisting of mostly asphalt rubble and shell material, resulting from overwash, usually inhibited change of any kind. Where the pavement existed, there were no significant increases or decreases in dune height. Related is the lack of any new vegetation in these areas even through a 1 year period. The may be some fundamental mechanism that presence of this pavement inhibits new vegetation growth, and thus dune growth. Ways to remove this pavement may be important to the long-term recovery of secondary dunes.

Fourier analyses of profiles were able to capture changes in dune height and the wavelengths corresponding to those changes. It cannot, however, give any insight into the morphological changes occurring through time and may only be used to indicate deposition or erosion at a particular wavelength (or possibly that the dominant wavelength is also an indicator of vegetation distribution changes). The 2-D Fourier analysis of LIDAR data yielded poor results in terms of the resolution capable of capturing morphologic trends, but worked well for an ideal case, although the method of 2-D signal processing is well-known and works well in many other applications (especially image processing, conversion to .juegos, etc). Therefore the technique employed here may be too crude and more sophisticated and robust methods need to be used, such as the p-Welch method, windowing, etc., to maximize the resolution capabilities.

St. George Island experienced major erosion. The most significant morphologic changes across the barrier were the sheer removal of the foredune and secondary dune complexes and development of numerous washover fans, aprons, and overwash throats. Storm surge for the area was approximately 7 feet above the predicted tide, and combined with wave run-up, was more than sufficient to inflict costly damage to the barrier. The potential for overwash seemed to increase where the foredunes were either discontinuous and/or low in elevation, recognized by an increase in the number of washover deposits and corresponding overwash throats. These areas are likely to initialize the channelization of water flow, concentrating the energy and increasing sediment loss to the area. These areas also showed a lack of beach widening, and the distribution of sediment may have occurred just as much offshore as onshore based on the lack of washover penetration based on the accompanying profiles.

The analyses of gradient and curvature distributions seemed to work well and made sense physically. Post-storm topography is flatter and therefore gradient and curvature distributions become narrower and more centered around zero. This could be a useful tool for determining the
future state of recovery of the barrier as a whole since it is difficult to obtain detailed information of secondary dunes across the entire barrier.
REFERENCES


BIOGRAPHICAL SKETCH

Anthony Michael Priestas was born November 4, 1975 in Sandusky, Ohio, and raised in west central Gulf coast of Florida between Pinellas and Pasco Counties. He graduated from Gulf High School in June of 1993 in New Port Richey, Florida, where he was active in the Naval ROTC program. He enlisted in the Florida Army National Guard in July 1993, and was honorably discharged after nine years of service as a generator mechanic. He enrolled at St. Petersburg College, Tarpon Springs, FL in 2000 and completed an A.A. degree (with honors) before transferring to Florida State University in fall 2002. He graduated from FSU in summer 2005 as a dual-major in Geology (with honors, cum laude), and Interdisciplinary Geophysics (cum laude), and completed an honors thesis under the direction of Sherwood Wise, Jr. He enrolled in the FSU graduate program in Geology as a master’s student in fall 2005 under the direction of Sergio Fagherazzi. He is currently working toward his PhD, studying salt marsh systems and dynamics with Professor Fagherazzi at Boston University. Anthony has one older brother, Thomas.