In the past, classification systems for the analysis of morphodynamic variability have been developed in an attempt to understand large scale coastal behavior. The motivation behind the creation of these classification systems has been to provide a framework of analysis, in order to understand large scale response to seasonal variability, changes in incident wave conditions such as wave angle and height, and other forcing parameters. These schemes have, in general, been based upon subjective observation of wave breaking patterns and subsequent classification into discrete morphological states. Although these systems provide understanding into the morphodynamics of beaches, they are limited by their qualitative nature and by the inability to describe subtle changes in conditions as beaches progress within a given state.

In this study, an objective and quantitative evaluation system of morphodynamics was developed, thus allowing for a more complete analysis of beach variability. The data for this study was provided by the Argus network, a
series of video cameras with aerial views of beaches around the world. Intensity contrasts in time exposure images reveal areas of preferential wave breaking, which research has shown is closely tied to the underlying bed morphology. Morphometric statistics describing the range of variability within theses breaking patterns were developed, thus allowing quantitative differentiation of morphological condition. Because each of the numerical statistics is continuous, morphodynamic change could be analyzed over the entire range of conditions without losing information to the process of categorization.

Once statistics were developed, the analysis system was applied to images from four of the Argus camera sites. Relationships between changing wave conditions and alteration in morphometric statistics were analyzed, along with cyclical patterns in seasonal variability. Large scale response patterns found at each site were compared to each other, thus allowing for some broad generalizations to be made about large scale coastal response to changing environmental conditions.
Quantitative Analysis of Nearshore Morphological Variability
Based on Video Imaging

By
Patricia Soupy Alexander

A THESIS
Submitted to
Oregon State University

In partial fulfillment of
The requirements for the
Degree of

Masters of Science

Presented August 27, 2001
Commencement: June 2002
Master of Science thesis of Patricia Soupy Alexander presented on August 27, 2001

Approved:

Redacted for privacy

Major Professor, representing Oceanography

Redacted for privacy

Dean of College of Oceanic and Atmospheric Sciences

Redacted for privacy

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Redacted for privacy

Patricia Soupy Alexander, Author
ACKNOWLEDGEMENTS

"Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world."
- Albert Einstein

It is my experience that Einstein was right about knowledge and imagination and their relative importance in the world. So, I would like to thank my advisor, Rob Holman, not only for the knowledge he has given me about nearshore science, but more importantly for fostering my imagination: specifically, the image I had the first day I arrived ("well, I would think if you want to understand everything about beaches, you’d just...").

"There are two ways to write error-free programs. Only the third one works."
- Anon.

I would also like to thank John Stanley for all his technical support, for without John, the lab just wouldn’t be the same (eh, Bruce?). Thanks to the Argus world for all their support, as well, and for always responding to every email I sent that started with “So, I’ve got a favor to ask...”. At this point, I owe a small microbrewery’s worth of beer to people from at least three continents. In particular, thanks to Graham Symonds for all the insight while I was in Australia, and for making my trip there incredibly enjoyable and memorable (and kangaroo attack free). Thanks to my fellow students, Chris, Joe, and Hillary, for advice and understanding. Thanks to our RA’s, Drew and James, for their insight and for greasing the wheels of Argus image preparation. Speaking of which... thanks to the wheels (uh, I mean, undergrads), Dan, Kristian, David, and especially Logan,
for all their hard work. Logan may never be able to look at a picture of the Netherlands again.

"No matter how many communities anybody invents, the family always creeps back."
-Margaret Mead

Thanks also to my family for all of their support. In particular, thanks to my mother for always reassuring me that it would be worth it in the end. Verdict’s not in yet, I suppose, but I certainly appreciate her reassurances anyway.

"A friend is one who knows you and loves you just the same."
-Elbert Hubbard

To all my friends from Corvallis: Kyle and Tyra, Billy and Nicole and everyone from Michael’s Landing and Suds ‘n’ Suds (including Mick), thanks for giving me a little life to call my own outside of school. Thanks to Stacy and Laura for not kicking me out of their office, and to Stacy, for the occasional chocolate vehicle. Thanks very, very, very much to all my good fire-ant friends from ‘back home’: Anna, thanks for moving to Washington, for introducing me to snowboarding, and for just burnin’ incense. A.J., thanks for never once even mentioning how you have a cool oceanography job with the same degree I had before I started here, and for “weekly inspirations”. And, of course, Chris. Thanks for everything, and for leaving me the option of running away to New Hampshire. That brewery will happen one day yet, just wait!!!

"Money is the most egalitarian force in society. It confers power on whoever holds it."
-Roger Starr
The research behind this thesis was funded by the Office of Naval Research, grant #N00014-96-10237.

Finally, thanks to winter in the Rocky Mountains, without which this thesis may never have happened.
# TABLE OF CONTENTS

1. INTRODUCTION .............................................................................1  
   1.1 Overview of Problem .................................................................1  
   1.2 Previous Classification Schemes ................................................3  

2. DESCRIPTION OF DATA SET ....................................................13  
   2.1 The Argus Program .....................................................................13  
   2.2 Description of Field Sites ..........................................................16  
      2.2.1 Noordwijk, The Netherlands .............................................17  
      2.2.2 Agate Beach, Oregon, United States .................................19  
      2.2.3 Duck, North Carolina, United States .................................21  
      2.2.4 Palm Beach, New South Wales, Australia ..........................22  

3. ANALYZING IMAGES ...................................................................24  
   3.1 Extracting Features .....................................................................24  
      3.1.1 Images Used For This Study .............................................24  
      3.1.2 Image Preparation ...........................................................25  
      3.1.3 Locating the Shoreline .......................................................26  
      3.1.4 Extracting Sand Bar, Terrace, and Rip Channel Locations ....32  
   3.2 Observational Limitations ..........................................................39  
      3.2.1 Investigation of Breaking Criterion Over Known Bathymetry ......40  
      3.2.2 Estimated Window of Viewing Possibility............................45  
      3.2.3 Effects of Tidal Variation on Bar Location ............................49  
   3.3 Statistical Analysis of Argus Images ..........................................51  
   3.4 Analysis of Variability ..............................................................56  

4. RESULTS .....................................................................................61  
   4.1 Noordwijk, The Netherlands ....................................................61
TABLE OF CONTENTS (continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.1 Environmental Statistics</td>
<td>62</td>
</tr>
<tr>
<td>4.1.2 Morphometric Statistics</td>
<td>63</td>
</tr>
<tr>
<td>4.1.3 Relationships Between Environmental and Morphometric Statistics</td>
<td>65</td>
</tr>
<tr>
<td>4.2 Agate Beach, Oregon, United States</td>
<td>67</td>
</tr>
<tr>
<td>4.2.1 Environmental Statistics</td>
<td>68</td>
</tr>
<tr>
<td>4.2.2 Morphometric Statistics</td>
<td>69</td>
</tr>
<tr>
<td>4.2.3 Relationships Between Environmental and Morphometric Statistics</td>
<td>77</td>
</tr>
<tr>
<td>4.3 Duck, North Carolina, United States</td>
<td>80</td>
</tr>
<tr>
<td>4.3.1 Environmental Statistics</td>
<td>81</td>
</tr>
<tr>
<td>4.3.2 Morphometric Statistics</td>
<td>82</td>
</tr>
<tr>
<td>4.3.3 Relationships Between Environmental and Morphometric Statistics</td>
<td>88</td>
</tr>
<tr>
<td>4.4 Palm Beach, New South Wales, Australia</td>
<td>91</td>
</tr>
<tr>
<td>4.4.1 Environmental Statistics</td>
<td>92</td>
</tr>
<tr>
<td>4.4.2 Morphometric Statistics</td>
<td>93</td>
</tr>
<tr>
<td>4.4.3 Relationships Between Environmental and Morphometric Statistics</td>
<td>96</td>
</tr>
<tr>
<td>4.5 Discussion</td>
<td>98</td>
</tr>
<tr>
<td>5. CONCLUSIONS</td>
<td>107</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>110</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Beach profile terminology. From Komar, 1998</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Beach divisions based on wave breaking. From Komar, 1998</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>Wright and Short beach states. From Wright and Short, 1983</td>
<td>6</td>
</tr>
<tr>
<td>1.4</td>
<td>Modifications of Wright and Short classification scheme by Lippmann and Holman. From Lippmann and Holman, 1990</td>
<td>8</td>
</tr>
<tr>
<td>1.5</td>
<td>Pictures of the Lippmann and Holman beach states. From Lippmann and Holman, 1990</td>
<td>9</td>
</tr>
<tr>
<td>2.1</td>
<td>An example of an Argus snapshot from Palm Beach, Australia</td>
<td>13</td>
</tr>
<tr>
<td>2.2</td>
<td>An example of an Argus time exposure from Palm Beach, Australia.</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>An example of an Argus time exposure from Duck, North Carolina. Note the single linear offshore sand bar</td>
<td>14</td>
</tr>
<tr>
<td>2.4</td>
<td>An example of an Argus rectification of Duck, N.C., created by merging the views from five cameras</td>
<td>15</td>
</tr>
<tr>
<td>3.1</td>
<td>The circle which will form the basis of the straightened frame of reference for Palm Beach, Australia</td>
<td>25</td>
</tr>
<tr>
<td>3.2</td>
<td>Illustration of the transformation of coordinates method</td>
<td>26</td>
</tr>
<tr>
<td>3.3</td>
<td>An example of an Argus image of Palm Beach in both the original and straightened frames of reference</td>
<td>26</td>
</tr>
<tr>
<td>3.4</td>
<td>A high and low tide image taken on the same day at Duck, N.C.</td>
<td>27</td>
</tr>
<tr>
<td>3.5</td>
<td>The intensity difference between the images shown in figure 3.4.</td>
<td>27</td>
</tr>
<tr>
<td>3.6</td>
<td>An illustration of tidal change overlaid on bathymetry</td>
<td>28</td>
</tr>
<tr>
<td>3.7</td>
<td>A close up of the region of tidal change</td>
<td>28</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>3.8.</td>
<td>Intensity difference between the high and low tide images overlaid on bathymetry and water level</td>
<td>29</td>
</tr>
<tr>
<td>3.9.</td>
<td>The difference between the shoreline location found by the intensity differencing technique and by bathymetric survey</td>
<td>30</td>
</tr>
<tr>
<td>3.10.</td>
<td>An example of a cross shore intensity profile</td>
<td>32</td>
</tr>
<tr>
<td>3.11.</td>
<td>The three dimensional convolution of Gaussian standard deviation, cross shore location, and convolution energy.</td>
<td>33</td>
</tr>
<tr>
<td>3.12.</td>
<td>Energy of convolution at each cross shore location summed over the possible Gaussians widths at that location</td>
<td>34</td>
</tr>
<tr>
<td>3.13.</td>
<td>The peaks of the intensity Gaussians identified with convolution analysis</td>
<td>34</td>
</tr>
<tr>
<td>3.14.</td>
<td>The resulting sand bar that has been identified by grouping the peaks in figure 3.13.</td>
<td>35</td>
</tr>
<tr>
<td>3.15.</td>
<td>The complex bar bifurcations often seen at Agate Beach that can make bar sorting difficult</td>
<td>36</td>
</tr>
<tr>
<td>3.16.</td>
<td>Palm Beach rips with clearly defined rip heads</td>
<td>38</td>
</tr>
<tr>
<td>3.17.</td>
<td>Palm Beach rips without rip heads</td>
<td>38</td>
</tr>
<tr>
<td>3.18.</td>
<td>Intensity (magnified by 2) and calculated $\gamma$ (magnified by 3) over known bathymetry</td>
<td>42</td>
</tr>
<tr>
<td>3.19.</td>
<td>Examples of gamma at high (*) and low (+) tide.</td>
<td>43</td>
</tr>
<tr>
<td>3.20.</td>
<td>Profile of probable depth with bar for Duck, N.C.</td>
<td>46</td>
</tr>
<tr>
<td>3.21.</td>
<td>$X_{\text{max}} - B_{OL}$ for cases where the bar is visible (upper) and not visible (lower) for Duck</td>
<td>48</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.22.</td>
<td>Breaking depth changes with tidal elevation change at Duck, N.C.</td>
<td>49</td>
</tr>
<tr>
<td>3.23.</td>
<td>A view of Duck, N.C., with both shoreline and bar location indicated</td>
<td>52</td>
</tr>
<tr>
<td>3.24.</td>
<td>The shoreline and bar location from figure 3.23, with Sh_L, Sh_S, B_IL, and B_IS included</td>
<td>52</td>
</tr>
<tr>
<td>4.1.</td>
<td>The wave height data from Noordwijk, the Netherlands</td>
<td>61</td>
</tr>
<tr>
<td>4.2.</td>
<td>The wave period data from Noordwijk, the Netherlands</td>
<td>62</td>
</tr>
<tr>
<td>4.3.</td>
<td>The innermost bar location at Noordwijk, the Netherlands</td>
<td>63</td>
</tr>
<tr>
<td>4.4.</td>
<td>The distance from shore to the innermost bar at Noordwijk</td>
<td>63</td>
</tr>
<tr>
<td>4.5.</td>
<td>The standard deviation of the innermost bar at Noordwijk</td>
<td>64</td>
</tr>
<tr>
<td>4.6.</td>
<td>Wave height correlated with shoreline location at Noordwijk</td>
<td>65</td>
</tr>
<tr>
<td>4.7.</td>
<td>The cross correlation of wave height and innermost bar location at Noordwijk, the Netherlands</td>
<td>65</td>
</tr>
<tr>
<td>4.8.</td>
<td>The cross correlation of wave height and the distance from shore to the innermost bar at Noordwijk</td>
<td>66</td>
</tr>
<tr>
<td>4.9.</td>
<td>Wave height data from Agate Beach, Oregon</td>
<td>68</td>
</tr>
<tr>
<td>4.10.</td>
<td>Wave period data from Agate Beach, Oregon</td>
<td>68</td>
</tr>
<tr>
<td>4.11.</td>
<td>The shoreline location at Agate Beach, Oregon</td>
<td>69</td>
</tr>
<tr>
<td>4.12.</td>
<td>The standard deviation of shoreline location at Agate Beach</td>
<td>69</td>
</tr>
<tr>
<td>4.13.</td>
<td>The location of the innermost bar at Agate Beach, Oregon</td>
<td>70</td>
</tr>
<tr>
<td>4.14.</td>
<td>The distance from shore to the innermost bar at Agate Beach</td>
<td>71</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.15.</td>
<td>The standard deviation of the innermost bar at Agate Beach, Oregon</td>
<td>71</td>
</tr>
<tr>
<td>4.16.</td>
<td>The standard deviation of the distance from shore to the innermost bar at Agate Beach, Oregon</td>
<td>72</td>
</tr>
<tr>
<td>4.17.</td>
<td>The location of bar 2 at Agate Beach, Oregon</td>
<td>72</td>
</tr>
<tr>
<td>4.18.</td>
<td>The distance from shore to bar 2 at Agate Beach, Oregon</td>
<td>73</td>
</tr>
<tr>
<td>4.19.</td>
<td>The location of bar 3 at Agate Beach, Oregon</td>
<td>73</td>
</tr>
<tr>
<td>4.20.</td>
<td>The annual signal in bars 2 and 3 at Agate Beach, Oregon</td>
<td>74</td>
</tr>
<tr>
<td>4.21.</td>
<td>The distance from shore to bar 3 at Agate Beach, Oregon</td>
<td>75</td>
</tr>
<tr>
<td>4.22.</td>
<td>The spacing between the innermost bar and bar 2 at Agate Beach</td>
<td>75</td>
</tr>
<tr>
<td>4.23.</td>
<td>The distance between bar 2 and bar 3 at Agate Beach, Oregon</td>
<td>76</td>
</tr>
<tr>
<td>4.24.</td>
<td>The cross correlation of wave height with innermost bar location at Agate Beach</td>
<td>77</td>
</tr>
<tr>
<td>4.25.</td>
<td>The cross correlation of wave height with the distance from shore to the innermost bar at Agate Beach, Oregon</td>
<td>78</td>
</tr>
<tr>
<td>4.26.</td>
<td>The cross correlation of wave height with the location of bar 2 at Agate Beach</td>
<td>78</td>
</tr>
<tr>
<td>4.27.</td>
<td>The cross correlation of wave height with the location of bar 3 at Agate Beach</td>
<td>79</td>
</tr>
<tr>
<td>4.28.</td>
<td>The correlation between $H_s$ and the distance between the innermost bar and bar 2 at Agate Beach</td>
<td>79</td>
</tr>
<tr>
<td>4.29.</td>
<td>Wave height data from Duck, N.C</td>
<td>81</td>
</tr>
<tr>
<td>4.30.</td>
<td>Inverse rip spacing at Duck</td>
<td>82</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.31</td>
<td>Shoreline location at Duck, N.C., for the entire data set</td>
<td>83</td>
</tr>
<tr>
<td>4.32</td>
<td>Shoreline location at Duck, N.C., for C0 (1993-1997) only</td>
<td>83</td>
</tr>
<tr>
<td>4.33</td>
<td>Innermost bar location at Duck, N.C., for the entire data set</td>
<td>84</td>
</tr>
<tr>
<td>4.34</td>
<td>Innermost bar location at Duck, N.C., for the C0 data set</td>
<td>85</td>
</tr>
<tr>
<td>4.35</td>
<td>Distance from shore to the innermost bar at Duck, N.C., for the entire data set</td>
<td>85</td>
</tr>
<tr>
<td>4.36</td>
<td>Distance from shore to the innermost bar at Duck, N.C., for the C0 data set</td>
<td>86</td>
</tr>
<tr>
<td>4.37</td>
<td>The standard deviation of the innermost bar for the Duck, N.C., C0 data set</td>
<td>86</td>
</tr>
<tr>
<td>4.38</td>
<td>The standard deviation of the distance from shore to the innermost bar for the Duck, N.C., C0 data set</td>
<td>87</td>
</tr>
<tr>
<td>4.39</td>
<td>Bar locations at Duck, N.C., for the entire data set</td>
<td>88</td>
</tr>
<tr>
<td>4.40</td>
<td>The cross correlation of wave height and innermost bar location</td>
<td>89</td>
</tr>
<tr>
<td>4.41</td>
<td>The cross correlation of wave height with distance from shore to the innermost bar, Duck, N.C.</td>
<td>90</td>
</tr>
<tr>
<td>4.42</td>
<td>The cross correlation of wave height with shoreline location at Duck, N.C.</td>
<td>90</td>
</tr>
<tr>
<td>4.43</td>
<td>Wave height data from Palm Beach, Australia</td>
<td>92</td>
</tr>
<tr>
<td>4.44</td>
<td>The innermost bar location at Palm Beach, Australia</td>
<td>93</td>
</tr>
<tr>
<td>4.45</td>
<td>The distance from shore to the innermost bar at Palm Beach</td>
<td>93</td>
</tr>
<tr>
<td>4.46</td>
<td>The standard deviation of the distance from shore to the innermost bar at Palm Beach, Australia</td>
<td>94</td>
</tr>
</tbody>
</table>
LIST OF FIGURES (continued)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.47.</td>
<td>The shoreline location at Palm Beach, Australia</td>
<td>94</td>
</tr>
<tr>
<td>4.48.</td>
<td>Inverse rip spacing at Palm Beach, Australia</td>
<td>95</td>
</tr>
<tr>
<td>4.49.</td>
<td>Wave height cross correlated with inverse rip spacing</td>
<td>96</td>
</tr>
<tr>
<td>4.50.</td>
<td>Wave height cross correlated with shoreline location at Palm Beach, Australia</td>
<td>96</td>
</tr>
<tr>
<td>4.51.</td>
<td>The cross correlation of wave height and innermost bar location at Palm Beach, Australia</td>
<td>97</td>
</tr>
<tr>
<td>4.52.</td>
<td>The cross correlation of wave height and distance from shore to the innermost bar at Palm Beach.</td>
<td>97</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.</td>
<td>Overview of characteristics of the four sites used in this study</td>
<td>17</td>
</tr>
<tr>
<td>3.1.</td>
<td>The statistics describing beaches. Those statistics in the upper bold box are environmental, those in the lower bold box are morphometric</td>
<td>55</td>
</tr>
<tr>
<td>4.1.</td>
<td>The wave height data from each of the study sites</td>
<td>98</td>
</tr>
<tr>
<td>4.2.</td>
<td>The wave period data from each of the study sites</td>
<td>99</td>
</tr>
<tr>
<td>4.3.</td>
<td>The shoreline location data from each of the study sites</td>
<td>102</td>
</tr>
<tr>
<td>4.4.</td>
<td>Innermost bar statistics from each of the study sites</td>
<td>103</td>
</tr>
</tbody>
</table>
### LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>beach slope (unit-less)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>threshold value used in bar amplitude calculations (m)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>surf scaling parameter (unit-less)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>ratio of significant wave height to water depth (unit-less)</td>
</tr>
<tr>
<td>$\gamma_b$</td>
<td>ratio of significant wave height to water depth at which a wave will break (unit-less)</td>
</tr>
<tr>
<td>$\gamma_{bar}$</td>
<td>ratio of significant wave height to water depth over the crest of a bar (unit-less)</td>
</tr>
<tr>
<td>$\gamma_{RMS}$</td>
<td>ratio of root mean square wave height to water depth (unit-less)</td>
</tr>
<tr>
<td>$\gamma_{RMSb}$</td>
<td>ratio of root mean square wave height to water depth at which a wave will break (unit-less)</td>
</tr>
<tr>
<td>$\mu_G$</td>
<td>Gaussian mean location (m)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>polar angle coordinate (radians)</td>
</tr>
<tr>
<td>$\Theta$</td>
<td>phase angle of annual cycle</td>
</tr>
<tr>
<td>$\rho_{crit}$</td>
<td>95% significance level of correlation</td>
</tr>
<tr>
<td>$\rho_{SS}$</td>
<td>autocorrelation of statistic ‘S’</td>
</tr>
<tr>
<td>$\rho_{SeSm}$</td>
<td>cross correlation of some environment statistic ‘$S_e$’ with some morphometric statistic ‘$S_m$’</td>
</tr>
<tr>
<td>$\sigma_G$</td>
<td>Gaussian standard deviation (m)</td>
</tr>
<tr>
<td>$\sigma_S$</td>
<td>standard deviation of statistic ‘S’ (m)</td>
</tr>
<tr>
<td>$\sigma_S^2$</td>
<td>variance of statistic ‘S’ (m$^2$)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>$\sigma_w$</td>
<td>incident wave radian frequency ($s^{-1}$)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>lag times in correlation analysis (days)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>the effective degrees of freedom divided by the total record length (unit-less)</td>
</tr>
<tr>
<td>$\xi_b$</td>
<td>Iribarren number (unit-less)</td>
</tr>
<tr>
<td>$a$</td>
<td>coefficient of cosine parameter in least squares fit (unit-less)</td>
</tr>
<tr>
<td>$a_b$</td>
<td>breaker amplitude (m)</td>
</tr>
<tr>
<td>$A$</td>
<td>Gaussian amplitude (m)</td>
</tr>
<tr>
<td>$b$</td>
<td>coefficient of sine parameter in least squares fit (unit-less)</td>
</tr>
<tr>
<td>$B_#$</td>
<td>barriness</td>
</tr>
<tr>
<td>$B_{I%}$</td>
<td>percent of longshore locations at which the innermost bar appears in an image (unit-less)</td>
</tr>
<tr>
<td>$B_{ID}$</td>
<td>mean distance from shore to the innermost bar (m)</td>
</tr>
<tr>
<td>$B_{IDS}$</td>
<td>standard deviation of the distance from shore to the innermost bar (m)</td>
</tr>
<tr>
<td>$B_{IL}$</td>
<td>mean cross shore position of innermost bar (m)</td>
</tr>
<tr>
<td>$B_{iS}$</td>
<td>standard deviation of innermost bar (m)</td>
</tr>
<tr>
<td>$B_L$</td>
<td>cross shore bar location (m)</td>
</tr>
<tr>
<td>$B_{L_{max}}$</td>
<td>cross shore position of most offshore bar in an image (m)</td>
</tr>
<tr>
<td>$B_{O%}$</td>
<td>percent of longshore locations at which an offshore bar appears in an image (unit-less)</td>
</tr>
<tr>
<td>$B_{OD}$</td>
<td>mean distance from shore to an offshore bar (m)</td>
</tr>
</tbody>
</table>
LIST OF SYMBOLS (continued)

Symbol

BoDs standard deviation of the distance from shore to an offshore bar (m)
BoL mean cross shore position of an offshore bar (m)
BoS standard deviation of an offshore bar (m)
BS standard deviation of bar location (m)
C phase velocity of an individual wave (m/s)
C(t) cycles (annual or otherwise) which could be isolated each statistic
Cg group velocity of waves (m/s)
dsea depth of surf zone at seaward edge (m)
dshore depth of surf zone at shoreward edge (m)
dx Tide cross shore width of the intertidal zone (m)
dz Tide difference between a high and low tidal elevation
Dback(x) mean depth profile of a beach (m)
Dfn distance from peak ‘n’ to flag ‘f’ (m)
Dprob(x) cross shore profile of probable depths (m)
E(x) energy of convolution as a function of cross shore location
Ew wave energy (joules)
f flag numbers in nearest neighbor analysis
fc frequency of cycle fit to data set
F total number of flags in nearest neighbor analysis
g gravity (9.8 m/s)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G(\sigma_G,x)$</td>
<td>Gaussian curves of varying standard deviations</td>
</tr>
<tr>
<td>$h$</td>
<td>water depth (m)</td>
</tr>
<tr>
<td>$h_b$</td>
<td>depth at which a wave breaks (m)</td>
</tr>
<tr>
<td>$H_{RMS}$</td>
<td>root mean squared wave height (m)</td>
</tr>
<tr>
<td>$H_{RMSb}$</td>
<td>root mean squared wave height just prior to breaking (m)</td>
</tr>
<tr>
<td>$H_S$</td>
<td>significant wave height (m)</td>
</tr>
<tr>
<td>$H_{Sb}$</td>
<td>significant wave height just prior to breaking (m)</td>
</tr>
<tr>
<td>$I(y,x)$</td>
<td>intensity at any cross shore and longshore position</td>
</tr>
<tr>
<td>$k_w$</td>
<td>wave number (1/m)</td>
</tr>
<tr>
<td>$L$</td>
<td>wavelength (m)</td>
</tr>
<tr>
<td>$L_\infty$</td>
<td>deep water wave length (m)</td>
</tr>
<tr>
<td>$L_{buoy}$</td>
<td>wavelength of waves at a buoy (m)</td>
</tr>
<tr>
<td>$MSL$</td>
<td>mean sea level (m)</td>
</tr>
<tr>
<td>$n$</td>
<td>peak numbers in nearest neighbor analysis</td>
</tr>
<tr>
<td>$n_w$</td>
<td>scaling factor relating individual to group wave velocity (unit-less)</td>
</tr>
<tr>
<td>$NGVD$</td>
<td>National Geodetic Vertical Datum (m)</td>
</tr>
<tr>
<td>$N$</td>
<td>record length</td>
</tr>
<tr>
<td>$N^*$</td>
<td>number of effective degrees of freedom</td>
</tr>
<tr>
<td>$N_p$</td>
<td>total number of peaks found at each longshore location</td>
</tr>
<tr>
<td>$N_{rips}$</td>
<td>total number of rips in an image</td>
</tr>
</tbody>
</table>
### LIST OF SYMBOLS (continued)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_y$</td>
<td>number of alongshore observations in an image</td>
</tr>
<tr>
<td>$P_w$</td>
<td>wave power (watts)</td>
</tr>
<tr>
<td>$r$</td>
<td>polar radius coordinate (m)</td>
</tr>
<tr>
<td>$S$</td>
<td>representative of each statistic ($B_L, H_S$, etc.)</td>
</tr>
<tr>
<td>$\bar{s}$</td>
<td>mean of statistic ‘$S$’</td>
</tr>
<tr>
<td>$S_b$</td>
<td>bar amplitude (m)</td>
</tr>
<tr>
<td>$S_{b_{\text{max}}}$</td>
<td>maximum bar amplitude (m)</td>
</tr>
<tr>
<td>$S_r$</td>
<td>inverse rip spacing (1/m)</td>
</tr>
<tr>
<td>$S_{hL}$</td>
<td>mean shoreline cross shore position (m)</td>
</tr>
<tr>
<td>$S_{hS}$</td>
<td>shoreline standard deviation (m)</td>
</tr>
<tr>
<td>$T$</td>
<td>significant wave period (s)</td>
</tr>
<tr>
<td>$x$</td>
<td>cross shore coordinate in rectified images (m)</td>
</tr>
<tr>
<td>$x_0$</td>
<td>cross shore coordinate of the center of a circle in an original frame of reference used to straighten curved beaches (m)</td>
</tr>
<tr>
<td>$x_1$</td>
<td>cross shore coordinate which defines an origin for a straightened frame of reference within the original frame of reference (m)</td>
</tr>
<tr>
<td>$x_f$</td>
<td>cross shore location of flag number ‘$f$’ (m)</td>
</tr>
<tr>
<td>$X$</td>
<td>cross shore coordinate in straightened frame of reference (m)</td>
</tr>
<tr>
<td>$X_{\text{max}}$</td>
<td>offshore edge of the wave breaking window of viewing (m)</td>
</tr>
<tr>
<td>$y$</td>
<td>longshore coordinate in rectified images (m)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$y_0$</td>
<td>longshore coordinate of the center of a circle in an original frame of reference used to straighten curved beaches (m)</td>
</tr>
<tr>
<td>$y_1$</td>
<td>longshore coordinate which defines an origin for a straightened frame of reference within the original frame of reference (m)</td>
</tr>
<tr>
<td>$y_f$</td>
<td>longshore location of flag number ‘f’ (m)</td>
</tr>
<tr>
<td>$y_m$</td>
<td>longshore location being analyzed with nearest neighbor technique</td>
</tr>
<tr>
<td>$y_{max}$</td>
<td>one longshore edge of an image</td>
</tr>
<tr>
<td>$y_{min}$</td>
<td>one longshore edge of an image</td>
</tr>
<tr>
<td>$Y$</td>
<td>longshore coordinate in straightened frame of reference (m)</td>
</tr>
<tr>
<td>$z_0$</td>
<td>depth at which cross shore depth profile crosses $x = 0$</td>
</tr>
<tr>
<td>$z_{low}$</td>
<td>low tide (m)</td>
</tr>
</tbody>
</table>
This thesis is dedicated to the Earth.
To the trees: sorry for all the copies, guys.
Chapter 1: INTRODUCTION

1.1 Overview of Problem

One of the most complicated areas of oceanographic study is the nearshore region, the zone of shallow water extending from the shoreline to just beyond the outer region of wave breaking. Within this region, dynamic forces such as incident wave breaking and longshore and rip currents move sediment into complicated patterns of sand bars, troughs, rip channels, and terraces. In order to understand the relationship between forcing and response, a method needs to be developed by which the features themselves can be quantified and statistically compared with changes in incident conditions.

Certain terminology exists to describe beaches; this terminology is illustrated in figure 1.1. The profile itself is divided into several regions based on shape and sediment location. The offshore region is a reasonably flat area of sand outside of the region of wave breaking, and is often
separated from the inshore region, extending shoreward to the beach face, by a longshore bar. The foreshore region lies just shoreward of the inshore region, and includes the beach face. The foreshore, also referred to as the intertidal zone, is alternately dry during low tide and wet during high tide. Shoreward of the foreshore lies the backshore, which consists of the dry sand regions. The backshore often consists of one or more berms, flat portions of the beach that have been formed by sediment deposition (Komar, 1998).

A variety of forces and conditions affect the nearshore region. The most obvious are waves, which enter the nearshore with a particular angle, period, and height, and grow in height as the water becomes shallower until they begin to break, forming the breaker zone, within the outermost region of the nearshore zone. The divisions of the beach profile based on wave breaking are illustrated in figure 1.2. After the waves break and form into bores, they travel across the surf zone, extending beachward from the inner edge of the breaker zone. Shoreward of the surf zone lies the swash zone, a region alternately covered with water and exposed to the air as waves run up and subside (Komar, 1998).
In the study of the nearshore region, the morphology of the beach is understood to be the organization of the sediments into various sized forms. One of the largest and most obvious of these forms is the sand bar, a ridge of sediment typically orientated in the longshore direction, rising anywhere from 0.5-5 meters above the beach slope. These features are typically 10-30 meters wide, although in extreme cases can be close to 100 meters wide. The sand bar is separated from the beach face by a trough region, which can either be continuous or broken at points where a sand bar has welded itself to the beach. Sand bars can be either longshore uniform or not, and can either be reasonably linear or crescentic shaped, covered by ripples of various sizes through the length of the entire form. In some cases, the circulation of water in rips, strong currents flowing offshore from the beach, will cut gaps in the sand bar known as rip channels (Komar, 1998). On occasion, sand bars will orient in the cross shore direction, forming transverse bars that stretch from the beach face offshore (Konicki, 1999).

Another feature observed on some beaches is a low tide terrace, a flat accumulation of sand at the base of the beach face. At high tide, the terrace is under water and is subject to wave forcing, but at low tide the terrace is exposed and does not interact with the waves. This feature is also referred to as a swash bar.

1.2 Previous Classification Schemes

Research has been undertaken in the past to create schemes capable of characterizing beaches into discrete morphodynamic states, permitting comparisons
between different sites and analyses of change over time. The most commonly used system is the Wright and Short (1983) method, developed in the late 70's and early 80's. This classification scheme divides beaches into six distinct states, ranging from dissipative, through four intermediate states, to fully reflective. Beaches are characterized as progressing through the six states with changes in wave conditions and seasonal variability.

The six defined beach stages (figure 1.3) are:

(i) Dissipative
(ii) Longshore Bar-Trough
(iii) Rhythmic Bar and Beach
(iv) Transverse Bar and Rip
(v) Ridge Runnel/Low-Tide Terrace
(vi) Reflective

The beach states are distinguished from each other by the surf scaling parameter, \( \varepsilon \).

\[
\varepsilon = \frac{a_b \cdot \sigma_w^2}{g \cdot \tan^2 \beta}
\]  

(1)

where \( a_b \) = breaker amplitude, \( \sigma_w \) = incident wave radian frequency, \( g \) = acceleration due to gravity, and \( \beta \) = beach gradient. Beach state can also be related to the Iribarren number (\( \xi_b \)), another parameter used to describe beaches:

\[
\xi_b = \frac{\beta}{(H_b/L_\infty)^{\frac{1}{2}}} = (\pi/\varepsilon)^{\frac{1}{2}}
\]  

(2)

\( H_b \) is the wave height just prior to breaking and \( L_\infty \) is the deep water wave length.

A completely reflective state is expected whenever \( \varepsilon < 1.0 \) (\( \xi_b > 2 \)), although it has been noted that strong reflection may persist at higher \( \varepsilon \) values (2.0-2.5). Reflective beaches are characterized as having surging breakers and standing
wave motion. The surf zone is narrow, with weak dissipation of wave energy (Wright and Short, 1983).

The dissipative extreme is characterized by high $\epsilon$ values, ranging from 10 to over 100, and low Iribarren numbers, $\xi_b = 0.2-0.3$. The surf zone is saturated with spilling breakers, and virtually all wave energy is turbulently dissipated before reaching the swash zone. Between the two extremes are found four intermediate states, each containing dissipative and reflective qualities, and covering a large range of $\epsilon$ values.

The state closest to fully dissipative in the Wright and Shore scheme is the longshore bar-trough. The beach face is steeper than in the dissipative state, and waves which break over the outer face of a bar reform within the trough. Runup is fairly high, and cusps are sometimes found. The bar and trough seen in this state are more pronounced than on a dissipative beach.

The rhythmic bar and beach state is similar to the longshore bar-trough, in that a trough region separates the reflective beach face from a dissipative offshore bar. In contrast to the previous state, rhythmic, crescentic features in the longshore characterize the sand bar. Moderate rip circulation is found.

The crescentic features in a rhythmic bar and beach state can grow shoreward, setting up the next classification state. The transverse bar and rip topography is characterized by dissipation over flat transverse bars interspaced by embayments at the base of strong rip currents. Although this state is fairly stable, the occurrence and spacing of rips can vary with changes in wave conditions.
Figure 1.3: Wright and Short beach states. From Wright and Short, 1983.
The ridge and runnel/low tide terrace beach state is characterized by a flat accumulation of sand at the low tide level. Although the offshore face of the terrace is reasonably dissipative, at high tide the steeper beach face is more reflective. Weak rips, most probably residuals left from a previous state, occasionally cut through the terrace (Wright and Short, 1983).

Although the Wright and Short classification scheme allows for differentiation between sites, the analysis itself is somewhat subjective, based upon an observer's classification of state. Because the analysis is based on observation of incident wave breaking patterns, only the large scale structure of the bar is identified; smaller features are not distinguished. In addition, analysis based on discrete states limits the understanding of change over time. Progression through the states can be seen, but complex changes within a given state, such as the changing shape of bars in the rhythmic bar and beach state, are not described. This lack inhibits attempts to statistically compare different beaches, or correlate change over time with environmental conditions such as wave height, direction, and period. In addition, the scheme only classifies beaches based on wave breaking patterns, and does not tie directly to the bathymetry of the beach. A beach can change state because of either changes in the bathymetry, or changes in wave condition; for instance, during low wave conditions, a barred beach could be classified as reflective if the significant wave height is not large enough to cause breaking over the bar. Finally, the scheme only addresses characteristics of the
innermost bar, and cannot distinguish characteristics or changes of the outermost bar(s) of a multiple bar system.

Figure 1.4: Modifications of Wright and Short classification scheme by Lippmann and Holman. From Lippmann and Holman, 1990.
Figure 1.5: Pictures of the Lippmann and Holman beach states. From Lippmann and Holman, 1990.
In order to improve on the Wright and Short scheme, using observations at the Field Research Facility (FRF) at Duck, N.C., Lippmann and Holman (1990) created an analysis based on four specific criteria, and expanded the six Wright and Short states into the eight possible states differentiated by the four new criteria. Figure 1.4 from their study shows the characteristics of the new states and how they differ from the Wright and Short scheme. The longshore bar and trough state was separated into two states, one characterized as longshore uniform and one characterized by non-rhythmic, longshore variable features. The transverse bar and rip was also split into two new categories, based on longshore rhythmicity. The criteria established for assessing beach state were existence or absence of a bar, dominant bar scaling, longshore variability, and nature of the trough as either continuous or discontinuous. An observer progressed through a flow chart of these criteria in order to characterize a beach into one of eight states. Real beach examples of the eight states are illustrated in figure 1.5.

The Lippmann and Holman system improved on the Wright and Short method by streamlining the process of identification, and clarifying what criteria were required for each state. Increasing the number of states allowed a better understanding of more subtle changes in condition, as well; however, keeping discrete states still prohibits a full understanding of the continuous process of beach evolution with changing environmental conditions. The technique also still relies on subjective classification; it was found that 75% (+/- 8%) of the classifications
for a given image agreed with the consensus classification, indicating that in some cases a beach’s classification within this system depends on the subjective judgment of the classifier (Lippmann and Holman, 1990). Like the Wright and Short scheme, this classification system is also geared toward wave breaking patterns, and is difficult to relate to actual bathymetry. In addition, it is subjective, allowing human interpretation to effect the classification results. The discrete states identified in the Lippmann and Holman scheme, as well as in the Wright and Short scheme, prevent a quantitative analysis of beach response to environmental conditions, and limit understanding of subtle changes of beach morphology within any given morphological state.

The morphometric analysis developed in this study improves on the previous schemes in a number of ways. The analysis itself is much more objective, based on computer analysis of images of wave breaking, thus reducing the subjectivity of human interpretation that can lead to error. In addition, a series of continuous variables are used, thus allowing for a complete understanding of subtle as well as large scale beach response. The numeric variables can also be statistically correlated with changes in environmental parameters; this quantitative analysis was not possible with the discrete states of previous classification schemes. The new scheme also addresses actual bathymetric data as well as wave breaking, so a more complete nearshore data set can be analyzed for an understanding of beach response.
With this new analysis method, several questions in nearshore science can be investigated. Despite the fact that sand everywhere is controlled by the same basic physics and fluid forcing on the simplest level, beaches around the world take on a wide range of appearances. Some tend to have long, linear sand bars, others have broad terraces cut by rips, still others have a complicated and interconnected system of sand bars. Some beaches undergo accretion, some erosion. Even at one single site, over time a beach can take on a variety of forms, as illustrated in the wide variety of states in previous classification schemes. With the current analysis, the specific relationship between certain aspects of beach morphology, such as shoreline location, sand bar location, and sand bar shape can be correlated with changes in environmental conditions, such as wave height and period. Beach behavior can be numerically compared between sites, so that behavioral trends at one site can be isolated from those at another site. Using this more objective and numerical comparison, one can better postulate on the causes for observed similarities and differences between sites.
Chapter 2: DESCRIPTION OF DATA SET

2.1 The Argus Program

The Argus camera network, a series of cameras collecting data at numerous beach locations around the globe, provided the data for this research. The premise of Argus camera use in nearshore analysis is that waves preferentially break over shallow features such as sand bars. These areas of increased breaking appear in an image as lighter intensity sections, in clear contrast to darker regions of less wave breaking.

An example of an Argus snapshot from Palm Beach, Australia.

Figure 2.1: An example of an Argus snapshot from Palm Beach, Australia.

Fluctuations due to modulations in incident wave heights are averaged out by using ten minute time exposure images. An example of a time exposure image, with clearly identifiable shoreline, terrace, and rip channels, is found in figure 2.2. Figure 2.3 shows an example of a time exposure where a single linear bar is visible in addition to the shore break. Since the real world
Figure 2.2: An example of an Argus time exposure from Palm Beach, Australia.

location of anything within the image is a function of the spatial orientation of the camera, with straightforward transformation equations the image can be rectified to provide a 'bird's eye' view, in a process described in more detail by Lippmann and Holman, 1989. The image transformation process results in positional accuracies of around a pixel, for a typical resolution of 0.1% of the distance from the camera to the point of interest (Holland et al, 1997). In the current study, the rectifications were also averaged over a spatial distance of 2-5

Figure 2.3: An example of an Argus time exposure from Duck, North Carolina. Note the single linear
Figure 2.4: An example of an Argus rectification of Duck, N.C., created by merging the views from five cameras.

meters in the cross shore and 5-15 meters in the longshore (depending on the site). This resolution was sufficient for the current study of large scale morphodynamics and noticeably reduced computation time.

In order to expand the capabilities of the Argus technique, multiple cameras have been installed with views covering various portions of the shoreline. These camera views can be merged together to provide more complete longshore spatial coverage of the nearshore region, as illustrated in figure 2.4.

Ground truth testing has been performed to determine the accuracy of the Argus technique in isolating sand bar position based on preferential breaking. Lippmann and Holman (1989) compared surveyed beach profiles obtained in the SUPERDUCK experiment in October 1986 with estimations of sand bar location made with the Argus video technique. Ground truth bathymetry data were acquired with the coastal research amphibious buggy (CRAB), a surveying tool permanently located at the FRF, Duck, N.C. The study found that the bar location estimates obtained with the video technique corresponded well to actual sand bar locations.
The errors in bar crest position were generally less than 5-10% of the cross shore distance between the shoreline and the bar crest position, with an extreme error of 35% of the cross shore distance. In general, this resulted in an average rms error of 15 m, with a tidal dependence (Lippmann and Holman, 1990); however, recent work at another site (Egmond aan Zee, in the Netherlands) has shown that the rms error can be as great as 40 m due to tidal variation (Ruessink, 2001). The tidal dependence of intensity maxima location over a bar will be discussed in greater detail later in this thesis.

2.2 Description of Field Sites

Four sites from around the world were used in the current study. These sites include a wide range of environmental conditions, including various wave heights, periods, and tidal ranges. Also included are both pocket beaches and beaches located on uninterrupted coastlines. These sites have a range of $\xi_b$ values, and exhibit at various times all six stages in the Wright and Short classification, and all eight of the Lippmann and Holman stages. A brief description of each field site is included below, along with table 2.1 comparing basic information for each site. In the table, $H_S$ is the mean significant wave height, and $T$ is the mean dominant wave period. The beach slope is defined as the average slope of the surf zone, extending from the shoreline to the most offshore point where waves typically break at the site. The Iribarren number ($\xi_b$) is calculated for the typical wave conditions at each of the sites.
<table>
<thead>
<tr>
<th>Site</th>
<th>Iribarren Number</th>
<th>Beach Slope</th>
<th>Wave Height</th>
<th>Wave Period</th>
<th>Tide Range</th>
<th>W &amp; S Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noordwijk</td>
<td>0.11</td>
<td>0.015</td>
<td>1.2 m</td>
<td>5.0 s</td>
<td>micro-tidal</td>
<td>dissipative/intermediate</td>
</tr>
<tr>
<td>Agate Beach</td>
<td>0.13</td>
<td>0.015</td>
<td>2.5 m</td>
<td>12 s</td>
<td>meso-tidal</td>
<td>dissipative</td>
</tr>
<tr>
<td>Duck</td>
<td>0.35</td>
<td>0.035</td>
<td>0.9 m</td>
<td>8.9 s</td>
<td>micro-tidal</td>
<td>intermediate</td>
</tr>
<tr>
<td>Palm Beach</td>
<td>0.50</td>
<td>0.040</td>
<td>1.5 m</td>
<td>9.8 s</td>
<td>micro-tidal</td>
<td>intermediate/reflective</td>
</tr>
</tbody>
</table>

Table 2.1: Overview of characteristics of the four sites used in this study.

2.2.1 Noordwijk, The Netherlands

The site at Noordwijk, The Netherlands is located along the Holland coast, also referred to as the Central Dutch Coast. This coastline is approximately 120 km long, and is orientated approximately NNE-SSW. The coast faces the semi-enclosed North Sea, which is open to the Atlantic Ocean in the North but which is separated from the Atlantic in the south by the English Channel. The coast is made of sandy deposits. The beach itself is wave dominated (Wijnberg, 1995).

The surf zone in this region has a slope of between 0.0065 and 0.017. A number of offshore bars are almost always present at the field site at Noordwijk. There can be anywhere from between one and four bars, which in general are
reasonably longshore uniform linear sandbars. Low and high tide terraces are also occasionally seen at the field site (Wijnberg, 1995).

The annual mean wave height at Noordwijk is 1.2 m, with an annual mean wave period of 5 seconds. In general, the waves come in from the SW and NNW direction, although during the fairer weather months of the late spring and summer the waves most often approach from the NW. As is typical for the northern hemisphere, the months of April to August (summer) have relatively calmer weather than the winter storm months, although the coastline is occasional hit by summer storms. During the stormy winter months, the monthly mean wave height rises to 1.7 m, while in the summer it drops to 1 m.

Like all of the Holland coast, Noordwijk is a micro-tidal coast with a mean tidal range of about 1.6 m. The tidal current velocities are almost always below 1 m/s. Although tides do not have a large effect on the coast, the outflow from the River Rijn creates a density driven circulation which produces an onshore bottom current of a few centimeters a second, varying with the river’s discharge (Wijnberg, 1995).

The human influence on the Holland coast has been relatively extreme compared with the other sites included in this study, dating back to the Middle Ages. A seawall was constructed near Petten in the 16th century, and coastal modification has continued ever since. A seawall in the same location exists there today; this site is north of the Noordwijk field site. Groins have also been built in the eroding northern and southern parts of the Holland coast, and beach
nourishment has occurred at several locations. Only about 7 km of the dune field behind the Holland coast is free of human intervention; modifications range from slope adjustment or remodeling to planting vegetation and constructing sand fences. It is unknown exactly how this long history of modification affects the beach response at Noordwijk (Wijnberg, 1995).

Argus cameras have been in place at Noordwijk since March 1995, at which time two cameras were installed, one facing in each direction along the beach. The cameras themselves are located atop the Huis ter Duin Hotel. In September 1998, three additional cameras were installed, and the station can now provide a 180° view of the Noordwijk site.

2.2.2 Agate Beach, Oregon, United States

Agate Beach, Oregon, is located at the northern end of the Newport littoral cell. The littoral cell itself stretches between two basaltic headlands, Yaquina Head to the north and Cape Perpetua to the south, and is divided into two sub-cells by rock jetties constructed to stabilize the entrance to Yaquina Bay. Agate Beach is the 2.5 km region just south of Yaquina Head, extending south to the rocks dividing it from Nye Beach (Haxel, 2001). The littoral cell is believed to be a closed system of sediments (Komar, 1997), and consists of medium grain sand, mostly quartz and feldspar. The median grain diameters are around 0.2 mm. Since Agate Beach borders one of the dividing headlands, northern alongshore transport results in sand piling up at this site, while southern alongshore transport results in
heavy erosion in this region as sediments move south in the littoral cell with no source to replenish Agate Beach. Sediment transport processes are affected by the presence of two creeks, Big Creek and Little Creek. When the rainfall in this area increases during the winter, the creeks cut through the beach and carry beach sediments into the surf and swash zones, creating offshore deltas. During the summer, the lack of rain causes minimal flow in the creeks and the upper beach dries out (Haxel, 2001).

Agate Beach faces the Pacific Ocean to the west, and is backed by sea cliffs to the east. The northern end of Agate Beach is protected from swells approaching from the northwest by Yaquina Head, which extends 1.5 km into the ocean. The southern end of the beach therefore is impacted to a much greater extent by the high energy waves and storm events which occur in this region. The annual mean wave height is considerably higher than at the other study sites, around 2.5 m, and the annual wave period is approximately 12 s (Tillotson and Komar, 1997). The tides at Agate Beach are semi-diurnal, with a range of 2-3 m. The beach slope at Agate is very shallow, (0.015), resulting in a wide surf zone with a width up to 1 km during the high energy conditions of winter storms (Haxel, 2001).

An Argus camera has been in place at Agate Beach since 1992. This camera is mounted atop Yaquina Head, and provides a view of approximately 2 km of coastline length, extending offshore to about 600 m. In 1995, an additional camera was added at the site, also atop Yaquina Head. This camera looks farther offshore, extending the view of the site to include the entire surf zone.
Wave data for Agate Beach were supplied by National Data Buoy Center station 46050, located in 130.1 m of water off the coast of Newport, Oregon. Tide data were provided by National Oceanic and Atmospheric Administration (NOAA)/National Ocean Service (NOS) tide station 9435380, which collects a tide elevation data point every 6 minutes and is located off South Beach, Oregon.

2.2.3 Duck, North Carolina, United States

The Argus camera station at Duck, NC is located at the Field Research Facility (FRF) established by the U.S. Army Corps of Engineers. Situated on the Outer Banks, a barrier island chain off the coast of NC, Duck is located along a 100 km stretch of unbroken coast extending from Rudee Inlet to Oregon Inlet, and faces the Atlantic Ocean to the east. Relatively few coastal structures, such as seawalls and groins, exist in the area, with the notable exception of the FRF research pier. This 561.1 m concrete structure is used for a variety of nearshore research purposes. The barrier islands themselves are composed of Holocene sediments overlying Pleistocene deposits. The shoreline in the region is extraordinarily stable, showing remarkably little accretion or erosion over long periods (Birkemeier, 1985). The beach is an intermediate energy beach, typically exhibiting two linear sandbars at approximately 125 m and 300-600 m from the shoreline. The annual mean significant wave height is 0.9 m, with a mean annual period of 8.9 s, and a mean tidal range of 0.97 m (Birkemeier, 1985);
Time exposure images of Duck were first taken in 1985 with a 35 mm camera mounted on scaffolding built on the crest of a dune (Holman and Lippmann, 1987), with long term image collection beginning in 1986. Because only one time exposure was taken daily, the effect of tides on water level and breaking patterns were aliased, so these initial images were not used in the current study. In 1993, an automated Argus station was installed on a 43 m tower at the facility, and snapshots and time exposures were taken hourly from that point onward (Konicki, 1999). Other improvements to the Argus capabilities at this site include the expansion of the system to eight cameras, including three northward facing, three southward facing, one directly offshore, and one which provides an alternative view of the pier area. In the present study, only the five cameras necessary to provide a complete 180° field of view were used.

Tide data for Duck were provided by National Oceanic and Atmospheric Administration (NOAA)/National Ocean Service (NOS) tide gauge No. 865-1370, located at the end of the FRF pier. This acoustic tide gauge collects a tide data point every six minutes. Wave data for the study were provided by wave rider buoy 630, located at 18 m water depth off the coast of Duck.

2.2.4 Palm Beach, New South Wales, Australia

The site at Palm Beach, Australia, is located approximately 30 km north of central Sydney, Australia (Ranasinghe, 2000). This pocket beach stretches 2.1 km between the Barrenjoey headland to the north and the Little Head headland to the
south, and is classified as an open ocean embayment. Palm Beach consists mostly of rounded quartz sand of approximately 0.30 mm, and has exhibited net erosion during the past 30 – 40 years (Wright, 1980). Palm Beach is a micro-tidal, swell dominated beach with a slope of about 0.04. The waves at Palm Beach have an annual mean offshore wave height of 1.5 m, which can increase to 3-6 m during storms. The waves typically approach from the SSE, although swells occasionally come in from the NE (Ransinghe, 2000).

The Argus station at Palm Beach was installed in the Barrenjoey lighthouse, located atop Barrenjoey headland, in January of 1996. The cameras are 110 m above mean sea level, and face south toward Palm Beach. The station consists of two video cameras with 12 mm and 16 mm lenses respectively, directed at Palm Beach in its entirety and focused in on the northern part of the beach. Only the 12 mm camera will be used, since it provides sufficient data for this study. The tide data for Palm Beach were acquired from a tide gauge at Patonga, slightly to the NW of Palm Beach itself. The offshore wave characteristics were obtained with a wave rider buoy located at Long Reef, 20 km south of Palm Beach, in a depth of 80 m (Ransinghe, 2000).
3.1 Extracting Features

3.1.1 Images Used For This Study

The Argus data set at each site consists of ten minute time exposures taken over the course of all daylight hours, 365 days a year from the date the cameras were installed at each site. In order to limit this extensive data set somewhat, the first step in analysis was to select out three images a day for each study site from the time the cameras were installed at that site until December 31, 2000. These three images were selected using tidal data, and represent the highest high tide and the lowest low tide during daylight hours, as well as one image with the tidal level closest to the mean level of these two tides. By restricting the data set in this manner, the changes in breaking due to tidal elevation change could be studied. This understanding is of considerable importance, since the relationship between bathymetry, water level and wave breaking must first be understood before any kind of comprehensive analysis of beaches can take place based on the Argus images. Even with restricting the data set to three images a day and four of the Argus sites, the 28 collective years from the four sites yielded over 30,000 images for analysis. Obviously, if the image from a specific tidal level was poor or unavailable due to inclement weather or camera difficulties, it was not used for the analysis; however, this data set is still one of the largest used in nearshore study.
3.1.2 Image Preparation

Before useful data could be extracted from the Argus images, two sites, Agate Beach and Palm Beach, required preliminary image modification due to beach shape. We wished to measure cross shore and longshore positions of features independently of low frequency trends introduced by beach curvature, therefore, at these two sites images were transformed to a coordinate system relative to a curve fitted to the trend of the beach itself.

![Palm Beach, 6/30/99, Original Image](image)

Figure 3.1: The circle which will form the basis of the straightened frame of reference for Palm Beach, Australia.

The transformation process began by fitting a circle to the overall curvature of the beach (see figure 3.1). Each point in the original image \((y,x)\) was redefined in terms of polar coordinates \((r,\theta)\) relative to the fitted circle and a point selected as the new origin in the straightened frame of reference \((y_1,x_1)\) (See figure 3.2). For
every point \((Y,X)\) in the straightened frame of reference, \(r\) and \(\theta\) could be calculated, and converted to the original \((y,x)\) coordinates:

\[
x = x_0 - (r - X) \cdot \cos(\theta) \tag{3}
\]

\[
y = y_0 - (r - X) \cdot \sin(\theta) \tag{4}
\]

With \(\theta\) calculated as

\[
\theta = \pi/2 - \frac{Y/r - \sin^{-1}(x_0 - x_1)/r}{2} \tag{5}
\]

In this manner, the intensity at each point \((Y,X)\) in the straightened frame of reference was determined from the intensity in the original image at the corresponding \((y,x)\). An example of an image from Palm Beach in the original and straightened frames of reference is shown in figure 3.3.

At Palm Beach,
Ranasinghe (2000) fitted a log spiral curve in order to uncurve the beach; however, the circle method is capable of uncurving the beach in the region of interest for this study and thus allows for a uniformity of procedure between sites.

### 3.1.3 Locating the Shoreline

One of the most obvious features to isolate on a beach is the shoreline, in order to track erosion or accretion and to provide a reference for bar and terrace cross shore positions. In our study, we define the shoreline as the intersection of water and sand in our images. In order to isolate the shoreline, two images from the same site on the same day were used, one taken at high tide and one at low tide. The intensity difference between these images is shown in Figure 3.5.

**Figure 3.4:** A high and low tide image taken on the same day at Duck, N.C.

**Figure 3.5:** The intensity difference between the images shown in figure 3.4.
high tide and one at low tide; examples are shown in figure 3.4. The premise behind shoreline isolation was that these two images would not be dramatically different, with the exception of the breaking changes over a sand bar due to water depth variation and the region in the foreshore that was covered by water at high tide and exposed at low tide (the intertidal region). The first step in isolating the shoreline was to calculate the intensity difference between the high and low tide images; an example of an intensity difference image is shown in figure 3.5. The low tide image was subtracted from the high tide image, so the variation in intensity due to tidal shift would be a relatively high positive number where a light shore break in the high tide image had been replaced by darker sand in the low tide image.

Next, the cross shore width of the intertidal zone was calculated. This technique is illustrated in figures 3.6 and 3.7.
With a known tidal range, $dz_{tide}$, and an approximate beach slope, $\beta$, the cross shore width of the intertidal zone could be calculated as:

$$dx_{tide} = \frac{dz_{tide}}{\beta} \quad (6)$$

In the case illustrated above, the tidal shift was 0.758 m, resulting in a cross shore intertidal zone width of 7.6 m. A peak in the intensity difference image of this width was then found at each cross shore location.

Since the cross shore position of the peak in intensity change at the intertidal zone could be affected by changes in shorebreak width, the shoreline position at each cross shore location was determined as the most shoreward position of the intensity change peak above an empirically determined threshold percentage of the maximum intensity change. An example of the tidal change in intensity overlaid on bathymetry and water level at one longshore location is shown in figure 3.8. Although it is possible that the technique
could be refined in order to find both a high and low tide shoreline location, for this study only the high tide shoreline location was found.

In order to test the validity of this shoreline location technique, ground truth shoreline locations at Duck, N.C., were compared with shoreline locations determined in the manner described above. Bathymetry data from Duck were obtained with the use of the Coastal Research Amphibious Buggy (CRAB), a surveying device permanently located at the FRF facility at Duck. Shoreline locations, considered to be the cross shore intersections of the surveyed beach with the still water level at high tide, were determined at the bathymetric survey locations for that day. These shoreline locations were then compared with shoreline locations determined for that day with the intensity differencing technique. An example of the difference in shoreline locations found with the two techniques is shown in figure 3.9. In this case, the mean error between the shoreline locations was 2.5 m, with an rms error of 8.33 m. This error was representative of the error found on the 10 days when CRAB shorelines could be compared with the shorelines found with
the intensity differencing technique. No systematic difference between the two techniques was found.

Based on comparisons with ground truth shorelines at Duck, the confidence limit of the image differencing technique at that site was around 8 m. Based on observations at Palm Beach, the confidence limit was estimated as the same as at Duck; however, ground truth tests could not be performed due to lack of survey data. Unfortunately, the technique was not always as successful at other sites. At Agate Beach the cliff behind the beach sometimes cast shadows over the sand at various times during the day, which could alter the intensity difference between high and low tides. In addition, the shallow beach slope at this location (0.01) results in a high water table which often produces a large region of wet sand, even at low tide, hindering shoreline location. The shore break at Agate is also not as well defined as at Duck. All of these factors combined to lower the estimated confidence limit at Agate to 20 m. At Noordwijk, the difference in intensity between the sand and the shore break is not as pronounced as at Duck, which could result in inaccurate shoreline locations, and an estimated confidence limit of 10 m. Despite these problems, however, the intensity difference technique was a reasonable estimator of shoreline location. In cases where the technique could not be applied successfully, the shoreline location was manually identified.
3.1.4 Extracting Sand Bar, Terrace, and Rip Channel Locations

Both sand bars and terraces appear as peaks in cross shore intensity profiles obtained with Argus imaging, as shown in figure 3.10. In previous studies, the peak in intensity has generally been located either subjectively or through basic intensity maxima location techniques; unfortunately, the maximum intensity of the peak over a sand bar relative to the rest of the intensity profile can vary greatly based on both actual water conditions such as tidal level and wave height as well as image characteristics such as lighting changes, weather limitations on image quality, and individual camera variation. Because of these variations, it is difficult to objectively locate sand bars by setting thresholds for intensity maxima; therefore, we created a different method for objectively isolating sand bar locations by utilizing the shape of the peaks located over sand bars and terraces. Empirically it has been determined that these features almost always result in a Gaussian (G(x)) type curve of intensity,

\[ G(x) = A \cdot \exp\left(-\left(\frac{x - \mu_G}{\sigma_G}\right)^2\right) \]  

(7)
defined by the parameters $A$ (amplitude), $\mu_G$ (mean location), and $\sigma_G$ (standard deviation).

In order to extract sand bar and terrace locations, each cross shore intensity profile ($I(y',x)$) in a given image was analyzed separately. A series of Gaussians of varying standard deviations were created ($G(\sigma_G,x)$), with $\sigma_G$ limited to the standard deviations expected for sand bars or terraces. The intensity profile was convolved with each of the Gaussians, with convolution defined as:

$$I(y',x) * G(\sigma_G,x) = \int I(y',x-s) \cdot G(\sigma_G,s) \cdot ds$$

(8)

An example of the convolution of an intensity profile with the series of Gaussians is shown in figure 3.11. The convolution between the series of Gaussians and the intensity profile is three dimensional, with the first and second dimensions being cross shore location and Gaussian standard deviation, and the third dimension being energy of convolution. In order to robustly identify cross shore locations with Gaussians which could be bars or terraces, the three
dimensional convolution was summed over the range of possible Gaussian standard deviations at each cross shore location, determined empirically for each site. This summation resulted in a calculated energy of convolution \( E(x) \) at each cross shore location (figure 3.12):

\[
E(x) = \sum_{\sigma_G = \sigma_G_{\text{max}}(x)}^{\sigma_G = \sigma_G_{\text{min}}(x)} G_{\sigma_G}(x) \ast I(y', x) \quad (9)
\]

Cross shore locations with a high energy of convolution relative to the Gaussian shapes were identified as peaks in this summed convolution. This technique has proven to be quite robust at all of the sites in identifying the peaks

Figure 3.12: Energy of convolution at each cross shore location summed over the possible Gaussians widths at that location.

Figure 3.13: The peaks of the intensity Gaussians identified with convolution analysis.
associated with sand bars, although peaks which were not sand bars and were removed later in the process were also identified. An example of the peaks found using this analysis at Duck, N.C., is shown in figure 3.13.

Once all the peaks were located at each longshore location they had to be grouped together into contiguous sand bars. This process was accomplished through a nearest neighbor calculation constrained by a maximum separation distance. The analysis started at one longshore edge of each image, \( y_{\text{min}} \), which had some number of peaks \((N_p)\) at cross shore locations \(x_1, x_2, \ldots, x_{n=NP}\). Each peak was given a flag number \(f\), where \(f = 1, 2, \ldots, N_p\). For each flag, the cross shore location \(x_f\) and longshore location \(y_f\) \((y_f = y_{\text{min}})\) were recorded. Analysis proceeded in the longshore, with the distance \(D_{fn}\) between each cross shore peak \((x_1, x_2, \ldots x_{n=NP})\) at the new longshore location \(y_m\) being calculated to the cross shore and longshore location of each flag \((x_{f=1,2,\ldots,F}, y_{f=1,2,\ldots,F})\), where \(F\) was the total number of flags.

\[
D_{fn} = \sqrt{(x_n - x_f)^2 + (y_m - y_f)^2}. \tag{10}
\]
If a given peak $x_n$ was the closest of all the peaks at a longshore location $y_m$ to the location of a flag $f$, with location $(x_f, y_f)$,

$$D_{fn} = \min(D_{fn=1\rightarrow N_p})$$

(11)

and the distance between the peak and the flag was less than the maximum distance allowed, 250 m, the peak was given the same number as the flag ($x_n$ was flagged 'f'). The cross shore location of the flag was changed to the location of the peak, $(x_f = x_n, y_f = y_m)$ so that the grouping process could track sandbars as they meandered closer and farther from shore. If the peak was not within the maximum distance to any flag, or if it was not the closest peak at its longshore location to any flag, it was assigned a new number and became a new flag, $f = F+1$, with location $x_f = x_n, y_f = y_m$. The maximum distance allowed between a flag and a peak was determined to be the largest gap one would expect to see in a sand bar, and was set at 250 m. The final bar locations found after nearest neighbor analysis for the image shown in figure 3.13 are shown in figure 3.14. At the end of
the grouping process, any flagged group with fewer than 5 observations was eliminated.

Although this grouping technique was quite accurate in tracking continuous bars, some subjective quality control was required. Occasionally non-relevant features in an image, such as glare or the pier at Duck, created false peaks that were grouped together with actual sand bars and needed to be removed. In addition, the shorebreak and dry sand beach were sometimes identified as sand bars, and needed to be removed. Finally, complicated bar bifurcations sometimes made it difficult for sand bars to be grouped together objectively, particularly at the Agate Beach site. An example of complex bar bifurcation can be seen in figure 3.15. In all of the cases, the errors were subjectively corrected, or if the subjective modification required was too great or an observer could not determine what peaks needed to be grouped together, the image was not used.

Identifying rip channels in Argus images has proved to be considerably more difficult than identifying the shoreline, sand bars, or terraces. Ranasinghe (2000) used a technique to identify rips based on mean intensity profiles along a bar. A shoreline and breaker edge were identified at each alongshore location, and the mean surf zone intensity at each location was calculated between these two boundaries. The longshore intensity profile was bandpass filtered to remove low frequency trends and high frequency noise, and rips were identified as troughs in the longshore intensity profile (Ranasinghe, 2000). Although the technique had some success at Palm Beach, it was not always capable of identifying rip channels,
and had less success when applied to other sites. The variety of appearances rip channels can have in time exposures alters the shape of the mean longshore intensity profile; for instance, in some cases there are clearly defined rip heads of concentrated breaking (figure 3.16), which would result in only minor dips in the longshore intensity profile, while in other cases there is no rip head (figure 3.17), which results in a more clearly defined dip in the longshore intensity profile. This variation makes it difficult to establish thresholds for isolating rips. Since no objective method of robustly locating rips in the Argus images was identified, the number of rips in each image for statistical analysis was subjectively determined by an observer. The criterion for rip identification, however, was standardized. A rip was a visible cut of low intensity through a high intensity region of wave breaking over a sand bar or terrace. A rip was identified if there was a defined rip head (narrow, crescentic
area of breaking) offshore from the cut, or if, as in the case of figure 3.17, the cuts covered a sufficient cross shore span to be clearly identified despite the lack of a rip head. Since gaps in a sand bar can also result from diminished breaking during low wave conditions, or because crescentic features in the bar can cause more offshore regions to have little or no breaking, gaps without rip heads were scrutinized carefully. A rip was not identified if the gap in the sand bar was inordinately large (>100 m) or small (< 15 m), or if the region of breaking through which the cut ran was not wide enough in the cross shore for it to be determined if there was truly a rip present (bar width < 25 m).

3.2 Observational Limitations

As was mentioned previously, the Argus procedure is limited in extracting morphometric data to times when the environmental conditions are such that waves break over features of interest. Obviously, it is important not to confuse the absence of breaking with the absence of a sand bar or other feature; therefore, the relationship between breaking location and environmental conditions was investigated so that observations when the statistics were affected by wave condition variations rather than feature variation could be excluded from the data set. This screening was particularly important in the case of longshore variable features such as crescentic sand bars, in which case it was possible for waves to break over shoreward parts of the bar and not seaward portions, thus biasing mean location statistics landward.
3.2.1 Investigation of Breaking Criterion Over Known Bathymetry

As a wave enters the surf zone, its wave height begins to increase as the depth of water decreases, until the particle velocity at the crest of the wave exceeds the phase velocity of the wave (C), causing the wave to break. A ratio ($\gamma_{RMS}$) can be defined relating the root mean square wave height ($H_{RMS}$) to the water depth (h).

$$\gamma_{RMS} = \frac{H_{RMS}}{h}$$  \hspace{1cm} (12)

When this ratio ($\gamma_{RMS}$) reaches some critical value ($\gamma_{RMSb}$), the wave has reached the wave height at which it will break ($H_{RMSb}$) in the water depth where it will break ($h_b$).

$$\gamma_{RMSb} = \frac{H_{RMSb}}{h_b}$$ \hspace{1cm} (13)

Empirical investigations of $\gamma_{RMSb}$ for monochromatic waves have resulted in values of 0.7-1.2 (Galvin and Eagleson, 1965; Iverson, 1952), while investigations of $\gamma_{RMSb}$ for random waves on natural beaches have resulted in lower values of 0.42 (Thornton and Guza, 1982) and 0.32 (Sallenger and Holman, 1985). In the previous studies, $\gamma_{RMSb}$ was found to depend upon beach slope; however, for the purposes of determining a wave breaking criterion in the current study, the effect of slope was relatively negligible and was therefore not included.

In the current study, wave height data are significant wave heights ($H_S$) as opposed to $H_{RMS}$, where
We can determine a ratio of significant wave height to water depth ($\gamma$),

$$\gamma = \frac{H_s}{h}$$ (15)

Therefore, in our case we have a new breaking criterion ($\gamma_b$) defined as the ratio of the significant wave height at wave breaking ($H_{sb}$) to the water depth at breaking ($h_b$).

$$\gamma_b = \frac{H_{sb}}{h_b}$$ (16)

We have investigated the value of $\gamma_b$ using Argus images and known bathymetry data obtained for Duck, N.C., with CRAB surveys. We focused primarily on those days when waves broke over a sand bar at low tide but not at high tide, indicating that the $\gamma_b$ threshold was somewhere between the calculated $\gamma$ at low and high tides over the sand bar. Waves were shoaled over the known bathymetric profiles using Airy linear wave theory. The power of a wave ($P$) remains constant before breaking, with $P$ dependent on the wave energy ($E_w$) and group wave velocity ($C_g$),

$$P = E_w \cdot C_g$$ (17)

By knowing that the energy is dependent on density ($\rho_w$), gravity ($g$), and wave height ($H_{RMS}$),

$$E_w = \frac{1}{8} \cdot \rho_w \cdot g \cdot H_{RMS}^2$$ (18)
we could relate the wave height and group velocity at a buoy where environmental conditions were measured to the wave height and group velocity at any point ‘a’ in the profile as:

\[
\frac{1}{g} \cdot \rho \cdot g \cdot H_{\text{RMSbouy}} \cdot C_{\text{bouy}} = \frac{1}{g} \cdot \rho \cdot g \cdot H_{\text{RMSa}} \cdot C_a
\]  

(19)

The group wave velocity is equal to the velocity of individual waves (C) multiplied by a coefficient (nw).

\[
C_g = C \cdot n_w
\]  

(20)

where \( n_w \) depends on water depth (h) and wave number (k_w)

\[
n_w = \frac{\sqrt{2}}{2} \cdot \left( 1 + \frac{2 \cdot k_w \cdot h}{\sinh(2 \cdot k_w \cdot h)} \right)
\]  

(21)

In deep water, \( n_w \) is equal to \( \frac{1}{2} \), and as the wave enters shallower water \( n_w \) increases until the waves are in shallow water and \( n_w \) becomes 1. Wave number is a function of wavelength (L),

\[
k_w = \frac{2 \cdot \pi}{L}
\]  

(22)

Group velocity at the buoy could be calculated as

\[
C_{\text{bouy}} = \frac{g \cdot T_{\text{bouy}}}{2 \cdot \pi} \cdot \tanh\left( \frac{2 \cdot \pi \cdot h_{\text{bouy}}}{L_{\text{bouy}}} \right) \cdot n_w
\]  

(23)

where T is the wave period, \( h_{\text{bouy}} \) is the depth at the buoy, and L is the wavelength.
\[ L_{buoy} = \frac{g}{2 \pi} T_{buoy}^2 \cdot \tanh\left( \frac{2 \pi h_{buoy}}{L_{buoy}} \right) \]  

(24)

We assumed the shallow water approximations of Airy theory for our surf zone depths,

\[ C_{gs} = \sqrt{g \cdot h_s \cdot n_w} \]  

(25)

with \( n_w = 1 \), and thus could relate the wave height at any point ‘a’ in our profile to the recorded wave height and calculated velocity at the buoy as:

\[ H_{sa} = \sqrt{\frac{H_{buoy}^2 C_{shw}}{2 g}} \]  

(26)

(HRMS has been converted to \( H_S \)).

With the calculated wave heights at each cross shore location and the depth from CRAB profiles, we could calculate \( \gamma \) over our bathymetric profiles, as shown in figure 3.18 (intensity and \( \gamma \) profiles have been magnified). In cases where waves of approximately the same height broke at low tide \( (z_{low}) \) and not at high tide \( (z_{high}) \) on a particular day, the ratio of wave height to water depth over the bar \( (\gamma_{bar}) \) could be constrained as:

\[ \gamma_{bar} (z_{high}) < \gamma_b < \gamma_{bar} (z_{low}) \]  

(27)

Figure 3.19: Examples of gamma at high (*) and low (+) tide.
Figure 3.19 shows calculated $\gamma_{\text{bar}}$ for high and low tides on one of the days when waves were breaking over the sand bar at high tide and not at low tide; given multiple observations of cases such as these, we isolated our $\gamma_b$ to be 0.5. This threshold value (magnified by 3) is shown in figure 3.18; at the cross shore position where gamma crosses this threshold over the bar, there is an increase in intensity signaling that waves are indeed beginning to break. In figure 3.19, all of the values of $\gamma_{\text{bar}}(z_{\text{high}})$ are below the threshold value while all of the values of $\gamma_{\text{bar}}(z_{\text{low}})$ are above the threshold value, as would be expected given that waves were breaking over the sand bar at low tide and not at high tide.

Based on the ratio of significant wave height to RMS wave height, the breaking criterion using significant wave heights can be related the breaking criterion using RMS wave heights as

$$\gamma_{\text{RMSb}} = \gamma_b \cdot 0.7$$

(28)

Our $\gamma_b$ therefore converts to a $\gamma_{\text{RMSb}}$ of 0.35. Previous research has found $\gamma_{\text{RMSb}}$ to equal to anywhere from 0.78 (McCowan, 1894) to 1.2 (Ippen and Kuhn, 1954), with the higher end representing the value found in laboratory experiments on solitary waves. Values as low as 0.32-0.42 (Sallenger and Holman, 1985; Thornton and Guza, 1982) have been found for random waves on natural beaches, although some question exists as to whether these lower values actually pertain to bores breaking as opposed to incident waves.
3.2.2 Estimated Window of Viewing Possibility

In the case of our data set, we wished to determine the farthest location offshore it would be possible for waves to break (thus giving us a view of bathymetry), based on the environmental data available from the buoys at each site. By determining this location \( X_{\text{max}} \) we could exclude from our data set those statistics related to images where \( X_{\text{max}} \) was shoreward of the expected location of sand bars (\( \text{BL} \)). (Bar location was estimated on days without breaking from previous and subsequent measurements of \( \text{BL} \)). In addition, we could exclude data where sand bars with significant longshore gaps (> 15% of the bar) were within two standard deviations \( (2*\text{BS}) \) of \( X_{\text{max}} \), due to the probability that the gaps were longshore locations where the cross shore position of the bar was offshore of \( X_{\text{max}} \), biasing \( \text{BL} \) towards shore without the inclusion of these unseen offshore positions.

The first step was to determine the maximum depth where waves of a particular height and period would break. This depth was calculated using the same Airy wave equations shown previously. The wave height at breaking \( (H_{sb}) \) was calculated as a function of the depth at breaking \( (h_b) \) as:

\[
H_{sb} = \sqrt{\frac{H_{\text{shore}} \cdot C_{\text{shore}}}{\sqrt{g \cdot h_b}} / 2}
\]

At breaking,

\[
\frac{H_{sb}}{h_b} = \gamma_b
\]
By replacing our equation for $H_{sb}$ into the $\gamma_b$ equation, we could determine the relationship between the depth of breaking and the wave height and celerity at the buoy.

$$h_b = \left( \frac{H_{sb}^2 \cdot C_{sh(x)}/2}{\gamma_b^2 \cdot \sqrt{g}} \right)^{\frac{3}{2}}$$  \hspace{1cm} (31)

Now that the depth of breaking was known, all that remained was to determine the maximum offshore position where one would expect to see a depth shallower than this breaking depth.

We accomplished this by creating a profile of the probable depth ($D_{prob(x)}$) at each cross shore location, relative to National Geodetic Vertical Datum (NGVD), if a sand bar was located at that position. This process began by creating a background profile ($D_{back(x)}$) of depths at each cross shore location ($x$) based on an approximate offshore beach slope ($\beta$) and a reference background depth ($z_{back}$).

$$D_{back} (x) = \beta \cdot x + z_{back}$$  \hspace{1cm} (32)

On top of this profile was added the probable height a sand bar crest would be at each cross shore position, as determined by a method created by Ruessink et al, (2001). Ruessink examined bar height at Duck, N.C., and four Dutch sites. He isolated a region of bar appearance between some shoreward depth ($d_{shore}$) and some seaward depth ($d_{sea}$). Between these depths bars had some amplitude ($S_b$),
with the limit of $S_b$ at $d_{shore}$ and $d_{sea}$ being equal to a threshold ($\delta$), found to be equal to 0.25 m. He could relate the maximum bar amplitude ($S_{b_{max}}$) to $d_{sea}$ as

$$S_{b_{max}} = 0.20(\pm0.02) \cdot d_{sea} + 0.05(\pm0.13)$$  \hspace{1cm} (33)$$

Ruessink then related the bar amplitude at any depth in the surf zone ($h$) to the previous parameters as

$$S_b(d) = \delta + (S_{b_{max}} - \delta) \cdot \exp \left( -\left( \frac{h - d_{shore}}{d_{sea} - d_{shore}} \right)^{0.63} - 0.5 \right)^2 / 0.088$$  \hspace{1cm} (34)$$

We could therefore calculate our probable depth with a bar as

$$D_{prob}(x) = D_{back}(x) + S_b(D_{back}(x))$$  \hspace{1cm} (35)$$

Of course, this depth profile is not the actual depth at any cross shore location; however, given previous studies of typical bathymetric parameters at each of the sites, we created a probable depth profile for the purpose of determining our wave breaking window of viewing. An example of probable depth estimates is shown in figure 3.20. $D_{prob}(x)$ is related to the water depth ($h(x,z_{tide})$) at any time as:

$$h(x, z_{tide}) = D_{prob}(x) + z_{tide}$$  \hspace{1cm} (36)$$

Therefore, for any breaking depth $h_b$ at some tidal level $z_{tide}$ we could determine the maximum offshore position $X_{max}$ where the depth profile $D_{prob}(x)$ became shallower than the breaking depth.

This technique was tested by comparing the most offshore bar location seen in an image ($B_{L_{max}}$) with the maximum possible offshore position ($X_{max}$). In cases where the bar was visible, $X_{max}$ should always be farther offshore than $B_{L_{max}}$. in
cases where the bar was not visible, $B_{L\text{max}}$ was estimated from observations on subsequent and previous days. Figure 3.21 shows $X_{\text{max}} - B_{L\text{max}}$ at Duck for both when the bar was visible and when it was not. This value should be positive ($X_{\text{max}} > B_{L\text{max}}$) for the bar to be seen and negative ($X_{\text{max}} < B_{L\text{max}}$) if the bar could not be seen. In the case where the bar was visible, $X_{\text{max}}$ was greater than $B_{L\text{max}}$ 95% of the time. However, in cases when the bar was not visible, $X_{\text{max}}$ was less than $B_{L\text{max}}$ only 26% of the time. This discrepancy (bars not being seen when theoretically they might be) could have been due to several factors. The bar height could have been less than the predicted height calculated using the Ruessink equations, or the estimated bar location could have been inaccurate due to bar migration during periods when the bar was invisible.

Using the method described above, statistics related to bars with locations ($B_L$) within two standard deviations ($2B_S$) of the maximum expected breaking location ($X_{\text{max}}$):

$$B_L + 2 \cdot B_S > X_{\text{max}}$$

(37)
and which had significant gaps in the bar (greater than 15% of the bar was not visible) were excluded from the data set.

### 3.2.3 Effects of Tidal Variation on Bar Location

In addition to affecting whether a bar appeared in an image, tidal level could have a significant influence on the cross shore location of wave breaking. Whereas at high tide waves of a given height would break toward the peak of a sand bar, at lower tidal levels waves of the same height would begin to break farther offshore, somewhere along the offshore slope of the sand bar (figure 3.22). This tidal effect is due to the fact that the minimum breaking depth slides down the offshore slope of the bar as the tide level drops. Unfortunately, since Argus bar location is a function of cross shore breaking position, the affect of tidal level needs to somehow be compensated for in order to prevent our bar locations statistics from being biased by the tide. We compensated for this effect by normalizing the bar locations to a standard tidal level, which we chose as mean sea level ($z_{\text{tide}} = \text{zero}$). Unfortunately, our method of shoreline detection results in the high tide shoreline being found, while the tidal dependence of bar location...
forces us to normalize the bar locations to a reference tidal level lower than high
tide. At some point in time, it is hoped that actual bar crest locations can be
isolated in Argus images independent of the tide level, eliminating this discrepancy.
On most days, we could find a mean bar location at both a higher and a lower tide.
(The mid-tide level bar location could be used as the higher tide bar location if the
bar did not appear in the high tide level image for that day.) Given the known tide
level difference between the two tidal levels we could calculate the slope
\( \frac{\Delta B_L}{\Delta z_{\text{tide}}} \) of the change in cross shore position of the bar vs. the change in tide.

\[
\frac{\Delta B_L}{\Delta z_{\text{tide}}} = \frac{B_{L(\text{high})} - B_{L(\text{low})}}{z_{\text{tide}(\text{high})} - z_{\text{tide}(\text{low})}} \quad (38)
\]

We could then normalize the bar location to our standard tide level, \( z_0 \) (equal to
zero, mean sea level), as

\[
B_{L(0)} = B_{L(\text{low})} + \frac{\Delta B_L}{\Delta z_{\text{tide}}} \cdot (z_{\text{tide}(0)} - z_{\text{tide}(\text{low})}) \quad (39)
\]

The reference tide level, \( z_0=0 \), is between the lower tidal level and the higher tidal
level. Therefore, \( B_{L(0)} \) is offshore of \( B_{L(\text{high})} \) and onshore of \( B_{L(\text{low})} \). In those cases
where waves did not break over the bar at the high or mid tide levels, we assumed
that the waves were breaking at the peak of the sand bar at low tide, and would
therefore not break farther onshore at our reference tide level. Therefore,
\( \frac{\Delta B_L}{\Delta z_{\text{tide}}} \) was assumed to be zero in these cases and the bar location at the
reference tide was assumed to be the same as the bar location at low tide.
3.3 Statistical Analysis of Argus Images

Once sand bar, terrace, and rip locations were identified in each of the images, the statistics which form the heart of the new objective classification scheme were extracted and filtered based on the window of possible breaking determined in section 3.2. Table 3.1 contains a list of the classification statistics and a general description of each one.

Three statistics for each image were environmental, taken from the wave and tide buoy information available at each of the sites. These statistics were significant wave height ($H_s$), wave period ($T$), and tide level relative to NGVD ($Z_{tide}$). This data was acquired from the buoys described in Chapter 2. All the other statistics were considered morphometric statistics; i.e., describing the morphology of the beach (see figures 3.23 and 3.24). Two morphometric statistics, inverse rip spacing ($S_R$) and barriness ($B_#$) related to the entire surf zone. $S_R$ was calculated as the number of rips ($N_{rips}$) identified in an image divided by the entire longshore distance of the image ($y_{max} - y_{min}$), thus obtaining a bulk statistic for the approximate number of rips per meter.

$$S_R = \frac{N_{rips}}{y_{max} - y_{min}}$$

(40)

Barriness ($B_#$) was calculated by averaging the number of bars observed at each alongshore location ($B_#(y_i)$) over the number of longshore locations in the image ($N_y$).
\[ B_s = \frac{\max(y) \sum_{y=\min(y)} B_s(y_i)}{N_y} \] (41)

For instance, if there were only three cross sections, with one, two, and one observed bars at each, \( B_s \) would be equal to \( (1+2+1)/3 = 1.33 \).

Two statistics were calculated for the shoreline in each image. The first was the longshore averaged shoreline position. \( Sh_L(y_i) \) is the shoreline location at each longshore location \( yi \).

\[ Sh_L = \frac{\max(y) \sum_{y=\min(y)} Sh_L(y_i)}{N_y} \] (42)

The subscript ‘L’ denoted that the location was relative to a standard reference coordinate system established at each of the sites; this notation was standard throughout the morphological statistics. The

Figure 3.23: A view of Duck, N.C., with both shoreline and bar location indicated.

Figure 3.24: The shoreline and bar location from figure 3.23, with \( Sh_L, Sh_S, B_{IL}, \) and \( B_{IS} \) included.
second shoreline statistic was the standard deviation of shoreline location.

\[
Sh_l = \frac{\sum_{yi=\min(y)}^{\max(y)} |Sh_l(yi) - Sh_l|}{N_y - 1}
\]  

(43)

Here, the subscript ‘S’ denoted standard deviation, another notation standard throughout the statistics. The standard deviation was normalized by \(N_y - 1\), so that the standard deviation squared was closest to the unbiased estimate of the variance. Examples of the mean shoreline location and standard deviation statistic are shown in figures 3.23 and 3.24.

Five statistics were calculated for the innermost and any offshore bars in the image. The first statistic extracted for the sand bars in an image was the mean bar location, \(B_{Il}\) and \(B_{O_0}\). The ‘I’ refers to the innermost bar location, and ‘O’ is some number greater than one indicating which offshore bar the statistic refers to; bar two would be the offshore bar just seaward of the innermost bar, with 0 increasing offshore. These locations were relative to the same reference coordinate system used for mean shoreline location, and were calculated from the cross shore bar position at each longshore location where the bar appeared \((B_{Il}(yi), B_{O_0}(yi))\) as

\[
B_{Il} = \frac{\sum_{yi=\min(y)}^{\max(y)} B_{Il}(yi)}{N_y}
\]  

(44)

Longshore locations where the bar did not appear were excluded from this calculation, reducing the denominator by one for each longshore location where the bar did not appear \((N_y \rightarrow N_y - 1\). The second statistic was the bar standard deviation, \(B_{IS}\) and \(B_{OS}\), calculated as
\[ B_{ls} = \frac{\max(y) \sum_{yi = \min(y)}^{\max(y)} |B_{Li}(yi) - B_{li}|}{N_y - 1} \]  

(45)

Again, longshore locations without the bar were excluded from the calculation. In addition to the two statistics relative to the reference coordinate system, the mean distance from the bar to the shoreline was averaged in the alongshore to create the statistics \( B_{ID} \) and \( B_{OD} \).

\[ B_{ID} = \frac{\sum_{yi = \min(y)}^{\max(y)} (B_{Li}(yi) - Sh_{li}(yi))}{N_y} \]  

(46)

Illustrations of these statistics are shown in figures 3.23 and 3.24. The standard deviation of these distances was also calculated as \( B_{IDS} \) and \( B_{ODS} \).

\[ B_{IDS} = \frac{\sum_{yi = \min(y)}^{\max(y)} |(B_{Li}(yi) - Sh_{li}(yi)) - B_{ID}|}{N_y - 1} \]  

(47)

Finally, the number of alongshore locations with the bar (\( N_{yBi} \)) was calculated as a percentage (\( B_{1\%} \) and \( B_{0\%} \)) of the total number of longshore locations, for the purpose of determining how large the gaps were in bars close to the offshore edge of the wave breaking window of viewing; bars with gaps larger than 15% of total longshore length were excluded.

\[ B_{1\%} = \frac{N_{yBi}}{N_y} \]  

(48)
<table>
<thead>
<tr>
<th>Statistic</th>
<th>Description (Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hs</td>
<td>The significant wave height (m)</td>
</tr>
<tr>
<td>T</td>
<td>The wave period (s)</td>
</tr>
<tr>
<td>(z_{\text{dce}})</td>
<td>The tidal level (m)</td>
</tr>
<tr>
<td>(S_R)</td>
<td>Inverse rip spacing (1/m)</td>
</tr>
<tr>
<td>(B_{#})</td>
<td>Barriness: the mean number of cross shore bars averaged in the alongshore (no units)</td>
</tr>
<tr>
<td>(S_{\text{hL}})</td>
<td>The mean shoreline location (m)</td>
</tr>
<tr>
<td>(S_{\text{hs}})</td>
<td>The shoreline location standard deviation (m)</td>
</tr>
<tr>
<td>(B_{\text{IL}})</td>
<td>The mean location of the innermost bar (m)</td>
</tr>
<tr>
<td>(B_{\text{IS}})</td>
<td>The standard deviation of the innermost bar (m)</td>
</tr>
<tr>
<td>(B_{\text{ID}})</td>
<td>The mean distance from the innermost bar to the shoreline (m)</td>
</tr>
<tr>
<td>(B_{\text{IDS}})</td>
<td>The standard deviation of the distance from the innermost bar to the shoreline (m)</td>
</tr>
<tr>
<td>(B_{%})</td>
<td>The percentage of longshore locations where the innermost bar was observed (no units)</td>
</tr>
<tr>
<td>(B_{\text{OL}})</td>
<td>The mean location of some offshore bar ‘O’ (m)</td>
</tr>
<tr>
<td>(B_{\text{OS}})</td>
<td>The standard deviation of some offshore bar ‘O’ (m)</td>
</tr>
<tr>
<td>(B_{\text{OD}})</td>
<td>The mean distance from offshore bar ‘O’ to the shoreline (m)</td>
</tr>
<tr>
<td>(B_{\text{ODS}})</td>
<td>The standard deviation of the distance from offshore bar ‘O’ to the shoreline (m)</td>
</tr>
<tr>
<td>(B_{%})</td>
<td>The percentage of longshore locations where an offshore bar ‘O’ was observed (no units)</td>
</tr>
</tbody>
</table>

Table 3.1: The statistics describing beaches. Those statistics in the upper bold box are environmental, those in the lower bold box are morphometric.
3.4 Analysis of Variability

At each of the four sites, the objective has been to determine the existence and magnitude of any annual or other cycles within the environmental and morphometric statistics, as well as to isolate any significant relationships between forcing by environmental variables and the response within the system. For this analysis only one observation of each statistic was used per day. Since only one shoreline was isolated per day (at a high tide level), this shoreline information was used in our analysis. Rip statistics were analyzed using data from the low tide images, since rips tend to be more apparent at low tide when sand bars, which highlight rips, tend to be more visible. The bar statistics used in our analysis were those that had been obtained after bar locations were normalized to mean sea level using the process described in chapter 3.

The first analysis step was to calculate the variance of each of our statistics \( S(t) \). The variance \( \sigma_s^2 \) was calculated from the record length \( N \) and the mean \( \bar{S} \) as:

\[
\sigma_s^2 = \frac{1}{N-1} \sum_{i=1}^{N} [S(i) - \bar{S}]^2
\]  

The standard deviation of each statistic \( \sigma_s \) is equal to the square root of the variance. Each statistic was then autocorrelated over a range of lag times \( \tau \), where \( \tau \) was equal to a set of lag indices \( k=0,1,2,\ldots \) multiplied by the sampling increment of our data set, \( \Delta t \).

\[
\tau = k\Delta t
\]
In our case, since our sampling increment was equal to 1 day, \( \tau = k \). Our maximum lag was equal to 90% of the record length, since at extremely long lags not enough data are present for a robust analysis. The autocorrelation of each statistic (i.e., the autocovariance normalized by the sample variance) was calculated as:

\[
\rho_{ss}(\tau) = \frac{1}{N - \tau} \sum_{i=1}^{N-\tau} (S(i) - \bar{S})(S(i+\tau) - \bar{S}) / \sigma_s^2
\]  

(51)

In order to determine if the autocorrelation was significant at any lag, we estimated the 95% significance level \( \rho_{\text{crit}}(\tau) \) from the effective degrees of freedom at each lag \( N^*(\tau) \). The number of effective degrees of freedom was used for this calculation since it is unrealistic to assume that each measurement of our statistics was independent.

\[
\rho_{\text{crit}}(\tau) = \frac{1.95996}{\sqrt{N^*(\tau)} - 1}
\]  

(52)

\( N^*(\tau) \) was calculated by using the artificial skill method, described in detail in Emery, 1997. In this method, it is assumed that \( N^*(\tau) \) is some fraction \( v \) of the record length at each lag \( N(\tau) = N - \tau \).

\[
N^*(\tau) = v \cdot N(\tau)
\]  

(53)

\( v \) is constant over all lags. A relationship (described in Emery, 1997) has been established between \( v \) and the artificial skill; i.e., the increase in \( \rho_{ss} \) which is unrelated to any true correlation at a particular lag. At long lags, where no true correlation is expected, it is assumed that any correlation is purely due to artificial skill; therefore, \( v \) can be calculated from \( \rho_{ss} \) at long lags as:
\[ v = \frac{1}{2 \cdot K} \sum_{i=k_l}^{k+K-1} [N(\tau_i) \cdot \rho_{SS}(\tau_i) + N(-\tau_i) \cdot \rho_{SS}(-\tau_i)] \]  \hspace{1cm} (54)

Where \( K \) is the total number of long lags and \( k_i \) is the smallest lag considered long.

For our analysis, we assumed a long lag to be any lag greater than 50% of the record length.

If our autocorrelation of a particular statistic \( (S(t)) \) revealed that there appeared to be an annual or other cycle, \( S(t) \) was regressed using a least squares fit onto the apparent cycle \( (C(t)) \):

\[ C(t) = a \cdot \cos(2 \cdot \pi \cdot f_c \cdot t) + b \cdot \sin(2 \cdot \pi \cdot f_c \cdot t) \]  \hspace{1cm} (55)

where \( a \) is the scaling coefficient of the cosine term, \( b \) is the scaling coefficient of the sine term, and \( f_c \) is the frequency of the cycle. The variance in \( C(t) \) was then divided by the total variance in \( S(t) \) to determine what fraction of the total variance could be explained by the cycle. In addition, for annual cycles \( (f_c = 1/365) \), the phase of the cycle \( (\Theta) \) was determined:

\[ \Theta = \tan^{-1}(\frac{b}{a}) \]  \hspace{1cm} (56)

A cycle with a peak at exactly the first of the year would have \( \Theta = 0 \).

This analysis was undertaken for each statistic relating to the innermost bar and any offshore bars, although wave breaking limitations at most of the sites resulted in insufficient observations of any offshore bars for a statistical analysis to take place. It is of course important to realize that “innermost bar” refers to the bar closest to shore at any given time, and does not necessarily track one individual sand bar. The analysis was also completed for the shoreline statistics and the
inverse rip spacing. Barriness was not analyzed for signals, since at most of the sites the number of bars is more of a function of the wave breaking window, which has already been discussed, as opposed to the actual number of bars in the bathymetric profile; however, if in the future this study is expanded to include bathymetric data, an analysis of barriness might reveal interesting trends at the sites.

Preliminary investigation into the relative importance of inter- and intra-annual variability within the data was also carried out. First, each statistic was run through a Loess filter to eliminate data gaps using the technique described in Schlax and Chelton, 1992. Then, a spectral analysis was performed (as described in Jenkins and Watts, 1968). The spectral energy was summed over low frequencies (periods greater than 365 days) and high frequencies (periods less than 365 days), and was converted to a percentage of the total spectral energy in order to compare the relative importance of inter- vs. intra-annual variation. Within all of the statistics at all of the sites, high frequency (intra-annual) variation accounted for the majority (>85% in almost all cases) of the total variation, indicating that the majority of beach behavior within our data set as parameterized by our statistics tended to occur on time scales of less than a year. Of course, our data set is limited to 5-9 years at each of our sites, so a longer record length may be needed to effectively investigate inter-annual variation which may be occurring on time scales of 5-10 years; however, this analysis does allow for some comparison of the relative importance of intra- vs. inter-annual variability at each of the study sites.
In addition to examining each of our statistics individually, morphometric statistics \((S_m(t))\) were cross correlated with environmental statistics \((S_e(t))\) to determine if the environmental statistics were significantly leading any of the morphometric statistics. The cross correlation (the cross covariance normalized by the product of the standard deviation of each statistic \((\rho_{SeSm})\)) was calculated as:

\[
\rho_{SeSm} = \frac{1}{N} \sum_{i=1}^{N-\tau} \frac{[S_e(i) - \overline{S_e}][S_m(i+\tau) - \overline{S_m}]}{\sigma_e \sigma_m}
\]  (57)

Once again, a 95\% significance level was calculated using the effective degrees of freedom. In this case, \(v\) is calculated as:

\[
v = \frac{1}{2K} \sum_{k=k_i}^{k_i+K-1} [N(\tau_k)\rho_{SeSm}(\tau_k)] \cdot [N(-\tau_k)\rho_{SeSm}(-\tau_k)]
\]  (58)

The correlation between an environmental statistic and a morphometric statistic was considered significant at a lag if it was above the 95\% significance level at that lag.
4.4 Noordwijk, The Netherlands

At the Noordwijk site, both the wave height and wave period showed an annual signal, as did several of the morphometric statistics. Several of the morphometric statistics also showed a significant relationship to changes in environmental statistics. Not enough observations of rips were made for a robust statistical analysis for annual or other cycles or for rip data to be correlated with environmental conditions. In addition, due to the relatively low wave heights at Noordwijk, there were very few observations of offshore bars. At times one could catch glimpses in the images of one or even two offshore bars; however, during most observations the gaps in the bars are most probably due to waves not breaking over offshore portions, increasing the likelihood that any statistics we extracted would be biased; therefore, offshore bars statistics were not analyzed for annual cycles or for correlations with environmental statistics.

Figure 4.1: The wave height data from Noordwijk, the Netherlands.
4.1.1 Environmental Statistics

The wave height (Hs) at Noordwijk showed an annual signal; figure 4.1 shows a plot of the wave height data from Noordwijk along with its annual signal and autocorrelation. The wave heights were higher during the winter and lower during the summer, with a phase angle of $-15^\circ$; the range was 0.49 m around a long term mean value of 1.04 m. The annual cycle explained 6.2% of the variation in wave height at Noordwijk. No other cycles could be found that were significant.

The wave period (T) at Noordwijk also showed an annual cycle; figure 4.2 shows a plot of wave period at Noordwijk along with its autocorrelation and annual signal. The waves had a longer period during the winter, and a shorter period during the summer, with a phase angle of $-8.1^\circ$; the range was 0.54 s around a long term mean value of 6.00 s. The annual cycle within the wave period data at Noordwijk accounted for 2.6% of the total variance in T.
4.1.2 Morphometric Statistics

Neither the shoreline location nor the shoreline standard deviation showed any annual or other signals at Noordwijk. However, the location of the innermost bar (BIL) did show an annual signal. Figure 4.3 shows a plot of BIL for Noordwijk, along with its autocorrelation and annual signal.

The bar was farther offshore during the winter, and more onshore during the summer, with a phase angle of 29°; the range of variation was 14.03 m around a long term mean value of 248.27 m. The annual cycle within the bar location accounted for 7.5% of the total variance in BIL. No other cycles of significance could be found for the Noordwijk innermost bar location. It can be noted, however, that there is a peak in autocorrelation at a long lag of around 1400 days. Given the length of our data set at this site (6 years), it is
impossible to determine if there is truly some interannual cycle at this time scale (around 4 years).

As would be expected, the distance from the innermost bar to the shoreline (B_{ID}) also showed an annual cycle, in which the bar was closer to the shore during the summer and farther away from the shore during the winter, with a phase angle of 43° (figure 4.4). The range of the annual signal was 21.09 m around a long term mean value of 116.36 m. The annual cycle in the distance from shore to the innermost bar accounted for 7.8% of the total variance in B_{ID}. Once again, a peak at a long lag (1400 days) appears in the autocorrelation, but with this data set it is impossible to determine if there is actually some cycle occurring at that time scale.

No annual or other signals could be found within either the standard deviation of the innermost bar or the standard deviation of the distance from the shore to the innermost bar (B_{IS} and B_{IDS}). Figure 4.5 shows a plot of the standard deviation of the innermost bar at Noordwijk, along with its autocorrelation. A peak in autocorrelation does occur at a long lag of 1400 days, further suggesting that perhaps the beach is going through some sort of interannual cycle of behavior.

Figure 4.5: The standard deviation of the innermost bar at Noordwijk.
With a longer data record, it would be possible to quantify that interannual cycle if it actually exists and is not some false peak due to a lack of sufficient data.

4.1.3 Relationships Between Environmental and Classification Statistics

A significant negative relationship was found between the wave height at Noordwijk and the shoreline location, as shown in figure 4.6. This negative correlation indicates that an increased wave height resulted in the shoreline retreating. This cross correlation was only significant at the 95% level for about a day or two, indicating that the shoreline reacted very quickly to changes in wave height. The correlation was not particularly strong, even at short lags, falling just above the 95% significance level. This weak correlation may explain

Figure 4.6: Wave height correlated with shoreline location at Noordwijk.

Figure 4.7: The cross correlation of wave height and innermost bar location at Noordwijk, the Netherlands.
why no annual signal was found within the shoreline location, despite the annual signal in wave height.

A significant relationship was also found between the wave height and the innermost bar location at Noordwijk; the correlation of $H_s$ and $B_{IL}$ is shown in figure 4.7. A positive correlation existed, indicating that increasing the wave height resulted in the innermost bar moving offshore. This correlation was significant for around 10 days. The correlation of wave height with the distance from shore to the innermost bar (see figure 4.8) also revealed a positive correlation. Once again, the bar moved away from shore when the wave height increased and towards shore when the wave height decreased. This correlation remained above the 95% significance level for approximately 10 days as well.

No significant relationship was found between wave height and standard deviation of the shoreline or the innermost bar. In addition, no relationship of any significance was found between the wave period and any of the morphometric statistics.
4.2 Agate Beach, Oregon, United States

At Agate Beach, OR, we identified an annual signal in both the wave heights and the wave period. In addition, several of the morphometric statistics, including the innermost bar and shoreline locations, showed cyclical behavior. In contrast to the other sites, the standard deviation of the shoreline and the innermost bar showed an annual cycle. Because of the relatively extreme wave conditions at Agate Beach that consistently caused the appearance of multiple bars, we were able to statistically analyze two offshore bars (labeled bars 2 and 3, with bar 2 lying between the innermost bar and bar 3). Both bars showed annual signals in their locations. In addition to the standard analysis performed at all sites, the presence of so many bars at Agate prompted one additional analysis, that of bar spacing. In this case, the distance between the innermost bar and bar 2 was averaged in the longshore ($B_{12D}$), as was the distance between bars 2 and bar 3 ($B_{23D}$). It was discovered that the spacing between the bars shows an annual cycle, as well. One additional bar (bar 4) did appear during relatively high wave conditions, particularly during the winter months; however, not enough observations existed for a robust statistical analysis. In addition, insufficient rips appeared in the images for inverse rip spacing to be analyzed. A more detailed description of all of the Agate Beach analysis follows.
4.2.1 Environmental Statistics

At Agate Beach, Oregon, the significant wave height ($H_s$) showed a strong annual signal, with a range of 1.94 m around a long term mean of 2.45 m. Figure 4.9 shows a plot of the wave height, its autocorrelation, and its annual signal. The wave height tended to be higher during the winter months, and lower during the summer months, with a phase angle of 13.8°. The annual signal found within the wave data explained 30% of the variance within $H_s$, a much higher percentage than at any of the other sites. Research in the past has indicated that wave heights in the Eastern North Pacific are progressively increasing (Allan and Komar, 2000); however, with the data record used in this study that trend was not isolated. No other significant signals were found within the wave height data at Agate Beach.
An annual signal was also found in the wave period (T). Figure 4.10 shows a plot of wave period, along with its autocorrelation and annual signal. The significant wave period had a summer to winter range of 4.35 s around a long term mean value of 12.05 s. The waves tended to be of a longer period during the winter and a shorter period during the summer, with a phase angle of 14.6°. The annual cycle in wave period explained 30% of the total variance within T. No other significant signals were found within the wave period data at Agate.

4.2.2 Morphometric Statistics

The shoreline location (ShL) at Agate Beach showed a rather interesting cycle (figure 4.11). ShL had a strong semiannual cycle, in which the shoreline was farthest landward during the spring and fall and farthest seaward during the summer. Figure 4.11: The shoreline location at Agate Beach, Oregon.

Figure 4.12: The standard deviation of shoreline location at Agate Beach.
summer and winter. The mean shoreline location was 196.5 m, with a range of 53.15 m in the semiannual cycle. The semiannual cycle could explain 20% of the variance within ShL, a significant improvement over an annual cycle which explained less than 1% of the variance in ShL. One possibility for this semiannual cycle may be the rotation of the beach through the seasons (Haxel, 2001). Since our ShL location is a longshore mean, seasonal rotation from the northern end of the beach to the southern end could result in a semiannual cycle appearing in our ShL statistics.

The standard deviation of shoreline location (ShS) did not show the semiannual cycle found within the shoreline location data; instead, only an annual signal was found. Figure 4.12 shows a plot of shoreline standard deviation along with its autocorrelation and annual cycle. The shoreline had a greater standard deviation during the winter, and a smaller standard deviation during the summer, with a range of 4.77 m around a long term mean of 17.31 m. The annual cycle explained 7.1% of the variance found within the shoreline standard deviation data.

The location of the

Figure 4.13: The location of the innermost bar at Agate Beach, Oregon.
innermost bar (BIL) also showed significant annual signal at Agate Beach (see figure 4.13). The bar tended to be farther offshore during the winter, and farther onshore during the summer, with a phase angle of 21°; the range was 18.95 m around a mean of 393.3 m. The annual signal explained 2.4% of the variance in BIL. The distance from shore to the innermost bar (BID) also showed an annual signal in which the bar was closer to the shore during the summer and farther from shore during the winter, with a phase angle of 30°. Figure 4.14 shows a plot of BID along with its annual signal and autocorrelation. BID varied by 26.63 m between summer and winter around a long term mean value of 198.39 m. The annual signal in BID explained 2.1% of the total variance in the distance from shore to the innermost bar at Agate Beach.
The standard deviation of the location of the innermost bar (BIS) as well as the standard deviation of the distance from the shore to the innermost bar (BIDS) showed an annual signal at Agate Beach. Figures 4.15 and 4.16 shows BIS and BIDS, respectively. The annual signal in BIS varied 12.6 m around a mean value of 26.36 m. This annual signal explained 10.8% of the variance in BIS at Agate. The bar tended to be straighter in the winter than in the summer, with a phase angle of 56°. The annual signal in the distance from the shore to the innermost bar had a slightly smaller range, varying by 9.44 m around a long term mean value of 30.38 m; the phase angle in this case was 83°. The annual cycle within BIDS explained 5.4% of the total variance. The bar tended to have a lower standard deviation in the late fall and winter months, and a higher

Figure 4.16: The standard deviation of the distance from shore to the innermost bar at Agate Beach, Oregon.

Figure 4.17: The location of bar 2 at Agate Beach, Oregon.
standard deviation in the late spring and summer months. (In other words, the bar tended to be somewhat straighter during the winter).

As was previously mentioned, two offshore bars were consistently visible within the Agate Beach images. The location of bar 2 (B2L), the bar just offshore from the innermost bar, did show an annual signal; B2L along with its autocorrelation and annual signal are shown in figure 4.17. B2L had a range of 73.13 m around a long term mean of 545.02 m, with the bar being farther offshore during the winter and farther onshore during the summer; the phase angle was 65°. The annual signal explained 8.2% of the variance in B2L.

The distance from the shore to bar 2 (B2D) also showed an annual signal, which can be seen in

![Distance From Shore to Offshore Bar 2. Agate Beach](image1)

**Figure 4.18:** The distance from shore to bar 2 at Agate Beach, Oregon.

![Autocorrelation of B2D](image2)

**Figure 4.19:** The location of bar 3 at Agate Beach, Oregon.
figure 4.18. In this case, $B_{2D}$ varied 87.30 m around a long term mean of 348.42 m, with the bar located farther away from shore during the winter and closer to shore during the summer. The phase angle was 59°. The annual signal explained 9.8% of the total variance found within the $B_{2D}$ statistic.

The location of bar 3 ($B_{3L}$) also showed an annual signal at Agate Beach (figure 4.19). The range of variation in $B_{3L}$ was 131.93 m, around a long term mean value of 633.74 m. Once again, the bar was closer to shore during the summer and farther from shore during the winter, with a phase angle of 45°. The annual signal in $B_{3L}$ explained 8.2% of the total variance of that statistic. An astute observer may note that the range of variation of bars 2 and 3 along with their mean locations raises the possibility that bar 2 and bar 3 may not actually be individual sand bars, but that instead particular sand bars are being labeled differently throughout the year. Figure 4.20 shows a plot of the annual signal of each of the two bars. Within this figure it can be noted that although bar 3 moves onshore during the summer, and in fact crosses the offshore winter position of bar 2, at that time during the year bar 2 has also moved onshore and the two bars are still being tracked separately.
The distance from shore to bar 3 (B3D) also showed an annual signal at Agate Beach, as can be seen in figure 4.21. In this case, B3D varied 156.23 m around a long term mean of 431.39 m; the bar was farther offshore during the winter, with a phase angle of 44°. The annual signal in B3D explained 21.2% of the total variance within B3D.

In contrast to the innermost bar at Agate, the two offshore bars did not show any significant trends in the standard deviation of either their location or their distance to shore. In each case, annual variation accounted for less than 1% of the total variance of the standard deviation.

Analysis of the bar spacing at Agate Beach did reveal annual signals. The mean cross shore distance between the innermost bar and bar 2 (B12D) showed an annual signal with a
range of 45.13 m around a long term mean of 123.27 m, as shown in figure 4.22. The bars were closer together during the summer, and farther apart during the winter, with a phase angle of 29°. The annual signal in the distance from the innermost bar to bar 2 explained 10.9% of the total variance within B_{12D}.

The distance between bars 2 and 3 at Agate Beach (B_{23D}) showed a similar annual cycle as was found in the distance between the innermost bar and bar 2; a plot of B_{23D} can be found in figure 4.23. Once again, the bars were closer together during the summer, and farther apart during the winter. The range of the annual signal was 77.05 m, around a long term mean value of 125.54 m. The annual signal within B_{23D} explained 20.6% of the total variance within the statistic.

Having data for all three bars visible at Agate throughout the year, as well as data on the spacings between these bars, allows for some general trends to be noted. During the summer months, all of the bars tend to be closer to shore than they are during the rest of the year. During the winter all of the bars move offshore; however, each offshore bar tends to move farther than any of the bars more shoreward, causing the spacing between the bars to increase as well. It is

![Figure 4.23: The distance between bar 2 and bar 3 at Agate Beach, Oregon.](image-url)
known that at least one additional bar exists at Agate (bar 4), which does appear occasionally during the winter months; however, without summer data, it is impossible to determine from this data set if bar 4 shows the same migration and spacing patterns as the three more shoreward bars.

4.2.3 Relationships Between Environmental and Morphometric Statistics

Once again, the annual signals in both the environmental statistics and the morphometric statistics raised the possibility that perhaps there was some significant forcing between wave height or wave period and the beach as parameterized by our statistics. Interestingly, although there was a positive correlation between wave height and innermost bar location at short lags, the correlation never crossed the 95% significance level; this cross correlation is shown in figure 4.24. The wave height did show a significant positive correlation with the distance from the shore to the innermost bar, as shown in figure 4.25. However, this correlation was only above the 95% significance level for about a day. One possibility may be that the innermost bar at Agate Beach has an instantaneous response (at least at a daily interval) to wave forcing, and is uncorrelated at any
longer lag. Another possibility may be that the offshore bars at Agate Beach are shielding the innermost bar, causing the response to wave forcing of the innermost bar to be less than at the other sites.

Both offshore bars at Agate Beach showed a significant correlation with wave height. The correlation between wave height and the location of bar 2 ($B_{2L}$) is shown in figure 4.26, while the correlation between wave height and the location of bar 3 is shown in figure 4.27. In both cases, the correlation remains above the 95% significance level for an extremely long time, at least 30 days in both cases. The correlation between the distance from shore to bar 2 and bar 3 showed a similar positive correlation out to lags of 30 days. In each case, the bar moves offshore
when the wave heights are high, and onshore when the wave heights are low; this correlates well with our annual signal data, in which both bars were farther offshore during the winter and farther onshore during the summer. The fact that the offshore bars are well correlated with wave height may be an indication that waves have a much stronger influence on the first bar they break over, as opposed to bars they encounter after they have reformed following a break. At Agate Beach, where waves in general break over two to three offshore bars before encountering the innermost bar, this may explain the weak correlation between wave height and the innermost bar location.

In addition to the relationship found between the individual offshore bar positions and the wave height, a significant

Figure 4.27: The cross correlation of wave height with the location of bar 3 at Agate Beach, Oregon.

Figure 4.28: The correlation between $H_S$ and the distance between the innermost bar and bar 2 at Agate Beach.
relationship was found between the spacings of bars and the wave height. Both the spacing between the innermost bar and bar 2 (shown in figure 4.28) and the spacing between bars 2 and 3 showed a significant positive relationship with the wave height, indicating that bars became farther apart when the wave height increased. This relationship corresponds well with our annual signal data, since the spacing between the bars tended to increase during the winter when the wave heights were higher. It is unknown exactly why wave height would have an effect on bar spacing. Since all bars responded to increased wave heights by moving offshore, one possibility is that the dissipation of wave energy through breaking over the offshore bars resulted in a decreased response of the inner bar.

No other significant relationships were found between wave height data and any of the other morphometric statistics. In addition, no significant relationships were found between the wave period and any of the morphometric statistics at Agate Beach.

4.3 Duck, North Carolina, United States

At Duck, N.C., we identified the presence of an annual signal within the wave height data and within several of the morphometric statistics, including the position of the innermost bar, the position of the shoreline, and the number of rips. We also noted a significant relationship between wave height and each of the aforementioned morphometric statistics. In addition to the analysis of the complete data set, we performed the same analysis on data from when the first camera (c0)
was installed, in 1993, until additional cameras were added in 1997. Because of the relatively restricted view in the longshore of this camera, we can determine if the behavior of the beach in that longshore area alone is significantly different from the behavior of the entire site. In particular, the entire data set includes information from both north and south of the pier, while c0 only views an area north of the pier; the beach probably acts somewhat differently on either side of this structure. The specific results of our analysis for both the complete data set and for c0 from 1993 to 1997 are included below.

4.3.1 Environmental Statistics

We determined that the wave height (H$_s$) had a significant annual signal, as would be expected; wave height, its annual signal, and its autocorrelation can be found in figure 4.29. H$_s$ increased during the winter, and decreased during the summer, with a phase angle of 6.2°. Based on a least squares fit to an annual cycle, it was determined that H$_s$ varied by 0.4 m around a long term mean value of 0.98 m. The annual cycle explained 5.7% of the variance within the wave height data. No other significant signals
could be found within the wave height data, and no cycles of any significance could be found within the wave period (T) data at Duck. Because wave height and period are unaffected by camera view, these statistics were not analyzed separately for the c0 analysis.

4.3.2 Morphometric Statistics

Duck, N.C., had sufficient observations of rips for an analysis; figure 4.30 shows a plot of inverse rip spacing (SR) and its autocorrelation, as well as the annual cycle isolated in the data. Within the entire data set, we found an annual signal varying 4.1 x 10^-4 m^-1 around a long term mean value of 0.5 x 10^-3 m^-1; the number of rips tended to increase during the summer and decrease during the winter, with a phase angle of -2.6°. This annual signal explained 5.2% of the variance within the data record. Of interest, there were virtually no rips seen in the data set before 1997, making an analysis of SR in the c0 data set impossible. Historically, rips have been found in the longshore region of beach viewed by c0, and in fact were visible by this camera during the 1980’s (this period of time was excluded from our data set.
due to aliasing of the tide based on sampling interval). The reason behind why so few rips appeared in this area during the early 90's is unknown.

The shoreline location (ShL) at Duck also underwent an annual cycle; figure 4.31 shows ShL along with its autocorrelation and the annual signal isolated in the data. The range of variation between summer and winter was 3 m around a long term mean of 116 m, with the shoreline located more offshore during the summer and more onshore during the winter. The phase angle of this variation was -37°. The annual signal explained 3.2% of the variance with shoreline location.

Within the complete data set, there is a noteworthy jump in shoreline location between 1996 and 1998, amounting to 10-15 m. This period of time corresponds to when first two cameras and then two additional cameras were added at Duck, thus
including more of the beach to the south of the original camera view. In fact, when the shoreline location data from c0 (the original camera) for 1993-1997 were analyzed (see figure 4.32), it was discovered that while an annual signal existed in this shoreline data as well, the mean location was somewhat farther offshore, at 123.5 m. In addition, the range of variation between summer and winter was much greater, at 11.03 m, although the shoreline still showed the trend of being farther offshore in the summer than during the winter. The phase angle of this cycle was -43°. The annual signal in the c0 data was considerably stronger, explaining 20.8% of the variance of ShL. The standard deviation of shoreline location at Duck for both the entire data set and the limited c0 data set revealed no annual or other signals.

The location of the innermost bar at Duck (BIL) showed a significant annual cycle within both the entire data set (figure 4.33) and the limited c0 data set (figure 4.34). Within the entire data set, the inner bar varied by 16.85 m around a long term mean value of 188.92 m, with the bar moving offshore during the winter and onshore during the summer. The phase angle of this cycle was 25.3°. The annual signal explained 11.6% of the variance in

Figure 4.33: Innermost bar location at Duck, N.C., for the entire data set.
the original bar location data. Within the c0 data set, the bar showed considerably more variation between summer and winter, with a range of 27.52 m, and had a long term mean location farther offshore than for the entire data set, at 210.20 m.

Once again, the bar was farther offshore during the winter, with a phase angle of 42°. In the c0 data set, 8.5% of the variance in the data could be explained by the annual signal.

The distance from the shoreline to the innermost bar (B_{ID}) also showed a significant annual signal in both the entire data set (figure 4.35) and the limited c0 data set (figure 4.36). In the entire data set, B_{ID} had a range of 16.65 m around a long term mean value of 74.27, with the bar moving farther away from shore during the winter; the phase angle was 19°. The annual signal was slightly stronger in B_{ID} for the entire data set than it was in
BIL, explaining 14.3% of the variance. As was the case for BIL, the annual signal within the c0 data set showed a greater range, with a variation of 29.44 m between summer and winter around a long term mean value of 86.9 m. The phase angle in this case was 19°, as well. The annual signal in BID explained 10.0% of the variance for the c0 data set.

Within the entire data set, the statistics of innermost bar standard deviation and standard deviation of the distance from shore to the innermost bar (BIS and BIDS, respectively) showed no significant annual cycles; in each of these statistics, the annual cycle which could be obtained with a least squares fit explained less than 1% of the variance in the data. Within the c0 data set, however, the standard deviations statistics showed an interesting signal.
Within both B_{IS} (figure 4.37) and B_{IDS} (figure 4.38), a 50 day cycle could be isolated. In the case of B_{IS}, the 50 day cycle explained 8.0% of the variance, as opposed to an annual cycle which only explained 2.7% of the variance. The 50 day cycle isolated within the B_{IDS} data explained 7.6% of the variance, as opposed to an annual cycle which explained less than 1% of the variance within B_{IDS}. The exact cause of this odd cycle within the c0 innermost bar standard deviation statistics is unknown, nor is it known why this cycle does not appear in the complete data set. One possible reason may be that bar standard deviation is related to some specific set of conditions, such as storm events, which occurred on a more regular basis between 1993 and 1997.

As was previously mentioned, not enough observations of an offshore bar existed for a statistical analysis to be undertaken; however, several qualitative observations can be made. At Duck the maximum number of bars that appeared in the images was two, the innermost bar quantified above and an outer bar at around 350 m that could only be imaged during high wave conditions. Because of the limitations of wave conditions, the outer bar only appeared during the winter and in
general did not cover the complete longshore coverage of the cameras (most probably due to the bar being too far offshore at certain longshore positions for the waves to break over it). In addition, the bar only appeared during the last few years of our data record. Previous study has found that there is a long term cycle (multiple years) at Duck whereby a bar forms close to shore and moves farther offshore over time, until at some point a new bar forms close to shore and the old bar decays (Plant et al, 1999). Our data (see figure 4.39) covers a sufficiently long time scale to span one of these cycles. We are seeing one bar (‘+’ in figure 4.39) which starts as an inner bar and begins to move offshore, until another bar (‘.’ in figure 4.39) forms close to shore and becomes the inner bar.

4.3.3 Relationships Between Environmental and Morphometric Statistics

Using autocorrelations of morphometric statistics, we found that many of these statistics had strong annual signals. Given that wave heights have a strong annual signal, it was reasonable to assume that wave height had some forcing effect on the beach as parameterized by our morphometric statistics. In order to test the
relationship between wave height and beach response, $H_S$ was cross-correlated with each of the morphometric statistics. We also cross-correlated wave period with each of the morphometric statistics to determine if any significant forcing could be found.

A significant relationship between wave height and innermost bar location ($B_{IL}$) was found within the data. Figure 4.40 shows a plot of this cross correlation, both over the entire record length and zoomed in to smaller lags. (It would not be expected that the wave height on one particular day would have a significant effect on anything upwards of a month later, although trends in wave heights such as multiple high wave days could effect the beach for much longer.) The annual signal in the cross correlation was due to the fact that both statistics individually have an annual signal. There is a strong positive correlation between wave height and bar location, indicating that an increase in wave height caused the bar to move offshore. This correlation corresponded well to our annual signal data, in which bar location moved offshore during the winter months when wave height was generally higher. This correlation remained above the 95% significance level for about 6 days.

![Figure 4.40: The cross correlation of wave height and innermost bar location](image)
Wave height was also cross-correlated with the distance from the shore to the innermost bar ($B_{ID}$). A plot of this cross correlation is shown in figure 4.41. As would be expected, a similar relationship existed between wave height and distance to shore as existed between wave height and bar location referenced to the site's coordinate system. Again, the annual signal in wave height and $B_{ID}$ produced an annual signal in the cross correlation. In this case the cross correlation remained above the 95% significance level for slightly longer than in the case of $H_s$ cross-correlated with $B_{IL}$. Wave height had a significant effect on the distance to shore for approximately ten days.

Figure 4.41: The cross correlation of wave height with distance from shore to the innermost bar, Duck, N.C.

Figure 4.42: The cross correlation of wave height with shoreline location at Duck, N.C.
Wave height was also correlated with the shoreline location ($\text{Sh}_L$); a plot of this cross correlation is shown in figure 4.42. There was a negative correlation between $\text{Hs}$ and $\text{Sh}_L$, indicating that the shoreline retreated as the wave height increased. This correlation between wave height and shoreline location was significant for about nine days. This negative correlation corresponds well with our annual signal in shoreline location; during the winter months, when wave heights tended to be higher, the shoreline tended to be located farther onshore.

None of the other statistics at Duck had a significant correlation with wave height, and none of the statistics showed a significant relationship with wave period. In general, increased wave heights at Duck resulted in shoreline retreat while the innermost bar moved offshore. As mentioned previously, the barriness recorded in the images does increase with increased wave heights, although this relationship is more a result of a larger wave breaking window of viewing than an actual increase in the number of bars.

4.4 Palm Beach, New South Wales, Australia

Palm Beach, Australia, had considerably fewer morphometric statistics in which annual or other cycles could be found. The wave height data did show a weak annual signal; however, no signal whatsoever could be found within the wave period data. Significant relationships between wave height and the bar and shoreline locations were found, indicating that the lack of annual signals in the morphometric statistics was probably related to the fact that the wave height itself
had such a weak annual signal. Not enough observations of offshore bars were made at this site for analysis to take place. Palm Beach was the site within the study group showing the greatest number of rips, and a statistically significant relationship was found between wave height and inverse rip spacing. A more complete discussion of the analysis of Palm Beach follows.

4.1 Environmental Statistics

At Palm Beach there was a relatively small annual signal in wave height \( H_s \) compared to the other sites. Figure 4.43 shows a plot of the wave height data for Palm Beach, as well as its autocorrelation and annual signal. The annual signal had a range of only 0.38 m between summer and winter, around a long term mean value of 1.57 m. The phase angle of this cycle was \(-49.72^\circ\). The wave heights were higher during the southern hemisphere winter and lower during the summer, as would be expected. The annual signal in wave height only explained 3.1% of the total variance in wave height. No other significant signal could be found within the wave height data, and no annual or other signal could be found within the wave period data.

![Wave Height/Annual Signal in Wave Height, Palm Beach](image)

Figure 4.43: Wave height data from Palm Beach, Australia.
4.4.2 Morphometric Statistics

As previously mentioned, there were noticeably fewer significant annual or other cycles within the morphometric statistics at Palm Beach. Within the inner bar location ($B_{IL}$), no annual cycle could be found; figure 4.44 shows a plot of the innermost bar location at Palm Beach. The distance from shore to the innermost bar ($B_{ID}$) also lacked a significant annual cycle; figure 4.45 shows a plot of $B_{ID}$ along with its autocorrelation. There is an increase in the autocorrelation at a long lag of around 1000 days. Unfortunately, this time scale (just over 3 years) is too long for a robust analysis to take place given the length of our data.

Figure 4.44: The innermost bar location at Palm Beach, Australia.

Figure 4.45: The distance from shore to the innermost bar at Palm Beach.
record (just under 5 years). When more data is available for this site it would be interested to examine whether there is an interannual cycle in bar behavior at this site.

No annual or other cycles of any significance could be found in either the standard deviation of the innermost bar’s location ($B_{1S}$) or the standard deviation of the distance from shore to the innermost bar ($B_{IDS}$). Figure 4.46 shows a plot of the standard deviation of the distance from the shore to the innermost bar, along with its autocorrelation. There is an increase in the autocorrelation at a long lag of around 1000 days; once again, however, no cycle of this length can be isolated using the current five year data set.

The mean shoreline location at Palm Beach also lacked the annual signals seen at Duck. Figure 4.47 shows a plot of the shoreline location,
along with its autocorrelation. A peak in autocorrelation does appear at the same long lag (1000 days) at which a peak appeared in both the bar location and standard deviation statistics, indicating that perhaps the entire beach has gone through some sort of interannual behavioral cycle; however, with this short data record this cannot be quantified. The shoreline standard deviation did not show any annual or other cycles, and in fact did not show the peak in autocorrelation at 1000 days that appeared in other Palm Beach statistics.

Considerably more rips appeared at Palm Beach than at any of the other sites in this study group, resulting in a comparatively high inverse rip spacing \( (S_R) \). A plot of \( S_R \) along with its autocorrelation can be found in figure 4.48. When \( S_R \) was analyzed for annual or other signals, none were found having any significance. The peak in autocorrelation at short lags was quite narrow, indicating that inverse rip spacing was not particularly stable and that rips formed and disappeared rapidly.
4.4.3 Relationships Between Environmental and Morphometric Statistics

A significant relationship at short lags was found between wave height and inverse rip spacing; this cross correlation is shown in figure 4.49. At a small lag (~1 day), there was a significant negative correlation, indicating that increases in the wave height resulted in decreases in the number of rips. The fact that the correlation was only significant at short lags indicated that rip spacing either responded very rapidly to changes in wave height, or that rip spacing was also being controlled by some other forcing mechanism. Inverse rip spacing did not have a significant correlation with wave period.

As found at other sites, there was a significant negative correlation between wave height and shoreline location, indicating that as the wave heights increased

Figure 4.49: Wave height cross-correlated with inverse rip spacing

Figure 4.50: Wave height cross-correlated with shoreline location at Palm Beach, Australia.
the shoreline retreated; a plot of the cross correlation of $H_s$ and $Sh_L$ is shown in figure 4.50. The negative correlation between wave height and shoreline location was only significant for approximately two days, indicating that the shoreline response to wave height variation was almost immediate. No significant relationship could be found between wave height and shoreline standard deviation.

There was a significant positive correlation between wave height and inner bar location; this correlation is shown in figure 4.51. This positive correlation indicates that as the wave height increased, the innermost bar moved offshore, as was the response at many of the sites in this study. The cross correlation remained above the 95% significance level for about 8 days. When wave height was cross-

![Figure 4.51: The cross correlation of wave height and innermost bar location at Palm Beach, Australia.](image)

![Figure 4.52: The cross correlation of wave height and distance from shore to the innermost bar at Palm Beach.](image)
correlated with the distance from shore to the innermost bar ($B_{ID}$), a similar positive correlation was found; this cross-correlation is shown in figure 4.52. In this case, the correlation remained above the 95% significance level for a slightly shorter period of time, around 6 days. The innermost bar location and distance to shore did not show any significant relationship to wave period, and the standard deviation of the innermost bar and the standard deviation of the distance from shore to the innermost bar ($B_{ID}$ and $B_{IDS}$) did not show a significant correlation with either wave height or wave period.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Hs</th>
<th>Range Hs</th>
<th>% Var. Hs</th>
<th>Phase Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noordwijk</td>
<td>1.04 m</td>
<td>0.49 m</td>
<td>6.20%</td>
<td>-14.5°</td>
</tr>
<tr>
<td>Agate Beach</td>
<td>2.45 m</td>
<td>1.94 m</td>
<td>30.20%</td>
<td>13.8°</td>
</tr>
<tr>
<td>Duck</td>
<td>0.98 m</td>
<td>0.40 m</td>
<td>5.70%</td>
<td>6°</td>
</tr>
<tr>
<td>Palm Beach</td>
<td>1.57 m</td>
<td>0.38 m</td>
<td>3.10%</td>
<td>-49.72°</td>
</tr>
</tbody>
</table>

Table 4.1: The wave height data from each of the study sites.

4.5 Discussion

The most dissipative beach in our data set is Noordwijk, with an average $\xi_b$ of 0.11 ($\xi_b$ varies somewhat with incident wave conditions). Like Duck this beach lies along an open coastline, although the beach slope (0.015) is somewhat shallower than at Duck (0.035). Wave heights at Noordwijk are around 1.04 m, with an annual signal in wave height that explains 6.20% of the total variance. The mean wave height, range of variation between summer and winter, percentage of
total variance explained by the annual signal, and phase angle for each of the four sites is included in table 4.1. Like Agate Beach, this site shows an annual signal in wave period, although it is not as strong a signal as at Agate Beach and only explains 2.60% of the total variance. The mean wave period, range of variation between summer and winter, percentage of total variance explained by the annual signal, and phase angle for each site is shown in table 4.2.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean T</th>
<th>Range T</th>
<th>% Var. T</th>
<th>Phase Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noordwijk</td>
<td>6.00 s</td>
<td>0.54 s</td>
<td>2.60%</td>
<td>-8.09°</td>
</tr>
<tr>
<td>Agate Beach</td>
<td>7.29 s</td>
<td>2.36 s</td>
<td>30.00%</td>
<td>14.6°</td>
</tr>
<tr>
<td>Duck</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
</tr>
<tr>
<td>Palm Beach</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
</tr>
</tbody>
</table>

Table 4.2: The wave period data from each of the study sites.

The other dissipative beach in our data set is Agate Beach, Oregon, with $\xi_b$ approximately 0.13. This beach, bounded to the north by a headland, has a shallow slope of around 0.015, and is affected by varying wave heights (mean = 2.45 m) to a greater degree than at the other sites. Agate Beach also has the strongest annual signal in both wave height and wave period, with the annual signal in both wave height and wave period explaining 30% of the total variance. When spectral analysis was performed to determine the percentage of intra- vs. inter-annual variability, it was found that 89% of the variation in wave height occurred at intra-annual time scales, as opposed to only 11% of the variation occurring at low
frequency (longer than a year) time scales. The wave periods at Agate (mean = 12.1 s) are relatively long compared with the other sites. Once again, a high percentage (92%) of the variability in wave period occurred at intra-annual time scales.

Duck, North Carolina, is an intermediate beach with a $\xi_b$ of around 0.35. Duck lies on a long, uninterrupted coastline with relatively milder wave conditions; wave heights at Duck are lower than at the other study sites, with a mean of 0.98. The annual signal in wave height explained 5.70% of the total variance, approximately the same percentage as at Noordwijk. There was no annual signal in wave period at Duck. The wave periods are slightly longer at this site than at Noordwijk, at around 8.9 s, but are not as long as wave periods at Agate Beach (12.05 s) and at Palm Beach (9.8 s). Duck is a much steeper beach than the other sites, with a slope of around 0.1.

Palm Beach is also an intermediate beach, but has the highest $\xi_b$ of the group, around 0.5; at times, the wave conditions are such that $\xi_b$ can increase to a point that the beach becomes reflective. Palm Beach is a pocket beach, bounded on both sides by headlands, and is most notably characterized by the high number of rips relative to any of the other study sites. The wave heights at Palm Beach (mean value = 1.6 m) are second highest only to Agate Beach. The annual signal in wave height at Palm Beach is relatively weak compared to the other sites, explaining only 3.10% of the variance. In addition, 98% of the variance in wave height at Palm Beach occurred at frequencies higher than a year; at the other sites, high
frequency variation accounted for a slightly lower percentage (87-94%). This high frequency variation is probably tied to a storm dominated climate. The wave period data at Palm Beach showed no annual signal, although wave periods were slightly longer (10.5 s) at Palm Beach than at most of the other study sites. The percentage of high frequency variance in wave period at Palm Beach was also relatively high (97%).

The barriness at most of the sites did show an annual signal; however, it is known from our investigation of wave breaking window of viewing that this cycle is more related to winter wave conditions pushing the edge of the window of viewing offshore, as opposed to additional features appearing during certain times during the year. An investigation of actual bathymetric data using this analysis technique might yield more revealing behavioral trends.

The inverse rip spacing could only be investigated at two of the sites, Palm Beach and Duck, since an insufficient number of rips appeared at the other sites for statistical analysis to take place. The two sites with the highest Iribarren numbers did have the most rips; however, without investigating the correlation between changing Iribarren numbers over time and inverse rip spacing it is impossible to determine if there actually is a significant relationship. At Duck, there was an annual signal in inverse rip spacing, in which more rips appeared during the summer than during the winter, when wave heights were higher; at Palm Beach, no annual signal could be found. At Palm Beach, a significant negative correlation was found between wave height and inverse rip spacing, indicating that increased
wave heights resulted in fewer rips; however, this correlation was not particularly strong. The decrease in the number of rips during periods of increased wave heights may actually be a viewing effect; the dark gaps in sand bars occurring at rip locations may simply be harder to identify in Argus images when there is increased wave breaking. From the data we have, it is impossible to make definitive conclusions for rip causation, although it does appear that periods of increased wave height may result in fewer rips.

The mean shoreline location statistic was found to have a different behavior at each of the sites; table 4.3 shows the shoreline location information from each of the sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>ShL Cycle</th>
<th>Mean ShL</th>
<th>Range ShL</th>
<th>% Var ShL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noordwijk</td>
<td>(no cycle)</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Agate Beach</td>
<td>Semi-Annual</td>
<td>196.46 m</td>
<td>53.15 m</td>
<td>20.30%</td>
</tr>
<tr>
<td>Duck</td>
<td>Annual</td>
<td>115.83 m</td>
<td>2.74 m</td>
<td>3.20%</td>
</tr>
<tr>
<td>Duck (c0)</td>
<td>Annual</td>
<td>123.5 m</td>
<td>11.03 m</td>
<td>20.80%</td>
</tr>
<tr>
<td>Palm Beach</td>
<td>(no cycle)</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 4.3: The shoreline location data from each of the study sites.

One possible reason for the wide range in behavior at each of the sites is that our mean shoreline location statistic cannot effectively track longshore sand movement, a large factor controlling shoreline behavior that varies from site to site. Even at Duck, where there was a measurable annual cycle, it only explained 3.20% of the total variance in shoreline location. Within the c0 data set at Duck, there was
a much stronger annual signal. One possible reason for the stronger annual signal in the c0 data is that annual changes in alongshore movement of sand average out over the entire site, whereas by focusing on a smaller longshore scale annual erosion and accretion can be tracked. At Agate Beach, there was an unusual semi-annual cycle in shoreline behavior, probably related to beach rotation during the year. No cycles whatsoever could be found at Noordwijk or Palm Beach within the shoreline location data. Interestingly, Agate Beach was the only site with an annual signal in shoreline standard deviation; this also may be related to beach rotation.

Although cycles in shoreline data were not universal at the sites, a relationship was established between shoreline location and wave height. At Palm Beach, Duck, and Noordwijk, increased wave heights resulted in shoreline retreat, with correlation above the 95% significant level for anywhere from two to six days. The shorelines measured in this study are the intersection of sand and water within the images; therefore, our measurement is effected by increased set-up (water pushed up onto the beach above still water level) during periods of increased wave height as well as by erosion and accretion effects.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Bid</th>
<th>Range Bid</th>
<th>% Var. Bid</th>
<th>Phase Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noordwijk</td>
<td>116.36 m</td>
<td>21.09 m</td>
<td>7.80%</td>
<td>43°</td>
</tr>
<tr>
<td>Agate Beach</td>
<td>198.39 m</td>
<td>26.63 m</td>
<td>2.10%</td>
<td>30°</td>
</tr>
<tr>
<td>Duck</td>
<td>74.27 m</td>
<td>16.65 m</td>
<td>14.30%</td>
<td>19°</td>
</tr>
<tr>
<td>Duck (c0)</td>
<td>86.9 m</td>
<td>29.44 m</td>
<td>10.00%</td>
<td>19°</td>
</tr>
<tr>
<td>Palm Beach</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
<td>(no cycle)</td>
</tr>
</tbody>
</table>

Table 4.4: Innermost bar statistics from each of the study sites
All but one of the sites showed an annual signal in both the innermost bar location and the distance from shore to the innermost bar, although the annual cycle was stronger at some sites than others. Table 4.4 contains innermost bar information from each of the sites.

In general, the innermost bar tended to anywhere from 75-200 meters offshore at all of the sites. As was previously mentioned, it is important to recognize that the innermost bar is the bar closest to shore at any given time, and does not necessarily track one individual sand bar. At all of the sites, there was a significant positive correlation between wave height and innermost bar location over lags of 7-10 days, indicating that increased wave heights result in offshore migration of the sand bar.

The site with the weakest correlation between wave height and innermost bar location was Agate Beach, the only site where waves consistently break over multiple offshore bars before encountering the innermost bar. It was discovered that the offshore bars at Agate Beach did have a more significant correlation with wave height, even at lags up to 30 days, and that both offshore bars showed a relatively strong annual signal in their location. The bar spacing at Agate Beach also showed a correlation with wave height, wherein the bar spacing increased during periods of increased wave heights. As waves break over each of the offshore bars, some wave energy is lost; this may explain both the more significant correlation of the offshore bars with wave height and the increased bar spacing.
The more offshore bars probably respond more rapidly to changes in wave height, since more wave energy is dissipated over them as opposed to the shielded innermost bar.

The annual signal in wave height at all of the sites but Palm Beach resulted in an annual signal in innermost bar location. At Palm Beach, the annual signal in wave height is relative weak compared to the other sites, which may explain why no annual cycle was found in innermost bar location. In addition, the intra-annual variability at Palm Beach (95%) was relatively higher than at the other sites (81-90%), a result of the high percentage of intra-annual variation in wave height (98%).

Duck and Noordwijk had the highest percentages of inter-annual variability (15% and 19% compared to 5% and 10% at Palm Beach and Agate Beach). One reason for this relatively higher percentage of low frequency variability is the inter-annual cycle in bar formation and migration that has been observed at these two sites. Bars form close to the shore and over the period of multiple years slowly migrate offshore, until a new bar forms close to shore to replace it (Plant et al, 1999). The percentage of inter-annual variability observed in the bars at these sites would probably be even higher if individual bars were tracked separately, as opposed to tracking the innermost bar as was done in this study.

In addition to the patterns of bar movement in response to wave height at each of the sites over time, comparing the innermost bar locations at each of the sites revealed that, with the exception of Palm Beach, those sites with higher wave
heights had innermost bars farther from shore. Once again the headlands at Palm Beach may be influencing the wave conditions by shielding the beach from some of the incident waves. In addition, the steep beach face is influencing the mean bar position. At steeper beaches, the deeper water close to shore inhibits the sand bars from moving as far offshore as is possible at shallower beaches.

Although no relationship could be found in the standard deviation of sand bars, and in general the sites did not show any sort of cyclical behavior, the ratio of the standard deviation of the innermost bar to the distance from shore ($B_{IDS}/B_{ID}$) was found to be quite consistent from site to site. $B_{IDS}/B_{ID}$ was between 0.15 and 0.18 at all of the sites. This seems to indicate that sites with larger wave heights such as Agate Beach have the same ratio of longshore bar variability to bar location, but simply occur on a larger scale. The offshore bars at Agate Beach had a slightly lower ratio of standard deviation to location ($B_{2DS}/B_{2D} = 0.10$, $B_{3DS}/B_{3D} = 0.08$); however, without more data on the offshore bars at other sites it is impossible to make any general conclusions about offshore bar standard deviation as a function of position.
Chapter 5: CONCLUSIONS

Based on this study of four sites from around the world using images derived from the Argus network, several conclusions can be reached about both the Argus system itself as a scientific tool and about observed trends in beach behavior:

1. A method of creating a site-specific wave breaking window of viewing was developed, allowing for the determination of cross shore positions where it is feasible that waves of a particularly height and period could break over bathymetric features at a particular tidal level. Using this method, the absence of breaking at some cross shore position can be determined to result from a lack of bathymetric feature at that location or result from the cross shore position lying offshore from the edge of the wave breaking window of viewing. Shoreward biased data for sand bars with gaps caused by non-breaking over offshore features can also be excluded from study.

2. A relationship between tidal level and breaking position over a sand bar was determined, and thus bar positions can be normalized to one tidal level. Although it would be preferential to be able to determine actual bathymetry from wave breaking data, using this method it is at least possible to reduce tidal biasing within the data set.

3. A relationship between wave height and shoreline location was determined, with increased wave heights resulting in shoreline retreat. This effect is probably a combination of actual beach erosion and increased set-up during
periods of increased wave height. The annual signals in wave heights at the sites were not replicated in the shoreline location data; however, this may be due to the inability of a mean shoreline location statistic to track variation caused by to longshore sediment transport.

4. A relationship was found between wave height and sand bar location. Increased wave heights resulted in sand bars moving offshore, and the annual cycle in wave heights at most of the sites resulted in annual migration behaviors in the sand bars. The exception was Palm Beach, where the annual signal in wave height was relatively weak and may not have been strong enough to force an annual signal in bar location; in addition, the headlands at the site shield the beach from some of the incident waves. At Agate Beach, where waves often break over multiple offshore bars, the offshore bars had stronger annual signals and stronger correlations with wave height data, indicating that perhaps the offshore bars shielded the innermost bar from wave effects.

In addition to the response of individual sand bars to wave height, there seems to be a relationship between the cross shore location of the innermost sand bar at each of the sites and the wave height. The site with the highest wave height, Agate Beach, had an innermost bar farthest from shore, whereas Noordwijk and Duck, with relatively lower wave heights, have innermost bars closer to shore. Bar position is also affected by beach slope; however, given that Noordwijk and Agate have approximately the same beach slope, the difference is bar location at these two sites is a result of wave height. Duck is a relatively steeper beach; therefore, at this
site, the effect of steep beach slope and low wave heights combine to result in a bar close to shore. At Palm Beach, there are relatively high wave heights, but the innermost bar is relatively close to shore. One possibility may be that pocket beaches behave differently than beaches on relatively open coastlines; the headlands no doubt refract the waves and prevent the beach from being struck by the full force of wave energy. In addition, the steep slope at Palm Beach inhibits offshore bar migration.

5. The ratio between the standard deviation of the innermost bar and the location of the bar relative to shore ($B_{IDS}/B_{ID}$) was determined to be a fairly robust value, varying from 0.15-0.18 at all of the study sites. This seems to indicate that although wave climate and average beach slope affect the cross shore scales of beaches and the number of bars over which waves break, $B_{IDS}/B_{ID}$ remains constant.

The nature of the analysis technique developed in this study allows for large amounts of data from sites around the world obtained through both bathymetric surveying and remote sensing techniques to be analyzed for behavioral trends and cycles over time, as well as statistical correlations between beach response and environmental forcing. In addition, sites can be compared to determine similarities and differences in behavior. In the future, it would be beneficial to apply the techniques developed in this study to many other sites and over much longer time scales, thus allowing for more robust analyses of beach behaviors.
BIBLIOGRAPHY


