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Assessing Cross-Shore and Alongshore Variation in Beach Morphology Due to Wave Climate

STORMS TO DECADES

By Shari L. Gallop, Mitchell D. Harley, Robert W. Brander, Joshua A. Simmons, Kristen D. Splinter, and Ian L. Turner

PURPOSE OF ACTIVITY

Long-term observational data sets of beach profile variability and underlying trends that have been measured regularly and uninterrupted for several decades are very rare (Barnard et al., 2012, 2015; Kuriyama et al., 2012; Splinter et al., 2014; Pianca et al., 2015; Turner et al., 2016). Only a few sites around the world have sustained routine decadal-scale monitoring of the coastline, with notable examples that include the US Army Corps of Engineers Field Research Facility in the United States (http://www.frf.usace.army.mil), the Hazaki Oceanographical Research Station in Japan (http://www.pari.go.jp/unit/edosy/en/main-facility/2.html), and Narrabeen-Collaroy Beach in Australia (http://www.narrabeen.wrl.unsw.edu.au). These unique data sets are critical for understanding how beaches respond to processes over a range of time scales, including storms that last hours to days, interannual climatic cycles such as the El Niño-Southern Oscillation (ENSO), and longer-term processes such as mean sea level rise. This type of knowledge is essential for predictive modeling and for making appropriate coastal management and planning decisions. A key skill set for coastal scientists and engineers is the ability to critically analyze, present, and summarize such data, as well as to link changes in the beach profile to forcing conditions. Therefore, the purpose of this activity is to utilize a novel and freely available online resource of beach profile data from Narrabeen-Collaroy Beach in New South Wales, Australia, to assess how the subaerial beach and the shoreline position vary (1) spatially due to alongshore-variable wave conditions, and (2) over multiple time scales in response to changing wave conditions and climate cycles.

AUDIENCE

This activity is aimed at university-level students in coastal oceanography, geoscience, and engineering, and could also be adapted for use by senior high school students. It engages students to interpret and manipulate real beach profile data to gain an understanding of beach adjustments and shoreline changes over multiple time scales, extending from short-term storms to longer-term patterns and trends over several decades. The activity consists of two parts. Part 1 focuses on familiarization with beach monitoring data formats and online plotting tools. Part 2 builds on this knowledge by engaging students in downloading data and interpreting causes of spatial and long-term temporal changes in beach morphology relative to the local wave climate. The activity is designed so that Part 1 can be completed on its own, or followed by Part 2 for more advanced students. In addition, it can be used for both assessable and non-assessable assignments that may be implemented via either supervisor instruction and/or as a student-driven learning exercise.

BACKGROUND

Beach Monitoring Data

In its most basic form, beach morphology (here defined as the cross-shore variation in elevation of the beach) can be monitored by obtaining a cross-shore beach profile that is perpendicular to the shoreline between a survey benchmark situated at the landward boundary of the subaerial beach and a point seaward of an arbitrary offshore distance, or at a lower elevation such as low tide. Note that "subaerial" refers to the beach elevated above mean sea level. A variety of survey methods are used to obtain beach profiles, ranging from simple techniques involving a measuring tape and a leveling rod (e.g., Emery, 1961; Delgado and Lloyd, 2004) to more sophisticated techniques such as Real Time Kinematic Global Positioning System (RTK-GPS), terrestrial laser scanning and Light Detection and Ranging (LiDAR; e.g., Pietro et al., 2010), and unmanned aerial vehicles (UAVs) or "drones" (e.g., Casella et al., 2016; Turner et al., 2016). These more advanced techniques permit faster survey data collection at higher spatial resolution, and can generate three-dimensional representations of beach morphology.

This activity focuses on two-dimensional beach profile data collected using a number of methods at Narrabeen-Collaroy Beach, located within the Northern Beaches region of Sydney in southeast Australia (Figure 1), which is the site of one of the longest beach morphological monitoring programs in existence (Turner et al., 2016).

Narrabeen Study Site

Narrabeen-Collaroy Beach (referred to here simply as "Narrabeen") is a 3.6 km-long sandy embayed beach consisting of fine to medium quartz sand (mean grain size $D_{50} \approx 0.3$ mm), with approximately 30% carbonate content. Narrabeen is microtidal (mean spring tidal range = 1.3 m) with moderate to high wave energy characterized by a mean deepwater significant wave height (H_s) of approximately 1.6 m and a corresponding peak wave period (T_p) of approximately 10 s. Waves typically arrive at the coastline from the south-southeast and are generated by mid-latitude cyclones in the southern Tasman Sea (Short and Trenaman, 1992; Harley et al., 2010). At Narrabeen, sheltering effects due to the southern headland (Long Reef Point, Figure 1) create a general gradient of decreasing wave heights from north to south under typical south-southeast waves (Turner et al., 2016). However, storm wave events originate from a number of sources and directions, including tropical cyclones from the northeast, east coast lows from the east (Harley et al., 2016), and intensified mid-latitude cyclones from the south (Turner et al., 2016).

Narrabeen Beach Data Set

Commencing in 1976, five cross-shore beach profile lines were established along Narrabeen Beach (Figure 1) and since then have been measured on an approximately monthly basis (551 surveys in total between April 1976 and March 2017). Prior to 2004, profile lines were surveyed at 10 m cross-shore intervals using a measuring tape and a leveling rod, the so-called "Emery method" (Emery, 1961). An assessment of the accuracy of surveys using this technique found that elevation data were accurate to within ±0.11 m (Harley et al., 2011). Since 2004, beach profiles have been measured using higher accuracy RTK-GPS (elevation accuracy ≈ ±0.03 m) and at an enhanced cross-shore resolution of every 1 m. For a full description of the Narrabeen-Collaroy coastal monitoring program, including other three-dimensional survey methods undertaken at the location, refer to Turner et al. (2016).

In 2016, the historical and ongoing monthly measurements of the five beach profiles were made freely available online at http://narrabeen.wrl.unsw.edu.au. This website enables users to explore and compare beach profile data collected during any part of or spanning the full four decades of observations. Online visualization and analysis tools enable plotting of beach profile lines, time series of shoreline positions and subaerial sand volumes, time series of beach indices (the Subaerial Volume Index [SVI] and Beach Orientation Index [BOI]), and time series of related climate cycles (the Southern Oscillation Index [SOI], an ENSO indicator) (e.g., Figure 2). The website also permits users to download (through a simple registration process) the entire beach profile data set, bathymetric data, hourly wave conditions at 10 m water depth adjacent to each profile location, and astronomical tide data at 15 minute resolution. Hourly wave conditions consist of significant wave height (H_s), peak wave period (T_p), and wave direction, and represent modeled inshore conditions based on offshore wave data collected from a wave rider buoy located 11 km from Narrabeen-Collaroy (in 80 m water depth). Turner et al. (2016) provide detailed descriptions of each data set. Users can then plot and further analyze the data using software packages of their choice, such as Matlab, Excel, or Python.

MATERIALS

This activity has minimal material requirements. For Part 1, participants need only a computer with Internet access and a web browser (e.g., Explorer, Safari, Chrome). To complete Part 2, an email address is also required to register and download the data. In addition, completion of all aspects of Part 2 requires students to have access to Matlab (a licensed software)

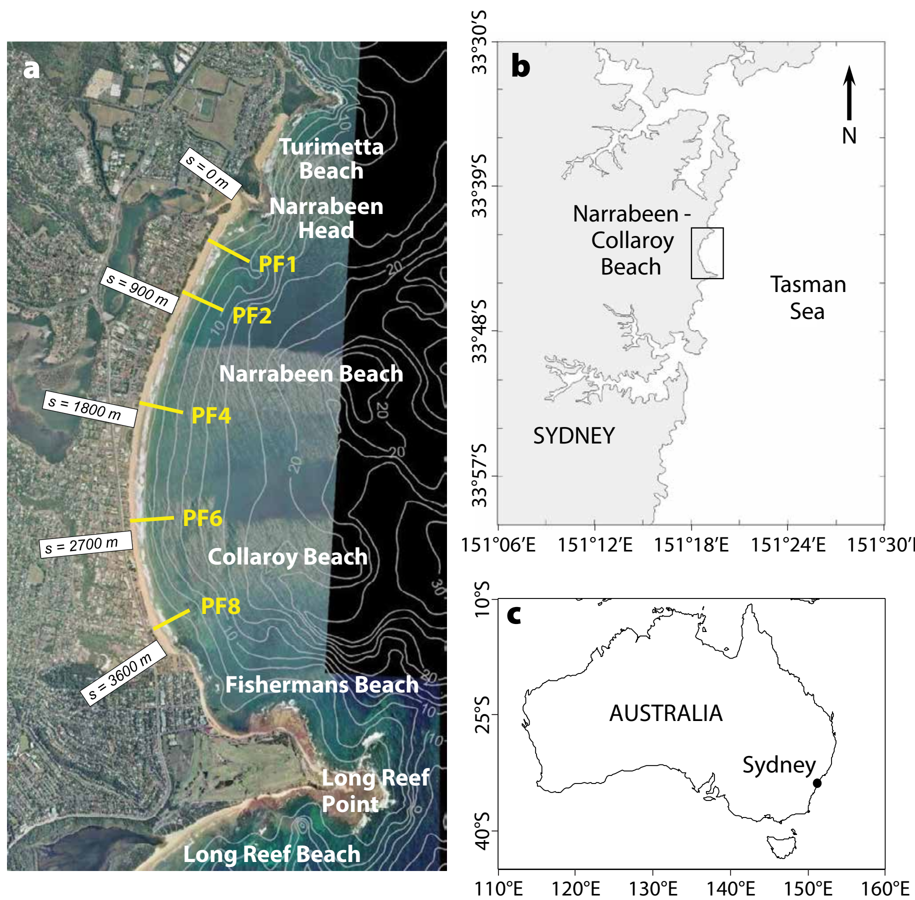

FIGURE 1. (a) Aerial photo of Narrabeen-Collaroy Beach showing the locations of the five historical survey profile lines (PF1, PF2, PF4, PF6, and PF8), depth contours at 2.5 m intervals, and the local alongshore coordinate system relative to Narrabeen Head. *Image credit: NSW Department of Lands* (b) The beach relative to Sydney. (c) Australia (adapted from Turner et al., 2016).

or another software package capable of simple numerical analysis and plotting, such as Microsoft Excel or Python. If students do not have access to an institutional Matlab license, it can be purchased from Mathworks for a student price. We use Matlab here because it is an industry standard for coastal scientists and engineers and facilitates learning transferable computer coding skills. We assume basic familiarity with Matlab; plentiful support and tutorials for new Matlab users are available at http://www.mathworks.com.

ACTIVITY PART 1: LONG-TERM BEACH PROFILE VARIABILITY AND CAUSES

Part 1 involves using the online beach profile data and plotting tools only, and will take approximately three to four hours to complete. It focuses on:

1. Familiarizing users with the Narrabeen Beach monitoring data and online plotting tools
2. Interpreting beach profile data and morphologic change over varying temporal and spatial scales
3. Examining time series of shoreline position along the beach
4. Understanding temporal changes in subaerial beach sand volumes
5. Relating morphological beach change to longer-term climatic cycles

Key References: Compulsory reading assignments prior to this part of the activity are Turner et al. (2016), Barnard et al. (2015), and Ranasinghe et al. (2004). Links to these key publications are available under Links & Publications on the Narrabeen monitoring data website.

Accessing the Data

First, visit http://narrabeen.wrl.unsw.edu.au and become familiar with the Narrabeen Survey Program via the Background tab in the main menu. When ready, begin to explore the beach profile data via the Explore Data tab. Here, spend 10–15 minutes using the three primary components of the data set via the three buttons: (1) Beach Profiles, (2) Time Series, and (3) Beach and Climate Indices. Within (1) and (2), first try selecting single profile lines (e.g., PF1) over different time periods in order to understand how the plotting tool works and how to interpret the information that each of these plots are presenting. Second, try more advanced plots using multiple profiles. For (3), select different time periods only. Note that instructors can set a specific

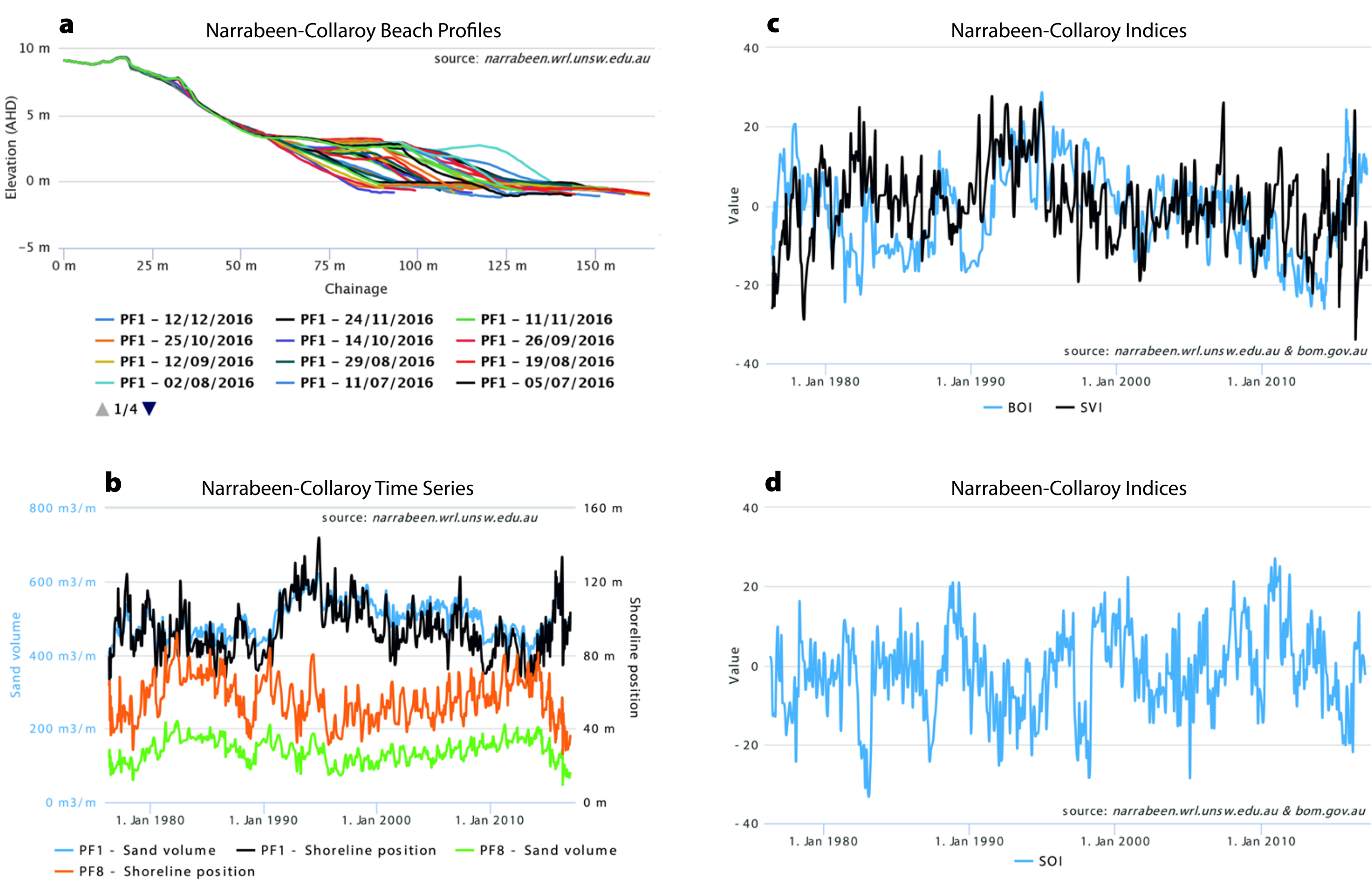

FIGURE 2. Examples of graphic output from the plotting tools provided at http://narrabeen.wrl.unsw.edu.au, showing (a) cross-shore beach profiles at PF1 in 2016, (b) time series of shoreline position and sand volume at PF1 and PF8 for 1976–2017, (c) Subaerial Volume Index (SVI) and Beach Orientation Index (BOI), and (d) Southern Oscillation Index (SOI) for 1976–2017.

time period for familiarization while student-led learning exercises may take as long as they like to explore the functionality of the Explore Data feature. The following questions involve plotting data using this feature.

Questions

1. Beach Profile Adjustment

Create a beach profile plot of one profile location shown in Figure 1 over the last six months. Answer the following:

- Between which elevation range has most of the change occurred over this time period? What do you think are the causes of these changes?
- When beaches gain sand, the shoreline tends to move seaward and the beach is said to be "accreting." When beaches lose sand offshore, the shoreline retreats landward and the beach is said to be "eroding." Is the beach eroding or accreting over this time period and how can you tell?
- Do you see any morphological features in the beach appear/disappear with time? Some examples of morphological features on the subaerial beach include berms, runnels, and dunes.

2. Temporal Fluctuations in Shoreline Position

Create a time series of shoreline position for profiles PF1 and PF8 over the last 10 years. You can see that beaches change on a short time scale, but also over longer periods (months to years). Answer the following:

- Can you identify any trends in the two time series that appear to be opposite (i.e., showing the shoreline moving in different directions, landward/seaward)?
- If so, describe these trends using specific dates to illustrate your examples. Over what time scales do these changes occur?
- What would this behavior indicate is happening to the overall planform of the beach?

3. Sand Volumes, Beach Accretion and Erosion

Using the Beach and Climate Indices button, you can plot how volumes of sand along the whole beach change compared to the long-term average. Plot the last 10 years of the SVI, which gauges the overall (i.e., averaged alongshore) accreted/eroded state of the beach relative to the long-term average (Harley et al., 2015).

- Describe how the beach has varied over this time in terms of sand volume. Has it been primarily accreting or eroding?
- Can you describe any cycles or trends in the data? If so, use dates to support your answer.

4. Causes of Beach Morphological Variability: ENSO

The beach profile data you have worked with above may show variability and change over time, but they do not reveal the cause of these changes. Most changes are largely due to wave activity, which in turn is related to climatic factors. Waves can change in magnitude and also in direction over time. This can cause beaches to erode/accrete, and also to oscillate, such as when the northern end (i.e., PF1) accretes while the southern end (i.e., PF8) erodes. One advantage of long-term data sets of beach profile variability is that they can be compared to long-term fluctuations in climate cycles in order to show relationships that may not be evident in shorter-term data sets (i.e., those only a few years in length, or less). In the Pacific Ocean where Narrabeen is located, the primary climate cycle ENSO is commonly quantified using the SOI. Similar climate cycles also exist for other ocean basins, including the North Atlantic Oscillation (NAO), the Indian Ocean Dipole (IOD), and the Southern Annular Mode (SAM).

The SOI is a number (index) calculated using the pressure difference between Tahiti in French Polynesia and Darwin in Australia. This index indicates the development and intensity of El Niño or La Niña events. Prolonged positive values >7 indicate a La Niña period, whereas prolonged negative values <-7 indicate an El Niño period. The SOI is updated monthly by the Australian Bureau of Meteorology (http://www.bom.gov.au).

The BOI is a gauge of the average orientation of the beach as measured by the mean sea level contour relative to the long-term average (Harley et al., 2015). A positive BOI means that the beach has a more clockwise orientation relative to the long-term average, whereas a negative BOI indicates a more counter-clockwise orientation. The BOI is an important indicator of beach rotation, where the two extremities of the embayment can be alternatively exposed to erosion due to a combination of both cross-shore and longshore sediment transport processes (Harley et al., 2011).

Use both the Subaerial Volume Index and the Beach Oscillation Index (available in Beach and Climate Indices) over the 10-year period used in Question 2 to explore relationships between ENSO (SOI) and overall sand volume changes (SVI) as well as beach rotation (BOI).

ACTIVITY PART 2: SPATIAL VARIABILITY IN WAVE CLIMATE AND STORMS

Part 2 focuses on:

1. Assessing alongshore variability in wave climate
2. The influence of alongshore variability in wave climate on beach profile change
3. The concept of beach profiles/shorelines being in equilibrium with forcing conditions, and how this affects the response to sequences of storms

Part 2 should take approximately two to three hours. Students will learn skills in sourcing and downloading different types of data, and plotting data using a combination of online tools with an option to use Matlab (or other suitable software package).

Key References: Important compulsory reading is Harley et al. (2016), Turner et al., (2016), and Wright and Short (1984). Links to these references are available under Links & Publications on the Narrabeen website.

also provides examples of how to compare wave conditions between two profiles over a certain period of time (in this case, one year).

Download Data

All data can be downloaded from the Narrabeen data repository: http://narrabeen.wrl.unsw.edu.au. In order to access the data, first navigate to this website and click on the Download Data tab. Here, you need to sign up as a new user by providing an active email address and filling out a number of information fields. Once registered, you will see a range of data available for download. For this activity, you only need to download the *Narrabeen Profile Data* and *Inshore Wave Data* by clicking on these buttons. Note that these will download as .csv files (comma -separated values). This is a commonly used data format that opens easily in a range of software programs such as Notepad, Microsoft Excel, and Matlab. Open both files in the program you are most familiar with (Microsoft Excel is suggested in the first instance) to have an initial look at the file content to familiarize yourself with the headings and data format.

Data Analysis

To plot beach profile data, you can use the built-in plotting tools provided on the website under Explore Data. Alternatively, you can plot the profiles in Matlab either by writing your own Matlab code or using (and potentially building on) the scripts (m-files) provided under Matlab Plotting Toolbox. This Matlab plotting toolbox is located on the website under the Download Data tab. As no plotting tools are provided on the website for the inshore wave data, we provide downloadable m-files (*Plot_select_profiles.m* and *Plot_inshore_waves.m*) to enable plotting of these wave time series in Matlab (see example in Figure 3). Each of these m-files includes detailed comments instructing the user about the function of each part of the code. Note that you will need to update the folder path to direct Matlab to where you have saved the data.

- *Plot_select_profiles.m* loads the profile data and shows example codes of how to overlay profiles at a particular location at different times and how to compare profiles from select dates.
- *Plot_inshore_waves.m* loads the inshore wave data and gives examples of how to plot waves at a single profile. It also provides examples of how to compare wave conditions between two profiles over a certain period of time (in this case, one year).

Questions

Use the background information above, online and/or Matlab plotting tools, and references provided to answer the following questions. Students are also asked to: (1) use peer-reviewed journal articles to support their answers, and (2) provide figures and/or tables to support their arguments.

1. Alongshore Variability in Wave Climate

Plot the inshore wave data in Matlab. How does wave height and direction differ at the south end (i.e., PF8) compared to the north end (i.e., PF1) of the beach and why?

2. Alongshore Variability in Beach Morphology

Describe and compare the beach profile variability at the north end compared to the south end of the beach and provide plots to demonstrate this. What is driving the difference in beach profiles?

3. Beach Response to Storms

The concept of beach morphodynamics means that beach morphology is constantly adjusting to the hydrodynamic conditions via sediment transport, and the morphology in turn is affected by hydrodynamics (Wright and Thom, 1977). Here, we explore the beach response to successive storms, focusing on a particularly stormy period in June 2007. During this period, there was a cluster of five east coast low storms (a type of extra-tropical cyclone similar to nor'easters on the eastern seaboard of the United States), which are summarized in the June 2007 East Coast Low information under the Links & Publications tab.

Plot the wave and beach shoreline/volume data at a select beach profile and answer the following:

- What was the change in beach volume due to the first storm?
- What was the change in beach volume due to the subsequent storms?

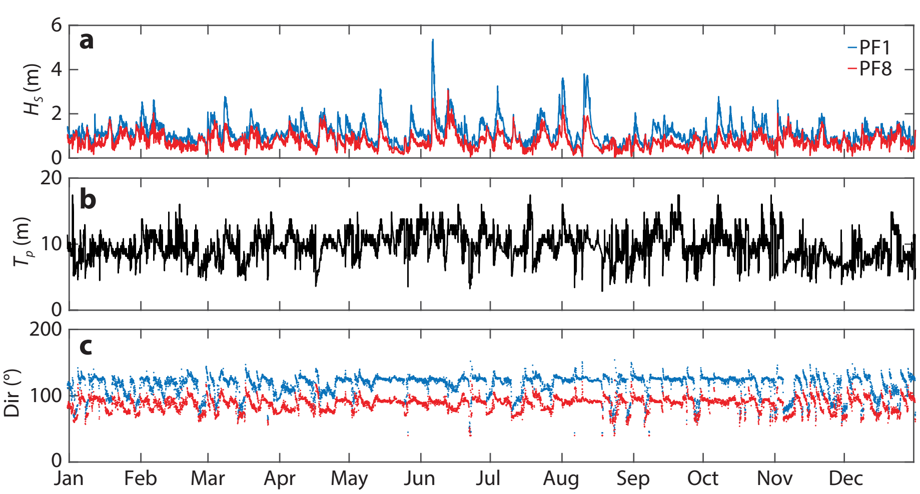

FIGURE 3. One of the graphics output by running *Plot_inshore_waves.m* to plot the inshore wave data, showing (a) significant wave height (H_s), (b) peak wave period (T_p), and (c) wave direction (from) at PF1 and PF8 in 2012. Users can edit the code to select which year to plot.

- What might have caused this difference in erosion response between the successive storms?

POSSIBLE MODIFICATIONS TO ACTIVITY

Depending on education level, students can do either or both of Parts 1 and 2, and there is flexibility to select and focus on certain questions.

Part 1

- Students could be asked to look at the following: How does the BOI relate to the shoreline position data used in Question 2? Can results from Question 2 be related to the SOI as well? What do positive/negative SOI events mean in the Sydney region? How do wave height and direction change during these events?
- Students could also calculate and plot time series of shoreline position and sand volume above mean sea level for a particular profile and answer: Are these two time series correlated? If so, why?

Part 2

- Students could analyze inshore wave data at a particular profile and, with knowledge of the profile orientation relative to north (listed in Table 4 of Turner et al., 2016), estimate the potential for longshore sediment transport using standard longshore sediment transport equations (refer to USACE, 1984).
- Students could also calculate the time series of shoreline position using the 0.7 m contour that is displayed on the online plotting tool and compare this with equivalent time series using other contour elevations (e.g., mean sea level, 2 m and 3 m contours). Which time series fluctuates the most and why?

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