A Transdiciplinary approach to developing a spectral numerical coastal-flow model based on passive macroalgal rafting phenenomea to shed light on ambient and stochastic dispersal and connectivity of nearshore and offshore marine communities and 3D hyperspectral hydrodynamic modelling in and around the coast of South Africa

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Contents

Summary

Marine ecosystems are maintained by a variety of complex interactions between abiotic and biotic variables such as temperature, wave exposure, pH, competition, and processes such as top-down and bottom-up control, predator-prey relationships and phenology (Doney et al. 2011; Harley et al. 2006; Burrows et al. 2011; McGowan et al. 1998). These abiotic and biotic variables, the interactions between them, and the various ecological processes, ultimately determine the community composition and ecological functioning of all ecosystems (Guimaraes & Coutinho 1996; Harley et al. 2006; Poloczanska et al. 2013; Jennings & Brander 2010; Polovina 2005; Johnson et al. 2011; Wernberg et al. 2016; Dayton et al. 1999). Climate directly and indirectly affects the way in which abiotic and biotic variables interact, but is often compounded by other impacts such as habitat destruction, pollution, and overfishing (Blamey et al. 2012; Blamey et al. 2015). Temperature and wave exposure have been recognised as important variables with regards to climate-driven changes within the ocean (Guimaraes & Coutinho 1996; McGowan et al. 1998; McQuaid & Branch 1984; Laufkötter et al. 2015; Belkin 2009; Filbee-Dexter et al. 2018; Miller et al. 2011; Smale et al. 2011; Smale & Moore 2017). In order to persist and survive within variable and changing environments, organisms must either migrate, adapt, or die.

Seaweeds are sessile organisms which are unable to migrate to new areas when local environmental conditions become unsuitable and therefore are forced to adapt to new conditions in order to avoid expiration (Dayton 1985; Tegner et al. 1997). The main form of mortality for seaweeds is through mechanical dislodgement by wave action (Schiel et al. 2006; Seymour et al. 1989; Thomsen et al. 2004; Cavanaugh et al. 2011; Graham et al. 1997; Demes et al. 2013; Edwards & Estes 2006). Seaweeds, particularly brown seaweeds, are able to undergo rapid morphological adaptation to the hydrodynamic environment (Miller et al. 2011; Friedland & Denny 1995; Wing et al. 2007; Wernberg & Thomsen 2005; Fowler-Walker et al. 2006; Dudgeon & Johnson 1992; Blanchette et al. 2002). This allows seaweeds to reduce mortality through mechanical dislodgement by inducing morphology which reduces overall drag. Seaweeds that are unable to avoid mechanical dislodgement either raft out to sea or wash up onto beaches. Not all beach-cast kelp may have originated from a nearby kelp population and may have originated from other sites or regions of the coast through rafting and ocean currents (Malm et al. 2004; Emery & Tschudy 1941; Filbee-Dexter & Scheibling 2012; Hobday 2000). Therefore, because kelp morphology is specific to its local environment the morphological features may be able to indicate, within a certain amount of probability, what site or region it most likely originated from. In other words, beach-cast kelp may be used as proxy for investigating the flow of coastal currents. Using kelp as a proxy for determining its original location will be calibrated by means of a hydrodynamic model which will be designed from already existing SWAN and Delft3D models. This combined approach will allow investigation into flow regimes around the west and south-west coasts of South Africa and the role they play in subtidal ecology. Furthermore, the model could be used to determine transport of plastic pollution around the coast. For instance, micro-plastics are recognised as a threat to marine life (Seltenrich 2015; Azzarello & Van Vleet 1987; Wright et al. 2013; Derraik 2002; Andrady 2011; Fendall & Sewell 2009; Ivar Do Sul & Costa 2014; O 'donoghue & Marshall n.d.; Ballent et al. 2012), however very little is known about how microplastics may be transported along the coast.

The increased use of plastic in society over the past half century has resulted in large amounts of plastic litter in both the marine and terrestrial environment (Andrady 2011; Wright et al. 2013; Cole et al. 2011). The problems associated with large plastic debris have received attention for many decades, whereas those connected to marine micro-plastics comparatively received very little attention. However, today it has become a prioritized area among political organizations, agencies and NGOs around the world. The micro-plastic debris present in the ocean are derived from marine and terrestrial sources (Derraik 2002; Wright et al. 2013; Cole et al. 2011; Seltenrich 2015), however there is little understanding of how microplastics may be distributed with ocean currents. Therefore, the coupling the adaptability of kelp morphology and the ability to simulate hydrodynamic processes can greatly improve our understanding of transport pathways and likely locations of

accumulation. This in turn may inform management decisions with regards to eliminating and managing marine pollution in South Africa.

Background

Seaweeds, browns in particular, are capable of adapting morphological characteristics to persist in changing and variable ocean environments. Changes in morphology have been shown to alter photosynthetic ability, nutrient uptake, and reduce probability of dislodgement with regards to variation and changes in sea temperature , wave exposure and light availability. Wave exposure has been shown to be an important driver of seaweed morphology, as the main mechanism of seaweed mortality is through the dislodgement. Changing morphology reduces drag and increases the probability of survival. However, locally adapted seaweed may still be dislodged in pulse disturbance events such as storms, and may raft far distances and wash up on beaches. Beach-cast may not always originate from adjacent kelp populations but rather from other regions which the individual is adapted for. Therefore, the kelp morphology may act as a proxy for investigating coastal currents and changes thereof. The advances in ocean hydrodynamic modelling has made great progress and has been applied in a variety of ways. This study will use advances in hydrodynamic modelling in combination with kelp morphological characteristics to investigate coastal currents. Once the model has been established it may be applied in other ways, such as investigating the transport of microplastics along the South African coastline. The harms of microplastics to the marine environment has gained much traction in recent years, but research in South Africa is lacking. The coupling of kelp morphology and the ability to simulate hydrodynamic processes can greatly improve our understanding of transport pathways and likely locations of accumulation. This in turn may inform management decisions with regards to eliminating and managing marine pollution in South Africa.

Pollution is a huge environmental problem that affects both terrestrial and marine ecosystems. Pollution from land enters the sea where it could harm or kill marine organisms or is transported by ocean currents to other coastal areas. In these areas the pollution could re-enter the ocean or be blown by wind into terrestrial ecosystem where it could once again be ingested by organisms causing harm or even death. Pollution is therefore a major threat to the environment and marine organisms. In recent years the effect of microplastics on the ocean has gained much traction with scientists and politicians alike. Microplastics cosiste of tiny particles of plastic and other pollution and are therefore are difficult to detect. Currently there is no hydrodynamic model that is able to determine dispersion, source and accumulation of microplastics along the South African coastline. Given the significant detrimental effect microplastics play in the ocean, it is important that such a mechanism be developed that will aid in better management of marine pollution in South Africa. Furthermore, this project allows for a multidisciplinary approach to be taken by combining ecology and coastal oceanography.

Abiotic and biotic factors interact in complex ways which indirectly determine behavioral and ecophysiological responses in organisms. For example, when storms or strong currents form in sub-tidal habitats, sea urchins form aggregations in order to reduce overall drag to avoid being swept away by currents. Organisms that are motile my migrate into more environmentally suitable areas when conditions become unfavorable or food sources become depleted. In changing environments migration may also allow organisms to extend their distributions. For example, ocean warming off the coast of Western Australia has allowed tropical fish species to extend their distribution into areas that were previously characterised as temperate reefs. Sessile organisms are unable to migrate into more environmentally suitable areas and are forced to either adapt or suffer expiration. Sessile organisms may respond to changing environmental conditions through changes in physiology. For example, plants may produce heat shock proteins that help buffer the effect of temperature increases. Sessile organisms may also adapt their morphology,in order to persist in changing and harsh environments, such as seaweeds.

Temperature and wave exposure have been shown to be important drivers of seaweed distribution, physiological functioning, ability to recover, population dynamics and morphology. Mechanical forces generated by the hydrodynamic environment, in the form of sudden strong ocean currents or storms, between 10- 20 m s-1 with accelerations of 400 m s-2 (Friedland and Denny 1995) are the biggest threat to kelp survival. Kelps are able to rapidly adapt their morphological characteristics to reduce drag and avoid dislodgement (Blanchette 1997). For example a study by Koehl et al. (2008) showed that transplanted Nereocystis luetkeana plants from a wave sheltered site to a wave exposed site changed their morphology to flat blades and narrow laterals that are less prone to drag forces in 4-5 days. Another study by Fowler-Walker, Wernberg, and Connell (2006) tested for differences in morphology of Ecklonia radiata between wave-sheltered and wave-exposed sites and through a combination of in situ sampling and transplantation of juvenile plants. The results showed that morphology differed between wave-sheltered and wave-exposed sites (thin thallus at sheltered sites and a narrow, thick thallus with a thick stipe at exposed sites), and was consistent with previous studies. Juveniles transplanted into wave exposed sites under went rapid morphological adaptation, whilst the opposite was true for wave-sheltered sites which showed slower morphological adaptation.

Kelp morphology may be distinct to a particular region with a specific hydrodynamic environment and has the ability to raft far distances using coastal currents, and may accumulate as beach-cast in areas far from its original location. Therefore, kelp morphology may be used as a proxy for determining its original location as well as aid in characterising coastal currents. However, this approach must be combined with advances in hydrodynamic modelling for a quantitative outcome.

Advances in numerical modelling has gained much traction in recent years and has been applied in a variety of ways with regards to ecological studies. For example, a study by Wang and Xia (2009) used the Delft3D-Flow model to assess the hydraulic suitability of a stream as a spawning ground for the Chinese Sturgeon (Acipenser sinensis) in the Yangtze River. The authors calculated the horizontal mean vorticity which was used to assess the hydraulic environment of spawning ground. The flow field state was determined through model simulation and field-measured data used to validate the model. The results added to existing scientific database for spawning ground hydraulic environmental protection. Different numerical models can often be integrated to model across ecosystem levels. For example a study by Leon et al. (2003) used integrated physical (Delft3D hydrological model) and bio-chemical (Agricultural Non-point Source model) processes models to investigate the possible impact on the Lake Malawi water quality due to management actions performed at the watershed level.

Since wave energy is an important driver in marine ecosystems, particularly kelp, the advances in hydrodynamic modelling offer a new opportunity for multifactorial and quantitative approach to research in marine ecosystems. The Delft3D and SWAN models have been used successfully in previous studies regarding brine plume discharge, impacts of storms, effects of climate change on the hydrological environment etc. The models have not been designed for shallow environments (<6m) and therefore may not be suitable to model coastal hydrological environments. However these models may be adjusted to suit coastal waters if they are combined with a new numerical model which can be calibrated to suit these needs.

In recent years there has been growing attention on plastic pollution, particularly in the ocean. Plastic pollution can be in the form of macro- and microplastics. Microplastics are tiny plastic granules used as scrubbers in cosmetics and air-blasting, and small plastic fragments that originate from larger pieces of plastic known as macroplastics, while macroplastics…insert definition here… The potential harms of of plastic pollution in the marine environment was highlighted in the 1970's and renewed interest has lead to research showing that plastic pollution in the ocean are widespread. Plastics may become bio-available to biota in the food-web which may cause problems with an organism's physiological functioning. Furthermore, the relatively large surface area and composition of microplastics provides an environment that is able of adhering to organic pollutants. In other words microplastics also act as a vector for transport and assimilation of organic pollutants.

Therefore, this study not only enables research into the ecological effects of the hydrological environment on an important habitat-forming organism, it also offers the opportunity to improve on current hydrological numerical models to suit coastal environments. This in turn will allow investigation into the flow and accumulation of microplastics which are regarded as a major threat to marine life. Furthermore, the calibrated model could be applicable to other ecological studies such as dispersal of benthic flora and fauna, climate change studies, forecasting as some examples.

Kelp environmental drivers

Important environmental drivers of kelp individuals and communities include light, substrata, salinity, sedimentation, nutrients, temperature and wave exposure. Although studies have investigated the effects of these important environmental drivers, the roles these factors play is often difficult to evaluate as such factors may never be fully independent of each other, i.e. environmental factors are to some extent are dependent on one another. Multifactorial studies have attempted to explain combined effects, however these studies are often limited to investigating combination of two or three environmental drivers as inclusion of too many factors can lead to results that are difficult to interpret. Environmental factors are highly variable on temporal and spatial scales and their effects may also be dependent on the life-stage of the organism, adding a further layer of complexity to investigations.

Light

Light is an important factor for kelp survival, however if light is limited or excessive this may negatively impact kelp survival or growth. Much of the past research into the role light plays into the functioning of kelp (Bruhn and Gerard 1996; ???). For instance, solar ultraviolet radiation has been shown to affect sub-canopy Ecklonia radiata sporophytes when the canopy of mature Ecklonia radiata was removed (Wood 1987). The sub-canopy sporophytes experienced tissue damage,photopigment destruction,reduced growth and decreased survivorship, thus inhibiting their settlement and survival (Wood 1987). Laboratory experiments revealed that the UV component of radiation, rather than intense radiation itself, was responsible for the effects mentioned above. High light stress has negative effects, such as photoinhibition and photo-damage on Ecklonia cava sporophytes (Altamirano and Murakami 2004). Altamirano and Murakami (2004) found that Ecklonia cava is more vulnerable to light stress conditions, and less likely to recover under unfavourable conditions (Altamirano and Murakami 2004). Bolton and Levitt (1985) showed that under sub-saturating irradiances and supra- optimal temperatures Ecklonia maxima to showed a decrease in reproductive rates and an increase in cell production. An additional finding of this study was that despite the decrease in reproductive rates, the final egg production per female was greater under these conditions. The authors interpreted this an ecological adaptation that may increase survival rates under times of stress or non - ideal conditions (Bolton and Levitt 1985).

Substrata

Salinity

Depth

Depth does not affect kelp ecosystems directly, however a change in depth causes fluctuations or changes in other environmental variables such as water motion, light and temperature. Water motion also decreases with depth, and some kelps better suited to deeper environments (*L. pallida*) replace those in the shallows (*E. maxima*) (Dayton 1985; Gerard 1982). The increase in depth can lead to a decrease in sunlight penetration, with some species better adapted for low-light conditions than others, such as (*L. pallida*). Temperature may also change along a depth gradient due to a reduction in sunlight penetration (Dayton 1985; Gerard 1982). Therefore depth does not directly play a role in kelp functioning but may alter more influential factors such as light and water motion.

Sedimentation

Nutrients

The importance of nutrients in the functioning of kelps is well understood (Dayton 1985; Gaylord, Nickols, and Jurgens 2012). Dissolved nitrogen, and in particular nitrate, are important; however research has also placed emphasis on phosphate and other trace compounds for functioning of kelps (Dayton 1985). Additionally, some kelps have the ability to store inorganic nitrogen in order to compensate for periods of low nutrient availability, which has been observed for Laminaria and Macrocystis (Dayton 1985; Gaylord, Nickols, and Jurgens 2012). Nutrient stratification is also an important factor, particularly for canopy type kelps. The concentration of nutrients at the surface is important to the functioning and maintenance of the canopy. For instance kelp canopies in California often deteriorate in the summer months when surface nitrate levels are low (Jackson 1977). Water motion is important in the assimilation of nutrients from the water column, and kelps have been shown to adapt blade morphology in order to create more turbulence around the boundary layer of the frond to enhance nutrient assimilation (Wheeler 1980). Temperature has also been closely linked with nutrient concentrations. Nutrients are often in higher concentrations in the water column during low temperature events. This is often an indication of an up-welling event, which brings cold and nutrient rich waters from the bottom to the surface of the water column. Temperature can play a direct role in the uptake of nutrients through effects on algal metabolism; however this may vary from species to species (???).

Temperature

Temperature is a driver of kelp species distributions and ecophysiological processes, as well as a lesser role in morphological adaptation…example here…The majority of kelp species are arctic and temperate organisms, and the warming of ocean temperatures is expected to cause a poleward biogeographical shift of species (Bolton et al. 2012). There is evidence to suggest that South African kelp forests are expanding due to ocean cooling (Bolton et al. 2012), possibly driven by an intensification and increase in coastal upwelling (Blamey and Branch 2012, Blamey et al. (2015)). In South Africa there has been a biogeographical shift eastward along the coast due to a change in inshore temperature regime, making South Africa no exception to changing ocean temperatures (Bolton et al. 2012). Macroalgae, such as kelps, can react to an increase in surface temperatures in one of three ways: they can migrate, adapt and die (Biskup et al. 2014). A study by Biskup et al. (2014) investigated the functional response of two kelp species (Laminaria ochroleuca and Saccorhiza polyschides) to rising sea temperatures. The functional responses of Saccorhiza polyschides was measured for both the subtidal and intertidal habitats, to see what affect non- optimal conditions (intertidal zone) had on the kelps (Rinde and Sjøtun 2005). The study found that Laminaria ochroleuca exhibited a poor ability to acclimatise and was dependent on the kelpâ€™s life history traits (Biskup et al. 2014). Therefore annual kelp species are more likely to survive under non-ideal condition, and the intertidal Saccorhiza polyschides, compared to the subtidal, showed a higher physiological flexibility to changing conditions (Biskup et al. 2014). This may be because the intertidal zone undergoes far more change than the subtidal and therefore kelps in the intertidal are forced to adapt to harsher conditions where fluctuations in temperature, sunlight, turbidity and water motion are common. The effects on temperature have also been investigated by Wernberg et al. (2010). The study looked at resilience of kelp beds along a latitudinal temperature gradient. Kelp abundance is likely to decline with the predicted warming of ocean waters Wernberg et al. (2010) and although kelps have the ability to acclimatize and adjust their metabolic performance, which in turn allows them to change their physiological performance to mitigate the seasonal fluctuations in temperature, this acclimatization is done at a cost Wernberg et al. (2010)…link to paragraph on kelp morphology…

Wave exposure

Other than temperature, wave exposure is also recognised as an important driver of the marine environment, and macroalgae are not exception. Wave exposure has been shown to play a role in determining distribution, abundance, diversity, composition, growth (Cousens 1982) and productivity (Pedersen and Nejrup 2012) of macroalgae communities. For example, the width, vertical zonation and diversity of algal communities often change predictably along gradients of wave exposure. Wave exposure may also drive macroalgae communities indirectly through the alteration in effect of another environmental driver. For instance, increasing degrees of exposure may positively influence the amount of area available to trap light on macroalgal fronds, as well as increasing nutrient uptake due to increased turbulence in the boundary layer around the frond (???). The most important direct effect of wave exposure on macroalgal communities is through mechanical dislodgement, which ultimately leads to expiration. Wave exposure is a complex abiotic variable which varies spatially and temporarily in the marine environment. Furthermore, the degree to which a macroalgae community is exposed, is dependent on local site characteristics, such as bathymetry and local wind patterns. Despite this fact, macroalgae have been able to persist in often harsh and variable wave environments. Macroalgae are sessile organisms and incapabable of migrating when local conditions become unsuitable. Therefore, macroalgae must adapt to the local wave climate in order to persist and survive, and achieve this through morphological adaptation. The morphology of macroalgae are not fixed genetic traits. A study by Koehl et al. (2008) showed that transplanted Nereocystis luetkeana plants from a wave sheltered site to a wave exposed site changed their morphology to flat blades and narrow laterals that are less prone to drag forces in 4-5 days. Advances in genetic techniques and taxonomy have revealed that species delineation based on morphology has been inaccurate, and organisms that were once considered two separate species are actually one species. For example, Moss (1948) investigated the anatomy, chemical composition of Fucus spiralis at three sites that varied in wave exposure (sheltered, medium exposure and exposed). The authors found that individuals in exposed sites showed less branching of thalli as well as variation physiological components, such as organic nitrogen, mannitol, laminarian and alginic acid concentrations. The authors also noted a 'crumpling effect' displayed by individuals from exposed sites and inferred that this strategy may reduce overall drag. Other studies show that macroalgae in wave exposed environments have morphologies that reduce overall drag, increase strength of attachment or increase flexibility. There is also evidence that morphological adaptation is driven by currents, and in fact may be driving hydrological performance of macroalgae. Duggins et al. (2003) examined the direct and indirect flow effects on population dynamics, morphology and biomechanics of several understorey macroalgae species. These species included Costaria costata, Agarum fimbriatum, and Laminaria complanata and *Nereocystis luetkeana*. The results showed that in wave impacted sites (wave exposed) had higher rates of mortality, and no significance was found between survival of individuals and tidal or current velocity. The authors concluded that although tidal and current velocity did not play a significant role in determining kelp survival, it did play a role in morphological adaptation. The results from this study suggest that high current and tidal stresses are the main driver of kelp morphological adaptation. This in turn make those individuals more resilient to dislodgement to wave exposure. Wave exposure is stochastic in nature compared to tidal and ocean currents which are more regular in their frequency and magnitude. Therefore the regular forces of tidal and ocean currents may make kelp individuals more resilient to mechanical dislodgement over time.

The morphological adaptation that macroalgae display are therefore driven by site conditions, therefore individuals must be morphologically flexible to persist in stochastic environments. This may be achieved through different strategies and are species-specific, which can be directly attributed the high diversity in morphological characters of algal communities. For example some algae have fronds and others are articulated coralline, and therefore these species would need to adapt their morphology differently in order to persist. In general, flat strap-like blades are common in areas that are exposed to high wave energy, while at protected sites blade morphology is wide and undulated.

Ocean and coastal waves

Introduction

Regardless of the location around the world, waves are a feature of any coastline and the marine environment, and are important manifestations of energy in the ocean. Waves are not the movement of water particles but rather the movement and propagation of energy through the ocean. The source of this energy can be formed locally, such as wind-driven waves, and or from distant locations in the ocean such as storms, know as *swell*.

This energy is transferred from deeper water into shallower water where it plays a role in driving complex marine ecosystems as well as shaping the environments that they live in. Energy that is left-over after these processes is transferred into heat energy, and heats up the sand and rocks on which each wave hits. This energy can also be harnessed in simple ways such as a surfer catching a wave, or more complex ways such as capturing energy from the ocean environment for electricity production. However, waves are stochastic in nature and therefore the energy that propagates through the ocean is not always consistent. Therefore, it is often difficult to quantify and predict wave energy in the marine environment. Despite this fact, waves are gaining more recognition for the role they play in shaping coastlines, beaches and hence the communities and organisms that depend on these systems.

Waves manifest themselves in different ways, which is also dependent on the energy creating force, and can be classified into different categories. For instance, "chop" are produced by local winds, while "tsunamis"" are rare waves that are formed during a earthquakes or landslides and can be produced from thousands of kilometers away. Waves in the ocean are known as "swell" and are produced from far distant storms, while the most consistent form of waves that interacts with the coastlines, usually twice a day, are called "tides". Tides are produced from differences in gravitational forces between the ocean, earth's crust, sun and the moon. These classifications can be broken down further and will be investigated later in this chapter. The focus of this chapter will be understanding wave theory and how waves form and propagate into shallow-coastal waters. This will be essential to later chapters that aim to model wave energy and calibrate the produced model with biotic variables.

Generating and restoring forces

Waves are formed due to the constant interaction between two forces, which are known as the "generating force" and the "restoration force". The generating force is the force which pushes water from one layer up into the other. Layers in the ocean are formed through differences in temperature (thermocline) and salinity (pycnocline) which creates a boundry for wave energy to move along. In other words, waves occur along the boundaries formed in the ocean by various abiotic processes, and therefore density boundaries are essential to the propagation of energy through the ocean.

The generating force and restoring force occur along these boundaries, the generating force pushes water up across ocean boundaries while the restoring force pulls it back to where the boundary was originally, trying to restore the balance in energy. This "tug of war" between the two forces creates an oscillating motion between the boundary layers which acts as a point of disturbance, sending out energy in all directions. The disturbance energy will continue to manifest itself provided the tug and pull between the two forces is occuring. Once the generating force stops, and ultimately the energy from the point of disturbance, the waves dissipate and water restores to its original state. A simple example would be blowing on water in a cup. The blowing of air onto the surface of the water in the cup creates a point of disturbance that pushes the air boundary into the water boundary. The restoring force is the surface tension of the water that is maintained through hydrogen bonds between water molecules. Once blowing on the water in the cup has stopped, the ripples or "waves" in the cup begin to diminish in size until the surface tension returns to its original state. The hydrogen bonds between the water molecules are stronger than the force of gravity, and therefore the force of the surface tension returns the water to its original state. These waves are known as "capillary waves" and is essentially residual energy after the generating source has stopped. The restoring force can also be in the form of gravity and are known as "gravity waves". Using the same example, if one blows too hard, the water boundary is pushed up into the air boundary, breaking the hydrogen bonds between water molecules which allows gravity to return the water to its original state. All waves in the ocean are either capillary waves or gravity waves, and their classification will be dependent on the restoring force involved.

In nature, there are three kinds of generating forces. These are wind, displacement of large volumes of water and uneven forces of gravitational attraction between the Earth, Moon and Sun. Different generating forces are associated with different wave heights, periods and the type of wave produced insert appropriate figure. Wind-generated waves comprise of capillary waves, chop, swell and seiche. Some seiche can form from landslides and earthquakes but most of these waves are known as a tsunami. Swell create the waves with the large heights (up to 100m), while tides can create the tallest.

Wave physics and scales

Waves have a number of characteristics which are depicted in figure ??, and is an idealised representation of what a wave is. The amplitude is the vertical distance from its midline or equilibrium surface or still water level to its highest point known as the crest. The equilibrium surface is the level the ocean would be if there were no waves, for a wave to form a disturbance must occur below or above this line. The trough is the same distance of the amplitude, however the measurement is taken from the equilibrium surface to the lowest point. Wave height is the vertical distance from crest to trough, and is equal to twice the amplitude. The wavelength is the horizontal distance from a crest/trough to the next crest/trough respectively. It is important to note that the energy propagating from a disturbance will not reach the ocean floor in deep-water environments. The depth below a wave where the water, and anything in the water, feels no motion or disturbance is known as the wave base. The wave base is calculated by descending vertically from the equilibrium surface by a value equal to halve the wavelength. The water particles in the ocean move in a circular orbit and hence return to their original position. This is because waves in the ocean represent moving energy, and not moving water.

Types of waves

There are a variety of waves that form in the ocean and all differ in terms of period or wavelength (??image??). The longest wave that can form in the ocean are known as trans-tidal waves, and are generated by fluctuations in magnetism between the Earth's crust and atmosphere. The magnetic push and pull between the Moon and the Sun creates waves with a slightly shorter wavelength, known as tides. Their period and wavelength can also range from a few hours to more than a day, and from a few hundred to a thousand kilometers respectively. Storm surge tend to have a slightly shorter wavelength and period compared to tides. When low atmospheric pressure systems and high wind speeds in a storm it elevates the ocean surface, generating storm surge, which may cause flooding in coastal areas as it approaches the coastline. Tsunami's are on the lower end of the scale, and are generated by earthquakes or submarine 'landslides. Their random nature makes them difficult to predict and increase amplitude as they approach the coast. This can make them considerably large along coastal areas and often cause immense damage and loss of life.

Measuring waves

Waves are often thought of as an elevation of the sea surface from a specific point over a period of time but this is obvisiously not he case. This is known as *surface elevation* and is the instaneous elevation of the sea surface abouve a specific point in a time record (see figure 1). Although surface elevation does not represent a wave, it can be used to create a wave profile. This is achieved by profiling the the surface elevation between two successive *downward zero-crossings* or *upwardward zero-crossings* (see figure 1). Both zero-crossings are symmetrical and essentially the same statistically. However, in practice the downward zero-crossings are preferred as it takes steepness of a approaching wave into account (the front, see figure 1) which is relevant to characterising breaking waves. It is important to note that surface elevation can be negative while a wave profile cannot.

Characterising waves in a wave record requires compromise both in the statistical sense and the practical, as it is a balance between keeping the record short enough to remain stationary and long enough for a reasonable averages to be calculated. The waves are characterised in terms of wave heights and wave periods for individual waves in the record and then averaged over that specific time. For example, a time record of 15-20 minutes is standard when calculating a wave profile.

Waves are complex and various approaches, techniques and devices have been developed in order to measure waves effectively. One of the ways that has been used extensively used in the past but less so today, are visual estimates which can be used to characterise *significant swell height* (Hs) and *significant swell period* (Tp). Visual estimates use 15 - 20 of the most well defined, higher waves of a number of wave groups to characterise Hs and Tp. Although these parameters are useful, they do not accurately reflect the waves

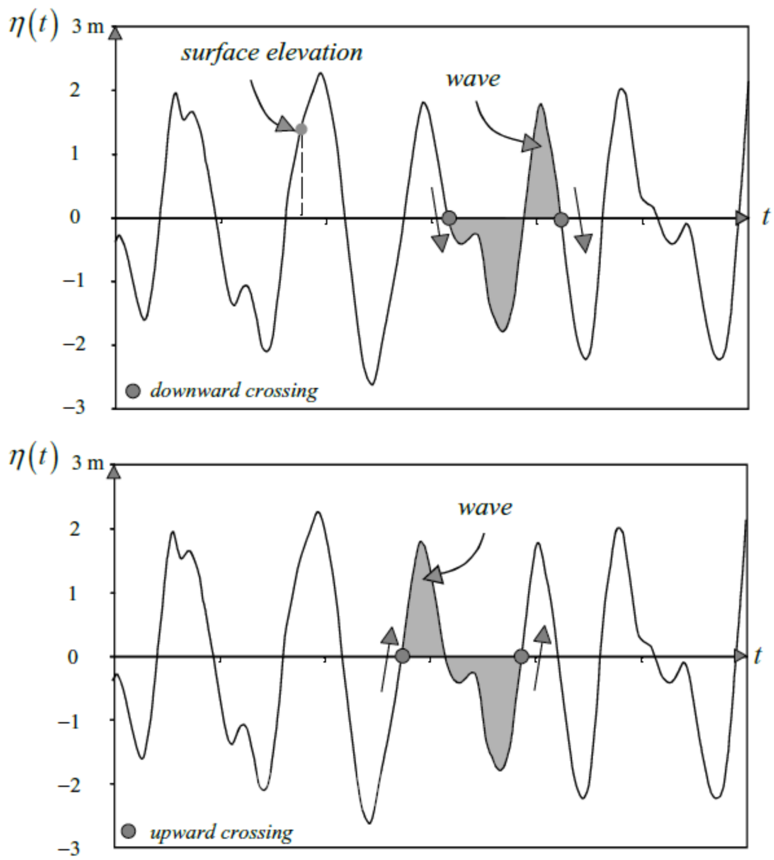

Figure 1: The definition of a wave in a time record of the surface elevation with downward zero-crossings (upper panel) and upward zero-crossings (lower panel).

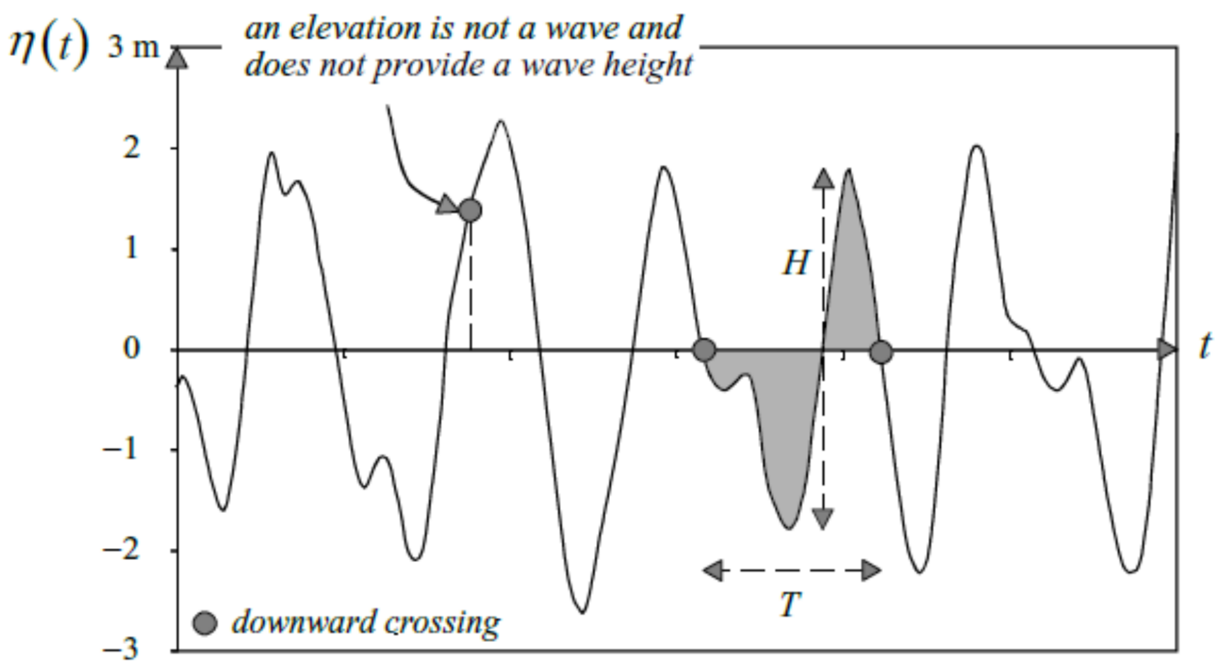

Figure 2: The definition of wave height and wave period in a time record of the surface elevation (the wave is defined with downwrd zero-crossings.

that are occurring in nature. Ocean waves are a combination of wind sea (short, irregular, locally generated waves) and swell (long, smooth waves, generated by distant storms) and so more parameters are needed to separate Hs and Tp driven by wind sea and swell, i.e. separate Hs and Tp parameters for wind sea and swell. However, even with separate parameters for the different types of waves would still not be enough to effectively characterise waves in the ocean. In order to characterise the detail and complexity of ocean waves a different approach must be used, know as the *spectral* approach. This approach is based on the idea that the sea surface can be characterised as the summation of a large number of harmonic wave components, known as the *random-phase/amplitude* model. The random-phase amplitude model is a summation of wave components on a discrete scale, however a continous scale is more relevant to characterising and measuring of waves in the ocean. The discrete spectrums are converted to continioius spectrums through various methods. Therefore, the random-phase amplitude model is used to obtain a *continious variance density spectrum* which is a statistical relevant measure for scientists and engineers.

The wave spectrum is based on several spectra, namely the amplitude spectrum, variance spectrum, variance density spectrum (discontinuous) and the variance density spectrum (continuous). A wave spectrum can be used to describe the sea surface as a stochastic process, however two conditions (assumptions) must first be met 1) the observation must be stationary and 2) the surface elevations must be Gaussian distributed. As mentioned previously, the random-phase/amplitude model approach characterises waves as harmonic and the time-record can be reproduced by the sum of a large number of harmonic waves using a *Fourier analysis*. A Fourier analysis allows values of the amplitude and phase for each frequency to be characterised, which in turn provides the amplitude and phase spectrum for a single time-record. The amplitude spectrum is can be calculated by averaging many time-records which determines the *average amplitude spectrum.* This approach allows the entire wave record to be characterised but is not statistically relevant and therefore is not applicable to hydrodynamic modelling. In order for to attain a statistically relevant value, the variance of each wave component must be calculated. The variance is regarded as statistically relevant as the sum of the variances (i.e. random surface elevation) of the wave components is equal to the variance of the sum of the wave components. In addition, LWT dictates that the energy of waves is proportional to the variance and is therefore an indirect measure of wave energy. This indirect measurement can also be used to determine other important wave components such as wave-induced particle velocity and pressure variations. Important to note that the measurement of variance are discrete and is therefore limited in characterising waves. A continuous scale is more applicable for hydrodynamic modelling purposes and is also closer to representing ocean waves and can be calculated by allowing the frequency interval () to approach zero.

Hydrodynamic modelling

Introduction

Wave exposure may be modeled through various methods which range from simple cartographic to more advanced numerical wave models. Traditional ecological measures of wave exposure usually incorporates integrative measures of hydrodynamic conditions at a particular site. Cartographic models can be qualitative or quantitative and were designed for the need of wave exposure measures to explain ecological distributions. A simple set of calculations on coastline and wind data, and relatively small input data sets are required. These are regarded as “fetch-based models”, which measure the length of open water associated with a site along a straight line. The output of such an approach is a simplified estimate of the potential wave energy for a specific set of sites. Advances in cartographical methods using fetch-based models has allowed for wave exposure measurements for larger areas, and has been suggested as a method for predicting macroalgal community structure (???). An example of such a model is the “BioEx model” which was developed by Baardseth and others (1970) to estimate wave exposure over large regions. BioEx requires frequency, strength and direction of winds, weighted by degree of exposure within various directions. BioEx is calculated as the sum of the index developed at different spatial scales (local, fjord and open). This method has been used in mapping of marine coastal biodiversity (???). Lindegarth and Gamfeldt (2005) criticised this approach, arguing that the choice of wave exposure method can influence ecological inference. The authors also highlighted the need for objective, reproducible and quantitative studies comparing exposure indices (Lindegarth and Gamfeldt 2005).

Other authors, such as Hill et al. (2010), have argued that these simple measures can be improved upon by including bathymetry data which allows the incorporation of diffraction into the calculation. Diffraction is topographically induced variations in wave direction. A model incorporating this complexity was developed by Isæus (2004), and is known as the "simplified wave model" (SWM). The model uses measurements of wind strength, fetch and empirically derived algorithms to mimic diffraction.

Advances in numerical modelling have been founded on physical wave theory on how a wave "behaves". This approach is based on a theoretical perspective rather than the need to answer ecological questions. Besides diffraction, numerical models incorporate more complexity by including wind forcing, wave-to-wave interactions and loss of energy due to friction and wave breaking. Numerical models have a variety of applications and are often incorporated within hydrodynamic general circulation models and are used operationally for forecasting the sea state (Group 1988; Booij, Ris, and Holthuijsen 1999; Smith, Sherlock, and Resio 2001). The downside of advanced numerical models is that are computationally intensive which creates limitations for large scale simulations. Therefore, their application along long stretches of variable coastline, inshore environments and ocean-wide simulations are limited due to the poor spatial coverage. However, numerical models can be designed for local or site specific coverage, provided the correct data is available. **. . . More to be added. . .**

Delft-3D numerical suite

The Delft-3D numerical suite provides an advanced approach to hydrodynamic modelling through consideration of various physical phenomena and is a quantitative estimate of wave exposure. The suite of models can be used for a range of applications such as simulating flow, sediment transport, waves, water quality, coastal morphological development and ecology. The suite of numerical models consists of two modules; Delft-3D WAVE and Delft- 3D FLOW.

Delft-3D WAVE

The Delft-3D WAVE module uses the SWAN (Simulating Waves and Nearshore) numerical models to simulate the generation and propagation of wind-generated waves in coastal environments. The SWAN model is based on discrete spectral action balanced equation and is fully spectral. Spectral refers to the consideration of all wave directions and frequencies and implies that short-crested random wave fields propagating from different directions can be accounted for. The final output of the model is wind-sea with superimposed swell.

Delft-3D FLOW

This module is a multi-dimensional hydrodynamic/transport simulation program which calculates non-steady flow and transport processes that result from tidal and meteorological forcing. The dimensions can be either 2D or 3D and can be placed on a rectilinear or curvilinear, boundary fitted grid.

Coastal flow

Kelp-rafting

Kelp-drag dynamics

Kelps in South Africa

The biogeographic distribution of kelp is limited by seawater temperature (Bolton 2010), where increasing temperature gradients reduce kelp distribution. Due to this limiting factor, the two main species of kelps in southern African waters, *Ecklonia maxima* and *Laminaria pallida*, are distributed along a section of the south coast from De Hoop, extending west around the Cape Peninsula, and thriving north into Namibia (Molloy and Bolton 1996, Stegenga et al. 1997). This distribution follows a temperature gradient, where sea temperatures increase as one moves south from Namibia, around Cape Point and towards De Hoop. Although the two species occur together for the majority of the coast, their basic morphologies and resource needs vary to a degree. The larger species, *E. maxima*, is distributed from Lüderitz to Cape Agulhas (Fig. 1) (Bolton and Levitt 1985,Probyn and McQuaid 1985, Bolton and Anderson 1987, Bolton et al. 2012). The biogeographic distribution of kelp is limited by seawater temperature (Bolton 2010), where increasing temperature gradients reduce kelp distribution. Due to this limiting factor, the two main species of kelps in southern African waters, Ecklonia maxima and* L. pallida*, are distributed along a section of the south coast from De Hoop, extending west around the Cape Peninsula, and thriving north into Namibia (Molloy and Bolton 1996, Stegenga et al. 1997).

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Buoyancy/drag properties

In order to determine the fraction of the kelp raft submerged the *Buoyancy Force* (BF) must be calculated. A theoretical example using a object of a regular shape (see figure 3) will be used to demonstrate the theory

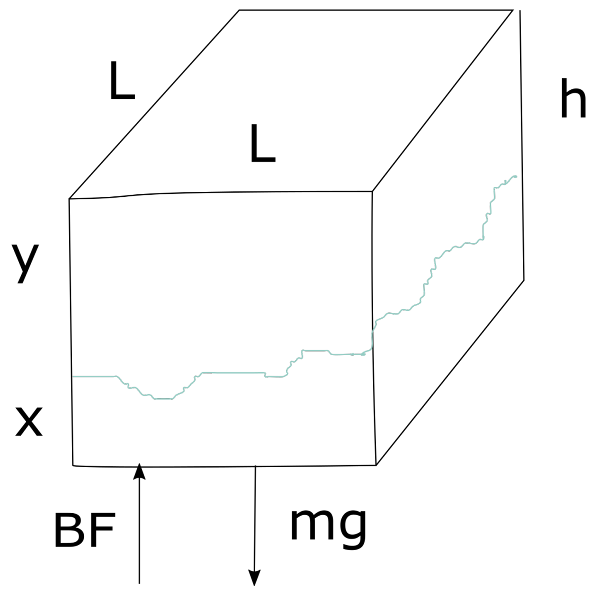

Figure 3: Conceptual model of bouyancy characteristics.

that will be applied to this component of the study. First, the fraction of the object submerged can be calculated, which in this case is represented by x (see figure 3).

An object will only float if the object density (ρ) is less than or equal to the density of the liquid in which the object is submerged, i.e. $\rho_{object} < \rho_{liquid}$. The bouyancy force ($BF$) is the force of the displaced liquid pushing the object in an upwards direction which is equal to the weight of the displaced liquid, $BF = W_{displaced-liquid}$. The weight of the displaced liquid can be calculated by multiplying the mass of the liquid by the gravitational constant g and so the weight of the displaced liquid can be calculated by:

$$W_{displaced-liquid} = mg$$

The equation is expanded upon by including the calculation for mass, $m = \rho V$, and so now the weight of the displaced liquid can be calculated as:

$$mg = \rho_{liquid} V g$$

where ρ represents the density of the liquid and V represents the portion of the object submerged. Since the object is floating, the BF can also be represented by the weight of the object and as mentioned previously the weight of the displaced liquid can also be represented by mg, which in turn can be written as $W_{displaced-liquid} = W_{object}$. Now through substituting the calculations for weight, volume and the dimensions of the object, the equation can be simplied to:

$$x = h\frac{\rho_o}{\rho_l}$$

where h is the overall height of the object, ρ_o represents the density of the object and ρ_l represents the density of the liquid. It is important to note that this equation is only applicable to objects that are floating i.e. $\rho_{object} < \rho_{liquid}$. The portion of a floating object above the water surface can also be calcuated using a similar approach, and instead of calculating the submerged portion (x) the calculation will now solve for the fraction above the surface which is represented by y (see figure 3). The same equation for calculating density ($\rho = \frac{m}{V}$) will also be used in solving for y. As mentioned previously, for floating objects the $BF = m_{object} g$ and the BF can also be defined as the weight of the displaced liquid ($BF = W_{displaced-liquid}$) and therefore the weight of the displaced liquid is equal to the weight of the object ($W_{displaced-liquid} = W_{object}$). On this basis equation ?? can be written as

$$m_{liquid} g = m_{object} g$$

Substituting the equation for density into equation ?? the equation is now:

$$\rho_o V_o g = \rho_l V_l g$$

. Important to note is that V_o represents the volume of displaced liquid i.e not the entire object volume (see figure 3). The constant g is removed through cancellation and now the equation can be written as:

$$\frac{V_l}{V_o} = \frac{\rho_o}{\rho_l}$$

We also now that the volume of the object submerged is equal to the volume of the displaced liquid and the fraction $\frac{V_l}{V_o}$ represents the portion of the object submerged. Therefore to calculate the portion above the surface this must be subtracted by 1, therefore:

$$1 - \frac{V_l}{V_o} = y$$

and since $\frac{V_l}{V_o} = \frac{\rho_o}{\rho_l}$ the equation can now be solved via density of the liquid and the object:

$$y = 1 - \frac{\rho_o}{\rho_l}$$

Solving the equation algebraically it can now be written as:

$$y = \frac{\rho_l - \rho_o}{\rho_l}$$

Aims of research

The aim of the project is to investigate coastal flow regimes along the west coast and south-west coast of South Africa and the role this may play in transport of kelp beach-cast and microplastics. This aim will be met through the following objectives:

1. Determine if the hydrodynamic environment is the main driver of kelp morphology and if this is specific to a location
2. Simulate kelp rafting by means of a hydrodynamic modelling and calibrate this model with in situ beach-cast morphometric data.
3. Use the calibrated hydrodynamic model to investigate dispersal of microplastics along the west coast and south-west coast of South Africa.

References