Quantifying passive kelp rafting phenomena and connectivity of nearshore communities around the coast of South Africa through development of a 3D spectral numerical coastal-flow model

R Coppin[[1]](#footnote-20)

C Rautenbach[[2]](#footnote-21)

AJ Smit[[3]](#footnote-22)

Table of 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. 2012; Burrows et al. 2011; McGowan, Cayan, and Dorman 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 (**???**; Harley et al. 2006; Poloczanska et al. 2013; Jennings and Brander 2010; Polovina 2005; Johnson et al. 2011; Krumhansl 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 over-fishing (Blamey and Branch 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 that 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 consist 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 velocity 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 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).

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.

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 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…

Other than temperature, wave exposure is also recognised as an important driver of the marine environment, and macroalgae are no 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 incapable 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 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.

# The mechanisms of morphological adaptation

## Waves and macroalgae characteristics

In the wave swept nearshore one would expect organisms to reflect the harsh hydrodynamic environment by being streamlined, small and amoured. This is certainly the case for an array of fauna which often comprise of hard, rigid bodies that are held firmly in place to the substratum such as limpets and isopods……

# 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 occurring. 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 obviously not he case. This is known as *surface elevation* and is the instantaneous elevation of the sea surface above a specific point in a time record (see figure ). 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 ). 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 ) which is relevant to characterising breaking waves. It is important to note that surface elevation can be negative while a wave profile cannot.



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).

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.



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

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 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, calculated by the *random-phase/amplitude* model. The random-phase amplitude model is a summation of wave components on a discrete scale, however a continuous scale is more relevant to characterising and measuring of waves in the ocean. The discrete spectrums are converted to continuous spectrums through various arithmetic methods. Therefore, the random-phase amplitude model is used to obtain a *continuous 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 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 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 so 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.

# Linear wave theory

# Currents

## Ocean currents

## Nearshore currents

# Ocean modelling

An ocean model is essentially a representation of physical processes in the ocean in the form of equations or computer code which aids in furthering our understanding of how the ocean works. Examples of physical processes include the exchange of energy, mass, and momentum between the ocean and external drivers; ocean movement/dynamics; and 3D mixing and dissipation processes. Examples of process which exchange energy, mass, and momentum between sources include, but are not limited to, radiation, evaporation, precipitation, river runoff and wind energy. Ocean movement and dynamics, as the name suggests, refers to processes which determine the movement of water in the ocean, such as horizontal advection and vertical convection. The 3D mixing and dissipation refers to processes that remove energy from the system such as turbulence caused by temperature differences and wind forcing. There are several approaches to modelling the ocean all of which have advantages and limitations. Conceptual or process models are limited in the different processes that can be incorporated into the model and are often regarded as simple, low resolution models. However conceptual or process models make it easier to interpret dynamics and processes in isolation, and can be run parallel to other models, and can accommodate larger simulations compared to more complex models. In essence, conceptual or process models are mathematical tools to aid in contributing to the theory of ocean processes. Another type of approach are Earth System Models of Intermediate Complexity (EMICs), which have a higher resolution and can run for long timescales with relatively low computation cost. These approaches have been used to investigate coupling of climate and abiotic processes, such as ice sheets and carbon feedback loops. Although EMICs incorporate more complexity, these approaches do not accurately reflect natural ocean processes; instead General Circulation Models (GCMs) provide a better description of the ocean. General circulation models are capable of incorporating multiple processes at a higher resolution. Generally speaking, currently GCMs provide the most accurate way of describing natural ocean processes.

Ocean models are popular tools for investigating future climate scenarios, but have a range of applications outside the realm of academia. Ocean models can also be used in operational oceanography in the maritime and shipping industry (now-casts and forecasts), experimental oceanography, and can be used to mechanistically interpret ocean observations. Ocean models are similar to atmospheric models but fundamentally differ in some respects. For example, atmospheric models involve air which is a compressible gas while ocean models involve seawater which is nearly in-compressible. These differences have significant impacts for how aspects of volume, temperature and pressure influence one another. In air, the interplay between these factors is largely linear and well understood, while in the ocean the relationship is non-linear and poorly understood. For ocean models the equation state used is

where, represents density and is a function of, temperature, salinity, and pressure. Although the equation state is more complex compared to that of air, some aspects are slightly simpler as seawater is in-compressible and therefore the water entering a grid box will be the same as the water exiting a grid box. Another major difference between ocean and atmospheric models is in ocean models salinity must be taken into account, while with atmospheric models humidity is an important factor. Ocean and atmospheric models also differ slighlty in terms of vertical structure i.e. layering. The surface of the ocean is where most heating and coolong occurs which cause the formation of a marine boundry or mixed layer. Below the mixed layer the ocean becomes more stratified which is ideal for determining flow. However, complications arise in the horizonal layer which does not continiously layer like the atmosphere. The horizontal layer in ocean models needs to take into account irregular bathymetry, shape and size of continental shelves/basins. Furthermore, run-off from rivers can cause changes in the density of seawater along the coasts, thereby altering their flow regimes. Therefore, ocean models need to resolve both the vertical and horizontal structuring, particulary along the ocean margins, which can be achieved through selecting the correct horizontal and vertical coordinate systems. Finally, the ocean interior is largely driven by density gradients compared to the atmosphere which is well mixed and so the equalibrium timescales are much slower relative to the atmosphere. For instance, an ocean model can take as long as 1000 years to start from rest.

Ocean models use similar equations to atmospheric models, with some minor differences (might add equation list). Theses equations form the basis of a ocean model, but more input is needed for a model to run successfully. Ocean models also need information on boundary conditions such as basin geometry, bathymetry and atmospheric pressure. The Atmospheric pressure can be solved for dynamically, or at the very least, the effects are approximated and imposed. Initial abiotic conditions are another important input into ocean models. Initial conditions include the mean state of temperature, salinity and velocity fields and can be calculated from climatology data or from a previously run ocean model. Finally, the forcing fields, both dynamic and static, are needed such as shortwave radiation, long-wave radiation, latent heat, evaporation, precipitation and land surface run-off. Examples of dynamic forcing fields include winds and tides. One of the most important steps in ocean modelling id defining the horizontal and vertical grids to be used. In terms of horizontal grids, there are two main types, namely regular and irregular grids. As the name suggests, a regular grid contains cells of the same size and dimensions i.e the grid cells are evenly spaced. When a regular grid is placed over a spherical earth, the grid cells vary in size and dimension resulting in a curvilinear grid. In addition, the grid lines converge at poles making modelling in those regions almost impossible. A popular solution is to use a tripolar grid laid over the Artic polar region which results in two poles positioned over land, creating more even spacing at the convergence points. The advantage of using regular grids is the decades of research on the subject, relatively straight forward analysis algorithms, and is computationally efficient. Problems arise with regular grids when increasing the resolution over a specific region, as the resolution must be increased along the entire latitude length. This leads to modelling areas not of interest (middle of the ocean) and is a waste of computational resources. As a result, the use of irregular grids in ocean modelling has been growing in popularity in recent years, as the spatial resolution can vary throughout the model.

There are different ‘types’ of irregular grids available such as using triangles meshed together to form a grid instead of rectangles or squares and is known as ‘finite element modelling’. The size of the triangles can be altered to construct a non-uniform horizontal resolution over the computational domain. For example, the model resolution can be finer for coastal regions and coarser resolution for areas in the middle of the ocean that are not of interest. Therefore, irregular grids can be customised according to what the model is attempting to resolve. Furthermore, irregular grids can accuratley represent areas/regions of complex coastal morphology, bathymetery and physical complex nearshore systems. However, finite element modelling is not without its disadvantages, one being that these models struggle to resolve flow driven by geostrophy and advection, both of which are important characteristics of large-scale ocean flow. Issues also arise when modelling regions which vary in terms of viscosity and diffusivity coefficients. In addition, the issues of numerical diffusion in ocean models is compounded by spatially variable advection schemes when using irregular grids, making these issues harder to resolve. In addition, issues arise when trying to match regions of low resolution with regions of high resolution which imposes limitations on how ocean models resolve certain processes. However, irregular grids are common in coastal and estuarine models which need a high resolution of a specific, spatially complex area. Despite the limitations of using irregular grids for large scale ocean modelling, some predict that the challenges will be overcome and the use of regular grids for large scale modelling will become common place. For example, the development of an irregular, adaptive grid which dynamically changes the resolution as a function of flow in time.

In terms of vertical grids, there are also different ‘types’ that can be used, all of which have advantages and limitations. The vertical grid is sometimes reffered to as ‘vertical coordinate system’, and several aspects need to be taken into account when selecting a vertical grid system. For example one needs to take into account that most of the movement in the ocean is driven by movement at the surface, the ocean is strongly stratisfied, flow occurs along density gradients, and complex bathymetry over the computational domain. As mentioned previously, there are variety of vertical coordinate systems to suite a variety of applications with , , and vertical coordinate systems regarded as the most popular. The absolute depth or -coordinate system is based on a series of depth levels and is easy to setup, is computationally efficient, and produces no pressure gradient errors. In addition, the resolution can be increased for a desired depth by simply reducing the spacing between the depth levels. However, when increasing the resolution along lateral boundaries (e.g. continental slopes) additional grid cells are needed. This leads to a similar problem as horizontal regular grids, where computational resources are wasted on areas which do not need to be resolved. The terrain following or -coordinate system is based on *frictional* depth scaled from 0 to 1. For example, a 0.01 level is 1% of the depth of the ocean, and 0.99 level represents the 99% of the depth of the ocean. The advantage of this approach is the bathymetery is accurately represented, which allows high resolution near the seafloor, regardless of depth or proximity to land. However, a -coordinate system does not resolve pressure gradients accurately as well as variable numerical advection schemes. The last popular approach is the isopycnal or density or -coordinate system, which defines the grid based on density layers. Density layers are important drivers of flow in the ocean interior, which the -coordinate system is able to characterise. The assumption made for this approach is ocean currents generally flow along surfaces of equal density for ocean interiors, meaning the flow is adiabatic. This approach works well for ocean interiors but performs poorly in shallow waters, where there is very little to no stratification in the water column. Therefore, in order for this approach to be applicable the fluid which flow is being resolved must be stratified. Since each of the approaches differ in terms of advantages and limitations, it is not uncommon to use a combination of coordinate systems known as hybrid coordinate systems. The hybrid coordinate system aims to optimise performance by combining the best suited coordinate system for a particular region. An example of a model that uses a hybrid coordinate system is the HYCOM model, which uses a combination of coordinates for the surface layer and density in the ocean below. Hybrid coordinate systems allow vertical coordinates to evolve in both temporally and spatially as the depth changes. Although a dynamically optimised coordinate system improves the results of the model, it is done at a high computational cost.

Another important component of an ocean model is the resolution, in other words the size of the grid. Important to note is that the ocean exhibits ‘multiple scale variability’, which refers to the variability in time and length scales of the ocean. For example, vertical turbulent mixing occurs along a different time and length scale compared to the formation of eddies and fronts. The range of time and space scales can be from molecular (mm and seconds) to basin scale (10 000km and 1000 years). Furthermore, some processes are coupled across scales such that large scale processes are coupled with small scale processes, and are known as ‘non-local interactions’. These non-local processes can have significant effects on both macro- and micro-scale components of the ocean. The resolution of a model is generally defined by the ability to permit or resolve eddies (see table below).

|  |  |  |
| --- | --- | --- |
| Resolution | Terminology | Definition |
| $^$ | Coarse | No eddies |
| $^$ | Eddy-permitting | Some eddies |
| $^$ | Eddy-resolving | Eddies generate at a realistic strength and rate |

Important to note is that the eddy ‘resolving-model’ does not resolve all eddies, or their assocaited aspects, but is a description of resolving eddies on what is currently known so far.

The parametrisation of processes in a model is another important component which must be accounted for to ensure computational resources are not wasted on processes which are negligible or too complex. In addition, the understanding of some processes include mesoscale eddy effects, dense overflows, submesoscale eddy effects, coastal processes, surface mixed layer process, friction, sub-grid scale mixing and ocean-ice interactions. Finally, the model needs to be validated to ensure it accurately represents a ‘natural’ ocean. Validation can be difficult as many observations are needed and the measurements themselves can be biased depending on the instruments used. Validation of ocean models has improved over the years due to initiatives such as the Argo Float Program. Other examples include satellites which are capable of measuring sea surface temperature, salinity and wind; while *in situ* instruments (buoys, ships, drifters, floats, temperature recorders, weather stations) provide direct measurements for validation purposes.

Ocean modelling is an important tool to help scientists understand how ocean processes are effected by climate change. However, ocean models are not perfect and challenges must be overcome to improve them, such as the effects of the internal wave field, model bias, dynamic ice sheets, mesoscale eddy fields, mixing and modelling drift. Furthermore, ocean modelling has provided a basis and information for the development of other tools such as hydrodynamic and trajectory modelling.

# 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 of 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), and has been used in mapping 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 which describes 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. Most models have been designed with a specific goal or objective in mind, and so no single model exists that is appropriate for all situations or applications. Although models are “situation specific”, completed models can set the foundation for future models with regards to resolving important oceanographic processes, identifying gaps, and identifying important tracer coefficients (**???**). Modelling of nearshore ecosystems has been reviewed by Jones (2002), and offers the reader a general overview of the discipline (**I must try and get this paper**).

## Practicalities of model design

Hydrodynamic models use the same primitive equations for ocean models, which calculate velocities, turbulence, temperature, and salinity, and hence, density (**???**). The equations used in hydrodynamic modelling need to be ‘discretised’, which means the equations are formulated to be evaluated at discrete temporal and spatial points. Additionally, hydrodynamic models use similar approaches to grid and coordinate structures (see ocean modelling section).

## 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.

# Drifting aspects of floating objects

The need to understand the effects of oceanographic conditions affecting trajectory of floating objects has largely been borne from the maritime industry. The applications in the maritime industry include locating lost cargo, locating naval and plane debris, search and rescue, and the hydrodynamic effects on naval architecture.

The trajectory of passively drifting objects on the sea surface is influenced by multiple factors, such as water currents, atmospheric wind, wave motion, wave induced currents, gravitational force and buoyancy force. To complicate matters, the previously mentioned factors do not act independently but instead influence one another. Furthermore, the gravitational and buoyancy forces on the object are determined by the objects shape. Therefore, all these factors need to be taken into account when modelling trajectory of drifting objects. Given the local wind, surface current, and the shape and buoyancy of the object are known, it is possible to estimate trajectory by the equation

where represents the current velocity relative to the earth, and represents the object drift velocity relative to the ambient water (Hackett, Breivik, and Wettre 2006). Ocean currents are determined by two components: the surface current (including the effects of Ekman drift, baroclinic motion, tidal and inertial currents) and Stokes drift induced by waves. The assumption made is influences all floating objects in the same manner, regardless of shape or size. Therefore, is equated with the surface current obtained from a numerical ocean model which has been parameterised on the wind velocity (Hackett, Breivik, and Wettre 2006). The effects of on a floating object is driven by wind and wave forces which is dependent on the shape and size of the floating object. In some cases the effects of wind or wave forces may be neglibible and only one aspect needs to be included or investigated seperately. Therefore, can be seperated into wind and waves into two sub-components which allows the equation to be adpated to suite the particluar situation (Hackett, Breivik, and Wettre 2006). For example, previous research has shown that the effects of waves on drifting objects are negligible when the length of the object is less than the wave length; and increase significantly when the lengths are approximately the same (Grue and Biberg 1993; Hodgins and Hodgins 1998). Furthermore, current velocity affects on drifting objects is considered to be negligible in this approach and ideally should be taken into account. The literature identifies waves as the primary influencer of trajectory for larger objects while wind is regarded as the primary influencer for smaller objects. The effects of wind on object drift trajectory is complex and is ofcourse dependent on the exposed portion of the object to the wind. The effect of wind on trajectory is often referred to as leeway.

## Leeway

An objects motion relative to the wind is sometimes referred to as “windage factors” or “leeway drift”, and is difficult to accurately and empirically describe. The difficulty is due to accurate measurements needed for the current velocity, wind velocity, wave height and wave direction. The appropriate approaches to measuring the afprmentioned parameters have been detailed by (**???**) and is dependent on the objects size and shape as well as the quality and quantity of data available to the modeler. Additionally, these factors do not act independently and instead influence one another, which compounds the complexity of calculating wind effects on drifting objects. To overcome this challenge, measurements of current and wind velocity, and wave height and direction are measured along the objects trajectory for a wide range of conditions.

Wind effects or windage factors can be calculated using the approach by Griffin, Oke, and Jones (2017), and can be expressed as

where is the velocity of the drifting object, is surface current velocity, is the ‘leeway’ velocity and is the velocity due to wave forces. As stated, is the velocity of the surface current and is averaged over the vertical extend of the drifting object. Velocity of the surface current is expressed as

where is the average velocity for the the top 5m of the ocean (estimated by an ocean model) and is the velocity effect of Stokes Drift due to wave action. It is important to note that the approximation of Stokes drift does not take into account finer-scale vertical differences of the velocity field, such as Coriolis-Stokes forcing. Stokes drift generally manifests in hydrodynamic environments with short-wavelengths and locally-generated waves. Griffin, Oke, and Jones (2017) mitigated the exclusion of finer-scale drivers of Stokes Drift by comparing modeled surface velocities with those of *in situ* drifters.

is the velocity of the object relative to the water due to effects of wind force directly on the object and can expressed by

where is a linear ‘windage’ or ‘leeway’ coefficient and is the wind speed at 10m height. The study by Griffin, Oke, and Jones (2017) used a 10m height to model drifting airplane debris, however this may be adjusted according to drifting object being modeled. The nature of (linear windage) is dependent on the object, for instance yachts tend to drift in a particular orientation to the wind, and so the angle of the drifting object is dependent on said orientation. Furthermore, drifting object which are more wind exposed and are less submerged will have high windage. Due to these factors, and to allow for a non-zero angle between and , (linear windage) can be a complex number.

is the velocity of the object as a result of direct wave force, and is dependent on the size and shape of the object. In instances when wave-wave interactions result in an small, unbalanced force then is assumed to be zero. Also, objects may be able to absorb wave energy which can result in a non-zero value. Since surface-waves are wind driven, the is calculated by

Important to note is that the effects of wind and waves on the trajectory of a drifting object may be influenced by the object’s orientation. This has been noted in modelling drift trajectories of ships (Allen and Plourde 1999; Hackett, Breivik, and Wettre 2006), and should be incorporated into the leeway drift component. The direct () and indirect ( and ) effects do not act independently and instead influence one another. with regards to this, Griffin, Oke, and Jones (2017) recommend incorporating an effective windage factor which would represent the combined effects of Stokes Drift, leeway drift and wave forces. Although a common approach, this may not be necessary in all circumstances particularly if individual effects of factors are being investigated. As mentioned previously, the magnitude of effects of wind and waves on an objects trajectory is depedent on the surface area/volume exposed to either influencer, which in turn is dependent on the bouyancy of the object. The object’s buoyancy may also change over time due to other influencers such as erosion and epibiont biomass.

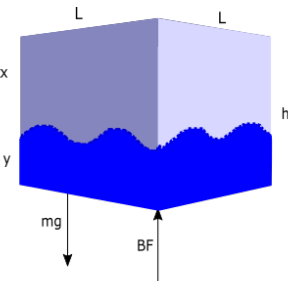
## Buoyancy of drifting objects in the oceans

The buoyancy is often a fixed value within a model and does not alter over time, such as @?? and @?? as examples. This may be because the effects of epibiont biomass on ships and wreckage is not regarded as a significant influencer. However, for smaller objects this may not be the case. This may be particulary true for living drifters such as macroalgae which are able to grow themselves, as well as provide a habitat for epiphytes and bryozoans which increase in biomass overtime. The buoyancy of objects at sea has been shown to be influeced by epibiont load (Hobday 2000b; **???**; Graiff et al. 2016; Macaya et al. 2016), which reduces drift times by reducing buoyancy with increasing biomass, which ultimatley leads to the object sinking. The bouyancy of the drifting object is determined by the growth rate of epiphytic species while drifting, which in turn will be depndent on environmental factors such as temperature and light which will vary along the objects trajectory Therefore, buoyancy should be parameterised by temporal epibiont biomass load.

Archimedes principles dictates that the buoyant force exerted on a small object is equal to the weight of the displaced fluid and acts in the opposite direction to the acceleraton vector. The net wieght is the weight of the object less the weight of a equal volume of fluid. A similar result can be achieved by using density of a object such that the “net density” is the density of the object less the density of the of the fluid. This can be expressed as:

This approach can also be applied to acclerating objects submerged in a fluid, in which case, the angular velocity must be considered. Acceleration is usually considered in short-term forecasts for large objects such as shipping containers or airplane debris. This does not fall within the scope of this thesis and therefore will not be considered.

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 ) will be used to demonstrate the theory 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 (see figure ).



Conceptual model of bouyancy characteristics.

An object will only float if the object density () is less than or equal to the density of the liquid in which the object is submerged, i.e. . The buoyancy 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 and is expressed as:

The weight of the displaced liquid can be calculated by multiplying the mass of the liquid by the gravitational constant and so the weight of the displaced liquid can be calculated by:

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

where represents the density of the liquid and represents the portion of the object submerged. Since the object is floating, the BF can also be expressed by the weight of the object and as mentioned previously the weight of the displaced liquid can also be expressed by , which in turn can be written as . Now through substituting the calculations for weight, volume and the dimensions of the object, the equation can be simplified to:

where is the overall height of the object, represents the density of the object and represents the density of the liquid.

It is important to note that this equation is only applicable to objects that are floating i.e. . The portion of a floating object above the water surface can also be calculated using a similar approach, and instead of calculating the submerged portion () the calculation will now solve for the fraction above the surface which is represented by (see figure ). The same equation for calculating density () will also be used in solving for . As mentioned previously, for floating objects the and the BF can also be defined as the weight of the displaced liquid (). Therefore, the weight of the displaced liquid is equal to the weight of the object (). On this basis equation ?? can be written as

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

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

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

and since the equation can now be solved via density of the liquid and the object:

Solving the equation algebraically it can now be written as:

Once the fractions of submerged and non-submerged portions of the object have been calculated the next calculation relevant to this study would be to calculate the weight needed to cause the object to sink or as least be completely submerged. This will relate to epiphyte loading on kelp rafts in order to determine raft longevity. If a weight is placed on the object in the conceptual model that has enough weight to fully submerge (but not sink) the object then an addition buoyancy force is needed, which will be represented by which is equal to the additional mass that has been added which can be expressed as . Based on the previous calculations and the laws of physics we know that:

The weight of the additional liquid displaced can now be calculated by substituting the density and volume of the additional displaced liquid along with the gravitational constant which is expressed as:

where the subscript represents the components of *additional liquid displaced*. The can also represent the change in volume () and so the expression can be expanded to:

} where represents the change in volume of the object, i.e .

## Drag parameters

Drag is the force an object experiences when moving in a fluid due to the rate in change of momentum (Vogel 2020). The drag around the surface of an object due to the viscosity of the fluid is known as ‘surface drag’. The drag induced by a quantity of fluid moving around the object is known as pressure drag/form drag/inertial drag. In general, large objects moving quickly tend to induce larger drag forces, however, this is not always the case. In some instances, the flow around the object changes from laminar to turbulent which ultimately reduces overall drag. (Maybe insert small section on why turbulent flow reduces overall drag on an object).

The type of flow, laminar or turbulent, is determined by fluid density (p), flow speed (U), object size (l) and fluid viscosity (v). These factors can be used to calculate the Reynolds number which is used to determine the type of flow. The expression used can be dependent on factors used such as whether the fluid is Newtonian or non-Newtonian and object shape.

# Kelp-rafting

Dispersal is recognised as important driver of biodiversity, composition and structure of ecological systems in the marine environment (Bernardes Batista et al. 2018; Helmuth, Veit, and Holberton 1994; Highsmith 1985; MacArthur and Wilson 2001; Jackson and Sax 2010). These processes are largely dependent on currents for dispersal of migrant populations which ultimately promote connectivity of marine ecosystems (Bernardes Batista et al. 2018; Mackas, Denman, and Abbott 1985, 1985; Zakas et al. 2009). This is particularly true for organisms which lack pelagic larvae, and are reliant on other modes of transport to reach new habitats through passive modes of dispersal from anthropogenic and natural sources. Anthropogenic sources include marine litter and structural debris while examples of organic sources include pumice and macroalgae in the form of kelp-rafts. Kelp-rafts have been identified as an important mode of passive dispersal of marine organisms, such as invertebrates [Helmuth, Veit, and Holberton (1994); whichmann2012], epiphytes (Macaya et al. 2016), grazers (Nikula et al. 2010), invasive species (Lewis, Riddle, and Smith 2005) and macroalgae themselves (Macaya et al. 2005) which either make landfall or are transported offshore where they eventually sink. A kelp-raft consists of an entanglement of macroalgae (one or multiple species) which have been dislodged from the benthic environment through hydrodynamic forces (mostly storms) and are positively buoyant by means of gas-filled pneumatocysts and/or reproductive organs. Kelps are capable of travelling vast distances (Fraser, Nikula, and Waters 2011) and are considered important dispersal vectors in temperate latitudes, such as the Southern California Bight (Hobday 2000a, 2000b).

Kelp-raft abundance has been shown to vary temporally and spatially in the ocean and around coastlines, which is dependent on seasonal growth patterns which ultimatley influences overall biomass of seaweed. For example, studies investigating the dispersal patterns of *Sargassum* in the West Pacific show increased abundance during growth seasons (spring and summer) as more biomass is available to fragment (Deysher and Norton 1981; Kingsford 1992). Temporal variability may also be related to seasonal storm frequency where more storms in a particular season relate to an increase in kelp-raft abundance. For example a study by Kingsford (1995) investigated the contribution of *Macrocystis pyrifera* rafts to habitat complexity in pelagic environments. The authors found that the abundance of *M. pyrifera* rafts increased during seasons where storms occurred more frequently.

The trajectory of kelp rafts are determined by a combination of oceanographic conditions and biological processes. Since kelp float, evidence points largely to wind driven surface currents as the main driver, although the relative importance of wind versus surface currents is largely unknown. For example a study by Harrold and Lisin (1989) used radio-trackers on both natural and artificial *Macrocystis pyrifera* kelp rafts to investigate seasonal trajectory patterns. The results showed that tracked kelp rafts were mostly deposited nearby the source population and that seasonal wind direction was the primary driver of trajectory for kelp rafts submerged roughly ~0.5 - 1m below the surface Harrold and Lisin (1989). However, the authors did note the influence of surface currents for some of their experiments when winds relaxed; which suggests that surface currents may play a larger role in determining trajectory for kelp rafts less exposed to wind or when prevailing winds are low. Other authors have identified the West Wind Drift as important driver of trajectory of floating *M. pyrifera* [Fraser, Nikula, and Waters (2011); ]

# 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).

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). Characterised by a large distal swollen bulb filled with gas, and smooth fronds, this species grows to approximately 10 meters (Bolton and Anderson 1987). There was, however, a 17-meter specimen collected in 2015 off Cape Point (Smit, unpubl. data).This species of kelp not only dominate the biomass of the South African nearshore, but plays an important ecological role (Bustamante and Branch 1996). The estimated productivity of *E. maxima* within South Africa varies between 350 and 1500g Cm-2yr-1 (Mann 1982). Across the majority of the coastline, Laminaria pallida remains a subsurface kelp, dominating the kelp biomass at depths greater than 10 meters (Field et al. 1980a, Bolton and Anderson 1987, Molloy and Bolton 1996). This species is distributed from Danger Point, east of the Cape Peninsula, to Rocky Point in northern Namibia, and reaches depths of greater than 20 meters (Field et al. 1980a, Molloy and Bolton 1996, Stegenga et al. 1997). Towards the north along the west coast, from around Hondeklipbaai, *L. pallida* replaces *E. maxima* as the dominant kelp species (Velimirov et al. 1977,Stegenga et al. 1997) and it also occupies increasingly shallow subtidal regions. The northern populations also exhibit an increase in stipe hollowness, compared to the solid stipe morphs in the species’ southern distributions (Molloy and Bolton 1996). This variation in morphology was thought to represent two distinct species, with the northern populations formerly described as *Laminaria schinzii* Foslie (Molloy and Bolton 1996). Genetic work has subsequently shown that the two morphs are in fact the same species (Rothman et al. 2017). In southern African waters, the primary production of *Laminaria pallida* is between 120 and 1900g C m2yr1, similar to that of *E. maxima* (Mann 1982). Primary production is not the only pathway.

# 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 morphological characteristics using a numerical model
2. Simulate kelp rafting by means of particle dispersion modelling.
3. Conduct field experiments using artificial rafts and *in situ* kelp to track the movement of kelp around the South African coastline using custom GPS trackers.
4. Use the experimental data to calibrate the model and investigate the role of storms in ocean dispersal patterns.

# References

Allen, A, and JV Plourde. 1999. “Review of Leeway: Field Experiments and Implementation. US Coast Guard Rep.” CG-D-08-99, 351.

Bernardes Batista, Manuela, Antônio Batista Anderson, Paola Franzan Sanches, Paulo Simionatto Polito, Thiago Lima Silveira, Gabriela Velez-Rubio, Fabrizio Scarabino, et al. 2018. “Kelps’ Long-Distance Dispersal: Role of Ecological/Oceanographic Processes and Implications to Marine Forest Conservation.” *Diversity* 10 (1): 11.

Blamey, Laura K, and George M Branch. 2012. “Regime Shift of a Kelp-Forest Benthic Community Induced by an ‘Invasion’of the Rock Lobster Jasus Lalandii.” *Journal of Experimental Marine Biology and Ecology* 420: 33–47.

Blamey, L K, L J Shannon, J J Bolton, R Crawford, F Dufois, H Evers-king, C Griffiths, et al. 2015. “Ecosystem change in the southern Benguela and the underlying processes.” *Journal of Marine Systems* 144: 9–29. <https://doi.org/10.1016/j.jmarsys.2014.11.006>.

Burrows, M T, D S Schoeman, L B Buckley, P Moore, E S Poloczanska, K M Brander, C Brown, et al. 2011. “The pace of shifting climate in marine and terrestrial ecosystems.” *Science* 334 (6056): 652–55.

Dayton, P K, M J Tegner, P B Edwards, and K L Riser. 1999. “Temporal and spatial patterns of kelp demography: The role of Oceanographic climate.” *Ecological Monographs* 69 (2): 219–50. [https://doi.org/10.1890/0012-9615(1999)069[0219:TASSOK]2.0.CO;2](https://doi.org/10.1890/0012-9615(1999)069%5B0219:TASSOK%5D2.0.CO;2).

Deysher, Larry, and Trevor A Norton. 1981. “Dispersal and Colonization in Sargassum Muticum (Yendo) Fensholt.” *Journal of Experimental Marine Biology and Ecology* 56 (2-3): 179–95.

Doney, Scott C, Mary Ruckelshaus, J Emmett Duffy, James P Barry, Francis Chan, Chad A English, Heather M Galindo, et al. 2011. “Climate Change Impacts on Marine Ecosystems.”

Fraser, C I, R Nikula, and J M Waters. 2011. “Oceanic rafting by a coastal community.” *Proceedings of the Royal Society B: Biological Sciences* 278 (1706): 649–55.

Graiff, Angelika, Jose F Pantoja, Fadia Tala, and Martin Thiel. 2016. “Epibiont Load Causes Sinking of Viable Kelp Rafts: Seasonal Variation in Floating Persistence of Giant Kelp Macrocystis Pyrifera.” *Marine Biology* 163 (9): 191.

Griffin, DA, PR Oke, and EM Jones. 2017. *The Search for Mh370 and Ocean Surface Drift*. Commonwealth Scientific; Industrial Research Organisation.

Grue, John, and Dag Biberg. 1993. “Wave Forces on Marine Structures with Small Speed in Water of Restricted Depth.” *Applied Ocean Research* 15 (3): 121–35.

Hackett, Bruce, Øyvind Breivik, and Cecilie Wettre. 2006. “Forecasting the Drift of Objects and Substances in the Ocean,” 507–23.

Harley, C, K M Anderson, K W Demes, J P Jorve, R L Kordas, T Coyle, and M H Graham. 2012. “EFfects of Climate Change on Global Seaweed Communities.” *Journal of Phycology* 48 (5): 1064–78. <https://doi.org/10.1111/j.1529-8817.2012.01224.x>.

Harley, Christopher DG, A Randall Hughes, Kristin M Hultgren, Benjamin G Miner, Cascade JB Sorte, Carol S Thornber, Laura F Rodriguez, Lars Tomanek, and Susan L Williams. 2006. “The Impacts of Climate Change in Coastal Marine Systems.” *Ecology Letters* 9 (2): 228–41.

Harrold, Christopher, and Susan Lisin. 1989. “Radio-Tracking Rafts of Giant Kelp: Local Production and Regional Transport.” *Journal of Experimental Marine Biology and Ecology* 130 (3): 237–51.

Helmuth, B, R R Veit, and R Holberton. 1994. “Long-distance dispersal of a subantarctic brooding bivalve (Gaimardia trapesina) by kelp-rafting.” *Marine Biology* 120 (3): 421–26. <https://doi.org/10.1007/BF00680216>.

Highsmith, Raymond C. 1985. “Floating and Algal Rafting as Potential Dispersal Mechanisms in Brooding Invertebrates.” *Marine Ecology Progress Series. Oldendorf* 25 (2): 169–79.

Hobday, Alistair J. 2000a. “Abundance and Dispersal of Drifting Kelp Macrocystis Pyrifera Rafts in the Southern California Bight.” *Marine Ecology Progress Series* 195: 101–16.

———. 2000b. “Age of Drifting Macrocystis Pyrifera (L.) c. Agardh Rafts in the Southern California Bight.” *Journal of Experimental Marine Biology and Ecology* 253 (1): 97–114.

Hodgins, Donald O, and Sandra LM Hodgins. 1998. *Phase Ii Leeway Dynamics Program: Development and Verification of a Mathematical Drift Model for Liferafts and Small Boats*. Seaconsult Marine Research Limited.

Jackson, Stephen T, and Dov F Sax. 2010. “Balancing Biodiversity in a Changing Environment: Extinction Debt, Immigration Credit and Species Turnover.” *Trends in Ecology & Evolution* 25 (3): 153–60.

Jennings, Simon, and Keith Brander. 2010. “Predicting the Effects of Climate Change on Marine Communities and the Consequences for Fisheries.” *Journal of Marine Systems* 79 (3-4): 418–26.

Johnson, Craig R, Sam C Banks, Neville S Barrett, Fabienne Cazassus, Piers K Dunstan, Graham J Edgar, Stewart D Frusher, et al. 2011. “Climate Change Cascades: Shifts in Oceanography, Species’ Ranges and Subtidal Marine Community Dynamics in Eastern Tasmania.” *Journal of Experimental Marine Biology and Ecology* 400 (1-2): 17–32.

Jones, JE. 2002. “Coastal and Shelf-Sea Modelling in the European Context,” 45–48.

Kingsford, Michael J. 1992. “Drift Algae and Small Fish in Coastal Waters of Northeastern New Zealand.” *Marine Ecology Progress Series*, 41–55.

———. 1995. “Drift Algae: A Contribution to Near-Shore Habitat Complexity in the Pelagic Environment and an Attractant for Fish.” *Marine Ecology Progress Series. Oldendorf* 116 (1): 297–301.

Krumhansl, Kira A, Daniel K Okamoto, Andrew Rassweiler, Mark Novak, John J Bolton, Kyle C Cavanaugh, Sean D Connell, et al. 2016. “Global Patterns of Kelp Forest Change over the Past Half-Century.” *Proceedings of the National Academy of Sciences* 113 (48): 13785–90.

Lewis, Patrick N, Martin J Riddle, and Stephen DA Smith. 2005. “Assisted Passage or Passive Drift: A Comparison of Alternative Transport Mechanisms for Non-Indigenous Coastal Species into the Southern Ocean.” *Antarctic Science* 17 (2): 183–91.

MacArthur, Robert H, and Edward O Wilson. 2001. *The Theory of Island Biogeography*. Vol. 1. Princeton university press.

Macaya, Erasmo C, Sebastian Boltana, Ivan A Hinojosa, Juan E Macchiavello, Nelson A Valdivia, Nelson R Vasquez, Alejandro H Buschmann, Julio A Vasquez, JM Alonso Vega, and Martin Thiel. 2005. “PRESENCE of Sporophylls in Floating Kelp Rafts of Macrocystis Spp.(PHAEOPHYCEAE) Along the Chilean Pacific Coast 1.” *Journal of Phycology* 41 (5): 913–22.

Macaya, Erasmo C, Boris López, Fadia Tala, Florence Tellier, and Martin Thiel. 2016. “Float and Raft: Role of Buoyant Seaweeds in the Phylogeography and Genetic Structure of Non-Buoyant Associated Flora,” 97–130.

Mackas, David L, Kenneth L Denman, and Mark R Abbott. 1985. “Plankton Patchiness: Biology in the Physical Vernacular.” *Bulletin of Marine Science* 37 (2): 652–74.

McGowan, J A, D R Cayan, and Le Roy M Dorman. 1998. “Climate-ocean variability and ecosystem response in the Northeast Pacific.” *Science* 281 (5374): 210–17. <https://doi.org/10.1126/science.281.5374.210>.

Nikula, Raisa, CI Fraser, HG Spencer, and JM Waters. 2010. “Circumpolar Dispersal by Rafting in Two Subantarctic Kelp-Dwelling Crustaceans.” *Marine Ecology Progress Series* 405: 221–30.

Poloczanska, Elvira S, Christopher J Brown, William J Sydeman, Wolfgang Kiessling, David S Schoeman, Pippa J Moore, Keith Brander, et al. 2013. “Global Imprint of Climate Change on Marine Life.” *Nature Climate Change* 3 (10): 919.

Polovina, Jeffrey J. 2005. “Climate Variation, Regime Shifts, and Implications for Sustainable Fisheries.” *Bulletin of Marine Science* 76 (2): 233–44.

Vogel, Steven. 2020. “Life in Moving Fluids: The Physical Biology of Flow-Revised and Expanded Second Edition.”

Zakas, C, J Binford, SA Navarrete, and JP Wares. 2009. “Restricted Gene Flow in Chilean Barnacles Reflects an Oceanographic and Biogeographic Transition Zone.” *Marine Ecology Progress Series* 394: 165–77.

1. University of the Western Cape [↑](#footnote-ref-20)
2. South African Weather Service [↑](#footnote-ref-21)
3. University of the Western Cape [↑](#footnote-ref-22)