Introduction

Kelp in general

Kelp forests are found in temperate and polar coastal regions around the world (Mann 1973).They are classified as a keystone species and are amongst the most productive ecosystems in the world (Mann, 1973; Fredriksen, 2003; Rysgaard and Nielsen, 2006; Merzouk, 2011).The most productive kelp forests are found in areas of frequent upwelling (Druehl 1981). These underwater forests provide shelter, food and are nursery grounds for various marine species (Merzouk, 2011). Kelp is considered as an ecosystem engineer and provides many ecosystem services that include purifying and removing waste produced by organisms living within the forest.

Many environmental factors influence kelp bed communities. Temperature generally determines the geographical distribution of marine organisms (Lüning 1990, Rothman 2015). However, for kelp beds, many other factors determine their distribution, these include: wave action, grazing (McQuaid and Branch 1984; Kalvas and Kautsky, 1993), nutrient levels, photoperiod (Luning 1980, 1990), tides, topography of substrata and depth among other ecological factors. Depth is directly related to light attenuation (Luning 1990) making it (depth) a major regulatory factor in the vertical distribution of kelp. Staehr and Wernberg (2009) discovered an inverse relationship between water temperature and water depth, i.e. for species in cold temperate waters, when water depth decreases by 10% there is a 5°C increase in temperature. In more turbid environments, depth limits decrease by 50%.

Kelp in South Africa

*Ecklonia maxima* is a species of large brown kelp from the order *Laminariales*; it is characterised by a long hollow stipe, a spear-shaped primary blade, and secondary blades that grow bilaterally. It is the more dominant species of the four kelp species (*Ecklonia maxima*, *Laminaria pallida*, *Macrocystis pyrifera* and *Ecklonia radiata*) found along the coast of Southern Africa. The former three species inhabit the cold nutrient rich waters of the Benguela Marine Province, while *E. Radiata* inhabits the warmer east coast of South Africa. *E. maxima* and *L. pallida* form extensive kelp beds along the South African west coast, in the southern portion of the Benguela region and parts of the Benguela–Agulhas transition zone (Bolton 2012). *E. maxima* forms a floating canopy up to depths of 19m and *L. pallida* forms the sub-canopy at depths of 20m or greater.

South Africa, like many other countries, is bordered by two large intense currents, the warm tropical Agulhas current on the east coast, and the cold nutrient rich Benguela on the west coast. The interaction of these two currents has profound effects on marine life. However, South Africa is unique in that the interaction of these currents occurs over a relatively short spatial scale, between Cape Point and Cape Agulhas, resulting in a large temperature gradient along the shore (Smit *et al.* 2013, 2017).Does this influence the kind kelp found in this area?

Temperature

*E. maxima* occur in areas of warm to cold temperate waters in the sub- and intertidal rocky substrate (Stenek and Johnson 2013, Rothman 2015), and its biogeographical range extends from north of Lüderitz, Namibia to west of Cape Agulhas in South Africa.This biogeographical range is largely determined by the kelp species tolerance of high summer maxima and low winter minima temperatures (Luning, 1984; van den Hoek and Luning, 1988; van den Hoek *et al.*, 1990; Adey and Steneck, 2001). Previously described as a cold water species by Griffiths and Mead (2011), *E. Maxima* has since been reclassified as a warm, temperate water species since it is found in False Bay where monthly mean temperatures in summer exceed 18 °C (Bolton 2012). False Bay`s high summer temperatures are a result of solar heating of entrained water (Anderson *et al*. 1997). *E. Maxima* does not grow in areas where the monthly mean winter temperature falls below 10°C (Bolton 2012).

Wave Parameters

Gerard and Mann, 1979; Cousens, 1982; Cheshire and Hallam, 1988; Molloy and Bolton, 1996; Ralph et al., 1998; Hurd, 2000; Blanchette*et al*., 2002; Roberson and Coyer, 2004 have stated that wave exposure is the most identified cause of morphological variation in kelp while Koehl (1986), Wheeler (1988) and Hurd (2000) demonstrated that wave exposure affects many of the morphological characteristics in kelp (Wernberg and Thomsen 2005). Because of the many parameters within wave exposure it is probable that different morphological variables would respond differently to each parameter. Generally, kelp growing in exposed areas are tougher, sturdier, and more strongly attached than those in sheltered areas. Frond characteristics of kelp in exposed areas are: narrow, thick, flat and smooth, whereas those in sheltered areas have blades that are wide and thin with ruffled margins.

Wernberg and Thomsen (2005) observed that *Ecklonia radiata* responded to intense wave exposure by having small narrow blades (Gerard 1987) with minimal spinosity to reduce drag, as well as larger holdfasts (Sjøtun and Fredriksen, 1995), thicker stipes (Cheshireand Hallam, 1988; Klinger and DeWreede, 1988) and thicker lamina (Cheshire and Hallam, 1988; Molloy and Bolton, 1996; Kawamata, 2001) for increased strength. Morphological adaptations are beneficial for mortality (Friedland and Denny, 1995; Blanchette et al., 2002, Wernberg and Thomsen, 2005) but are consequential in that it reduces rates of photosynthesis, productivity and growth (Gerard and Mann, 1979; Jackelman and Bolton, 1990; Blanchette et al., 2002, Wernberg and Thomsen, 2005).

Kelp needs to be flexible, to resist hydrostatic bending forces (Norton et al. 1982). It was suggested that kelp flexibility in the stipes might be related to wave exposure, especially in shallow water, implying that the kelp strategy for survival in high water motion environments is flexibility rather than strength and resistance (Rothman, 2015).

Climate Change

Global temperature change has impacted kelp ecosystems. The Agulhas current system has warmed significantly (1.5°C in 20 years) and a decrease in sea surface temperature (up to 0.5°C per decade) has been observed along the West Coast, near Port Alfred and in Nelson Mandela Bay (Port Elizabeth) (Rouault *et al*. 2009, Rouault *et al*. 2010, and Rouault*et al*. 2011). Bolton (2012) suggested that there is a high probability that kelp abundance was increasing (1986-2007) along the west coast of South Africa, where water temperatures are said to be getting cooler as a result of climate change. In addition, the altered wind and rainfall patterns change the intensity of the Benguela upwelling system (Rouault et. al 2010).

Owing to climate change and elevated sea temperatures the environment for successful kelp growth is at risk and this poses a huge threat to biodiversity within the ocean. Kelp are an important indicator of change as they are extremely responsive to environmental conditions and are very exposed to human activities such as harvesting, pollution, recreational fishing and sedimentation, which impact on the coastal zone (Krumhansl et al. 2016). Increased sea surface temperatures could result in a loss of abundance and alter the range of this keystone species (Merzouk 2011). There are three ways in which a species can respond to change in their environment: firstly, by migrating to a more favourable area, secondly, by adapting to the new environmental conditions and finally, by becoming extinct (Merzouk 2011).

The aim of this study is to determine how environmental factors such as temperature and wave exposure influence or affect the morphology of shallow water *Ecklonia maxima*. This will be accomplished by understanding how the various aspects of kelp morphology and environmental parameters differ at various sites along the Cape Peninsula. Also, we will investigate which parameters of temperature and wave exposure can best explain the morphological variation in the different kelp communities. This will be achieved by using a statistical analysis approach. We hypothesise that populations with similar temperature and wave exposure regimes will have similar morphologies and that temperature will influence morphological variables related to nutrient uptake, whereas wave exposure will influence morphology of the fronds.

**Methods**

* Study area

Sites were selected according to the geographic distribution of *E. Maxima*, under varying levels of wave exposure and temperature regimes along the south west coast of South Africa. The chosen sites were also a combination of exposed and sheltered sites, along the West Coast and False Bay regions, ranging from St. James in False Bay to Yzerfontein on the West Coast.

* Morphometric data collection

Sampling took place between March and October 2018 during low tide. The thirteen largest *Ecklonia maxima* individuals were collected by snorkel in an area where the kelp bed was ~1m deep and in shallow water (along the shoreline). Juvenile kelp (juvenile sporophytes) about 30cm in length were collected from shallow water on the shore. After the collection of kelp was completed, various morphological and biomass measurements were recorded. A measuring tape was used to measure the various morphological features, and the biomass was measured by cutting the kelp into two sections and placing the material in a net bag, which was weighed using a scientific spring scale.

The morphological factors that were measured are: primary blade length, primary blade width, frond length, stipe length, stipe circumference, number of tufts and epiphyte length. The biomass was divided into frond mass and stipe mass, were the sections were separated with a cut below the primary blade. These measurements allowed for comparisons in length, weight and thickness between sites and varying depths.

* Temperature data

The monthly shallow water temperature data was obtained from the South African Coastal Temperature Network (SACTN). The temperature dataset was a compilation of contributions made by several sources, using *in situ* data and digital underwater temperature recorders (UTRs).

* Wave parameters

All wave data, taken at three hour resolutions, were obtained from the South African Weather Service (SAWS). Short-crested waves, generated by wind into the coastal environment (), were modelled from the data using the Simulating Waves in the Nearshore (SWAN) model. SWAN enables the removal of wave parameters from particular gridded locations in the nearshore (). For this study, a 200 meter resolution was used, at both 7 and 15 meter contours.

Statistical methods:

Tests for normality were performed, and due to the morphological and temperature data not being normally distributed, non-parametric analyses were performed. The data was then standardised to a mean of 0 and a standard deviation of 1, in order to easily compare variables measured on different scales.

In order to visualise and compare the differences in morphology of kelp among sites, boxplots were constructed using the descriptive statistics of the morphometric data collected. The descriptive statistics include; minimum, maximum, 1st quartile(25th percentile), 3rd quartile (75th percentile), median and the interquartile range, which is the distance between the 1st and 3rd quartiles.

Boxplots of the morphometric data at the same sites but at various depths were also produced, in order to determine if there are differences in morphology of kelp at different depths.

A descriptive summary of the temperature and wave data was also conducted, including statistics such as minimum, maximum, mean, range and standard deviation. This was used to determine the monthly and annual climatologies of the sites sampled. These climatologies were used in the redundancy analysis (RDA) to identify the parameters of temperature and wave exposure which is the most influential in kelp morphology. RDAs help to summarise the variation in response variables (morphometric measurements), that is explained by explanatory variables (temperature and wave exposure parameters). This is achieved by performing multiple linear regressions between the response and explanatory variables.

All statistical analyses were conducted through The R-Project for Statistical Computing.

Results

* The site map can be found in the sitemap2 script
* Morphology graphs and key points can be found in “draft\_morph1”.
* Climatologies and RDA can be found in the r\_script “rda”