

# Trajectory model of passive kelp dispersal

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## Introduction

There is a range of objects, both natural and anthropogenic, floating in the ocean of which macroalgae are regarded as one of the most important passive dispersal mechanisms of marine taxa. Floating kelp acts as a passive dispersal mechanism for a range of marine taxa and is sometimes referred to as the ‘tumble-weed’ of the ocean (Edgar 1987; Bushing 1994; Norton 1992; Helmuth, Veit, and Holberton 1994; Holmquist 1994; Smith 2002; McCormick et al. 2008). Considerable research has been performed investigating macroalgae as a passive dispersal mechanism in the ocean, however, in recent years much of the focus has shifted towards microplastics.

Some macroalgae species are negatively buoyant and sink to the seafloor when detached from the substrate, while other species of macroalgae have air-filled pneumatocysts or stipes which allow the plants to reach the surface where light is more abundant. In turn, the positively buoyant pneumatocysts cause plants to float to the surface when dislodged from the substratum. The structure and number of pneumatocysts varies between species. For example species from the genera *Macrocystis*, *Sargassum*, *Ascophyllum*, and *Fucus* have thalli with many small pneumatocysts, while other kelp species such as *Nereocystis luetkeana*, *Pelagophycus porra*, *Ecklonia radiata*, *Ecklonia maxima* have a single, large pneumatocysts (Dayton 1985; Smith 2002; Thiel and Gutow 2005; Graiff et al. 2016; Batista et al. 2018). In some cases the stipe itself is air-filled, such as with *E. maxima* and *E. radiata*. Although there have been reports of floating Chlorophyta species and some Rhodophyta species, Phaeophyceae species are the most commonly reported forms of floating algae. This is most likely because the green and red species reported floating are not actually positively buoyant, but instead are kept at the surface by gas trapped inbetween or in the thalli (Dromgoole 1982; Bäck, Lehvo, and Blomster 2000). The giant kelp *Macrocystis pyrifera* (Helmuth, Veit, and Holberton 1994; Kingsford 1995; Hobday 2000; Macaya et al. 2005; Graiff et al. 2016; Batista et al. 2018) and the bull kelp *Durvillaea antarctica* (Collins et al. 2010; Tala et al. 2013, 2017; Saunders 2014; Smith 2002; Wichmann, Hinojosa, and Thiel 2012; Batista et al. 2018) have been the focus of much of the research regarding spatial and temporal dispersal patterns, the ecological role of rafting, marine connectivity and raft-time.

The raft-time is the amount of time macroalgae floats at the surface before becoming negatively buoyant and begins to sink to the ocean-floor. Raft-time, also referred to as raft longevity, is determined by epibiont load, macroalgal growth rate and the loss of kelp biomass over time through fragmentation. Epibiont load consists of epiphytic and bryozoan species which tend to grow more rapidly in higher light and temperature environments, such as the ocean surface (Thiel and Gutow 2005, 2005; Graiff et al. 2016). The increase in epibiont load reduces the buoyancy of floating macroalgal rafts over time eventually causing them to sink to the seafloor, while also potentially increasing drag (Hobday 2000; Tala et al. 2013; Craw and Waters 2018). Fragmentation of kelp biomass over time may also reduce raft times further, while growth may counteract the effects of epibiont load and fragmentation provided the environmental conditions are favorable (Graiff et al. 2016; Macaya et al. 2016). For instance a study by Rothäusler et al. (2011) investigated the abiotic and biotic factors influencing raft time and dispersal potential of the giant kelp *M. pyrifera* by a combination of tethering experiments and field surveys. The results showed the physiological performance of kelp declined with increasing epiphyte biomass and that higher temperatures increased growth rate of epibionts and fragmentation of kelp. The authors concluded from the results of both the experiments and field surveys that *M. pyrifera* dispersal is dependent on low temperature and moderate irradiance conditions, with high temperatures and higher irradiance reducing overall raft-time and hence dispersal potential (Rothäusler et al. 2011).

Many past authors have also taken various approaches to estimate not only the raft-time of macroalgal rafts but also the oceanographic influencers of macroalgae trajectory. Past research points to macroalgae

trajectory being largely determined by prevailing wind conditions and surface currents (Thiel and Gutow 2005, @thiel2005; Hobday 2000; Fraser, Nikula, and Waters 2011a; Rothäusler et al. 2011, 2011). Although ocean currents are regarded as the primary influencer, the relative importance of wind versus surface current is still not known; although the role of wind has been recognised as important in several studies. For example, a study by Harrold and Lisin (1989) investigated the seasonal trajectories of radio-transmitter tagged *M. pyrifera* in nearshore Monterey Bay. The results showed that kelp rafts with little surface area exposed to the wind were largely driven by a combination of wind and wind waves, however the relative importance of wind and wind waves was not clear. In addition, the tagged kelp trajectories were more consistent with the formation of eddies during winter. Previous studies have identified wind as an important mechanism of dispersal in wind dominated ocean systems. For example the subAntarctic latitudes the West Wind Drift causes continuous unidirectional surface flow and is regarded as an important potential mechanism for dispersal of floating kelp. Other studies have used genetic approaches to determine macroalgae raft trajectory characteristics by inferring source location from genetically similar populations (Nikula, Spencer, and Waters 2013). For example, a study by Fraser, Nikula, and Waters (2011b) on the rafting capabilities of *Durvillaea antarctica* used a combination of population genetics and relative age estimate of ‘goosebarnacles’ attached to the raft. The presence of goosebarnacles suggests a long raft time as these species have a slow growth rate; while the genetic analyses showed these species are able to raft up to ~ 390km from their local origin. The authors suggested that wind and water-movement were the primary influences of trajectory, however, this was only inferred from the genetic results and local climatology data (Fraser, Nikula, and Waters 2011a).

Other aspects such as buoyancy and drag also play a role in determining the trajectory and rate of transport for surface floating material. However, the past research on macroalgal trajectory has not investigated these factors which have been shown to be important aspects of trajectory for other materials such as icebergs, marine craft and microplastics. The “sail” area of an object floating at sea is the surface area exposed to the wind which results in air form drag, while the area of the object below the surface of the water is exposed to surface currents which result in water form drag. Drag coefficients related to wind and surface current have been shown to be important properties to consider when estimating trajectory and forecasting drift for search and sea rescue operations. Drag is ultimately determined by the size and shape of the object which are properties that vary considerably with macroalgae species. In addition, past research conducted within the maritime industry has shown that the size and shape of a vessel determine the relative importance of waves or wind as influencers of trajectory, as well as orientation of the object. If the length of the object is longer than the significant wave height then waves will be the primary influencer of trajectory while the opposite is true for smaller objects where the effect of waves is regarded as negligible (Breivik et al. 2011; Griffin, Oke, and Jones 2017).

Although various approaches have been used in the past to investigate floating macroalgae trajectory, very few studies have employed the use of Lagrangian trajectory modelling. Furthermore, none of the existing studies using this modeling approach have considered macroalgal morphology (i.e. shape) as an influencer on drag and ultimately trajectory. Currently, work by (???) which investigated the effect of inertia and radial size on the trajectory of pelagic *Sargassum* rafts. The study used a custom growth model to estimate changes in biomass and ultimately radial size, while a customised Hybrid Coordinate Ocean Model (HYCOM) for the trajectory simulations was used. The results showed that trajectory of pelagic *Sargassum* was significantly influenced by inertia and the radial size of the rafts. Lagrangian trajectory modeling is a useful tool, however, the various models available often assume the object to be a spherical particle, which is obviously not the case for both biological and anthropogenic forms of marine debris in nature. The radial size included by (???) is an improvement, however this approach does not take into account the complex morphology on an individual level into account.

To accurately determine the trajectory of marine macroalgae these aspects need to be taken into account. Past research by (???) and (???) have provided estimates of drag for various objects based on experimental work, which consisted of both direct and indirect methods of the Leeway model. However, this work does not consider biological material such as macroalgae. Although drag estimates do exist, these have been calculated for macroalgae not detached from the substratum and are regarded as fixed-point estimates. Methods used in the field of chemical engineering provide an alternative approach to estimating drag of macroalgae by means of formulae to calculate drag based on shape. Chemical engineers in the field of fluid dynamics which come across similar problems when including drag use an approach known as a ‘sphericity factor’. A sphericity

factor is the ratio of the surface area of a sphere having the volume as the irregular shaped particle ( $s$ ) to the actual surface area of the particle ( $s_d$ ) such that

$$\psi = s/s_d$$

. The values are dependent on the shape of the object and a range of values have been determined based on numerous experimental work. A table of various shapes and the associated sphericity factor is provided in the appendix.

There are considerable gaps in the literature with regards to macroalgae trajectory such as buoyancy, air form drag, water form drag, epibiont load, growth, fragmentation, size, shape and orientation which have not been investigated numerically in the past. In order to determine the coefficients needed for the transport model, a series of experiments are proposed. These experiments will aim to determine aspects of buoyancy, epiphyte growth rates and transport rate, all of which have been regarded as important coefficients needed for an accurate model. The experiments will be performed numerically to determine the main influencers of passive solitary kelp dispersal.

## Methods

### Model and parameterisation

Numerical calculations of particle trajectory with a Lagrangian method (Delandmeter and Van Sebille 2019), and be described by the equation

$$X(t + \Delta t) = X(t) + \int_t^{t+\Delta t} v(x, \tau) d\tau + \Delta X_b(t)$$

where  $X$  is the three-dimensional position of a particle,  $v(x, t)$  is the three-dimensional velocity field at the location in the ocean model,  $X_b(t)$  is a change in position due to ‘behaviour’ of the particle. This can range from swimming in fish to sinking or beaching.

The model is based on parameterisations that have been used for previous studies investigating iceberg, capsized marine vessels and microplastics. It should be noted that most of the previous studies regarding macroalgae trajectory have investigated rafts and not solitary floating individuals. A kelp raft will vary in size and can range from a few meters across to large dense mats the size of a sports field. Furthermore, some authors suggest that most macroalgae become entangled through ocean currents and not through the hydrodynamic forces that dislodge them. In addition, large kelp rafts are not a characteristics around the coast of the Cape Peninsula but rather solitary kelp are (Pers. Obs). Therefore, the trajectory of solitary *E. maxima* individuals will be considered. Previous studies have made the assumption that kelp rafts move with the same velocity as the ocean current, and instead model an ensemble of particles which trajectories are determined by a combination of ocean currents and/or the effects of winds on currents. In addition, these studies assume the particle is fully buoyant and does not vary with time.

The velocity of the kelp sporophyte is a function of mass and time, as the mass of the individual will vary temporarily with changes in growth rate, erosion and epibiont load (mass), which in turn will effect buoyancy and thereby the surface area exposed to wind drag and seawater drag.

A momentum equation can be used to describe how the mass of the kelp individual changes temporarily. A previous study by Andersson, Scibilia, and Imsland (2017) who used this approach to describe the change in velocity of an iceberg over time which has been adapted to suite the current project; and taking into account the additional parameterisations:

$$m \frac{du_i}{dt} = F_{corr} + F_a + F_c + F_r + F_e$$

where  $m$  is the overall kelp mass,  $u_i$  is the starting kelp velocity,  $d$  is the distance,  $F_{corr}$  is Coriolis Force,  $F_a$  is the air drag force,  $F_c$  is the seawater drag force,  $F_r$  is the effect of waves on the kelp,  $F_e$  is the epibiont load force.

The holdfast, stipe and kelp-head (fronds, primary blade and pneumatocyst) will be the focus of calculating the overall seawater drag force. Past studies refer to the surface area of the object exposed to wind forces as the “sail” area/volume, and the surface area exposed to the waves as the “keel” area/volume. The volume of the objects is required to calculate the seawater drag force and is expressed as,

$$F_c = F_{kelphead} + F_{holdfast} + F_{stipekeel}$$

where  $F_c$  is overall seawater drag force,  $F_{kelphead}$  is the estimated drag coefficient for the top portion of the plant (fronds, primary blade, pneumatocyst),  $V_{holdfast}$  is the estimated drag coefficient for the holdfast,  $V_{stipekeel}$  is the estimated drag coefficient for the volume of the stipe submerged. The assumption made is that the kelp-head and holdfast will not change in volume while floating and that the entire holdfast will be submerged. Provided the exposed volume of the kelp exposed to the air is known the submerged portion  $V_{stipekeel}$  and overall mass can be calculated based on Archimedes law (Andersson, Scibilia, and Imsland 2017):

$$V_{stipekeel} = V_{stipesail} \frac{p_{ice}}{p_w - p_{ice}}$$

and so,

$$m = (V_{stipesail} + V_{stipekeel})p_{ice} = (1 + \frac{p_w}{p_w - p_{ice}})V_{stipesail}p_{ice}$$

To calculate the volume of the stipe a idealised cylindrical form is used with height being substituted for height such that:

$$V = \pi r^2 l$$

## Results

## Discussion

## Appendix

Insert table of sphericity factors.

Andersson, L E, F Scibilia, and L Imsland. 2017. “A study on an iceberg drift trajectory.” In *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*. Vol. 8. <https://doi.org/10.1115/OMAE2017-62159>.

Batista, M B, A B Anderson, P F Sanches, P S Polito, T C L Silveira, G M Velez-Rubio, F Scarabino, et al. 2018. “Kelps’ long-distance dispersal: Role of Ecological/Oceanographic processes and implications to marine forest conservation.” *Diversity* 10 (1). <https://doi.org/10.3390/d10010011>.

Bäck, Saara, Annamajja Lehvo, and Jaanika Blomster. 2000. “Mass Occurrence of Unattached Enteromorpha Intestinalis on the Finnish Baltic Sea Coast,” 155–61.

Breivik, Øyvind, Arthur A Allen, Christophe Maisondieu, and Jens Christian Roth. 2011. “Wind-Induced Drift of Objects at Sea: The Leeway Field Method.” *Applied Ocean Research* 33 (2): 100–109.

Bushing, William W. 1994. “Biogeographic and Ecological Implications of Kelp Rafting as a Dispersal Vector for Marine Invertebrates” 22.

Collins, C J, C I Fraser, A Ashcroft, and J M Waters. 2010. “Asymmetric dispersal of southern bull-kelp (*Durvillaea antarctica*) adults in coastal New Zealand: testing an oceanographic hypothesis.” *Mol. Ecol.* 19 (20): 4572–80.

- Craw, D, and J Waters. 2018. “Long distance kelp-rafting of rocks around southern New Zealand.” *N.Z. J. Geol. Geophys.* 61 (4): 428–43.
- Dayton, P K. 1985. “Ecology of Kelp Communities.” *Annual Review of Ecology and Systematics* 16 (1): 215–45. <https://doi.org/10.1146/annurev.es.16.110185.001243>.
- Delandmeter, Philippe, and Erik Van Sebille. 2019. “The Parcels V2. 0 Lagrangian Framework: New Field Interpolation Schemes.” *Geoscientific Model Development* 12 (8): 3571–84.
- Dromgoole, FI. 1982. “The Buoyant Properties of Codium.” *Botanica Marina* 25 (8): 391–98.
- Edgar, GJ. 1987. “Dispersal of Faunal and Floral Propagules Associated with Drifting *Macrocystis Pyrifera* Plants.” *Marine Biology* 95 (4): 599–610.
- Fraser, C I, R Nikula, and J M Waters. 2011a. “Oceanic rafting by a coastal community.” *Proc. Biol. Sci.* 278 (1706): 649–55. <https://doi.org/10.1098/rspb.2010.1117>.
- . 2011b. “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.
- 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 bi-valve (*Gaimardia trapesina*) by kelp-rafting.” *Marine Biology* 120 (3): 421–26. <https://doi.org/10.1007/BF00680216>.
- Hobday, A J. 2000. “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. [https://doi.org/10.1016/S0022-0981\(00\)00255-0](https://doi.org/10.1016/S0022-0981(00)00255-0).
- Holmquist, JG. 1994. “Benthic Macroalgae as a Dispersal Mechanism for Fauna: Influence of a Marine Tumbleweed.” *Journal of Experimental Marine Biology and Ecology* 180 (2): 235–51.
- Kingsford, Michael J. 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.
- 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.
- McCormick, Thomas B, Lorraine M Buckley, Jennifer Brogan, and Lyn M Perry. 2008. “Drift Macroalgae as a Potential Dispersal Mechanism for the White Abalone *Haliotis Sorenseni*.” *Marine Ecology Progress Series* 362: 225–32.
- Nikula, Spencer, and Waters. 2013. “Passive rafting is a powerful driver of transoceanic gene flow.” *Biology Letters* 9 (1): 20120821. <https://doi.org/10.1098/rsbl.2012.0821>.
- Norton, TA. 1992. “Dispersal by Macroalgae.” *British Phycological Journal* 27 (3): 293–301.
- Rothä usler, Eva, Iván Gómez, Iván A Hinojosa, Ulf Karsten, Leonardo Miranda, Fadia Tala, and Martin Thiel. 2011. “Kelp Rafts in the Humboldt Current: Interplay of Abiotic and Biotic Factors Limit Their Floating Persistence and Dispersal Potential.” *Limnology and Oceanography* 56 (5): 1751–63.

- Saunders, G W. 2014. “Long distance kelp rafting impacts seaweed biogeography in the Northeast Pacific: The kelp conveyor hypothesis.” *Journal of Phycology* 50 (6): 968–74. <https://doi.org/10.1111/jpy.12237>.
- Smith, S D A. 2002. “Kelp rafts in the Southern Ocean.” *Global Ecology and Biogeography: A Journal of Macroecology* 11 (1): 67–69. <https://doi.org/10.1046/j.1466-822X.2001.00259.x>.
- Tala, F, I Gómez, G Luna-Jorquera, and M Thiel. 2013. “Morphological, physiological and reproductive conditions of rafting bull kelp (*Durvillaea antarctica*) in northern-central Chile (30°S).” *Marine Biology* 160 (6): 1339–51. <https://doi.org/10.1007/s00227-013-2186-8>.
- Tala, F, M A Penna-Díaz, G Luna-Jorquera, E Rothäusler, and M Thiel. 2017. “Daily and seasonal changes of photobiological responses in floating bull kelp *Durvillaea antarctica* (Chamisso) Hariot (Fucales: Phaeophyceae).” *Phycologia* 56 (3): 271–83.
- Thiel, M, and L Gutow. 2005. “The Ecology of rafting in the marine environment. II. The rafting organisms and community.” *Oceanography and Marine Biology: An Annual Review* 43 (1): 279–418.
- Wichmann, C-S, I A Hinojosa, and M Thiel. 2012. “Floating kelps in Patagonian Fjords: an important vehicle for rafting invertebrates and its relevance for biogeography.” *Mar. Biol.* 159 (9): 2035–49. <https://doi.org/10.1007/s00227-012-1990-x>.