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Giant kelp rafts wash ashore 450 km from the nearest populations and against the dominant ocean current

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On 9 August 2020, two local marine naturalists (authors W. Marshall-Grey and J. Rankin) on the south coast of New South Wales, Australia noticed a significant amount of a large unfamiliar kelp washed up on a local beach. A browse through Graham Edgar's iconic marine guidebook for temperate Australia (Edgar, 2012), followed by some quick confirmations via phone and email, revealed that the unfamiliar seaweed was giant kelp (*Macrocystis pyrifera*, Figure 1): a species whose closest known populations are >450 km away to the south (in

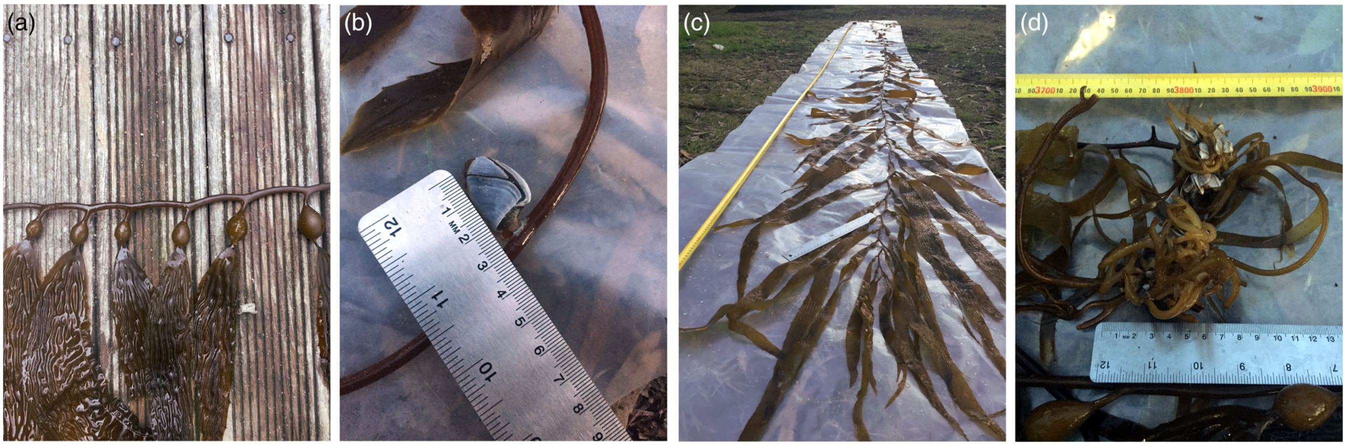

FIGURE 1 Giant kelp (*Macrocystis pyrifera*) and attached goose barnacles (*Lepas australis*) washed ashore in southern New South Wales, Australia: (a) one of the first giant kelp samples that was collected on 9 August and used to confirm the species' identification; (b) a large goose barnacle that had recruited to the floating kelp; (c) one of the largest whole kelp washed ashore and (d) with its holdfast still intact. Photos by W. Marshall-Grey and J. Rankin.

Tasmania and western Victoria) and whose transport to New South Wales would have required oceanic rafting over several weeks and hundreds of kilometers against the prevailing south-flowing East Australian Current (Figure 2). Subsequent community-led searches over the following days confirmed four more locations of often-substantial amounts of giant kelp wrack, as well as many more anecdotal and unconfirmed accounts.

The first observations were at Aslings Beach, Eden (37.048° S, 149.920° E) on 9 August where a few dozen piles of "fresh" giant kelp had washed ashore. These comprised whole individual giant kelp several meters in length with their holdfasts still intact (Figure 1), but also large fragments without holdfasts. Organized surveys on 11 August at the same location found ~20 large piles of giant kelp ~0.7 × 0.4 m (diameter × height) in size, along with some piles closer to ~1 × 1 m. Haphazard sampling revealed larger fragments and whole kelp of an average length of 1.6 ± 0.7 m (mean ± SD, $n = 12$). Surveys on the same day at Main Beach, Merimbula (36.896° S, 149.917° E) recorded over 70 similar-sized piles of giant kelp and an average kelp length of 3.9 ± 1.6 m (mean ± SD, $n = 25$) (Figure 1). Numerous piles and large individuals were also confirmed from Pambula (36.946° S, 149.915° E) on 13 August. While the last confirmed sightings were from 14 August when several large fresh fragments (~1–3 m length) were found entangled around commercial oyster racks within the estuarine confines of Nelson Lagoon (36.680° S, 149.984° E). Subsequent searches over the following days found only small, desiccated, and decaying piles of giant kelp. Presumably the larger piles had begun to decompose and been buried and/or washed back to sea (Griffiths et al., 1983).

Rudimentary estimates (i.e., 110 piles of 0.112 m^3 volume) suggest that >10 m^3 (or >8000 kg wet mass, conservatively estimating that kelp density is 80% that of water), of giant kelp washed ashore along this 40-km stretch of coastline over this short period. Consistent across the observations and photos were that the giant kelp looked "fresh" and healthy with limited necrosis or dead tissue, and with intact floats or "pneumatocysts."

Also growing on many of the kelp were goose-barnacles (Figure 1b,d). These are pelagic crustaceans that only recruit onto floating objects at sea (Mesaglio et al., 2021; Skerman, 1958), and to our knowledge have not been recorded growing on attached giant kelp. Identified as southern goose-barnacles (*Lepas australis*), there were more than a dozen on each individual kelp that was inspected during the first collection effort, the largest of which had capitulum (i.e., shell) lengths of ~20 mm. Using known growth rates for *L. australis* (0.46 mm/day, Skerman, 1958), we estimated the age of these large barnacles (and thus a minimum drifting time of the kelp rafts) of 43 days (also see Fraser et al., 2010; Mesaglio et al., 2021).

The dominant oceanographic feature along Australia's east coast is the poleward-flowing East Australian Current and its extension (Figure 2a). This complex and energetic boundary current transports warm, nutrient-poor waters southward from tropical latitudes until north of Sydney, Australia, where the flow mostly separates eastward towards New Zealand, but also extends southward as a system of large eddies (Oke et al., 2019, see Figure 2a). These "mesoscale" eddies in the southern extension, akin to oceanographic whirlpools 10–100 km across, transport East Australia Current water and heat all the way south to Tasmania (Figure 2a). Climate change projections suggest eddy activity in the southern extension will increase

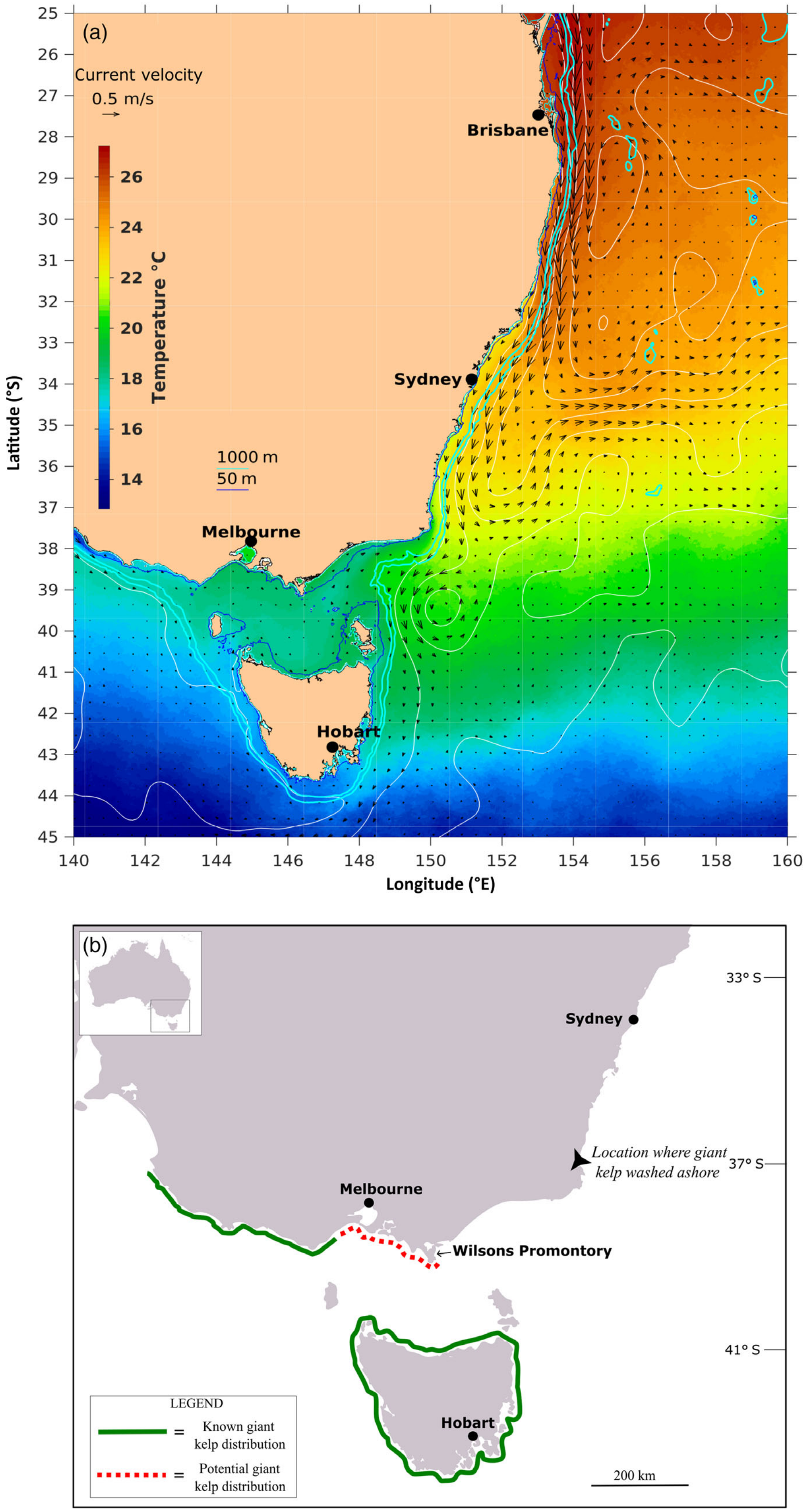

FIGURE 2 (a) Map of sea surface temperature showing the warm south-flowing East Australian Current (currents denoted by black arrows), the east-flowing primary current (at approximately 34° S), and the continuing southern extension towards Tasmania (note the large eddy at 39°–40° S); and (b) southeast Australia showing where the giant kelp was found washed ashore (the starred marker), along with the approximate known (green line) and potential (red line) distributions of giant kelp in Australia.

through the 21st century, and in fact, the increasing presence of these warm, nutrient-poor waters off eastern Tasmania have already been associated with ~95% declines in giant kelp forest cover since the 1950s (Butler et al., 2020; Johnson et al., 2011). These giant kelp forests are now nationally recognized as an endangered marine community and are the focus of habitat restoration efforts (Layton & Johnson, 2021).

The closest known giant kelp populations to southern New South Wales occur across the north/northeast coast of Tasmania (approximately 40.78° S, 148.25° E), some 450 km away (Figure 2b). More distant populations (>550–700 km) occur further south along the Tasmanian coast (approximately 43.21° S, 148.03° E), but also on the mainland of Australia in western Victoria (approximately 38.66° S, 142.99° E) (Figure 2b). Closer still is Wilsons Promontory (39.00° S, 146.37° E), a large peninsula and biogeographic feature in eastern Victoria (Figure 2b), which is only ~400 km away and the site of anecdotal (but conflicting) reports of giant kelp in the recent past.

Based on these, we hypothesized several potential points of origin of the giant kelp that washed ashore in southern New South Wales. A subsequent assessment of regional oceanographic conditions over the ~43-days prior to the first sightings (i.e. the period of time derived from the barnacle growth rates) revealed several atypical processes that together may have enabled the extensive northward transport of the floating rafts of kelp.

Winter storms are a common occurrence in southeast Australia and can often remove extensive areas of kelp from rocky reefs. Two particularly strong storm fronts moved through Tasmania/Victoria in early May and early July 2020 and could have been responsible for the initial dislodgment of the giant kelp from the reef. From the end of June until 9 August, there were weak northerly surface currents that extended from north/northeast Tasmania across Bass Strait and towards eastern Victoria, where they met strong northeasterly coastal currents that extended all the way to Eden, New South Wales (OceanCurrent, 2020).

To examine the potential of these currents to transport floating kelp rafts over several weeks and hundreds of kilometers, we conducted surface-particle drift simulations (Figure 3) using OceanMaps and surface current maps and data (OceanCurrent, 2020) covering the period 26 June–8 August. OceanMaps is an ensemble ocean analysis and forecasting system and incorporates ocean currents and wind information, but not tidal data (Huang et al., 2020; Appendix S1). We released simulated particles across the region of kelp sightings on the New South Wales coast, and then "back-tracked" them using surface current velocities and wind data for the preceding 43 days, following the method of Griffin et al. (2001). Noting that 43 days is the minimum drifting time of the kelp rafts, the simulations confirmed that possible regions of origin could have been northern Tasmania (i.e., which have the nearest known populations of giant kelp), Wilsons Promontory, or somewhere along the pathway of the simulated particles. Based on a general trajectory from northern Tasmanian to southern New South Wales, the maximum putative distance covered by the kelp rafts was ~600 km, which over 43 days equates to a drift speed of ~0.16 m/s. This is similar to other drift speed estimates for floating kelp rafts (~0.20 m/s, Fraser et al., 2010).

Four kelp samples were also collected for genetic analyses: unfortunately, only one yielded sufficient DNA for analysis. Based on population genetic analyses, that sample showed greatest similarity to other tested giant kelp populations from northeast Tasmania, relative to populations from western Victoria and southern Tasmania (M. Velasquez, C. Layton, C. R. Johnson, C. I. Fraser, et al., *unpublished manuscript*).

It appears these giant kelp rafts may have been transported as part of northward winter flows nearshore of the dominant south-flowing East Australian Current eddies (Baines & Murray, 1995). But regardless of the region of origin, the presence of this species in such substantial quantities, hundreds of kilometers out of range, and after moving so far northward against the dominant southward flow of the East Australian Current, is undoubtedly an unusual phenomenon. Critically, this observation would most likely have been left unappreciated if not for the knowledge and curiosity of two keen-eyed local naturalists, and subsequent enthusiasm from other local citizen scientists.

Passive rafting events, especially into out-of-range or novel regions, have long been considered a critical biological process shaping the dispersal and distribution of organisms, even those that typically have relatively short dispersal distances (such as kelps). Nonetheless, direct observations of such events are relatively rare, and such incidental observations can be highly valuable at illuminating environmental and oceanographic processes that are often still a mystery (e.g., Boxall, 2009). In this case, these observations enhance our understanding of dispersal and connectivity of habitat-forming kelps and their associated taxa, even against prevailing conditions (e.g., Fraser et al., 2010). The long-distance transport of such a substantial quantity of kelp biomass also generates intriguing questions around the export of subsidies from highly productive kelp forests to other marine environments (Griffiths et al., 1983; Smale et al., 2018), and the topical but still unclear role of kelp forests in carbon export and sequestration (Gallagher et al., 2022; Smale et al., 2018).

Ultimately, while the dominant ocean current in this region is south flowing, there are finer nearshore processes that can facilitate northward flows, and which in some circumstances can be exceptional and allow

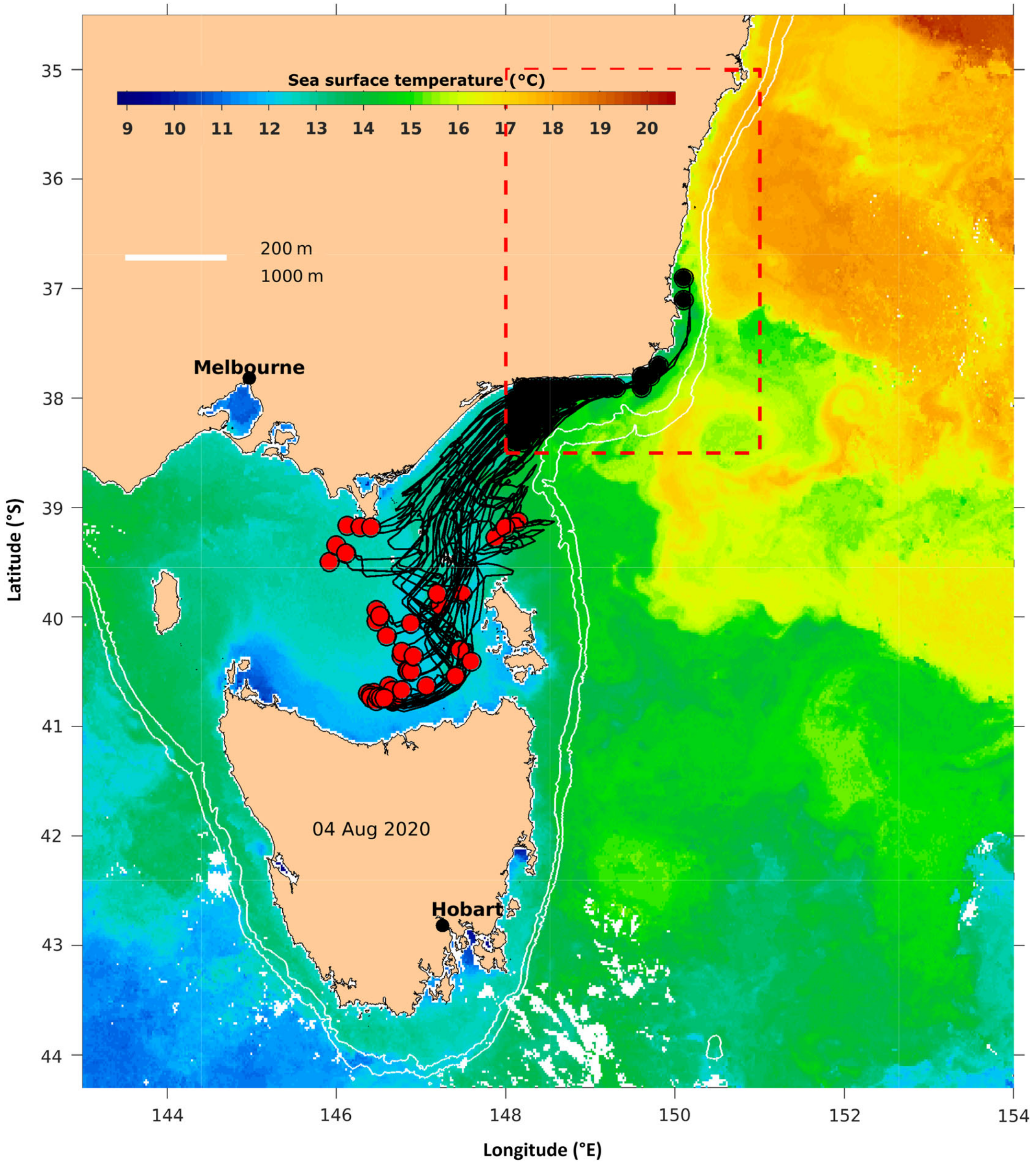

FIGURE 3 Surface-particle drift simulations, showing trajectory (black lines) of particles released across the region of kelp sighting (black dots) and their simulated points of origin from 43 days earlier (red dots). Colors are a mean composite of remotely sensed sea surface temperature in a 6-day window centered on 4 August 2020 (IMOS, 2021). Both the 200- and 1000-m depth contours are marked with white lines.

for significant northward movement. So, although these processes are known, their capacity for such significant northward transport often remains unappreciated in the absence of such events as we have described here.

AUTHOR CONTRIBUTIONS

Cayne Layton conceived and coordinated this work and led production of the manuscript; Harrison Vermont, Ashley D. Burke, Libby Hepburn, William Marshall-Grey, and Jayde Rankin coordinated and conducted the on-ground observations and collections; Helen Beggs, Gary B. Brassington, Neil Holbrook, and Gabriela Semolini Pilo conducted the oceanographic analyses and simulations; Thomas Mesaglio provided expert-knowledge and analyses of the barnacles; Elahe Parvizi and Marcel Velásquez conducted the genetic analyses; all authors contributed to revision and editing of the manuscript.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Layton et al., 2022) are available at Temperate Reef Base. The data associated with OceanCurrent (2020) is available at "Ocean current observations 28 June–15 August. Integrated Marine Observing System" (http://oceancurrent.imos.org.au/product.php?product=daily&region=SE&date=20200808120000&rtype=SR&movie=1).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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