2016 Heard Island Expedition Project Description

Definition

TITLE

RAFTING FROM SOUTH GEORGIA/SOUTH SANDWICH ISLANDS AS AN IMMIGRATION PATHWAY TO HEARD ISLAND

Abstract

The possible pathway for immigration to Heard Island by rafting from South Georgia and the South Sandwich Islands will be investigated. Potential rafting objects, especially floating kelp, wood, and non-biological debris, will be collected, documented, and examined to determine whether they appear to involve rafting. The project is stimulated by model calculations of the direct wind- and current-driven link between South Georgia and Heard Island.

Principal Investigator	Robert W. Schmieder	Cordell Expeditions
Co-Investigator	Erik van Sebille	Imperial College London
Co-Investigators	Onsite team members	Cordell Expeditions

Context

Background

Floating objects provide potential rafting for organisms over great oceanic distances. The ubiquity and stability of plastic could provide very effective rafts for many organisms, particularly plant propagules and microscopic embryos or even adult animals. It is obvious that certain natural biological materials (seaweeds, logs, leaves, fur, feathers, etc.) could also provide rafts, hence be significant vectors for immigration.

While some of these rafts are clearly anthropogenic, others just as clearly are of completely natural origin. Whether plastic rafts and natural materials resulting from terrestrial outfall (e.g., construction projects) should be considered anthropogenic or natural dispersion may be a matter of semantic convenience; what is important is the flux of biological materials to Heard Island. Because wind-driven rafting of floating debris is a worldwide concern, we are interested in its importance to Heard Island, regardless of the exact nature of the rafts.

Durvillaea antarctica [Photo R. W. Schmieder, Heard Island 1997]

Among the best candidates for rafting is the large resident kelp *Durvillaea antarctica*, shown in the photo at left. Edgar and Burton (2000) describe experiments with shallow-water macrofauna at Heard Island. These authors set up anchored stands of *D. Antarctica* in two locations (Atlas Cove and Corinthian Bay) and monitored the populations of about 40 species of invertebrates found on Heard Island. Pointing out the proximity of Kerguelen and the similar oceanic conditions to Macquarie Islands, the authors concluded that geographic position is much more important in dispersal than contemporary conditions. That is, dispersal mechanics dominates immigration.

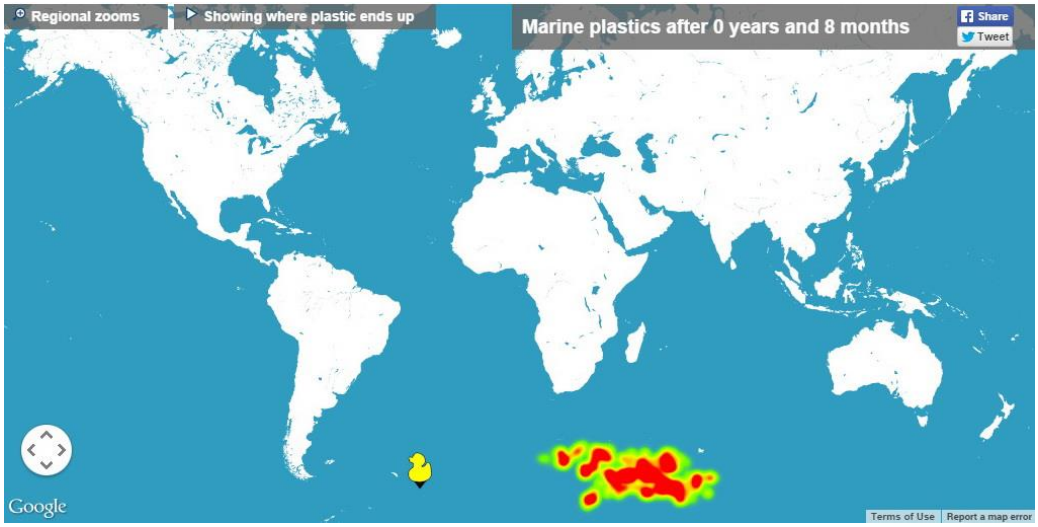
In considering the Edgar-Burton experiment, we find it a bit unconvincing that recruitment to tethered stands could appropriately represent the survivability of species rafting to Heard Island. While the nearness of Kerguelen and the strong overlap of the species list is convincing that exchange between these islands is efficient, the short distance argues that storm-driven rafting on the more common *Macrocystis pyrifera* (not found at Heard Island), with the subsequent destruction of the raft is efficient. This scenario makes use of the 10x more common raft alga from Kerguelen, and invoking the less-common *D. Antarctica* unnecessary.

In view of this uncertainty, we have considered another immigration pathway, namely rafting from South Georgia. Here, the mechanism is supported by the constant east wind and current, in contrast to the infrequent and undirected (on average) pathway from Kerguelen to Heard Island. In other words, a constant release of loaded rafts from South Georgia and South Sandwich Islands, followed by their rather direct transport to Heard Island, could be a significant alternative pathway. Because the species diversity at SGI and SSI are different from that of Kerguelen, it could alter the diversity at HI. We describe this mechanism now.

One of the principal authors (Sebille) has developed a Lagrangian simulation of dispersion of plastic (or any similar) debris from any point in the ocean. The simulation (adrift.org.au) enables the user to select any point on the world map to inject floating debris. The simulation then computes the drift of the material forward in time, up to 10 years. Other researchers have developed similar tools for tracking the movement of plastic debris in the ocean, for instance, Maes and Blanke (2015).

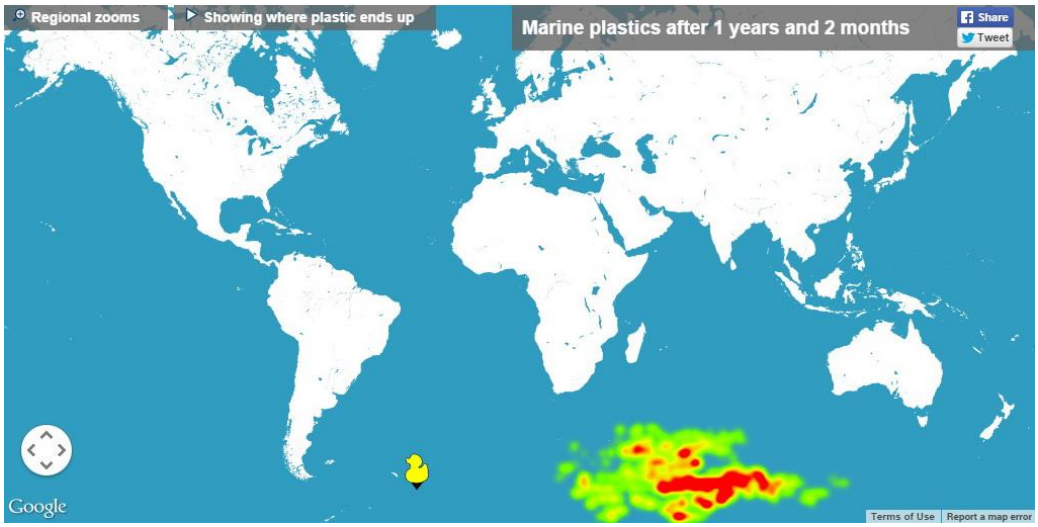
We have used this tool to investigate potential pathways of rafting to Heard Island. We find that the circumpolar current effectively shields the Southern Ocean from rafts originating from north of the Antarctic Convergence. Essentially, the current deflects the rafts, and the only polar flux is due to the relatively slow transverse mixing, or more probably, exceptional weather/current events (e.g., Kerguelen). There is one exception to this shielding: the islands of South Georgia and South Sandwich lie at about the same latitude as Heard Island, and to the west. This puts them on a direct wind and current connection to the latter.

The following two images are screen-captures from the Adrift simulation. The duck icon represents the point at which the simulation injected the rafts. The first images shows that after 8 months the debris is spread out over a 1000 NM irregular swatch just arriving at Heard Island.



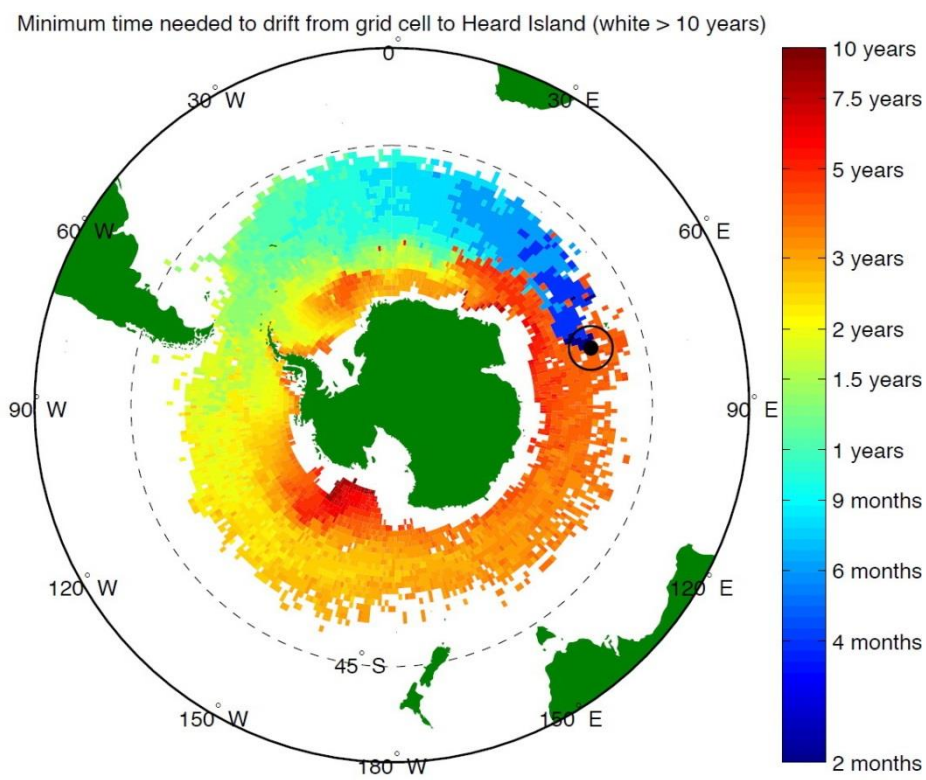
Predicted distribution of rafts 8 months after release at South Georgia Island. The leading edge of the distribution is just approaching Heard Island.

The next image shows that after 1 year 2 months the distribution is even more spread out, and is centered on Heard Island. It is significant that the highest density is exactly at the latitude of Heard Island. The raft assembly moves at about 3 NM/day, or about 100 NM/month.



Predicted distribution of rafts 1 year 2 months after release at South Georgia Island. The distribution is essentially centered on Heard Island, with the great majority of density in a long path that directly traverses the island.

The Adrift simulation also provides maps of drift times for arrival at Heard Island. The following chart shows a color-coded image of the drift times required for rafts to arrive at Heard Island. For instance, South Georgia and South Sandwich islands lie in the region colored light blue-green, which is the code color for about 1 year of drift time. Closer to Heard Island (to the west), the drift times are much shorter (dark blue), but there are of course no obvious sources of rafts (except for possible events such as a shipping disaster). The relatively uniform red-orange area south of Heard Island has drift times of ten years or more.



Thus it is clear that with further increase in time, the distribution continues to move clockwise (seen from above) around Antarctica, and will continue to diffuse both laterally and longitudinally. Eventually it returns, in principal, to Heard Island, but by that time it is so diffuse that we can safely neglect it. Besides, the rafters would not be survivors from the original launch, but rather hitchhikers, a very unlikely occurrence. Thus, we feel that this mechanism would only work for the proposed transfer directly from SGI and SSI to HI.

Other than anthropocentric debris from SGI and SSI (which we expect to be very small), are there sources of rafting materials there? In fact, South Georgia is well-known for its extensive stands of kelp. For instance, Kelp Bay (54°27'S 36°7'W) is a small open bay close east-southeast of Doris Bay on the north coast of South Georgia. It is filled with kelp and there is no anchorage [Wikipedia]. Here is a photo of Hercules Bay, SGI:

Kelp stand on South Georgia Island [Source: AllPosters.com].

A species list of seaweed of South Georgia is available in the report of Wells, et al. (2011). Comparing it with the list for Heard Island (Woehler and Green, 2006). Out of 12 species of vascular plants on Heard Island, four are also known from South Georgia:

- ✓ *Deschampsia antarctica*
- ✓ *Poa annua*
- ✓ *Montia fontana*
- ✓ *Acana magellanica*

Of these, *Poa annua*, is considered potentially an alien introduced by humans. Given its abundance on South Georgia, it is possible introduction from natural distribution may have some merit.

Motivation and goals

The relatively robust prediction that South Georgia could be a source of rafting materials at Heard Island provides rather strong motivation to attempt to document this pathway. The primary goal is to identify objects carrying propagules that apparently have rafted to Heard Island from *any* source, and to identify the source. If a rafting species is found that is endemic to SGI or SSI, it will provide evidence that this pathway is viable. Correlation with the biodiversity of South Georgia could provide supportive evidence for this pathway.

Description

Onsite

Equipment	Camera, GPS, clean containers, digital microscope
Location(s)	Beaches, open windblown areas, rocky catchments for floating materials. There is a preference for fresh, live rafts, but all anthropocentric debris will also be collected.
Procedure	The onsite work will consist mainly walking the intertidal zones to locate, document, and collect items that are obviously (or suspected) not part of the natural environment of Heard Island. All members of the team will be trained to recognize, document, and collect such items. Of greatest interest will be objects with attached biota that appears likely to be alien to Heard Island. Likewise, items that are porous, cracked, vesicular, or are conglomerates will be particularly important as potentially supporting rafting species.

Records

Photo-documentation	Each item will be documented by GPS location, photographs of the local environment, and a close-up image of the item as found. Selected objects will be examined in the digital microscope, and images uploaded to colleagues who might be able to guide further collections based on these images. Selected specimens will be fixed and returned for detailed laboratory analysis and identification.
Logging	The individual collectors will document the locations, procedure, and specimens in their individual logs. These logs will be combined at the conclusion of the visit.
Nonliving specimens	Any foreign non-biological item and any biological item that may be recognizable as foreign will be documented and collected.
Live specimens	A selection of collected items will be conserved in plastic or glass containers (jars, Ziploc bags, etc.) and kept cold. Onboard ship the containers will be kept at low temperature to prevent chemical change. These specimens will be transferred to live labs for processing, including molecular affinity determinations.

Post-expedition procedure

Destination(s) of records	Cordell Expeditions will retain custody of the logs and specimens. Items likely to carry plants will be transferred to the University of California, Berkeley for culture and identification. Items likely to carry invertebrates will be transferred to the Los Angeles Museum of Natural History. Other collaborators are at the California Academy of Sciences, the National Museum of Natural History, and numerous other biological faculties and laboratories that have been previous collaborators with Cordell Expeditions.
Processing of records	Culturing of the collected items, with identification of recognizable species as they emerge.
Publication(s) expected	Paper in the Heard Island monograph. Journal articles as appropriate.
Definition of success	Identification of any species that has likely affinity with a parent population on South Georgia.

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Supplementary material

Suppl. 1 – South Georgia and South Sandwich Islands

Synopsis of the ecosystems of South Georgia and South Sandwich Island

South Georgia and the South Sandwich Islands (SGSSI) are a British overseas territory in the southern Atlantic Ocean. It is a remote and inhospitable collection of islands, consisting of South Georgia and a chain of smaller islands known as the South Sandwich Islands. South Georgia is 167.4 kilometres (104 mi) long and 1.4 to 37 km (0.9 to 23.0 miles) wide and is by far the largest island in the territory. The South Sandwich Islands lie about 520 kilometres (320 mi) southeast of South Georgia. The total land area of the territory is 3,903 square kilometres (1,507 sq mi).

There is no native population on the islands; the present inhabitants are the British Government Officer, Deputy Postmaster, scientists, and support staff from the British Antarctic Survey who maintain scientific bases at Bird Island and at the capital, King Edward Point, as well as museum staff at nearby Grytviken.

Plants

The parts of the islands that are not permanently covered in snow or ice are part of the Scotia Sea Islands tundra ecoregion. Native vegetation on South Georgia is limited to grasses, a few other small flowering plants, mosses, lichens and ferns. A number of introduced species have become naturalised; many of these were introduced by whalers in cattle fodder, and some are considered invasive. There are no trees or shrubs.

Birds

South Georgia supports many sea birds, including albatross, a large colony of King Penguins and penguins of various other species, along with petrels, prions, shags, skuas, gulls and terns. Birds unique to the archipelago are the South Georgia Shag, South Georgia Pipit, and the South Georgia Pintail. Both South Georgia and the South Sandwich Islands have been identified as Important Bird Areas (IBA) by BirdLife International.

Mammals

Seals frequent the islands, and whales may be seen in the surrounding waters. There are no native land mammals, though reindeer, brown rats and mice have been introduced through the activities of man. The rats, being brought to the island as stowaways on sealing and whaling ships in the late 18th century, have destroyed tens of millions of ground-nesting birds' eggs and chicks, and scientists plan to eradicate them over four years starting 2011. It will be by far the largest rodent eradication attempt in the world to date. The project is being led by zoologist Anthony Martin of The University of Dundee who states, "This is a man induced problem and it's about time that man put right earlier errors." In July 2013, the success of the main phase of the extermination of the rats, which took place in May that year, was announced. 180 tonnes of rat poison, brodifacoum, has been dropped over 70% of the island, in what was the world's largest ever operation of this kind. The island is currently separated by glaciers, but as the climate warms the island's natural glaciers are slowly melting. As this continues, there will no longer be a natural barrier preventing the rats from spreading. 100% eradication is hoped to be achieved by 2015.

Reindeer were introduced to South Georgia in 1911 by Norwegian whalers for meat and for sport hunting. In February 2011, the authorities announced that due to the reindeer's detrimental effect on native species and the threat of their spreading to presently pristine areas, a complete cull would take place, leading to the eradication of reindeer

from the island. The eradication began in 2013 with 3,500 Reindeer killed, and nearly all the rest were killed in early 2014. Eight stragglers have been seen since and will be dealt with in 2014/15 summer.

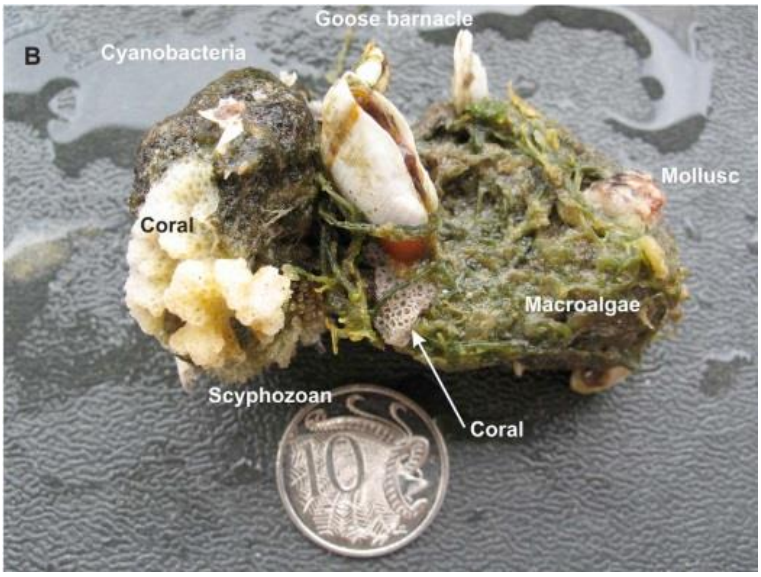
Marine ecosystem

The seas around South Georgia have a high level of biodiversity. In a recent study (2009–2011), South Georgia has been discovered to contain one of the highest levels of biodiversity among all the ecosystems on Earth. In respect to species, marine inhabitants endemic to this ecosystem outnumber and (in respect to biodiversity) surpass well-known regions such as the Galápagos or Ecuador. The marine ecosystem is thought to be vulnerable because its low temperatures mean that it can repair itself only very slowly. On 23 February 2012, in order to protect marine biodiversity, the territory's government created the world's largest protected area – the South Georgia and the South Sandwich Islands Marine Protection Area – comprising 1.07 million km^2.

[Source: Wikipedia]

Suppl. 2 - Other kinds of rafts

The photo below shows another kind of raft, a conglomerate formed of sponges, algae, and barnacles.



Two pieces of pumice bound together by Cyanobacteria (photosynthetic filament-forming Bacteria, principally *Rivularia* sp.) and Macroalgae (Seaweed, Caulerpasp.) collected from Broadbeach in southeastern Queensland on 27 December 2007. Also present are two Cauliflower Corals (*Pocillopora* sp.), a Colonial Scyphozoan (Order Coronatae, the benthic larval stage of a Crown Jellyfish), Goose Barnacles (*Lepas anserifera*) and a Pearl Oyster (*Pinctada* sp.) Bryan et al. (2012).

[Source: http://sciencythoughts.blogspot.com/2012/08/the-biology-of-pumice-rafts.html]

Evaluation

HIMI Management Plan

The present project is sanctioned by Items **A3** and **C1** of **Table 2, Section 5.5** of the Heard Island and McDonald Islands Marine Reserve Management Plan 2014-2024, *viz.*:

> A3) Surveys to determine the presence and extent of possible non-native species
>
> C1) Identification of introduction pathways for non-native species and associated potential consequences.

Section 5.5 of the HIMI Management Plan provides the following:

> Research within the Reserve is required for the integrated and ecologically sustainable management of the broader HIMI region. … Scientifically robust evidence is needed to make effective conservation management decisions. … Research and monitoring activities must be undertaken in accordance with the research and monitoring priorities identified in Table 2 and the Australian Antarctic Science Strategic Plan. … Research also facilitates the fulfilment of public reporting requirements.

In combination with the remarks about Table 2 (above), we interpret this statement to mean that the research described in this document is consistent with the AAD mission for management of the HIMI. We also note that all authorities and functions provided in the EPBC and the EPMO quoted in the HIMI Management Plan have been given to the Director of the AAD, hence are covered in the permit requested from the AAD by Cordell Expeditions.

The HIMI Management Plan further provides

> … the policies … require … that: any biological resources taken are not intended to be used for commercial purposes; … that samples will not be given to other people … without permission … [Parts of this excerpt are omitted solely for space requirements in this document, and are not meant to be omitted in the agreement.]

We do affirm that this project has no commercial interest or activity, and that Cordell Expeditions guarantees conformance with the above statement, both in words and meaning.

Priority

Given the direct match with one of the Reserve Monitoring and Research Priorities (C1), this project ranks near the top priority for the 2016 Expedition.

Importance of specimens

The project is predicated on obtaining specimens that have, or are likely to have, rafted from South Georgia. It is unlikely that such specimens, and possible current rafters, will be recognized immediately onsite. Rather, the strategy is to collect objects that could support or harbor rafting species, and process them to provide clear identifications. Clearly, the collection, conservation, and analysis of such specimens is essential to this work.

Risks

There are no inherent risks in the work of this project, other than the risks associated with human access to the collection sites.

DR. ERIK VAN SEBILLE

Faculty of Natural Sciences, The Grantham Institute for Climate Change

Erik is an oceanographer and climate scientist, investigating the time scales and pathways of the global ocean circulation. His research focuses on how currents and eddies in the ocean transport heat and nutrients, as well as marine organisms and plastics between different regions of the ocean.

Erik received his PhD in physical oceanography in 2009 from Utrecht University in the Netherlands. He worked in Europe, the USA, Australia and now the United Kingdom. He authored more than 50 peer-reviewed articles on ocean circulation in journals including Science, Nature Communications, PNAS, Global Change Biology and Proceedings of the Royal Society B.

Erik currently holds a lectureship jointly between Imperial's Grantham Institute and Department of Physics. He is also an Associate Investigator of the Australian Research Council (ARC) Centre of Excellence for Climate System Science.

Erik is the winner of the 2016 European Geosciences Union (EGU) Ocean Division Outstanding Young Scientist Award. In 2013, Erik was awarded a Discovery Early Career Researcher Award (DECRA) by the Australian Research Council.

Erik is a strong science communicator, with appearances on international television, radio and newspapers. He was a Media Fellow with the Australian Government Climate Commission and has co-hosted a section on sea level rise in Tuvalu in the international documentary series Tipping Points. He is a sought-after international expert on oceanography, having done over 200 interviews with media outlets including CCN, BBC, NBC, ABC, New York Times, Wall Street Journal, Guardian, TIME magazine, AP, and Reuters.

Erik initiated and developed the website adrift.org.au where visitors can interact with how floating debris would spread through the ocean. The website has attracted 70,000 visitors in its first year and has been used internationally in media outlets to illustrate the way plastics and other debris such as from the Fukushima tsunami and from flight MH370 moves through the ocean.

SEBILLE PUBLICATION LIST (with some abstracts)

1. Sherman P, van Sebille E, Modeling marine surface microplastic transport to assess optimal removal locations, *Environmental Research Letters*, ISSN: 1748-9326

2. Biastoch A, Durgadoo JV, Morrison AK, van Sebille E, Weijer W, Griffies SM et al., 2015, Atlantic multi-decadal oscillation covaries with Agulhas leakage., *Nature Communications*, Vol: 6, ISSN: 2041-1723

   The interoceanic transfer of seawater between the Indian Ocean and the Atlantic, 'Agulhas leakage', forms a choke point for the overturning circulation in the global ocean. Here, by combining output from a series of high-resolution ocean and climate models with in situ and satellite observations, we construct a time series of Agulhas leakage for the period 1870-2014. The time series demonstrates the impact of Southern Hemisphere westerlies on decadal timescales. Agulhas leakage shows a correlation with the Atlantic Multi-decadal Oscillation on multi-decadal timescales; the former leading by 15 years. This is relevant for climate in the North Atlantic.

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   © 2015 Elsevier Ltd. Some of the most important development goals for the countries and territories of the Western and Central Pacific Ocean (WCPO) involve the sustainable management of their fisheries in light of environmental, economic and social uncertainties. The responses of fish populations to variability in the marine environment have implications for decision making processes associated with resource management. There is still considerable uncertainty in estimating the responses of tuna populations to short-to-medium-term variability and longer-term change in the oceanic environment. A workshop was organised to examine how advances in oceanography, fisheries science and fisheries economics could be applied to the tuna fisheries of the WCPO and in doing so identify research priorities to improve understanding relevant to progressing management. Research priorities identified included: (i) improved parameterisation of end to end ecosystem model components, processes and feedbacks through expanded biological observations and incorporation of higher resolution climate models; (ii) development of seasonal and inter-annual forecasting tools enabling management responses to short-term variability in tuna distributions and abundances; (iii) improved understanding of the population dynamics of and the energy transfer efficiencies between food web components; (iv) assessment of the optimal value of access rights and overall fishery value under multiple scenarios of tuna distribution and abundance and influences on decision making by fisheries managers and fleets and (v) development of management strategy evaluation frameworks for utilisation in the implementing and testing of fishery management procedures and to help prioritise research directions and investment. Issues discussed and research priorities identified during the workshop have synergies with other internationally managed fisheries and therefore are applicable to many other fisheries.

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2. Garzoli SL, Dong S, Fine R, Meinen CS, Perez RC, Schmid C, van Sebille E, Yao Q et al., 2015, The fate of the Deep Western Boundary Current in the South Atlantic, *DEEP-SEA RESEARCH PART I-OCEANOGRAPHIC RESEARCH PAPERS*, Vol: 103, Pages: 125-136, ISSN: 0967-0637

3. Graham RM, De Boer AM, van Sebille E, Kohfeld KE, Schlosser C et al., 2015, Inferring source regions and supply mechanisms of iron in the Southern Ocean from satellite chlorophyll data, *Deep Sea Research Part I: Oceanographic Research Papers*, Vol: 104, Pages: 9-25, ISSN: 0967-0637

4. Grist JP, Josey SA, Jacobs ZL, Marsh R, Sinha B, Van Sebille E et al., 2015, Extreme air–sea interaction over the North Atlantic subpolar gyre during the winter of 2013–2014 and its sub-surface legacy, *Climate Dynamics*, ISSN: 1432-0894

   Exceptionally low North American temperatures and record-breaking precipitation over the British Isles during winter 2013–2014 were interconnected by anomalous ocean evaporation over the North Atlantic subpolar gyre region (SPG). This evaporation (or oceanic latent heat release) was accompanied by strong sensible heat loss to the atmosphere. The enhanced heat loss over the SPG was caused by a combination of surface westerly winds from the North American continent and northerly winds from the Nordic Seas region that were colder, drier and stronger than normal. A distinctive feature of the air–sea exchange was that the enhanced heat loss spanned the entire width of the SPG, with evaporation anomalies intensifying in the east while sensible heat flux anomalies were slightly stronger upstream in the west. The immediate impact of the strong air–sea fluxes on the ocean–atmosphere system included a reduction in ocean heat content of the SPG and a shift in basin-scale pathways of ocean heat and atmospheric freshwater transport. Atmospheric reanalysis data and the EN4 ocean data set indicate that a longer term legacy of the winter has been the enhanced formation of a particularly dense mode of Subpolar Mode Water(SPMW)—one of the precursors of North Atlantic Deep Water and thus an important component of the Atlantic Meridional Overturning Circulation. Using particle trajectory analysis, the likely dispersal of newly-formed SPMWis evaluated, providing evidence for the re-emergence of anomalously cold SPMW in early winter 2014/2015.

5. Peña-Izquierdo J, Van Sebille E, Pelegrí JL, Sprintall J, Mason E, Llanillo PJ, Machín F et al., 2015, Water mass pathways to the North Atlantic oxygen minimum zone, *Journal of Geophysical Research C: Oceans*, Vol: 120, Pages: 3350-3372, ISSN: 2169-9275

   © 2015. American Geophysical Union. All Rights Reserved. The water mass pathways to the North Atlantic Oxygen Minimum Zone (naOMZ) are traditionally sketched within the cyclonic tropical circulation via the poleward branching from the eastward flowing jets that lie south of 10°N. However, our water mass analysis of historic hydrographic observations together with numerical Lagrangian experiments consistently reveal that the potential density level of σ<inf>θ</inf> = 26.8 kg m⁻³ (σ26.8, approximately 300 m depth) separates two distinct regimes of circulation within the Central Water (CW) stratum of the naOMZ. In the upper CW (above σ26.8), and in agreement with previous studies, the supply of water mainly comes from the south with a predominant contribution of South Atlantic CW. In the lower CW (below σ26.8), where minimal oxygen content is found, the tropical pathway is instead drastically weakened in favor of a subtropical pathway. More than two thirds of the total water supply to this lower layer takes place north of 10°N, mainly via an eastward flow at 14°N and northern recirculations from the northern subtropical gyre. The existence of these northern jets explains the greater contribution of North Atlantic CW observed in the lower CW, making up to 50% of the water mass at the naOMZ core. The equatorward transfer of mass from the well-ventilated northern subtropical gyre emerges as an essential part of the ventilation of the naOMZ.

6. Qin X, Sen Gupta A, van Sebille E, 2015, Variability in the origins and pathways of Pacific Equatorial Undercurrent water, *JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS*, Vol: 120, Pages: 3113-3128, ISSN: 2169-9275

7. Schuyler QA, Wilcox C, Townsend KA, Wedemeyer-Strombel KR, Balazs G, van Sebille E, Hardesty BD et al., 2015, Risk analysis reveals global hotspots for marine debris ingestion by sea turtles., *Glob Chang Biol*

   Plastic marine debris pollution is rapidly becoming one of the critical environmental concerns facing wildlife in the 21st century. Here we present a risk analysis for plastic ingestion by sea turtles on a global scale. We combined global marine plastic distributions based on ocean drifter data with sea turtle habitat maps to predict exposure levels to plastic pollution. Empirical data from necropsies of deceased animals were then utilised to assess the consequence of exposure to plastics. We modelled the risk (probability of debris ingestion) by incorporating exposure to debris and consequence of exposure, and included life history stage, species of sea turtle and date of stranding observation as possible additional explanatory factors. Life history stage is the best predictor of debris ingestion, but the best-fit model also incorporates encounter rates within a limited distance from stranding location, marine debris predictions specific to

the date of the stranding study and turtle species. There is no difference in ingestion rates between stranded turtles vs. those caught as bycatch from fishing activity, suggesting that stranded animals are not a biased representation of debris ingestion rates in the background population. Oceanic life-stage sea turtles are at the highest risk of debris ingestion, and olive ridley turtles are the most at-risk species. The regions of highest risk to global sea turtle populations are off of the east coasts of the USA, Australia and South Africa; the east Indian Ocean, and Southeast Asia. Model results can be used to predict the number of sea turtles globally at risk of debris ingestion. Based on currently available data, initial calculations indicate that up to 52% of sea turtles may have ingested debris.

8. Sen Gupta A, Brown JN, Jourdain NC, van Sebille E, Ganachaud A, Vergés A et al., 2015, Episodic and non-uniform shifts of thermal habitats in a warming ocean, *Deep-Sea Research Part II: Topical Studies in Oceanography*, Vol: 113, Pages: 59-72, ISSN: 0967-0645

   © 2014 Elsevier Ltd. Ocean temperatures have warmed in most regions over the last century and are expected to warm at a faster rate in the future. Consistent with the view that marine species are thermally constrained, there is growing evidence that many marine species have already undergone poleward range shifts in line with warming trends. This study uses historical observations of ocean temperature and climate model projections to examine the movement of isotherms that mark the boundaries for species' thermal habitats. In particular, we compare the rates of isotherm movement between different ocean regions and at different time scales and examine to what extent the implied movement is uniform or sporadic. Widespread long-term warming implies poleward shifts of isotherms in almost all regions. However, as the speed of isotherm movement is inversely related to local meridional SST gradients and the pattern of ocean warming is heterogeneous, speeds vary considerably between regions, season and over time. At present on decadal and longer timescales, changes due to low frequency natural SST variability can dominate over human-induced changes. As such, there are multidecadal periods in certain regions when we would expect to see range shifts that are much faster or in the opposite direction to that implied by a monotonic warming. Based on central estimates from the latest suite of climate model projections, median isotherm speeds will be about seven times faster in the 21st century compared to the 20th century under business as usual emissions. Moreover, SST warming is projected to be greater in summer than in winter in most oceanic regions, contrary to what is projected to occur over land. As such net poleward isotherm speeds, particularly in the northern hemisphere summer, are projected to be considerably faster than in winter. Finally we show that isotherms can exhibit erratic migration rates over time, even under uniform warming.

9. Teske PR, Sandoval-Castillo J, van Sebille E, Waters J, Beheregaray LB et al., 2015, On-shelf larval retention limits population connectivity in a coastal broadcast spawner, *MARINE ECOLOGY PROGRESS SERIES*, Vol: 532, Pages: 1-12, ISSN: 0171-8630

10. Van Sebille E, 2015, The oceans' accumulating plastic garbage, *Physics Today*, Vol: 68, Pages: 60-61, ISSN: 0031-9228

    A piece of plastic discarded into the sea travels far and wide, carried by complex currents. Eventually, the material settles into one of five distinct garbage patches in the subtropical oceans.

11. Van Sebille E, England MH, Zika JD, Sloyan BMet al., 2015, Tasman leakage in a fine-resolution ocean model, *Geophysical Research Letters*, Vol: 39, ISSN: 0094-8276

    Tasman leakage, the westward flow of thermocline waters south of Australia from the Pacific to the Indian Ocean, is one of the lesser-studied of the inter-ocean exchanges. Here, some of the properties of the Tasman leakage are inferred from Lagrangian particles integrated using the three-dimensional velocity fields of the 1/10 degree resolution OFES model. The mean Tasman leakage in this model is 4.2Sv, with a standard deviation of 4.3Sv. The heat flux associated with this leakage lies in the range 0.08-0.18 PW. There is large variability in the Tasman leakage on both sub-weekly and inter-annual scales, but no trend over the 1983-1997 period. Despite the large weekly variability, with peaks of more than 20Sv, it appears that less than half of the Tasman leakage is carried within eddies. Copyright 2012 by the American Geophysical Union.

12. Wilcox C, Van Sebille E, Hardesty BD, 2015, Threat of plastic pollution to seabirds is global, pervasive, and increasing, *Proceedings of the National Academy of Sciences of the United States of America*, Vol: 112, Pages: 11899-11904, ISSN: 1091-6490

Plastic pollution in the ocean is a global concern; concentrations reach 580,000 pieces per km(2) and production is increasing exponentially. Although a large number of empirical studies provide emerging evidence of impacts to wildlife, there has been little systematic assessment of risk. We performed a spatial risk analysis using predicted debris distributions and ranges for 186 seabird species to model debris exposure. We adjusted the model using published data on plastic ingestion by seabirds. Eighty of 135 (59%) species with studies reported in the literature between 1962 and 2012 had ingested plastic, and, within those studies, on average 29% of individuals had plastic in their gut. Standardizing the data for time and species, we estimate the ingestion rate would reach 90% of individuals if these studies were conducted today. Using these results from the literature, we tuned our risk model and were able to capture 71% of the variation in plastic ingestion based on a model including exposure, time, study method, and body size. We used this tuned model to predict risk across seabird species at the global scale. The highest area of expected impact occurs at the Southern Ocean boundary in the Tasman Sea between Australia and New Zealand, which contrasts with previous work identifying this area as having low anthropogenic pressures and concentrations of marine debris. We predict that plastics ingestion is increasing in seabirds, that it will reach 99% of all species by 2050, and that effective waste management can reduce this threat.

13. van Sebille E, Scussolini P, Durgadoo JV, Peeters FJ, Biastoch A, Weijer W, Turney C, Paris CB, Zahn Ret al., 2015, Ocean currents generate large footprints in marine palaeoclimate proxies., *Nat Commun*, Vol: 6

Fossils of marine microorganisms such as planktic foraminifera are among the cornerstones of palaeoclimatological studies. It is often assumed that the proxies derived from their shells represent ocean conditions above the location where they were deposited. Planktic foraminifera, however, are carried by ocean currents and, depending on the life traits of the species, potentially incorporate distant ocean conditions. Here we use high-resolution ocean models to assess the footprint of planktic foraminifera and validate our method with proxy analyses from two locations. Results show that foraminifera, and thus recorded palaeoclimatic conditions, may originate from areas up to several thousands of kilometres away, reflecting an ocean state significantly different from the core site. In the eastern equatorial regions and the western boundary current extensions, the offset may reach 1.5 °C for species living for a month and 3.0 °C for longer-living species. Oceanic transport hence appears to be a crucial aspect in the interpretation of proxy signals.

14. van Sebille E, Waterman S, Barthel A, Lumpkin R, Keating SR, Fogwill C, Turney Cet al., 2015, Pairwise surface drifter separation in the western Pacific sector of the Southern Ocean, *Journal of Geophysical Research: Oceans*, Pages: n/a-n/a, ISSN: 2169-9275

15. van Sebille E, Wilcox C, Lebreton L, Maximenko N, Hardesty BD, Van Franeker JA, Eriksen M, Siegel D, Galgani F, Law KL et al., 2015, A Global Inventory of Small Floating Plastic Debris,*Environmental Research Letters*, Vol: 10, Pages: 124006-124006, ISSN: 1748-9326

Microplastic debris floating at the ocean surface can harm marine life. Understanding the severity of this harm requires knowledge of plastic abundance and distributions. Dozens of expeditions measuring microplastics have been carried out since the 1970s, but they have primarily focused on the North Atlantic and North Pacific accumulation zones, with much sparser coverage elsewhere. Here, we use the largest dataset of microplastic measurements assembled to date to assess the confidence we can have in global estimates of microplastic abundance and mass. We use a rigorous statistical framework to standardize a global dataset of plastic marine debris measured using surface-trawling plankton nets and coupled this with three different ocean circulation models to spatially interpolate the observations. Our estimates show that the accumulated number of microplastic particles in 2014 ranges from 15 to 51 trillion particles, weighing between 93 and 236 thousand metric tons, which is only approximately 1% of global plastic waste estimated to enter the ocean in the year 2010. These estimates are larger than previous global estimates, but vary widely because the scarcity of data in most of the world ocean, differences in model formulations, and fundamental knowledge gaps in the sources, transformations and fates of microplastics in the ocean.

16. Caley T, Peeters FJC, Biastoch A, Rossignol L, Van Sebille E, Durgadoo J, Malaizé B, Giraudeau J, Arthur K, Zahn R et al., 2014, Quantitative estimate of the paleo-Agulhas leakage,*Geophysical Research Letters*, Vol: 41, Pages: 1238-1246, ISSN: 0094-8276

    The Indian-Atlantic water exchange south of Africa (Agulhas leakage) is a key component of the global ocean circulation. No quantitative estimation of the paleo-Agulhas leakage exists. We quantify the variability in interocean exchange over the past 640,000 years, using planktic foraminiferal assemblage data from two marine sediment records to define an Agulhas leakage efficiency index. We confirm the validity of our new approach with a numerical ocean model that realistically simulates the modern Agulhas leakage changes. Our results suggest that, during the past several glacial-interglacial cycles, the Agulhas leakage varied by ~10 sverdrup and more during major climatic transitions. This lends strong credence to the hypothesis that modifications in the leakage played a key role in changing the overturning circulation to full strength mode. Our results are instrumental for validating and quantifying the contribution of the Indian-Atlantic water leakage to the global climate changes. Key Points A quantitative index for the Agulhas leakage has been developed Paleo-Agulhas leakage over the past 640,000 years has been quantified We provide reference points for further analyses and interpretations ©2014. American Geophysical Union. All Rights Reserved.

17. Cetina-Heredia P, Roughan M, Van Sebille E, Coleman MA et al., 2014, Long-term trends in the East Australian Current separation latitude and eddy driven transport, *Journal of Geophysical Research: Oceans*, Vol: 119, Pages: 4351-4366

    An observed warming of the Tasman Sea in recent decades has been linked to a poleward shift of the maximum wind stress curl, and a strengthening of the poleward flow along the coast of southeastern Australia. However, changes in the East Australian Current (EAC) separation latitude, as well as in the contribution of the EAC, the EAC extension and its eddy field to the total southward transport due to such a strengthening remain unknown. This study uses 30 years (1980-2010) of the Ocean Forecast for the Earth Simulator (OFES) sea surface height and velocity outputs to obtain a three decade long-time series of (i) the EAC separation latitude, (ii) the southward transport along the coast of southeastern Australia (28°S-39°S), and (iii) the southward transport across the EAC separation latitude. A Lagrangian approach is implemented and the spin parameter Ω is used to provide a quantitative distinction between the transports occurring outside and inside (cyclonic and anticyclonic) eddies. Significant positive trends of the low pass southward transports indicate that the intensification of the poleward flow has occurred both within the EAC and in the EAC extension. In addition, a significant increase in southward transport inside and outside eddies is found. Importantly, the contribution of eddy driven transport has a large temporal variability and shows a sharp increase from 2005 onward. Finally our results show that the EAC has not penetrated further south but it has separated more frequently at the southernmost latitudes within the region where it typically turns eastward. Key Points The EAC separation latitudinal range has not changed considerably form 1980 to 2010 EAC water transport across the EAC separation point has increased from 1980 to 2010 EAC water transport inside eddies has increased particularly from 2005 onward © 2014. American Geophysical Union. All Rights Reserved.

18. Den Toom M, Dijkstra HA, Weijer W, Hecht MW, Maltrud ME, Van Sebille E et al., 2014, Response of a strongly eddying global ocean to North Atlantic freshwater perturbations, *Journal of Physical Oceanography*, Vol: 44, Pages: 464-481, ISSN: 0022-3670

    The strongly eddying version of the Parallel Ocean Program (POP) is used in two 45-yr simulations to investigate the response of the Atlantic meridional overturning circulation (AMOC) to strongly enhanced freshwater input due to Greenland melting, with an integrated flux of 0.5 Sverdrups (Sv; 1 Sv ≡ 106m3 s-1). For comparison, a similar set of experiments is performed using a noneddying version of POP. The aim is to identify the signature of the salt advection feedback in the two configurations. For this reason, surface salinity is not restored in these experiments. The freshwater input leads to a quantitatively comparable reduction of the overturning strength in the two models. To examine the importance of transient effects in the relation betweenAMOCstrength and density distribution, the results of the eddy-resolving model are related to water mass transformation theory. The freshwater forcing leads to a reduction of the rate of light to dense water conversion in the North Atlantic, but there is no change in dense to light transformation elsewhere, implying that high density layers are continuously deflating. The main focus of the paper is on the effect of the AMOC reduction on the basinwide

advection of freshwater. The low-resolution model results show a change of the net freshwater advection that is consistent with the salt advection feedback. However, for the eddy-resolving model, the net freshwater advection into the Atlantic basin appears to be unaffected, despite the significant change in the large-scale velocity structure. © 2014 American Meteorological Society.

19. Froyland G, Stuart RM, van Sebille E, 2014, How well-connected is the surface of the global ocean?, *Chaos*, Vol: 24

    The Ekman dynamics of the ocean surface circulation is known to contain attracting regions such as the great oceanic gyres and the associated garbage patches. Less well-known are the extents of the basins of attractions of these regions and how strongly attracting they are. Understanding the shape and extent of the basins of attraction sheds light on the question of the strength of connectivity of different regions of the ocean, which helps in understanding the flow of buoyant material like plastic litter. Using short flow time trajectory data from a global ocean model, we create a Markov chain model of the surface ocean dynamics. The surface ocean is not a conservative dynamical system as water in the ocean follows three-dimensional pathways, with upwelling and downwelling in certain regions. Using our Markov chain model, we easily compute net surface upwelling and downwelling, and verify that it matches observed patterns of upwelling and downwelling in the real ocean. We analyze the Markov chain to determine multiple attracting regions. Finally, using an eigenvector approach, we (i) identify the five major ocean garbage patches, (ii) partition the ocean into basins of attraction for each of the garbage patches, and (iii) partition the ocean into regions that demonstrate transient dynamics modulo the attracting garbage patches.

20. Hellweger FL, van Sebille E, Fredrick ND, 2014, Biogeographic patterns in ocean microbes emerge in a neutral agent-based model., *Science*, Vol: 345, Pages: 1346-1349

    A key question in ecology and evolution is the relative role of natural selection and neutral evolution in producing biogeographic patterns. We quantify the role of neutral processes by simulating division, mutation, and death of 100,000 individual marine bacteria cells with full 1 million-base-pair genomes in a global surface ocean circulation model. The model is run for up to 100,000 years and output is analyzed using BLAST (Basic Local Alignment Search Tool) alignment and metagenomics fragment recruitment. Simulations show the production and maintenance of biogeographic patterns, characterized by distinct provinces subject to mixing and periodic takeovers by neighbors (coalescence), after which neutral evolution reestablishes the province and the patterns reorganize. The emergent patterns are substantial (e.g., down to 99.5% DNA identity between North and Central Pacific provinces) and suggest that microbes evolve faster than ocean currents can disperse them. This approach can also be used to explore environmental selection.

21. Palmer J, Turney C, Hogg A, Hilliam N, Watson M, van Sebille E, Cowie W, Jones R, Petchey F et al., 2014, The discovery of New Zealand's oldest shipwreck - possible evidence of further Dutch exploration of the South Pacific, *Journal of Archaeological Science*, Vol: 42, Pages: 435-441, ISSN: 0305-4403

    European exploration of New Zealand and the wider South Pacific is traditionally considered to have commenced with the documented voyages of Dutch explorer Abel Tasman in A.D. 1642 and British Captain James Cook in A.D. 1769, with no direct evidence of activity during the intervening years. Here, we report on the discovery of a shipwreck on the west coast of Northland in northern New Zealand that likely occurred during that interval. The vessel was constructed from at least two tropical hardwoods and comprises planks and rib sections, measuring c. 25-27m long with a beam of c. 6.5-7.5m. Radiocarbon (14C) dating of contiguous decadal blocks allows us to wiggle match these dates against the Northern Hemisphere 14C calibration curve to obtain a precise calendar age for the wood. Taking into account the missing sapwood and probable period for timber seasoning we obtain a likely construction date for the ship of around A.D. 1705±9 years. The dominance of Dutch maritime trade during this time period, their known vessel construction in the tropics and the presence of copper on the hull of the wreck, all point to the likelihood of the vessel being of Dutch construction. Intriguingly, journal entries by Cook and expedition members suggest at least one other European ship visited New Zealand after Tasman but prior to his arrival. The general limited lifespan of ships at the time makes this discovery the oldest known wreck from the region. Importantly, the age of the Northland vessel probably predates the first reported

European landing by Captain Cook, as well as suggesting other vessels may have attempted to follow-up on the discovery recorded by Tasman. © 2013 .

22. Qin X, van Sebille E, Sen Gupta A, 2014, Quantification of errors induced by temporal resolution on Lagrangian particles in an eddy-resolving model, *Ocean Modelling*, Vol: 76, Pages: 20-30, ISSN: 1463-5003

    Lagrangian particle tracking within ocean models is an important tool for the examination of ocean circulation, ventilation timescales and connectivity and is increasingly being used to understand ocean biogeochemistry. Lagrangian trajectories are obtained by advecting particles within velocity fields derived from hydrodynamic ocean models. For studies of ocean flows on scales ranging from mesoscale up to basin scales, the temporal resolution of the velocity fields should ideally not be more than a few days to capture the high frequency variability that is inherent in mesoscale features. However, in reality, the model output is often archived at much lower temporal resolutions. Here, we quantify the differences in the Lagrangian particle trajectories embedded in velocity fields of varying temporal resolution. Particles are advected from 3-day to 30-day averaged fields in a high-resolution global ocean circulation model. We also investigate whether adding lateral diffusion to the particle movement can compensate for the reduced temporal resolution. Trajectory errors reveal the expected degradation of accuracy in the trajectory positions when decreasing the temporal resolution of the velocity field. Divergence timescales associated with averaging velocity fields up to 30. days are faster than the intrinsic dispersion of the velocity fields but slower than the dispersion caused by the interannual variability of the velocity fields. In experiments focusing on the connectivity along major currents, including western boundary currents, the volume transport carried between two strategically placed sections tends to increase with increased temporal averaging. Simultaneously, the average travel times tend to decrease. Based on these two bulk measured diagnostics, Lagrangian experiments that use temporal averaging of up to nine days show no significant degradation in the flow characteristics for a set of six currents investigated in more detail.

23. Rosso I, Hogg AM, Strutton PG, Kiss AE, Matear R, Klocker A, van Sebille E et al., 2014, Vertical transport in the ocean due to sub-mesoscale structures: Impacts in the Kerguelen region, *Ocean Modelling*, Vol: 80, Pages: 10-23, ISSN: 1463-5003

    The summertime phytoplankton bloom near the Kerguelen Plateau is in marked contrast to the low-chlorophyll conditions typical of the Southern Ocean and is thought to arise from natural iron fertilisation. The mechanisms of iron supply to the euphotic zone in this region are poorly understood, and numerical studies of iron transport have until now omitted fine-scale (sub-mesoscale) dynamics which have been shown to significantly increase vertical transport in other parts of the ocean. We present the first sub-mesoscale-resolving study of the flow and vertical transport in this region. The modelled transport and flow structure agree well with observations. We find that an increase in horizontal resolution from mesoscale-resolving (1/20°) to 1/80° resolves sub-mesoscale filamentary frontal structures in which vertical velocities are dramatically higher and are consistent with available observations. Lagrangian tracking shows that water is advected to the surface from much greater depth in the sub-mesoscale-resolving experiment, and that vertical exchange is far more rapid and frequent. This study of sub-mesoscale vertical velocities sets the foundation for subsequent investigation of iron transport in this environment. © 2014 Elsevier Ltd.

24. Spence P, van Sebille E, Saenko OA, England MHet al., 2014, Using Eulerian and Lagrangian approaches to investigate wind-driven changes in the Southern Ocean abyssal circulation, *Journal of Physical Oceanography*, Vol: 44, Pages: 662-675, ISSN: 0022-3670

    This study uses a global ocean eddy-permitting climate model to explore the export of abyssal water from the Southern Ocean and its sensitivity to projected twenty-first-century poleward-intensifying Southern Ocean wind stress. The abyssal flow pathways and transport are investigated using a combination of Lagrangian and Eulerian techniques. In an Eulerian format, the equator-and poleward flows within similar abyssal density classes are increased by the wind stress changes, making it difficult to explicitly diagnose changes in the abyssal export in a meridional overturning circulation framework. Lagrangian particle analyses are used to identify the major export pathways of Southern Ocean abyssal waters and reveal an increase in the number of particles exported to the subtropics from source regions around Antarctica in response to the wind forcing. Both the Lagrangian particle and Eulerian analyses identify transients

as playing a key role in the abyssal export of water from the Southern Ocean. Wind-driven modifications to the potential energy component of the vorticity balance in the abyss are also found to impact the Southern Ocean barotropic circulation. ©

25. Van Sebille E, Sprintall J, Schwarzkopf FU, Sen Gupta A, Santoso A, England MH, Biastoch A, Böning CW et al., 2014, Pacific-to-Indian Ocean connectivity: Tasman leakage, Indonesian Throughflow, and the role of ENSO, *Journal of Geophysical Research: Oceans*, Vol: 119, Pages: 1365-1382

    The upper ocean circulation of the Pacific and Indian Oceans is connected through both the Indonesian Throughflow north of Australia and the Tasman leakage around its south. The relative importance of these two pathways is examined using virtual Lagrangian particles in a high-resolution nested ocean model. The unprecedented combination of a long integration time within an eddy-permitting ocean model simulation allows the first assessment of the interannual variability of these pathways in a realistic setting. The mean Indonesian Throughflow, as diagnosed by the particles, is 14.3 Sv, considerably higher than the diagnosed average Tasman leakage of 4.2 Sv. The time series of Indonesian Throughflow agrees well with the Eulerian transport through the major Indonesian Passages, validating the Lagrangian approach using transport-tagged particles. While the Indonesian Throughflow is mainly associated with upper ocean pathways, the Tasman leakage is concentrated in the 400-900 m depth range at subtropical latitudes. Over the effective period considered (1968-1994), no apparent relationship is found between the Tasman leakage and Indonesian Throughflow. However, the Indonesian Throughflow transport correlates with ENSO. During strong La Niñas, more water of Southern Hemisphere origin flows through Makassar, Moluccas, Ombai, and Timor Straits, but less through Moluccas Strait. In general, each strait responds differently to ENSO, highlighting the complex nature of the ENSO-ITF interaction. Key Points Pacific and Indian Oceans are connected through ITF and Tasman leakage Both pathways are important for global circulation but are not correlated A Lagrangian analysis of pathways finds effect of ENSO in Archipelago © 2014. American Geophysical Union. All Rights Reserved.

26. Vergés A, Steinberg PD, Hay ME, Poore AG, Campbell AH, Ballesteros E, Heck KL, Booth DJ, Coleman MA, Feary DA, Figueira W, Langlois T, Marzinelli EM, Mizerek T, Mumby PJ, Nakamura Y, Roughan M, van Sebille E, Gupta AS, Smale DA, Tomas F, Wernberg T, Wilson SK et al., 2014, The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts., *Proc Biol Sci*, Vol: 281

    Climate-driven changes in biotic interactions can profoundly alter ecological communities, particularly when they impact foundation species. In marine systems, changes in herbivory and the consequent loss of dominant habitat forming species can result in dramatic community phase shifts, such as from coral to macroalgal dominance when tropical fish herbivory decreases, and from algal forests to 'barrens' when temperate urchin grazing increases. Here, we propose a novel phase-shift away from macroalgal dominance caused by tropical herbivores extending their range into temperate regions. We argue that this phase shift is facilitated by poleward-flowing boundary currents that are creating ocean warming hotspots around the globe, enabling the range expansion of tropical species and increasing their grazing rates in temperate areas. Overgrazing of temperate macroalgae by tropical herbivorous fishes has already occurred in Japan and the Mediterranean. Emerging evidence suggests similar phenomena are occurring in other temperate regions, with increasing occurrence of tropical fishes on temperate reefs.