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Lagrangian analysis of multi-satellite data in support of open ocean Marine Protected Area design

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A B S T R A C T

Compared to ecosystem conservation in territorial seas, protecting the open ocean has peculiar geopolitical, economic and scientific challenges. One of the major obstacle is defining the boundary of an open ocean Marine Protected Area (MPA). In contrast to coastal ecosystems, which are mostly constrained by topographic structures fixed in time, the life of marine organisms in the open ocean is entrained by fluid dynamical structures like eddies and fronts, whose lifetime occurs on ecologically-relevant timescales. The position of these highly dynamical structures can vary interannually by hundreds of km, and so too will regions identified as ecologically relevant such as the foraging areas of marine predators. Thus, the expected foraging locations suggested from tracking data cannot be directly extrapolated beyond the year in which the data were collected. Here we explore the potential of Lagrangian methods applied to multisatellite data as a support tool for a MPA proposal by focusing on the Crozet archipelago oceanic area (Indian Sector of the Southern Ocean). By combining remote sensing with biologging information from a key marine top predator (*Eudyptes chrysolophus*, or Macaroni penguin) of the Southern Ocean foodweb, we identify a highly dynamic branch of the Subantarctic front as a foraging hotspot. By tracking this feature in historical satellite data (1993–2012) we are able to extrapolate the position of this foraging ground beyond the years in which tracking data are available and study its spatial variability.

1. Introduction

The open ocean environment represents the largest realm on Earth (99% of the biosphere) (Game et al., 2009) and plays a key role in our economy with >50% of the fish consumed by humans coming from open ocean fisheries (<http://www.greenfacts.org/en>). Under pressure by increasing resource exploitation, pollution and maritime traffic, it is one of the least protected ecosystems on Earth. Juridically encompassing both national exclusive economic zones (EEZ) and “high seas”, i.e. not part of any country's EEZ, beyond 200 nautical miles from any nation's territory, open ocean regions present difficulties in their spatial management and enforcement (Hobday and Hartog, 2014). Only 3% of the marine environment is protected,

and of this fraction, high seas protected areas constitute a minority (Game et al., 2009): in 2013, the U.N. Millennium Goal Report states that less than 1% of the high seas are protected.

At the scale of 1000 s of km, Longhurst (2010) described world oceans' biogeographical provinces according to abiotic and biotic pelagic factors. He identified four biogeographical provinces within the polar biome in the Southern Ocean: the South Subtropical Convergence province (SSTC), the Subantarctic water ring Province (SANT), the Antarctic province (ANTA) and the Polar Southern province (APLR). Each of these provinces theoretically delimits the particular types of environmental or hydrological forcing that can be encountered. More recently, De Broyer et al. (2014) used a bioregionalisation multivariate procedure to delineate regions according to sea

Abbreviation: MPA, Marine protected area; EEZ, Exclusive economic zone; FSLE, Finite size Lyapunov exponent; SAM, Southern annular mode; SST, Sea surface temperature; ACC, Antarctic Circumpolar Current; APLR, Polar southern province; ANTA, Antarctic province; SANT, Subantarctic Water province; SSTC, South Subtropical Convergence

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surface temperature, depth and sea ice. The identified provinces are proxies of ecoregions which are “assemblages of flora, fauna and the supporting geophysical environment contained within distinct but dynamic spatial boundaries” (Vierros et al., 2009). Depending on the availability of data, the approach to the bioregionalisation can be based on species lists by regions or mapping of species distributions (either observed data or prediction of species or community presence/abundance based on environmental factors). For example, Koubbi et al. (2011) determined ecoregions based on modelling mesopelagic fish assemblages in the Indian part of the Southern Ocean.

However, how to identify key ecological areas 100 s of km wide (the typical manageable size of a pelagic Marine Protected Area, MPA) inside these basin-wide biogeographical provinces is not trivial. In particular, the practical and juridical need of defining fixed boundaries for a Marine Protected Area clashes with the intrinsically dynamical nature of ecologically relevant pelagic features, whose position is not fixed in time (Scales et al., 2014; Maxwell et al., 2015). Unlike terrestrial and benthic systems, from which most management approaches are borrowed, the ecosystems of the open ocean upper layer are only weakly constrained by bottom topography, often thousands of meters below. Life of pelagic marine organisms depends on oceanographic features like eddies, the ocean equivalent of atmospheric cyclones and anticyclones, and fronts, highly dynamical boundaries between distinct water masses. Such features belong to the so-called (sub-)mesoscale regime, which spans spatial scales of 1–100 km, and temporal ones ranging from few days to months. Eddies and fronts create a dynamical “seascape” characterised by strong gradients in physical and biogeochemical properties including temperature, salinity and nutrient availability (Mahadevan and Campbell, 2002; Gaube et al., 2013; Klein and Lapeyre, 2009; Pérez-Muñuzuri and Huhn, 2010; Lévy et al., 2012). These features have been observed to structure the distribution of ocean life from phytoplankton (both in terms of primary production (Strass et al., 2002; Abraham, 1998; Martin, 2003; Lehahn et al., 2007; Lévy et al., 2015), community structure (d’Ovidio et al., 2010) and biodiversity (Sunagawa et al., 2015; De Monte et al., 2013) to zooplankton (Labat et al., 2009), bacteria (Baltar et al., 2010), micronekton (Sabarros et al., 2009; Godø et al., 2012) and top predators (Bailleul et al., 2010; Cotté et al., 2011; Waluda et al., 2001; Polovina et al., 2006; Nel et al., 2001; De Monte et al., 2012; Cotté et al., 2007; Scales et al., 2014). Identifying which of these dynamical features are of relevance for marine organisms, finding the boundaries of the ecoregion in which they evolve, and anticipating their drift in response to scenarios of climate change are therefore issues of primary concern in the definition of open ocean MPAs. Due to the chaotic nature of the ocean dynamics and to the temporal dependence of their external forcing, mesoscale features present a high degree of interannual variability. Much like atmospheric weather patterns, oceanic fronts and eddies may show some predictability, but their position and trajectory can vary by hundreds of km from one year to another. This characteristic poses a problem when biologging data have to be extrapolated in time for the establishment of an MPA (Delord et al., 2014). An oceanographic feature that has been targeted by some tagged animals during some years may appear at a different location in the future, possibly falling outside the perimeter of an MPA established with previous information. In order to address this issue, multisatellite data, which nowadays span several decades, offer a potentially powerful tool, because once an ecologically relevant physical feature has been identified, its interannual variability, drift, and statistical relation to modes of climate variability can be identified. This way, the perimeter of an MPA can be designed so to include this spatial range of variability, encompassing possible trends under scenarios of climate change.

The ecological potential of combining satellite data and biologging is in large part yet to be explored. Only recently data from remote-sensing (Surface Chlorophyll concentration, Sea Surface Temperature, etc.), their Lagrangian analyses (De Monte et al., 2012; Cotté et al., 2011; Hernández-Carrasco et al., 2011), biologging (Rutz and Hays, 2009), in situ measurement networks, and high resolution models have

converged together to a spatial and temporal resolution capable to resolve mesoscale (and in some cases even submesoscale) dynamical mechanisms. Remotely sensed sea surface temperature has been used to infer location and frequency of thermal fronts as proxies for biodiversity in the planning of marine protected areas (Miller and Christodoulou, 2014; Miller et al., 2015). Because of the lack of data on the prey distribution (macrozooplankton and micronekton), information from biologging (in particular animal tracking data) is regularly used in habitat modelling for large marine animals to predict the spatial distribution of foraging grounds for top predators (Torres et al., 2008; Hazen et al., 2013). All these studies have used the environmental fields measured from satellite (like Sea Surface Temperature or Sea Surface Height). However, in recent years advanced analytical tools have been developed, which allow the extraction of dynamical information of the oceanic environment. Adapted to satellite observations of the ocean a few decades ago (Abraham, 1998; d’Ovidio et al., 2009; Waugh and Abraham, 2008; Hernández-García et al., 2002; Hernández-Carrasco et al., 2011; Beron-Vera et al., 2008; Olascoaga et al., 2006), Lagrangian tools in particular now provide a mature and powerful technique for exploring the (sub)mesoscale regime, yielding useful ecological properties like stirring pathways (i.e. where from and how a water parcel has reached a specific location), retentive regions, and frontal systems (d’Ovidio et al., 2013, 2015). More recently, these tools have been shown to be particularly adapted to complement biologging observations, helping to interpret the environmental context which shapes the habitat and behavior of various marine vertebrates, including seabirds, whales, and seals (Tew Kai et al., 2009; De Monte et al., 2012; Della Penna et al., 2015; Cotté et al., 2015, 2011; Bon et al., 2015; d’Ovidio et al., 2013). Nevertheless, to our knowledge Lagrangian tools have not been considered as a tool for conservation. This work aims to bridge this gap, adapting the Lagrangian approach to a specific conservation context (the definition of an MPA in the Southern Ocean) and exploring its potential.

In this study we combine Lagrangian analysis of remote sensing and biologging to identify which open ocean transport structures are targeted by Macaroni penguins - *Eudyptes chrysolophus* - which are key consumers of the Southern Ocean foodweb and have important colonies on Crozet Island (Indian Sector of the Southern Ocean). The Macaroni penguins are listed by IUCN as a vulnerable species (Crossin et al., 2013). Our study focuses on the incubating phase of their life cycles and identifies a dynamic branch of the Subantarctic front as a foraging ground for these penguins. Once this oceanographic feature targeted by penguins has been identified in terms of remote sensing data, we map its position for years in which biologging data are not available. In particular, we employ the multi-decade temporal availability of altimetry information in constructing an interannual density kernel. Studying the correlation between the location of the estimated foraging ground and a climatic mode, we finally evaluate internal vs. climatic interannual variability, thus inferring possible trends in its position in the face of climate change.

1.1. Regional context

1.1.1. The Crozet ecosystem

The Crozet archipelago is located in the Indian sector of the Southern Ocean (Fig. 1 a) and represents a region of high productivity in the otherwise High Nutrient Low Chlorophyll environment of this basin (see Sanial et al. (2014), Pollard et al. (2007a), Venables et al. (2007), Pollard et al. (2007b) for more details). The re-suspension of iron-enriched sediments from the Crozet Plateau is thought to naturally fertilize the iron depleted waters downstream and trigger a diatom dominated phytoplanktonic bloom during the southern springtime. The chlorophyll-rich plume is initially carried north toward the Antarctic Circumpolar Current (ACC), which then disperses it eastward (Fig. 1 b). Crozet bloom’s spatial distribution is largely constrained by the dynamical landscape of mesoscale fronts and structured by

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