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Remote sensing of ocean fronts in marine ecology and fisheries

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Contents

Abstract. This paper provides a concise review of remote sensing of ocean fronts and its applications in marine ecology and fisheries, with a particular focus on the most popular front detection algorithms/techniques: Canny (1986), Cayula and Cornillon (1990, 1992, 1995), Miller (2004, 2009), Shimada et al. (2005), Belkin and O'Reilly (2009), and Nieto et al. (2012). A case is made for *feature-based approach* in marine ecology and fisheries that emphasizes *fronts* as major structural and circulation features of the ocean realm that play key roles in various aspects of marine ecology.

Keywords: Ocean front, Marine ecology, Fisheries, Front detection, Satellite imagery, Feature-based approach

1. Introduction

Remote sensing from satellites confers tremendous benefits to fisheries. The satellites' high flight altitude (>300 km) allows instant coverage of huge expanses of the ocean; the flight speed of 7.8 km/s ensures extremely fast and frequent coverage of the ocean every 1.5 h; sun-synchronous orbits allow repeat daily monitoring of the ocean at the same local time; high spatial resolution of modern sensors allows observations of submesoscale (<10 km), small-scale (<1 km), and micro-scale (<100 m) details of ocean structure and circulation; finally, concurrent usage of multiple sensors that measure different ecologically important characteristics has a synergetic potential to be exploited by the fisheries.

The above-listed benefits conferred by satellites have been realized by fishermen and fisheries managers long ago. Maps of sea-surface temperature (SST) based on satellite measurements have been widely available since the 1960s-1970s. Such maps were immediately used by fishermen since commercially exploited species have been known to prefer certain temperatures. Maps of SST have been routinely generated by meteorological centers and fisheries agencies in several countries, e.g., USA, UK, Canada, Japan, Australia, France, and Russia. Initially such maps have been broadcast by radio and available as analogue facsimile of maps produced manually by experts. With the advent of Internet, such maps, now generated automatically and objectively by computers, have been broadcast in digital form.

At the same time, even the early rudimentary satellite-based SST maps have documented most salient ocean ***circulation features such as fronts, eddies, and upwellings***. Visual observations from satellites and orbital manned stations have corroborated and reinforced such findings. The large- and mesoscale circulation features such as fronts, eddies, and upwellings have been traditionally recognized as ecologically important by marine biologists, while fishermen have long exploited their potential as fishing grounds, albeit largely in the coastal ocean. Now that satellites afforded a global view of the ocean, this information has become available for deep-sea fisheries as well.

Despite the commonly accepted ecological importance of major circulation ***features***, particularly fronts and eddies, their use in everyday activities and long-term planning of marine fisheries remained limited until recently. The main impediment to the wide practical acceptance of ***feature-based approach*** was the lack of computer software for efficient and effective processing of vast amounts of satellite data, including computer algorithms for feature extraction from satellite imagery. This situation has changed quite dramatically over the last 10 years, which warrants this review.

In this paper we focus largely on remote sensing of ***ocean fronts*** and applications of front detection in marine fisheries and fisheries oceanography. Fronts are main structural elements of the oceanic realm, impacting all trophic levels across a wide range of spatial and temporal scales, from meters to thousands of kilometers, and from days to millions of years (Laurs and Lynn, 1977; Holligan, 1981; Krause et al., 1986; Legeckis, 1986; Le Fèvre, 1987; Wolanski and Hamner, 1988; Olson et al., 1994; Acha et al., 2004; Bakun, 2006; Bost et al., 2009; Belkin et al., 2009, 2014; Woodson and Litvin, 2015; Snyder et al., 2017; Cox et al., 2018; Martinetto et al., 2020). Fronts are loci of enhanced primary and secondary production and higher concentrations of plankton aggregated by convergence toward fronts. Dense aggregations of phytoplankton and zooplankton attract planktivorous schooling fish, squid, and large piscivorous fish. Life stages of many fish species are associated with fronts, including spawning, nursing, feeding, and migrations.

The author's interest to fish-front links goes back to the R/V *Dmitriy Mendeleyev* Cruise 34 (1984-1985) focused on the ecology of Chilean jack mackerel *Trachurus murphyi*. During the cruise, underway SST and SSS data combined with CTD station data were used to detect fronts (Belkin, 1988). Front data were radioed daily to Dr. Nikolay A. Shurunov, a fisheries oceanographer aboard the Russian trawler *Pioner Nikolayeva*, which shadowed R/V *Dmitriy Mendeleyev* for a month, using the near-real time front data to increase fishing efficiency. The affinity of *Trachurus murphyi* to the Subtropical Front in the South Pacific has been confirmed in numerous studies and exploited by fishers (Ashford et al., 2011; Parada et al., 2017).

Since 1998, the author has been associated with the Graduate School of Oceanography of the University of Rhode Island (GSO/URI), where Peter Cornillon has initiated a global survey of ocean fronts (supported by NASA), and where Jean-François Cayula and Peter Cornillon developed the most sophisticated state-of-the-art front detection algorithm (Cayula and Cornillon, 1990, 1992, 1995). The Cayula-Cornillon algorithm (CCA) was used to generate a unique global front data base, allowing an unprecedented view of World Ocean fronts at submesoscale resolution in space (presently down to 1 km) and synoptic resolution in time (nominally every 12 hours), and their evolution at seasonal, interannual, and decadal scales from 1982 to date (Belkin et al., 2009). A long-term collaboration between the URI and NOAA since 2005 has resulted in the development of a novel front detection algorithm (Belkin and O'Reilly, 2009), BOA hereafter, adopted by NOAA in 2013. Maps of chlorophyll fronts generated by BOA are now freely available from NOAA as an operational ocean color product.

Both algorithms developed at the University of Rhode Island (CCA and BOA) are now widely used in ecological studies and marine fisheries. Meanwhile, a few alternative algorithms/techniques have been proposed and used for front detection and characterization in oceanography, marine ecology, and fisheries. Thus, these days researchers and practitioners have a choice of front detection/characterization algorithms/techniques. It is time to review the history of applications of front detection algorithms in marine ecology and fisheries. At the same time, this review will make a case for the feature-based approach to marine ecology and fisheries since fronts are the most stable and ecologically important features of the ocean realm. The structure of this paper is as follows. After providing a concise historical background of satellite missions relevant to fisheries in Section 2 and remote sensing in marine fisheries in Section 3, ecological roles played by fronts are emphasized in Section 4, followed by a review of front detection/characterization algorithms/techniques in Section 5 and their applications in marine ecology, fisheries oceanography, and marine fisheries in Section 6, followed by Section 7 where we discuss problems, suggest solutions, draw conclusions, and outline perspectives. The reference list, albeit long, includes only the most important and/or representative papers and does not pretend to be an exhaustive bibliography.

2. Satellite missions and sensors

Sea Surface Temperate (SST) is measured with space-borne infrared (IR) radiometers. The advent of satellite era, marked by the launch of the first artificial Earth satellite, the Russian *Sputnik-1* in 1957, was followed since 1967 by launches of weather satellites with IR radiometers that measured SST, a key ecological variable. Systematic high-quality measurements of SST have begun in 1981 (and continued uninterrupted to date) with the Advanced Very High-Resolution Radiometers (AVHRR) flown on NOAA polar-orbiting satellites (Minnett et al., 2020). Currently, spatial resolution of modern space-borne radiometers (e.g., VIIRS) is better than 1 km, while temporal resolution (12 h) is dictated by their sun-synchronous orbits. High-quality AVHRR SST data provided by the Pathfinder project are available from 1982 to date. Geostationary satellites allow their payload sensors to acquire images of the ocean every few minutes.

Sea Surface Chlorophyll (CHL) concentration is estimated from satellite ocean color data. Such data have become widely available first thanks to the CZCS (Coastal Zone Color Scanner) aboard the Nimbus-7 satellite (1978-1986), then thanks to the SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) aboard the OrbView-2 (aka SeaStar) satellite (1997-2010). The Moderate Resolution Imaging Spectroradiometers (MODIS) provided uninterrupted measurements of SST and CHL from the Terra satellite since 1999 and from the Aqua satellite since 2002. The Visible Infrared Imaging Radiometer Suite (VIIRS) that measures SST and CHL among other observables has been launched aboard the Suomi NPP satellite in 2011 and NOAA-20 satellite in 2017. The CHL data provided by the above instruments resolve CHL fronts associated with collocated SST fronts and often (especially in summer) reveal fronts that all but disappear in SST imagery because of small thermal contrast across such fronts.

Sea surface height (SSH) has been systematically continuously measured since 1992 in several satellite altimeter missions, starting with the TOPEX/Poseidon satellite in 1992-2006, and from the Jason-1, 2, and 3 satellites launched in 2001, 2008, and 2016 respectively. The SSH data provided by the above satellite altimeters resolve major large-scale fronts and many mesoscale fronts.

Sea surface salinity (SSS) has been measured by the SMOS satellite from 2009 till present and by the Aquarius radiometer aboard the SAC-D satellite in 2011-2015. The SSS data provided by SMOS and Aquarius resolve strongest salinity fronts in the open ocean and largest river plume fronts in the costal ocean.

Sea surface roughness (SSR) is measured by space-borne synthetic aperture radars (SAR) flown in Radarsat-1, Radarsat-2, PALSAR and in other satellite missions. Ocean fronts are often visible at the sea surface as *currents rips* or simply *rips* (Uda, 1938) that manifest in SAR imagery as bright lines due to elevated SSR of the rips (Isoguchi and Ebuchi, 2020).

Visible spectrum high-resolution imagery of the coastal ocean has been provided by the Landsat mission since 1972. The entire global archive of Landsat imagery is now freely available (Landsat Homepage | Landsat Science (nasa.gov)). Spatial resolution of Landsat imagery is 15 to 60 m, while temporal resolution is 16 days.

3. Remote sensing in marine fisheries

Satellite SST and CHL data that became readily available, respectively, since 1982 and 1997 have immediately found applications in marine fisheries. Thanks to the paramount importance of water temperature to marine biota, the first three decades of satellite oceanography (1960s-1980s) saw an explosion of interest to satellite SST mapping and its applications in fisheries (Fiedler et al., 1984; Laurs and Brucks, 1985; Cornillon et al., 1986; Pettersson et al., 1990; Boehlert and Schumacher, 1997; Santos 2000; Stuart, 2011; Wilson, 2011; Saitoh et al., 2011; Klemas, 2012, 2013; Minnett et al., 2020). The satellite imagery from the Coastal Zone Color Scanner (CZCS) flown on Nimbus-7 were used by fisheries oceanographers early on (Laurs and Brucks, 1985). With the advent of systematic continuous satellite observations of ocean color on a global scale (particularly with the launch of SeaWiFS and especially with the launch of MODIS-Terra and Aqua), ocean color data have been used to estimate CHL concentration and primary productivity; these results have been promptly used in marine fisheries (Stuart, 2011; Wilson, 2011; Saitoh et al., 2011). Numerous modeling studies of fish stocks used statistical models, in which SST and CHL featured as key ecological variables.

The past applications of SST and CHL data in marine fisheries were largely driven by (1) the data's free availability at no cost and (2) ecological importance of water temperature and chlorophyll concentration. Fishes respond to water temperature, and SST is a proxy of the average water temperature in the upper mixed layer, where many pelagic species spend most time. Therefore, SST is rightfully considered to be an important ecological parameter. Countless studies correlated SST with fish catch, CPUE, fish distribution, and different ontogenetic stages of various species. Specifically, certain SST ranges were linked to sites and timings of spawning, nursing, feeding, migration, and mating. Research-quality SST data from AVHRR flown on NOAA polar orbiting satellites have become available since 1982 thanks to the NOAA Pathfinder project. These data allowed a complete global coverage every 12 h. SST maps based on these data were made freely available from NASA and NOAA at a progressively better resolutions of 9 km, 4 km, and 1 km. Cloud contamination remains a major problem since infra-red radiometers cannot see through clouds. By compositing SST images over a week or two, most clouds could be eliminated (except cloud decks that persist for months); however, most important features (fronts and eddies) become blurred.

The important of CHL stems from the well-known connection between CHL and primary production (PP), which is the foundation of food web in all but a few marine ecosystems (save for benthic chemosynthetic ecosystems in the vicinity of hydrothermal vents). Satellite maps of CHL, once available, have quickly found their usage in marine fisheries. A continuous global archive of CHL maps is available since the launch of SeaWiFS in 1997. CHL data have become widely used since the launch of MODIS on Terra (1997) and Aqua (2002) satellites. These data are available free from NASA and NOAA at the same spatial and temporal resolutions as SST data described above. Cloud contamination hampers CHL imagery the same way as it corrupts SST imagery. Intercalibration of CHL data provided by different sensors/satellite missions remained a problem, which was addressed and largely mitigated under the Ocean Colour Climate Change Initiative project (https://www.oceancolour.org).

Satellite SSH data have found its applications in marine fisheries and ecology (e.g., Asch and Checkley, 2013; Liao et al., 2018; Byrne et al., 2019). The main benefit of SSH vs. SST and CHL is that SSH is an integral of vertical density structure of water column (or vertical integral) whereas SST and CHL characterize just a very thin surface layer. Therefore, maps of SSH reveal dynamic features such as eddies and fronts better than maps of SST and CHL. Another important advantage of SSH data is their all-weather nature because radar altimeters can see through clouds. The relatively low spatial resolution of SSH data is the main disadvantage of SSH data vs. SST and CHL data.

The availability of satellite SST and CHL data, including continuous (uninterrupted) global archives of SST (since 1982) and CHL (since 1997), combined with inherent simplicity of their use as scalar gridded data sets, facilitated wide acceptance of SST and CHL as environmental variables in numerous models of fish populations. Such models proliferated exponentially thanks in part to the availability of open access modeling software. Meanwhile, remote sensing applications in marine ecology and fisheries expanded beyond mapping SST and CHL and making such maps and data sets easily and freely available to researchers, fishermen and fisheries managers. A new paradigm based on the ***feature-based approach*** has been gaining the ever-growing popularity, especially in the last 10-20 years. Two classes of oceanic features stand out thanks to their ecological importance and ubiquity, namely ***fronts and eddies***.

4. Ecological role of fronts and eddies

The World Ocean consists of water masses separated by fronts that structure the seemingly continuous ocean into discrete habitats. Evidence mounts of animals seeking out optimum habitats depending on a particular life stage of a given species. In that respect, oceanic fronts are functionally similar to aquatic-terrestrial or purely terrestrial transition zones also called fronts or ecotones. Embedded into the global framework of persistent large-scale and mesoscale fronts are myriads of transient dynamic features such as mesoscale and submesoscale eddies, subsurface lenses, Lagrangian coherent structures, and upwelling zones as well as short-lived meso- and submesoscale fronts created by various processes, e.g., upwelling fronts in the wakes of hurricanes and typhoons. Marine animals have been observed seeking out such dynamic features, particularly mesoscale eddies and Lagrangian coherent structures/fronts as reported by Tew Kai et al. (2009; frigatebirds and tuna in Lagrangian coherent structures), Prants et al. (2014; Pacific saury in Lagrangian fronts), Gaube et al. (2017; loggerhead turtles in eddies), Braun (2018) and Braun et al. (2019; blue sharks in eddies), Watson et al. (2018; tuna in Lagrangian coherent structures) and Chambault et al. (2019; loggerhead turtles in eddies) among many others.

Despite the ever-growing recognition of ecological importance of persistent and transient oceanic ***features***, their usage in marine ecology and fisheries was rather limited until the last decade. Perhaps the main problem that hindered this recent development is ***feature detection and tracking*** in the ocean flow fields. Fortunately, this problem is being addressed. Computer algorithms have been developed to automate detection and tracking of dynamic features from satellite and in situ data and model outputs, including fronts, mesoscale eddies, upwelling zones, and Lagrangian coherent structures (Hobday and Hartog, 2014 (derived ocean features); Haller, 2015 (Lagrangian coherent structures); D'Ovidio et al., 2004 (Finite Size Lyapunov Exponents); Lian et al., 2019 (mesoscale eddies), El Aouni et al., 2020 (upwelling zones)). **This paper is primarily dedicated to ocean fronts.**

Fronts are the most ecologically important circulation and structural features of the ocean realm (Laurs and Lynn, 1977; Holligan, 1981; Krause et al., 1986; Le Fèvre, 1987; Kiørboe et al., 1988; Olson et al., 1994; Polovina et al., 2000, 2001; Acha et al., 2004; Bakun, 2006; Palacios et al., 2006; Bost et al., 2009; Dunn et al., 2011; Scales et al., 2014a; Woodson and Litvin, 2015; Watanuki et al., 2016; Snyder et al., 2017; Cox et al., 2018; Sarma et al., 2018; Martinetto et al., 2020). Each large-scale front is an *ecotone* defined as a narrow transition zone between two adjacent marine ecosystems. Each of these ecosystems inhabits a distinct water mass characterized by a unique combination of temperatures, salinities, nutrients, and microelements. Most large-scale fronts are strongest at the surface. They extend several hundred meters deep, thereby affecting distributions of oceanic variables in surface and subsurface layers. Some large-scale fronts are strongest in subsurface and/or intermediate layers. Finally, there are examples of deep/abyssal fronts that affect benthic ecosystems. Owing to their vertical extent on the order of 1 km, most large-scale fronts separate different water mass assemblies that feature distinct vertical structure/stratification types. Such stratification boundaries profoundly affect sound propagation at sea, thereby shaping ocean soundscapes.

Fronts affect various aspects of ecology of every living creature in the ocean: their migrations, feeding, mating, spawning, nursing, thermoregulation (mako sharks, some sea turtles, and tuna) etc. Fronts are hot spots of marine life as they often are loci of maximum biodiversity and elevated primary and secondary production (Palacios et al., 2006). Abundance of most fish peaks at or near fronts. Fronts are associated with convergences toward fronts that result in elevated levels of pollutants in sea water and in fishes and other organisms that spend considerable time in or near frontal zones. For example, using a fluid dynamics approach to ecosystem modeling of the anchovy–sardine regimes and salmon abundances in the California Current, Woodson and Litvin (2015, p. 1710) have shown that “fronts increase total ecosystem biomass, explain fishery production, cause regime shifts, and … affect fishery abundance and yield.”

Most large-scale and mesoscale fronts are known to feature enhanced primary and secondary productivity and elevated biodiversity. The biomass increase observed at fronts is often caused by current convergence that concentrates passive plankters such as phytoplankton and small zooplankton. Even in the absence of convergence, phytoplankton can grow at fronts (Marra et al., 2013).

Water-mass fronts in *oligotrophic* seas sometime feature elevated primary productivity (manifested in high CHL) thanks to upwelling of nutrient-rich subsurface waters in frontal zones. This phenomenon was observed in the South China Sea (SCS hereafter), where intrusions of oligotrophic Kuroshio waters spurred CHL growth as reported by Guo et al. (2017, p. 11,565): “Strong fronts due to Kuroshio intrusion and interactions with the SCS water are associated with intense upwelling, supplying high nutrients from the subsurface SCS water and increasing phytoplankton productivity in the frontal region.”

The elevated concentration of phytoplankton and small zooplankton attracts large zooplankton and small fish, the latter being preyed upon by larger piscivorous fish and apex predators. Yet, as noted by Woodson and Litvin (2015, p. 1710), “the effects of fronts as fishery productivity and biogeochemical cycling hotspots have not been included in models that assess fisheries production…”

Another ecologically important aspect of fronts is their role as ***biodiversity hotspots*** defined as regions with elevated biodiversity (Woodson et al., 2012; Scales et al., 2014; Svendsen et al., 2020). Biodiversity typically peaks at fronts, although exceptions are reported when biodiversity at a front is lower than biodiversity in two adjacent water masses separated by the front. For example, of 46 fish taxa identified in the Patagonian Shelf Large Marine Ecosystem, “demersal fish diversity increased at the tidal front of Península Valdés but decreased in the frontal zones of the Southern Shelf-Break and Magellan frontal systems” (Alemany et al., 2009, p. 2111).

The ***affinity of fish to ocean fronts*** has been long known to fishermen. In particular, the close association between fish and coastal fronts has been exploited by artisanal fishermen from time immemorial. The affinity of herring stocks to fronts in the Nordic Seas between Iceland and Norway was probably exploited by Norsemen since medieval times. There is little doubt that European fishermen discovered strong fronts of the North Atlantic Current and Labrador Current – they had to cross these currents/fronts - during their regular fishing expeditions to the Grand Banks of Newfoundland, where they fished for Atlantic cod since the early 16th century

(Kurlansky, 1998). In Japan, Michitaka Uda has published numerous papers on fronts and fisheries, including his PhD thesis published as a journal paper in English (Uda, 1938), in which he cited numerous descriptions ocean fronts known in Japan as "shiome" (しおめ in Kana; 潮目in Kanji), which means "junction line between two sea currents, line where two ocean currents meet" (https://jlearn.net/Dictionary/Browse/1953800-shiome). In English-speaking countries, the term "front" was not in use among fishermen until recently. Instead, fronts were called *current rips* or *rips* – not to be confused with *rip currents*.

A strong link between fronts and distribution and abundance of ***pelagic*** fishes has been reported in many studies worldwide and has been exploited by pelagic fisheries for a long time. A similar link between fronts and ***demersal*** fishes received less attention. Meanwhile, in some regions, e.g., in the Argentine Sea, it is the demersal fishes that are most important economically and ecologically, while local fronts are found to be preferable fishing areas for demersal fisheries as shown by distribution of fishing fleets and fishing effort (Alemany et al., 2014). The strong link between demersal fisheries and fronts of the Argentine Sea is paralleled by the strong concentration of scallop fishery along the Shelf-Break Front that borders the Patagonian Shelf (Bogazzi et al., 2005; Mauna et al., 2008). The prominent role of the Shelf-Break Front in the ecology of scallops is not surprising because this front is anchored at depth by bathymetry (shelf break). The stability of the Shelf-Break Front's near-bottom part (as opposed to the high variability of the surface manifestation of this front) ensures the stability of benthic habitat, which is apparently beneficial to the scallops.

The above-mentioned ample historical evidence notwithstanding, the link between fronts and fish has not been firmly established until recently. Two factors have contributed to this recent change. The first factor is the current abundance and free availability of satellite data on SST, CHL, and SSH mentioned in the previous section. The second factor is the proliferation of computer algorithms for front detection in satellite imagery review in the next section.

Occasionally, especially in earlier studies but also in some most recent studies, an elevated SST gradient was used as a front proxy (e.g., Herron et al., 1989; Bigelow et al., 1999); thus fronts (high-gradient zones) were effectively, if not explicitly, considered. Yet systematic use of frontal data in marine fisheries has not occurred until recently despite the commonly accepted and widely recognized importance of ocean fronts in marine ecology. Fortunately, the situation is changing quite rapidly.

The spatial and temporal affinity of fish to fronts is species-specific and is strongly dependent on a life stage of the fish. For example, in a study of Patagonian hoki *Macruronus magellanicus* on the southern Patagonian shelf, Alemany et al. (2018) have found out that younger fish (juveniles) preferred fronts where they preyed upon zooplankton, whereas larger fish (adults) showed no affinity to fronts as they preyed on larger items. Alemany et al. (2018, p. 191) concluded: "The positive relationship observed between small-sized fish and fronts may be related to the low trophic level of these fish and the abundance of small-sized prey in frontal zones."

Mesoscale eddies play important ecological roles that in some respect are similar to the ecological roles played by fronts. Indeed, such eddies often feature sharp gradients along their periphery. These peripheral zones around mesoscale eddies satisfy all three major criteria of a front as they are (1) high-gradient zones that (2) divide different water masses and (3) separate different types of vertical structure (stratification) inside and outside of the eddies.

As pointed out by Braun et al. (2019, p. 17187), "Debate regarding how and why predators use fronts and eddies, for example as a migratory cue, enhanced forage opportunities, or preferred thermal habitat, has been ongoing since the 1950s. The influence of eddies on the behavior of large pelagic fishes, however, remains largely unexplored." Combination of remote sensing of eddies with satellite tracking of animal movements has a potential to elucidate the impact of eddies on the ecology of fishes as exemplified by a recent study of blue sharks in the Gulf Stream region (Braun et al., 2019). It turned out that the sharks seek out anticyclonic (AC) eddies, particularly the ***interiors of AC-eddies***, for foraging. A remote sensing/satellite tracking study of juvenile loggerhead turtles in the Southwest Atlantic (Gaube et al., 2017) revealed a similar tendency as the turtles tend to congregate in the interiors of AC-eddies, apparently to feed, despite low-CHL concentrations in surface layers of these eddies. These observations (and some previous (Godø et al., 2012) and most recent (Arur et al., 2020) studies as well) show that AC-eddies are not lifeless ocean deserts as commonly thought in the past. Conversely, mesoscale AC-eddies support the most abundant mesopelagic fish community in the World Ocean (Braun et al., 2019). The above findings dovetail with a remote sensing study of loggerhead turtles in the Azores region (Chambault et al., 2019) that revealed the turtles' affinities for the ***inner cores of old AC-eddies***, supposedly due to the higher productivity of old, decaying AC-eddies. Contrasting with the above results of Gaube et al. (2017), Braun et al. (2019) and Chambault et al. (2019) that point to the higher productivity of the ***interiors*** of AC-eddies are observations reported by Godø et al. (2012) who found a fish biomass minimum in the centers of three AC-eddies in the Norwegian Sea. In the Mozambique Channel, Tew Kai and Marsac (2010) found good foraging conditions for frigatebirds and tuna along ***edges*** of mesoscale ***cyclonic*** eddies and suggested that these conditions arise from the aging process of the cyclonic eddies and their interaction with other eddies. Analyzing fisheries data from the NE Indian Ocean, Arur et al. (2014) found that higher catches were associated with ***the periphery of anticyclonic and the cores of cyclonic eddies*** (supposedly due to upwelling), while lower catches were associated with the periphery of cyclonic and the cores of anticyclonic eddies (supposedly due to downwelling).

The contradicting results cited above warrant further investigations of the fine-scale horizontal and vertical distributions of productivity in mesoscale eddies.

Occasionally, **CHL fronts develop at SST fronts around eddies**. In the South China Sea, Ye et al. (2018) documented SST fronts at peripheries of mesoscale anticyclonic eddies. These peripheral SST fronts exerted stronger influence on surface CHL than seasonal coastal and permanent offshore SST fronts. The CHL enhancement along peripheral SST fronts around eddies is ascribed to 'wind pump' upwelling generated by a typhoon that passed over the eddies (Yu et al., 2018). In the NE Pacific off British Columbia, a combined analysis of several years of SST and CHL imagery allowed the author to identify a large well-defined CHL ring collocated with a warm SST ring (AC-eddy); the CHL ring has likely developed over the pre-existing warm AC-ring (Belkin, I.M., 2020, Satellite climatology of SST and CHL fronts off British Columbia, in preparation).

Even though ecological roles played by fronts and eddies are often quite similar as noted above, ***automated detection of fronts and eddies*** from satellite data is typically performed with radically different algorithms. Following the publication of seminal paper by Chelton et al. (2011), the automated ***eddy detection*** from satellite data has grown into a mature field, with a multitude of eddy detection and tracking algorithms that are often based on different principles (e.g., Lian et al., 2019). Thus, eddy detection from satellite data warrants a separate review. In this paper we focus solely on ***front detection*** and its applications in marine ecology and fisheries.

5. Front detection in satellite imagery

The potential and importance of satellite observations of thermal and color (CHL) ***fronts*** for marine ecology and fisheries were recognized early on (Legeckis, 1978; Laurs et al., 1984; Boehlert and Schumacher, 1997; Polovina et al., 2000, 2001; Stuart, 2011; Wilson, 2011; Chassot et al., 2011; Saitoh et al., 2011; Alemany et al., 2014; Martinetto et al., 2020). Frontal maps are now generated by computer algorithms that detect fronts in satellite images of oceanic variables. Since fronts are narrow high-gradient zones in satellite images, the task of front detection is equivalent to *edge detection* in image processing. This terminology is consistent with ocean fronts being boundaries that separate different water masses; thus, each front is a water mass edge. In general-purpose image processing the tasks of edge detection and image segmentation (into uniform segments) are often complementary. In oceanography, the task of front detection in satellite imagery of oceanic variables can often be considered as complementary to the task of water mass identification, especially regarding large-scale fronts such as the Gulf Stream or Kuroshio.

Various approaches to front detection (or edge detection) in oceanography have been suggested and implemented (for a brief review see Introduction in Belkin and O'Reilly, 2009). The brief survey below covers algorithms and techniques that were used multiple times in studies of marine ecology and fisheries; as such, these approaches are *de facto* established. The most popular front detection algorithms/techniques (listed chronologically) are: Canny (1986), Cayula and Cornillon (1990, 1992, 1995), Shimada et al. (2005), Belkin and O'Reilly (2009), Miller (2009), and Nieto et al. (2012). Not all of them are independent as Miller (2009) and Nieto et al. (2012) are based on Cayula and Cornillon (1992).

Canny algorithm: Historically, the gradient approach was tried first, based on the most common and widely accepted definition of fronts as high-gradient zones separating relatively uniform water masses. The main disadvantage of the gradient approach is the noisiness of the gradient field since differentiation effectively amplifies any noise present in data. Various algorithms addressed this disadvantage. The most popular all-purpose gradient-based algorithm for edge detection in 2D imagery has been developed by Canny (1986). The Canny algorithm is implemented in Matlab, IDL, Python, C++, R, and Java. It was widely used to detect fronts in SST imagery (Castelao et al., 2005, 2006; Castelao and Wang, 2014; Wang Y.T. et al., 2015; Hu J.W. et al., 2016; Chen H.H. et al., 2019, 2020; Saldías and Lara, 2020; Wang Y.T. et al., 2020). The Canny algorithm was also used to detect fronts in CHL imagery (Wall et al., 2008; Chakraborty et al., 2019) and in SAR imagery, where some fronts manifest as bright lines of elevated sea surface roughness (Jones et al., 2012, 2013).

Cayula-Cornillon algorithm (CCA): The most sophisticated edge detection algorithm in satellite oceanography has been developed by Jean-François Cayula and Peter Cornillon at the University of Rhode Island in the 1990s for SST imagery (Cayula and Cornillon, 1990, 1992, 1995) and later successfully applied to CHL imagery. The Cayula-Cornillon algorithm (CCA) is based on histogram approach: a histogram of SST values of all pixels within an image of a front separating two water masses M1 and M2 would always have two modes corresponding to the water masses M1 and M2, while the front is a locus of SST values that correspond to a minimum between the two modes. At the University of Rhode Island, the CCA has been applied to all available AVHRR SST imagery since 1982, thereby creating a unique global archive of frontal maps that allowed a global survey of SST fronts to be conducted (Belkin and Cornillon, 2007; Belkin, Cornillon, and Sherman, 2009).

The CCA is available as a single image edge detector (SIED; Cayula and Cornillon 1992) and multiple window edge detector (Cayula and Cornillon 1995). The CCA gained a wide popularity and has been used in numerous studies to study SST fronts globally (Belkin and Cornillon, 2007; Belkin, Cornillon, and Sherman, 2009) and locally in the following regions:

Atlantic Ocean: Baltic Sea (Kahru et al., 1995), Mid-Atlantic Bight (Ullman and Cornillon, 1999, 2001; Stegmann and Ullman, 2004), Georges Bank (Mavor and Bisagni, 2001), Gulf of Maine (Schick et al., 2004), Western North Atlantic (Podesta et al., 1993), Western Iberian Basin (Peliz et al., 2005; Otero et al., 2009; Mantas et al., 2019), Sargasso Sea (Ullman et al., 2007), Canadian coastal waters (Cyr and Larouche, 2015), West Florida Shelf (Wall et al., 2008), North Atlantic Current region (Miller et al., 2013).

Pacific Ocean: Marginal and coastal seas (Belkin and Cornillon, 2003), Bering Sea (Belkin et al., 2003; Belkin and Cornillon, 2005; Belkin, 2016;), Okhotsk Sea (Belkin and Cornillon, 2004), Gulf of Alaska (Belkin et al., 2003), California Current (Kahru et al., 2012, 2018), East China Seas (Hickox et al., 2000); South China Sea (Wang et al., 2001; Yao et al., 2012), Tasman Sea (Hobday and Hartog, 2014); Chilean Northern Patagonia (Bedriñana-Romano et al., 2018).

Indian Ocean: Red Sea (Eladawy et al., 2017), North Indian Ocean (Mohanty et al., 2017; Sarma et al., 2018; Chakraborty et al., 2019; Sarkar et al., 2019).

Arctic Ocean: Chukchi Sea (Belkin et al., 2003), Beaufort Sea (Belkin et al., 2003), Canadian coastal waters (Cyr and Larouche, 2015), Beaufort Sea (Mustapha et al., 2016).

CCA applications to CHL imagery: Even though the CCA has been originally developed to detect fronts in SST imagery, it has been successfully applied to CHL imagery as well (Stegmann and Ullman, 2004; Bontempi and Yoder, 2004; Kahru et al., 2012).

CCA availability: Since 2010, the CCA-SIED has become publicly available as an R code included in the Marine Geospatial Ecology Tools (MGET) developed by Jason Roberts and collaborators at the Marine Geospatial Ecology Laboratory, Duke University (Roberts et al., 2010). Thanks to the free access to CCA-SIED as part of MGET (available at http://mgel.env.duke.edu/tools), the CCA gained even more popularity and has been used in numerous marine ecological studies reviewed in the next section.

Miller analysis: Peter Miller and collaborators have developed a novel and powerful technique based on combining and compositing frontal maps of different oceanic variables, e.g., SST and CHL (Miller, 2004, 2009; Miller et al., 2015a; Suberg et al., 2019). Miller's composite frontal map analysis has been used in marine ecological studies reviewed in the next section.

Nieto algorithm: The original CCA-SIED algorithm has been modified by Karen Nieto, Herve Demarcq, and Sam McClatchie and applied to the Canary Current System (Nieto, Demarcq, and McClatchie, 2012). The Nieto algorithm uses a combination of multiple sliding windows and significantly improves the CCA-SIED performance. The Nieto algorithm has been used in a few studies, including marine ecological studies (Nieblas et al., 2014; Roa-Pascuali, Demarcq, and Nieblas, 2015; Nieto et al., 2017; Xu et al., 2017).

Shimada algorithm: David Pozo Vázquez et al. have applied an entropic approach to edge detection in SST images (Vázquez et al., 1999). This approach (first proposed by Barranco et al., 1995) uses the Jensen-Shannon divergence (Lin, 1991) as a criterion of separation between histograms generated by a window sliding over an image. The Vázquez et al. (1999) algorithm has been modified and applied in satellite oceanography by Teruhisa Shimada and collaborators (Shimada et al., 2005). Shimada's algorithm has been used in a few studies of fronts in the China Seas, including marine ecology studies reviewed in the next section.

Belkin and O'Reilly algorithm (BOA): Igor Belkin at the University of Rhode Island and John E. O'Reilly at the NOAA have developed a novel gradient-based algorithm and applied it to SST and (Belkin and O'Reilly, 2009). The main novelty of the Belkin-O'Reilly algorithm (BOA) is a shape-preserving, scale-sensitive, contextual median filter applied selectively and iteratively until convergence. This filter eliminates noise while preserving stepwise fronts and two features endemic to CHL, namely (a) *roof edges* corresponding to *chlorophyll enhancement* at hydrographic fronts, and (b) *peaks* corresponding to *point-wise chlorophyll blooms*. Both features are common in CHL imagery. The BOA is universal as it can be applied to any scalar oceanic variable. For instance, in a study of the NE Pacific fronts off the British Columbia, the BOA has been successfully applied to SST, CHL, SSH, and satellite radar imagery (Gary Borstad, ASL Borstad Remote Sensing Inc., Canada, personal communication). The BOA has been originally developed in Matlab and converted to IDL by Jay O'Reilly (Belkin and O'Reilly, 2009). The BOA IDL code has been converted to C++ (Belkin et al., 2013) and officially adopted by NOAA to maps CHL fronts. Frontal maps produced by NOAA with the BOA C++ code are freely available daily from the NOAA. These frontal maps cover all U.S. waters in the Atlantic, Pacific, and Arctic Oceans and a few selected regions in the Atlantic (Caribbean Sea) and Pacific (Eastern Equatorial and Tropical Pacific).

BOA R code by Galuardi: The BOA pseudocode published by Belkin and O'Reilly (2009) has stimulated the BOA implementation in various computer languages. Ben Galuardi has implemented the BOA pseudocode in R and made his BOA-R code publicly available (https://github.com/galuardi/boaR).

BOA applications: The BOA has been released to numerous groups around the world after its publication in 2009 and has been successfully used to map ocean fronts in various regions, including the East China Sea (Liu D.Y. et al., 2018), Yellow Sea (Sun et al., 2018; Lin et al., 2019), South China Sea (Zeng et al., 2014; Guo et al., 2017), Kuroshio Current (Liu Z. and Hou, 2012) British Columbia waters (Belkin, I.M., 2020, Satellite climatology of SST and CHL fronts off British Columbia, in preparation) and other regions. The BOA applications in marine ecological studies are reviewed in the next section.

6. Feature-based approach to remote sensing in marine ecology and fisheries

The ever-growing recognition of the paramount importance of ***circulation features such as fronts and eddies*** combined with the development and validation of various algorithms for feature detection and tracking from satellite data have profoundly transformed this entire field and led to the incorporation of front and eddies into the ***dynamic ocean management*** (Hobday and Hartog, 2014; Alemany et al., 2014; Scales et al., 2014b; Woodson and Litvin, 2015; Hazen et al., 2018; Cox et al., 2018; Watson, 2018; Martinetto et al., 2020).

Table 1 sums up remote sensing studies of ecological role of ***fronts*** conducted with the most popular front detection and mapping algorithms and techniques (chronologically: Canny, 1986; Cayula and Cornillon, 1990, 1992, 1995; Miller, 2004, 2009; Shimada et al., 2005; Belkin and O'Reilly, 2009; Nieto et al., 2012). Also included in **Table 1** are remote sensing/marine ecology/fisheries studies that used a simple *gradient* calculation in lieu of more sophisticated front detection/mapping techniques listed above. The inclusive approach to **Table 1** is justified because the studies based on a simple gradient calculation could be extended and upgraded by using one of several advanced front detectors that are now freely available.

Table 1. Remote sensing of fronts in marine ecology and fisheries

CCA: Cayula-Cornillon algorithm (Cayula and Cornillon 1990, 1992, 1995)
SIED: Single-Image Edge Detection algorithm (Cayula and Cornillon 1992)
MGET: Marine Geospatial Ecology Tools (Roberts et al. 2010)
Miller: Multispectral composite frontal map analysis (Miller 2009)
Nieto: CCA modification by Nieto et al. (2012)
BOA: Belkin-O'Reilly algorithm (Belkin and O'Reilly 2009)
RG: BOA R code by Ben Galuardi (https://github.com/galuardi/boaR)
Shimada: Entropy-based edge detection algorithm by Shimada (2005)
Canny: Edge detection algorithm by Canny (1986)

Reference (first author, year)	**Region**	**Front detection algorithm/technique**	**Species**
Abdullah 2017	Arabian Sea	CCA-SIED	Tuna
Austin 2019	NE Atlantic off UK	CCA-SIED-MGET; Miller	Basking shark
Bedriñana-Romano 2018	Chilean Patagonia	CCA-SIED-MGET	Blue whale
Bigelow 1999	North Pacific	Gradient	Swordfish, blue shark
Bogazzi 2005	Patagonian Shelf	Gradient	Patagonian scallops
Braun 2018	North Atlantic	BOA-RG	Sharks
Brigolin 2018	Alboran Sea	CCA-SIED; Miller	Various fishes
Brodie 2015	Tasman Sea	CCA	Dolphinfish, kingfish
Byrne 2019	North Atlantic	BOA-RG	Shortfin mako shark
Camacho 2010	California Current	CCA-SIED	Whales and dolphins
Chakraborty 2019	North Indian Ocean	CCA-SIED; Canny	Various species
Chambault 2017	Gulf Stream	Gradient	Leatherback turtle
Chambault 2018	Baffin Bay, Hudson Bay	Gradient	Bowhead whale
Chen X.J. 2014	NW Pacific	Gradient	Neon flying squid

Cox 2016	Celtic Sea	CCA-SIED; Miller	Gannets
Dalla Rosa 2012	NE Pacific	CCA-SIED-MGET	Humpback whale
Dell 2011	Tasman Sea	CCA-SIED	Yellowfin tuna
Dodge 2014	Northwest Atlantic	BOA-RG	Leatherback turtle
Druon 2011	Mediterranean Sea	Gradient	Atlantic bluefin tuna
Druon 2017	Arctic Ocean	Gradient	Various species
Ebango Ngando 2020	Mauritanian upwelling	CCA-SIED	Mackerel, sardinella
Etnoyer 2006	NE Subtropical Pacific	Gradient	Blue whales, turtles
Francis 2020	Indian Ocean	CCA-SIED; Canny	Potential fishing zone
Friedland 2020	US Northeast Shelf	Gradient	Various species
Glembocki 2015	Patagonian Shelf	Gradient	Patagonian red shrimp
Haberlin 2019	Celtic Sea	CCA-SIED-MGET	Gelatinous zooplankton
Herron 1989	Gulf of Mexico	Gradient	Butterfish
Hidayat 2019	Bone Gulf, Indonesia	CCA-SIED	Skipjack tuna
Hsu 2017	West & Central Pacific	BOA	Skipjack tuna
Hua 2020	NW Pacific	Gradient	Pacific saury
Jakubas 2020	Svalbard	CCA-SIED	Little auks
Jishad 2019	Bay of Bengal	Gradient	Various species
Kulik 2019	Northwest Pacific	BOA-RG	Pacific saury
Lan 2012	South Indian Ocean	Shimada	Albacore tuna
Lennert-Cody 2008	Eastern Tropical Pacific	CCA-SIED	Bigeye tuna
Liao 2018	East China Sea	Shimada	Swordtip squid
Liu 2020	East China Seas	CCA-SIED-MGET	Anchovy
Louzao 2009	Western Mediterranean	CCA-SIED-MGET	Cory’s shearwater
Luo 2015	Western North Atlantic	BOA	Tuna, marlin, sailfish
Mauna 2008	Patagonian Shelf	Gradient	Patagonian scallop
Mazur 2020	US Northeast Shelf	CCA	American lobster
Miller 2015	NE Atlantic	CCA-SIED; Miller	Basking shark
Mitchell 2014	English Channel	CCA-SIED	Blue shark
Mugo 2014	NW Pacific	CCA-SIED-MGET	Tuna, squid, saury
Nieblas 2014	SE Tropical Indian Ocean	CCA-SIED-Nieto; Canny	Southern bluefin tuna
Nieto 2017	NE Pacific	CCA-SIED-Nieto	Albacore tuna
Nishizawa 2015	North Pacific	CCA-SIED-MGET	Albatrosses
Oh 2020	Japan Sea	BOA	Japanese flying squid
Pikesley 2013	Gabon-Angola	CCA-SIED-MGET	Olive ridley turtle
Pikesley 2015	Cape Verde	CCA-SIED-MGET	Loggerhead turtle
Podesta 1993	Mid-Atlantic Bight	CCA	Swordfish
Reese 2011	California Current	CCA-SIED	Sardine, anchovy, herring
Retana 2017	San Jorge Gulf, Arg.	CCA-SIED-MGET	Marine mammals
Royer 2004	Gulf of Lions, W. Med. Sea	Canny	Bluefin tuna
Sabal 2020	California Current	CCA-SIED	Salmon
Sabarros 2014	Benguela Upwelling	CCA-SIED-Nieto	Cape gannet

Sagarminaga 2014	NE Atlantic	BOA	Albacore tuna
Santiago 2019	Indian Ocean	BOA-RG	Yellowfin tuna
Santiago 2020	Atlantic Ocean	BOA-RG	Yellowfin tuna
Sarma 2018	Arabian Sea	CCA-SIED	Zooplankton
Scales 2014b	Celtic Sea	CCA-SIED; Miller	Gannet
Scales 2015	Canary Current	CCA-SIED; Miller	Loggerhead turtle
Scales 2016	South Atlantic	CCA-SIED; Miller	Grey-headed albatross
Schick 2004	Gulf of Maine	CCA	Bluefin tuna
Soldatini 2019	Baja California Peninsula	BOA	Black-vented shearwater
Sousa 2016	Gulf of Cadiz	CCA-SIED-MGET	Sunfish (mola mola)
Suhadha 2020	Bali Strait, Indonesia	CCA-SIED-MGET	Bali sardinella
Svendsen 2020	San Matias Gulf, Arg.	CCA-SIED-MGET	Various species
Swetha 2017	Northern Indian Ocean	CCA-SIED-MGET	Potential Fishing Zone
Thorne 2019	NW Atlantic	CCA-SIED-MGET	Pilot whale
Trew 2019	Gulf of Guinea	CCA-SIED-MGET	Mammals, turtles
Tseng 2014	Northwest Pacific	CCA-SIED	Pacific saury
Varo-Cruz 2016	Eastern North Atlantic	CCA-SIED-MGET	Loggerhead turtle
Wall 2009	West Florida Shelf	CCA-SIED; Canny	King mackerel
Wang J 2007	Patagonian Shelf	Gradient	Hake
Wang YC 2013	South China Sea	Shimada	Ichthyoplankton
Wang YC 2018	East China Sea	Shimada	Ichthyoplankton
White 2020	Nantucket Shoals	BOA	Ducks, scoters
Woodson 2012	California Current	BOA	Rockfishes, invertebrates
Xu 2017	NE Pacific	CCA-SIED-Nieto	Albacore tuna
Zainuddin 2020	Makassar Strait, Indonesia	CCA-SIED	Skipjack tuna
Zhou 2020	South Pacific	BOA; CCA-SIED-Nieto	Albacore tuna

Analysis of **Table 1** reveals two trends. First, the entire field of front detectors is dominated by the Cayula-Cornillon algorithm (CCA), especially the Single-Image Edge Detector (SIED; Cayula and Cornillon, 1992) implemented as an R code in the Marine Geospatial Ecology Tools (MGET) framework (Roberts et al., 2010). The CCA-SIED domination is especially prominent due to the Miller analysis (2004, 2009) and Nieto et al. (2012) algorithm being based on CCA-SIED.

Second, **the geographical distribution of the fisheries studies** included in **Table 1** is strongly non-uniform. Three regions stand out: (1) Patagonian Shelf and Shelf-Break (Argentine Sea); (2) North Indian Ocean, especially Arabian Sea and Bay of Bengal, and (3) Western North Pacific and its marginal seas.

The Patagonian Shelf and Shelf-Break feature several well-defined quasi-stationary year-round fronts. This region is thus unique in the entire World Ocean since there are no other regions with year-round fronts (Belkin, Cornillon, and Sherman, 2009). Fronts of the Patagonian Shelf and Shelf Break are targeted for their stocks of scallops (Bogazzi et al., 2005; Mauna et al., 2008), shrimp (Glembocki et al., 2015), hake (Wang J. et al., 2007), and various pelagic and demersal fish species (Alemany et al., 2014; Svendsen et al., 2020).

The North Indian Ocean is devoid of strong quasi-stationary fronts save for river plume fronts associated with the Ganges-Brahmaputra and Irrawaddy freshwater outflows/discharges (Belkin and Cornillon, 2007; Belkin, Cornillon, and Sherman, 2009). Nonetheless, numerous papers by Indian, Pakistani, and Indonesian researchers are dedicated to fronts and their effects on fisheries, particularly regarding Potential Fishing Zones (PFZ; Abdullah et al., 2017; Swetha et al., 2017; Sarma et al., 2018; Chakraborty et al., 2019; Hidayat et al., 2019; Jishad et al., 2019; Francis et al., 2020; Suhadha et al., 2020; Zainuddin et al., 2020), with tuna being the main target (Abdullah et al., 2017; Hidayat et al., 2019; Zainuddin et al., 2020).

The Western North Pacific and its marginal seas feature numerous diverse fronts formed by tidal mixing, river discharge, wind-induced upwelling, and water mass convergence (Hickox et al., 2000; Belkin, Cornillon, and Sherman, 2009). These fronts structure regional ecosystems and play important roles in local fisheries (Wang Y.C. et al., 2013; Chen X.J. et al., 2014; Mugo et al., 2014; Tseng et al., 2014; Liao et al., 2018; Wang Y.C. et al., 2018; Hua et al., 2020; Liu et al., 2020; Oh et al., 2020), with major target species being tuna (Mugo et al., 2014), squid (Chen X.J. et al., 2014; Mugo et al., 2014; Liao et al., 2018; Oh et al., 2020), saury (Mugo et al., 2014; Tseng et al., 2014; Hua et al., 2020), and anchovy (Liu et al., 2020).

The rest of the world is represented by few fisheries studies. Perhaps, **Table 1** is under-representing a vast body of remote sensing/fisheries studies of fronts conducted in China, Japan, Korea, Taiwan, and Russia since in these countries such studies are largely published in domestic fisheries journals in respective languages.

7. Conclusions

Physics: Fronts are formed by a wide variety of physical processes. Main physical frontal types have been known for a century such as tidal mixing fronts, water mass convergence fronts, coastal upwelling fronts, equatorial upwelling fronts, topographic upwelling fronts, river plume fronts, fronts of marginal ice zone etc. (Belkin, Cornillon, and Sherman, 2009). Depending on a particular front generation mechanism, a given front can be seasonal or perennial, and their predictability in space and time varies greatly, depending on several factors. Tidal mixing fronts (TMFs) are highly predictable in space and time as tides are predictable. Locations of TMFs are largely controlled by bathymetry, which anchors such fronts. However, during each season, exact locations of TMFs depend on air-sea interaction and establishment of summertime stratification.

Some fronts change their physical nature from one season to another. For example, the Zhejiang-Fujian Front in the East China Sea (Hickox et al., 2000) is a classical water mass front along the offshore boundary of the southward China Coastal Current during annual wintertime northeastern monsoon. However, during summertime southwestern monsoon the China Coastal Current reverses and retreats to the north, being pushed by the southwesterly winds blowing along the Zhejiang-Fujian Coast and driving upwelling, resulting in the Zhejiang-Fujian Front becoming an upwelling front.

Stability of fronts can be quantified by calculating frontal frequency at a given geographical location. Analysis of frontal frequency maps in various geographical regions of the World Ocean has shown that some well-known large-scale fronts (e.g., extensions of western boundary currents) do not transpire in such maps (Belkin and Cornillon, 2007; Belkin, Cornillon, and

Sherman, 2009). This phenomenon can be explained by the increased variability of such currents and associated fronts away from the western boundaries, in the open ocean, where topographic steering is absent or extremely weak. Many persistent fronts are quasi-stationary, e.g., shelf-break fronts and tidal mixing fronts. In such cases, a long-term map of pixel-based frontal frequencies portrays such fronts as ridges of elevated frequencies. Ridge lines in such maps are assumed to be the most likely paths of the respective fronts. Examples of such robust fronts and frontal frequency maps can be found, e.g., in Belkin and Cornillon (2003, 2004, 2005, 2007) and Belkin, Cornillon, and Sherman (2009).

Biology: Associations between fronts and biota are species-specific and critically dependent on a life stage of a given species. For example, skipjack tuna in the North Pacific spawn at the Subtropical Front (south of 30°N) but migrate to the Subarctic Front (around 40°N) for feeding. Most fronts feature maximum biodiversity, while some fronts feature minimum biodiversity when an elevated biomass at the fronts is maintained by a few super-abundant species of fish. Each physical aspect of every front – such as its spatial and temporal scales/extent, horizontal and vertical structure, development stage, TS-gradients, cross-frontal ranges of physical and biochemical parameters (nutrients, oxygen concentration), spatial and temporal variability of the front etc. - may affect different species differently and it may affect the same species differently depending on the current ontogenetic stage of the species.

Logistics: Comprehensive sets of frontal data (location, development stage, cross-frontal ranges of physical (T, S, density) and biochemical (nutrients, CHL, O2) parameters, vertical structure etc.) are not readily available in the great majority of cases. Most satellites can provide either all-weather low-resolution data or cloud-contaminated high-resolution data on T, S, SSH, and CHL. Satellite-borne synthetic aperture radar (SAR) data is the only exception from the above dichotomy as SAR provides all-weather high-resolution data. Temporal resolution of satellite data varies between 15 min. (geostationary satellites) and 16 days (Landsat). Data latency (time lag between data acquisition and uploading the data on the Web) is constantly improving. Currently, SST and CHL data provided by NASA and NOAA are available within 12-24 h; the agencies are aiming at reducing the data latency to 4-to-6 hours. Information on vertical structure (stratification) can be inferred from SSH data combined with collocated Argo buoys and climatological oceanographic data (e.g., World Ocean Database).

Frontal metrics and indexes: Each snapshot of a front (obtained with *in situ* and/or satellite data in 1D, 2D, or 3D) can be characterized by several numbers: location, vertical extent, horizontal extent, cross-frontal horizontal gradients, and ranges of physical (T, S, density) and biochemical (nutrients, oxygen concentration) variables at various depths. Fronts that separate qualitatively different types of stratification need additional non-numerical descriptors that reflect a qualitative change of vertical structure across the front. A comprehensive set of frontal parameters (metrics) inferred from *in situ* surface and subsurface data can be combined with satellite-derived frontal metrics such as cross-frontal gradients and ranges of SST, SSS, CHL, SSH as well as metrics of the front's persistence that are commonly evaluated by calculating pixel-based frontal frequency. The most challenging problem is how to combine such multiple diverse characteristics as those enumerated above. The multispectral composite frontal map analysis developed by Peter Miller seems to be the most promising (Miller, 2004, 2009; Miller et al., 2015a; Brigolin et al., 2018; Suberg et al., 2019).

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