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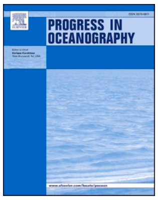

Three decades of continuous ocean observations in North Atlantic Spanish waters: The RADIALES time series project, context, achievements and challenges

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ABSTRACT

Ship-based time-series observations provide crucial data for understanding marine ecosystems, improving decision making in ocean and coastal management. However, only a few time series survive for more than a decade. RADIALES is one of the longest multidisciplinary programs in operation in the northern and northwestern coast of Spain. In the last 30 years, this program collected monthly data on physical, chemical and plankton observations in an array of five sections of stations representative of upwelling and stratified dynamics. Here, the main achievements, including key contributions to ecosystem conservation policies, are summarized. The development of this program, in line with similar initiatives in other countries, included phases focused on the study of seasonality, on comparative analysis, and lately on the analysis of decadal variability and regime shifts. Furthermore, in recent years there was a substantial improvement in the identification of plankton species by genomics. Among the main findings of RADIALES are the quantification of ocean warming at subsurface layers, the determination of climatologies in thermohaline, biogeochemical and biological variables, the inventory of plankton species (from bacteria to zooplankton) and the identification of regionally coherent regime shifts. Baselines defined by RADIALES series were instrumental for the assessment of environmental impacts (e.g. oil spills) and for the support of environmental policies (e.g. Marine Strategy Framework Directive). By contributing to international databases, data from programs as RADIALES combined with new instrumental observations will help to develop a more coherent and comprehensive understanding of the ocean ecosystems, enhancing our ability to detect and forecast risks.

Acronyms and Abbreviations: AGL, Oceanic-atmospheric buoy Augusto González Linares; ALOHA, A Long-term Oligotrophic Habitat Assessment; AVHRR, Advanced Very High Resolution Radiometer; BATS, Bermuda Atlantic Time-series Study; CalCOFI, California Cooperative Oceanic Fisheries Investigations; CARIACO, Carbon Retention in a Colored Ocean; CLIVAR, Climate Variability and Predictability; CTD, Conductivity, Temperature and Depth sensors; EMB, Ecosystem Based Management; EMODnet, European Marine Observation and Data Network; EOVs, Essential Ocean Variables; ESTOC, European Station for Time series in the Ocean Canary Islands; EuroGOOS, European Global Ocean Observing System; EuroSITES, European Open Ocean Observatory Network; GDAC, Global Data Assembly Centers; GLOBEC, Global Ocean Ecosystem Dynamics; GOOS, Global Ocean Observing System; HOT, Hawaii Ocean Time-series; ICES, International Council for the Exploration of the Sea; IEO, Instituto Español de Oceanografía; IFREMER, Institut Français de Recherche pour l'Exploitation de la Mer; IGBP, International Geosphere-Biosphere Programme; IGMETS, International Group for Marine Ecological Time Series; IMBER, Integrated Marine Biogeochemistry and Ecosystem Research; IOC, Intergovernmental Oceanographic Commission; IPCC, Intergovernmental Panel for Climate Change; IROC, ICES Report on Ocean Climate; JOGFS, Joint Global Ocean Flux Study; MSFD, European Marine Strategy Framework Directive; MSP, Marine Spatial Planning; NOAA, National Oceanic and Atmospheric Administration; OceanSites, Time series Environment observation System; R+D+i, Research and development and innovation; RADIALES, Estudio de las series históricas de datos oceanográficos; RAIA, Oceanic observatory for the Iberian shelf; SATS, Santander Atlantic Time-Series; SCOR, Scientific Committee on Oceanic Research; SeaDataNet, Pan-European Infrastructure for Ocean & Marine Data Management; SST, Sea Surface Temperature; UNESCO, United Nations Educational, Scientific and Cultural Organization; US NDBC, United States National Data Buoy Center; VACLAN/RADPROF, Variabilidad climática en el Atlántico Norte/ RADIALES Profundos; WOA, World Ocean Assessment.

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1. Introduction

1.1. Motivation to establish ocean long-term time series programmes: The year 1988

Ocean time series, in particular ship-based repeated measurements, is one type of observation programmes crucial to answer scientific questions and to improve decision making in ocean and coastal management (Jassby and Powell, 1990; Gamble, 1994; Edwards et al., 2010). These types of ocean observing systems provide the scientific oceanographic community with the long, temporally resolved, high-quality data sets needed to characterize ocean physics, climate, biogeochemistry, and ecosystem variability and change that can be used to examine, test, and refine many paradigms and stimulate the formulation of new insightful hypotheses about the functioning of the ocean (Legendre and Demers, 1984; Karl et al., 2003; Henson, 2014). They also help to disentangle natural and human induced changes in marine ecosystems (Reid and Valdés, 2011).

The history of long-term ocean time series started more than 100 years ago. In the Western English Channel and around the British Isles records go back to the late 19th century. A broad suite of ocean weather stations and marine time series sites was established in the middle of the 20th century in the Northern Hemisphere, e.g. Station M in the Norwegian Sea – 1948, NOAA[1] Ocean Station P Sea in the North Pacific – 1947, Henry Stommel's 'Hydrostation S' in the Sargasso Sea – 1954, Boknis Eck Time Series Station where monthly sampling began in April 1957 (Dickson, 1995; Owens, 2014).

During the last 35 years, there have been calls for comprehensive international core projects designed to answer some key oceanographic questions, often related to the understanding of crucial ocean processes, and to the sustainability and health of the ocean system. A good example of these initiatives were two IGBP programmes: JGOFS (1987–2003) and GLOBEC (1992–2009), initiated by SCOR and co-sponsored by the IOC in between 1987 and 2010, with the aim of advancing our understanding on how global change will affect the abundance, diversity, and productivity of marine populations and their ecosystems (GLOBEC, 1992; GLOBEC, 1993; Karl et al., 2003).

Many coastal and oceanic time series were established across different oceans and managed by different countries since the 1980′s and the 1990′s following the recommendations from international programmes such as JGOFS and GLOBEC. The year 1988 was particularly fruitful as several time series were established, survived and gained international prestige, these include for instance HOT[2], BATS, Plymouth L4, and RADIALES (Valdés et al., 2002, Karl et al., 2003; Harris, 2010) and these provide the reference baselines for different variables at local–regional scales and in different ocean biogeographical provinces (Table 1).

The Global Ocean Observing System (GOOS) was created in 1991 by the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) to better understand the ocean's role in global climate, in response to calls from the Second World Climate Conference, held in Geneva in October 1990. Sustained repeat measurements from ocean time series such as HOT, BATS, RADIALES and others created in 1988 or earlier, became fundamental national components of GOOS since its very beginning.

1.2. Scales of sampling and levels of understanding

We know that the dynamics of marine ecosystems is subject to a natural variability that manifests itself on different temporal and spatial scales, which interact with the biological cycles of the species, producing fluctuations in their abundance that are not always easy to explain and that make it very difficult to determine the equilibrium states of species and communities. Temporal variability occurs at all scales of the spectrum, but express preferentially at some of them. For the sake of ocean observing systems, the relevant scales are the seasonal (related to timing of processes) and long-term (inter-annual and decadal) cycles. Spatial variability is associated with horizontal and vertical movements of water overlaying on top of local conditions. The combined effect of the various components of spatial and temporal variability limits our ability to make predictions about how environmental changes can affect the physical properties and biological communities of water bodies over a given period of time. Furthermore, human uses (and abuses) of the ocean space such as fishing, pollution, coastal degradation, global warming, etc., also limits our ability to differentiate impacts of natural origin from those having an anthropogenic disturbance cause.

To reduce the uncertainty in the interpretation of the possible causes that generate changes in the ecosystem, it is necessary to have a reference state or baseline of local and regional patterns that we can refer for assessing and quantifying the changes that we observe. This is only possible through the establishment of systematic ocean observation programs with adequate spatial and temporal resolution, which allow the improvement of the quality and frequency of our observations and consequently the results of predictive models (Jassby and Powell, 1990, Gamble, 1994).

Time series observatories have permitted to make significant advances in our understanding of ocean processes in some well-studied systems. Depending on motivation, sampling frequency, and length, time series can be used for different purposes and are of critical importance to enable or facilitate: (i) the acquisition of ecosystem baselines of environmental factors and the marine organisms inhabiting the ocean, (ii) the rate and scale of environmental change, including climate change and biodiversity loss, (iii) the understanding of ocean, earth, and climate system processes, (iv) monitoring of ecosystem dynamics and its variability, (v) the detection of hazards and environmental disturbances and the estimation of recovery times, (vi) forecasting and anticipating ecosystem changes, and (vii) effective policymaking and sustainable management of the seas and oceans (Valdés and Lomas, 2017).

Nevertheless not all ocean regions are changing at the same rate or following the same pattern. This is in part because the ocean is characterized by interacting processes, which operate over nearly 10 orders of magnitude in time and space (Dickey, 2002; Fig. 1). Indeed, some regions are more sensitive to environmental change than others; exploring this temporal and spatial variability of ocean change, at a basin scale approach or greater (ocean, global), is largely the realm of earth ecosystem models at present. Indeed, it is only through models that we can learn about the spatial representativeness of existing time series (i.e. the footprint of a time series) and therefore inform decisions about where to site new time series (Henson et al., 2016).

While the implementation of first order ocean biogeochemical concepts and coupling to atmospheric forcing is reasonably well developed in these models (Keller et al., 2014), they are still limited by lack of mechanistic knowledge of relevant interactions among physical, chemical and biological ecosystem components across spatial and temporal scales and organization levels (Heinze et al., 2015). This is further exacerbated by the fact that observational time series generally have to be several-fold longer than the time scale they are trying to resolve, while models can produce multi-decade output with relative ease. For example, model output suggests that at least three decades would be required to resolve climate change response in the North Atlantic for certain variables (e.g., primary production) but less time span for others (e.g., sea surface temperature) (Henson et al., 2010, 2016).

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[1] A full list of acronyms and abbreviations is presented in Annex 1 at the end of the article.

[2] HOT remits to the time series programme. It is also possible to name it ALOHA, but note that this is the name given to the sampling station: A Long-term Oligotrophic Habitat Assessment.

Table 1
Data collection overview of CalCOFI, HOT, BATS, L4 and RADIALES time series projects.

Time Series:	CalCOFI	HOT	BATS	Plymouth L4	RADIALES
Starting date:	1949	Oct/1988	Oct/1988	March/1988	March/1988
# Sampling stations:	75–113	1	1	1	20
Sampling frequency:	Monthly (1949–1984) Seasonal (since 1985)	Monthly Repeated during 3 days	Monthly Dawn-Dusk	Weekly	Monthly (Weekly)
Domain:	Coastal/Neritic/Oceanic	Oceanic	Oceanic	Neritic	Coastal/Neritic/Oceanic
Depth range (m):	20–455	4800	4500	51	22–4644
Ecological regime:	Upwelling	Subtropical / Oligotrophic	Subtropical / Oligotrophic	Temperate	Upwelling / Temperate
Spatial coverage (nm)	200 × 375	55 (offshore)	45 (offshore)	5.5 (offshore)	60 × 260
Core measurements:					
Hydrography	CTD: water column profiles (temperature, salinity)				
Biogeochemistry	Rosette (selected depths): nutrients, organic matter, O_2, pCO_2, pH, Sediment traps				
Bacterioplankton	Rosette (selected depths): abundance, biomass, diversity, rates				
Phytoplankton	Rosette (selected depths): pigments, abundance, biomass, diversity, rates				
Zooplankton	Plankton nets: abundance, biomass, diversity				
Ichthyoplankton	Plankton nets: abundance, biomass, diversity (eggs & larvae)				

Data sources: CalCOFI (Ohman and Venrick, 2003), HOT (Karl and Lukas, 1996; Karl and Michaels, 1996), BATS (Knap et al., 1993; Michaels, 1995), Plymouth L4 (Harris, 2010), RADIALES (own data).

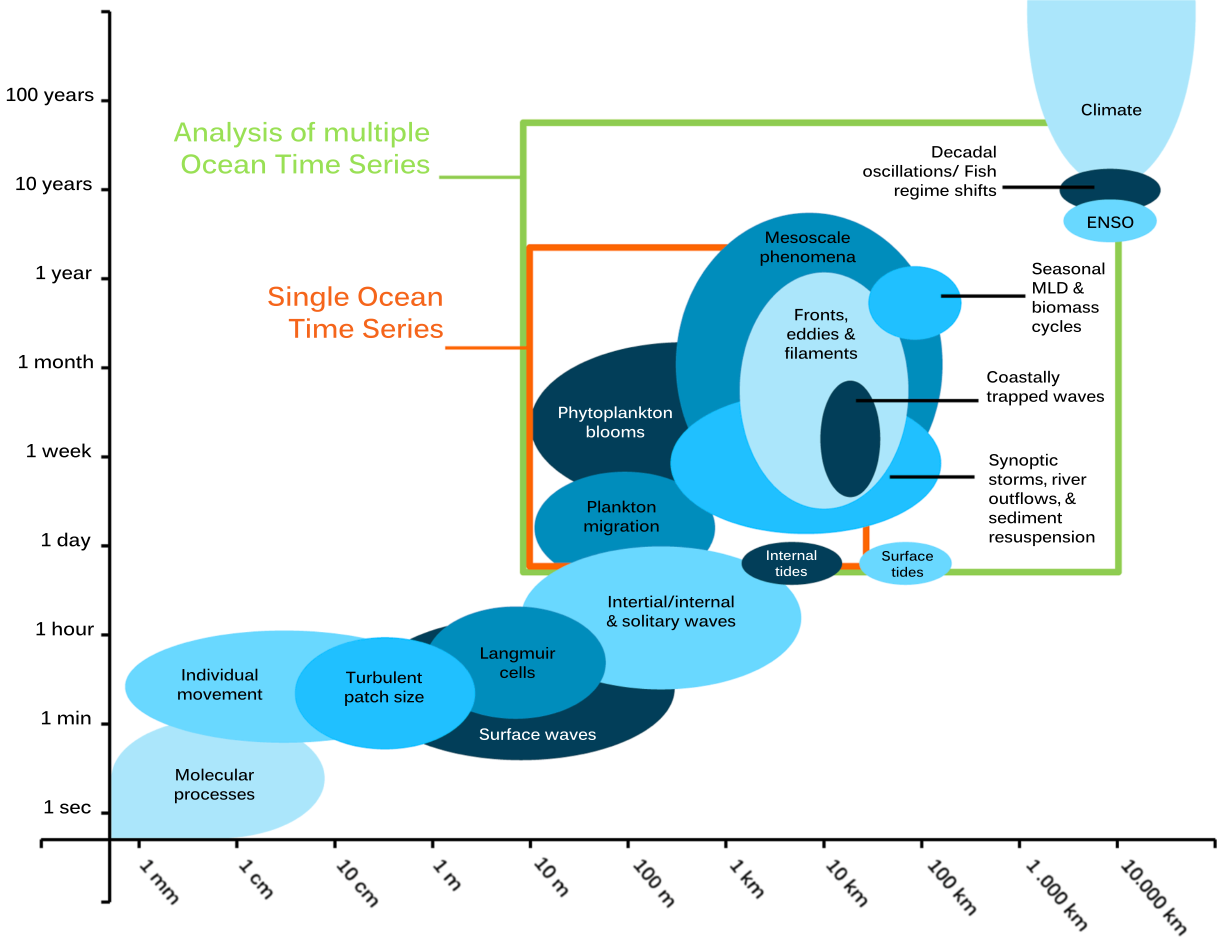

Fig. 1. Temporal and spatial scales of a range of ocean processes. The rectangles highlight the range of space- and time-scales that can be addressed by ship-based, time-series measurements (As in Valdés and Lomas, 2017;).
Adapted from Dickey, 2002

2. Radiales, three decades of continuous ocean observations in north atlantic spanish waters

2.1. History

Marine ecosystem components exhibit large fluctuations on a wide range of interacting scales, which limit our ability to forecast their dynamics and to distinguish between anthropogenic and naturally driven changes. Furthermore, the wide range of variation also makes it difficult to compare data differing either in sampling location or year of sampling. Identification of regime shifts would allow for the interpretation of past changes and predict future states of the marine ecosystems, as those caused by climate change (Beaugrand et al., 2015), and other anthropogenic factors such as over-exploitation of renewable resources

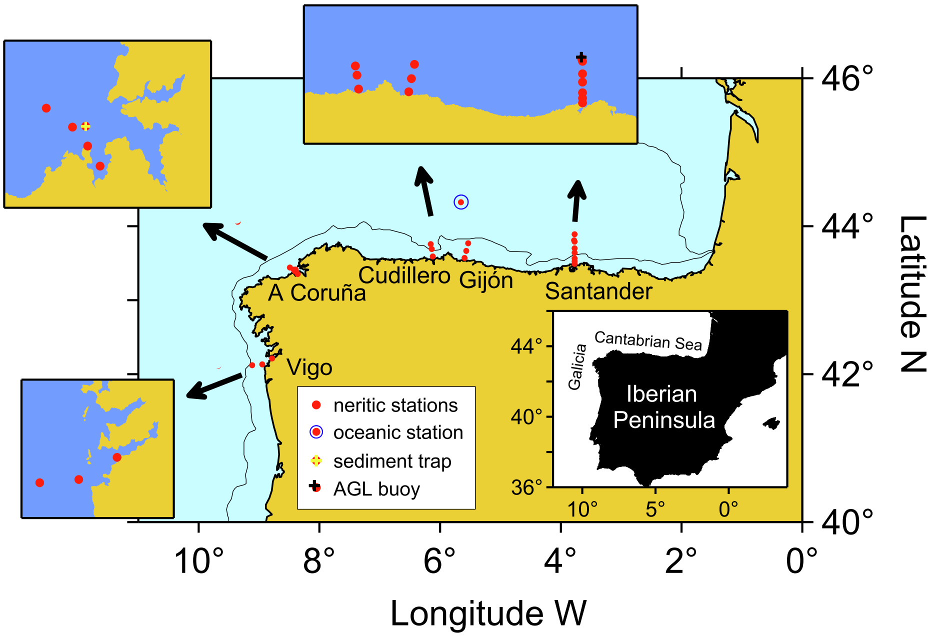

Fig. 2. Location of RADIALES sampling stations along the coast of N and NW Spain. The 200 m isobath is indicated by a continuous line. The position of the AGL buoy off Santander is also indicated.

(Baudron et al., 2020). Examples of ecosystem-wide regime shifts are increasingly reported suggesting a worldwide synchronicity, particularly in the Northern Hemisphere (Beaugrand et al., 2015; Alheit et al., 2019; Kröncke et al., 2019; Bode et al., 2020).

Because of these constraints, many authors have advocated the search for trends or regime shifts in time series as the best procedure to identify and compare common patterns of variation among different locations. With the same purpose, different panels and science plans developed in the frame of the IGBP (JGOFS, GLOBEC) and other initiatives (e.g. CLIVAR, EuroGOOS, EuroSITES, etc) encouraged the establishment of long-term observation programmes.

To understand the functioning of the ocean climate and marine ecosystems it is necessary to have simultaneous measurements of both environmental abiotic factors and the organisms living there. Coherent with the need to produce historical time-series of oceanographic data within the framework of these international programmes, in the mid-1980 s the IEO raised the need to carry out systematic and continuous observations (time series) of concurrent physical, chemical and biological community variables. Its main aim has been to understand the natural variability of oceanographic processes, to measure their ranges and thus to obtain reliable patterns and baselines, in order to be used as a reference for comparison in the face of environmental disturbances, studies on climate change, and the ecosystem dynamics at long-term time scales. On this premise, the IEO began in 1988 a periodic sampling program of the pelagic ecosystem in the bay and continental shelf of A Coruña. This program was consolidated in 1993 when the IEO structural project "Study of the temporal series of oceanographic data (RADIALES)" was approved and gradually extended to different locations of the Spanish coast, constituting a pioneering and very important initiative in the observation of the oceanic system and plankton ecology in our country. This research project constitutes the most complex and comprehensive contribution to ocean observation in Spain to date, and perfectly comparable to other time series started almost synchronously around the world (www.unesco.org/new/en/natural-sciences/ioc-oceans/sections-and-programmes/ocean-sciences / biogeochemical-time-series /) (Table 1).

The time series of sampling extends from 1988 (A Coruña and Vigo), 1991 (Santander), 1993 (Cudillero) and 2001 (Gijón). Tailored AVHRR SST images are obtained from an own satellite reception station operating since 1998 and an oceanic buoy moored at 2850 m depth off Santander provides hourly atmospheric and oceanographic data since 2007. To date, a total of 49 scientists, 54 technicians and 36 students from 7 different IEO laboratories and from the University of Oviedo have been involved in the project.

Currently, the research project includes 5 coastal transect in Northern Spain: Santander, Gijón, Cudillero, A Coruña and Vigo (Fig. 2). All transects run perpendicular to the shoreline following the steepest slope in bathymetry, and include at least three sampling stations of coastal, neritic and oceanic characteristics. Each station is visited at least monthly, with periods of higher temporal resolution mainly in spring and summer, to study local processes at some locations (i.e., A Coruña). At each site, sampling involves extensive physical, chemical and biological measurements, paying special attention to the sampling and analysis of essential ocean variables (EOVs) as temperature, salinity, inorganic nutrients, irradiance, in vivo fluorescence, chlorophyll *a*, and abundance and composition of several plankton groups, including prokaryotic and small eukaryotic abundance, biomass and diversity, biomass and phytoplankton/zooplanktonic species, and ichthyoplankton abundance. In some locations, measurements on productivity (e.g. primary production) or specific biochemical variables (e.g. inorganic and organic carbon) are also included (Table 1). These data are being obtained from 3 research vessels sampling the 5 coastal transects. All variables are sampled using standard oceanographic equipment (CTD, plankton nets, Niskin bottles, etc.) and analysed following JGOFS protocols (UNESCO, 1994; Bode et al., 2020).

Phases of the RADIALES project

- Start. The project was conceived in the Oceanographic Center of the IEO in A Coruña in 1987, starting the field work in March 1988. For its launch it was necessary to have the support of the IEO guarantying access to a logistical structure, human resources and scientific equipment. This first pilot experience served to demonstrate that a systematic and continuous sampling was feasible and its results could be offered to the scientific community in a short period of time.
- Expansion. Soon after the initiation of the project it was decided to extend its scientific scope to cope with the spatial variability of the region and to the gradient in primary production associate to the upwelling regime dominating in this area of the Iberian Peninsula. Thereafter, a process of expansion of the project to other coastal areas

Table 2
RADIALES' project performance/operation indicators.

Researchers (average/year)	23
Technicians (average/year)	32
Marine labs	4
Data Centers	1
Research vessels	3
Sampling days at sea (1988–2020)	2,031
Total number of water samples collected (1988–2020)[1]	27,429
Total number of plankton samples collected (1988–2020)[2]	8,376
Average annual budget IEO –2008–2020- (keuro/year)[3]	102
Average annual external funds –2008–2020- (keuro/year)[3]	235
Total scientific documents (1988–2020)	500
Documents with international co-authors (%)	20%
Number of international web repositories with RADIALES data	5

[1] Including dissolved gases, nutrients and seston.
[2] Including phytoplankton, zooplankton and bacteria.
[3] Excluding salaries and ship-costs.

was opened. In June 1991, sampling began on the Santander coastlines in a 20 nautical mile transect off Cabo Mayor reaching more than 2500 m depth. At the same time, the idea was implemented in oceanic waters off Vigo and a collaboration agreement was signed with the University of Oviedo to initiate a similar survey on the coast of Cudillero (W of Cabo Peñas). In both cases, the RADIALES project allowed the continuation of sampling of some variables that had been started previously, integrating them into a common scientific framework and providing support for their maintenance. Overall, there was already a reasonable regional coverage in the whole NW Spanish coast including the coastal and oceanic waters off Galicia and the Cantabrian Sea.

- Consolidation. From 1996 onwards, when several of the RADIALES series had already 5 years of sampling, the results and the project activities were disseminated at national and international level (Valdés et al., 2002). In 2001 the regional expansion was completed with the inauguration of the Gijón Oceanographic Center, and at the beginning of March of the same year of a new transect to the E of Cabo Peñas began its

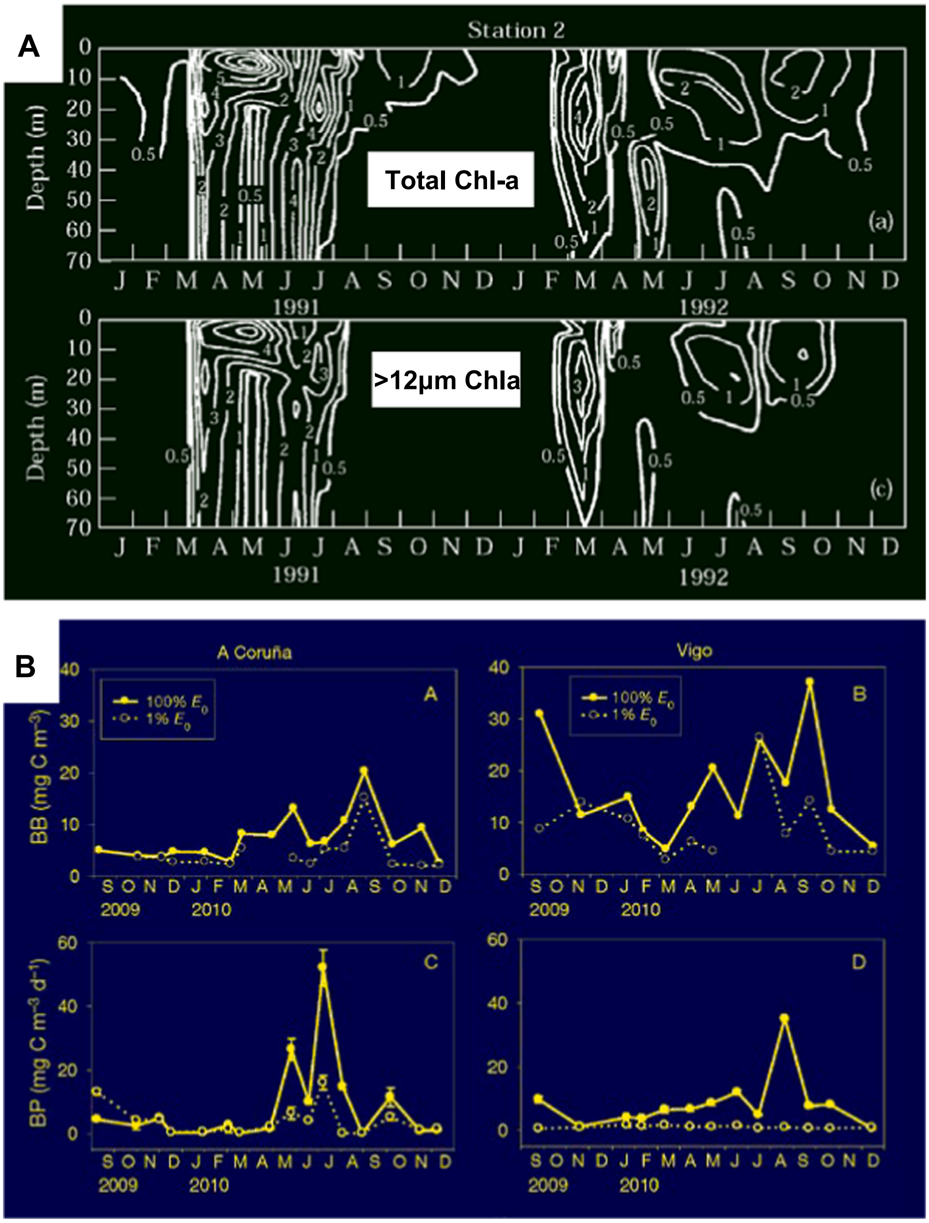

Fig. 3. Seasonal variability. (A) vertical distributions of total and greater than 12 μm chlorophyll-*a* (mg m^{-3}) at Station E2CO off A Coruña in 1991 and 1992 (modified from Casas et al., 1997). B: seasonal distribution of bacterial biomass (BB, mg C L^{-1}) and production (BP mg C m^{-3} d^{-1}) at Station E2CO off A Coruña and at Station E3VI off Vigo in 2009–2010 (modified from Teira et al. 2015).

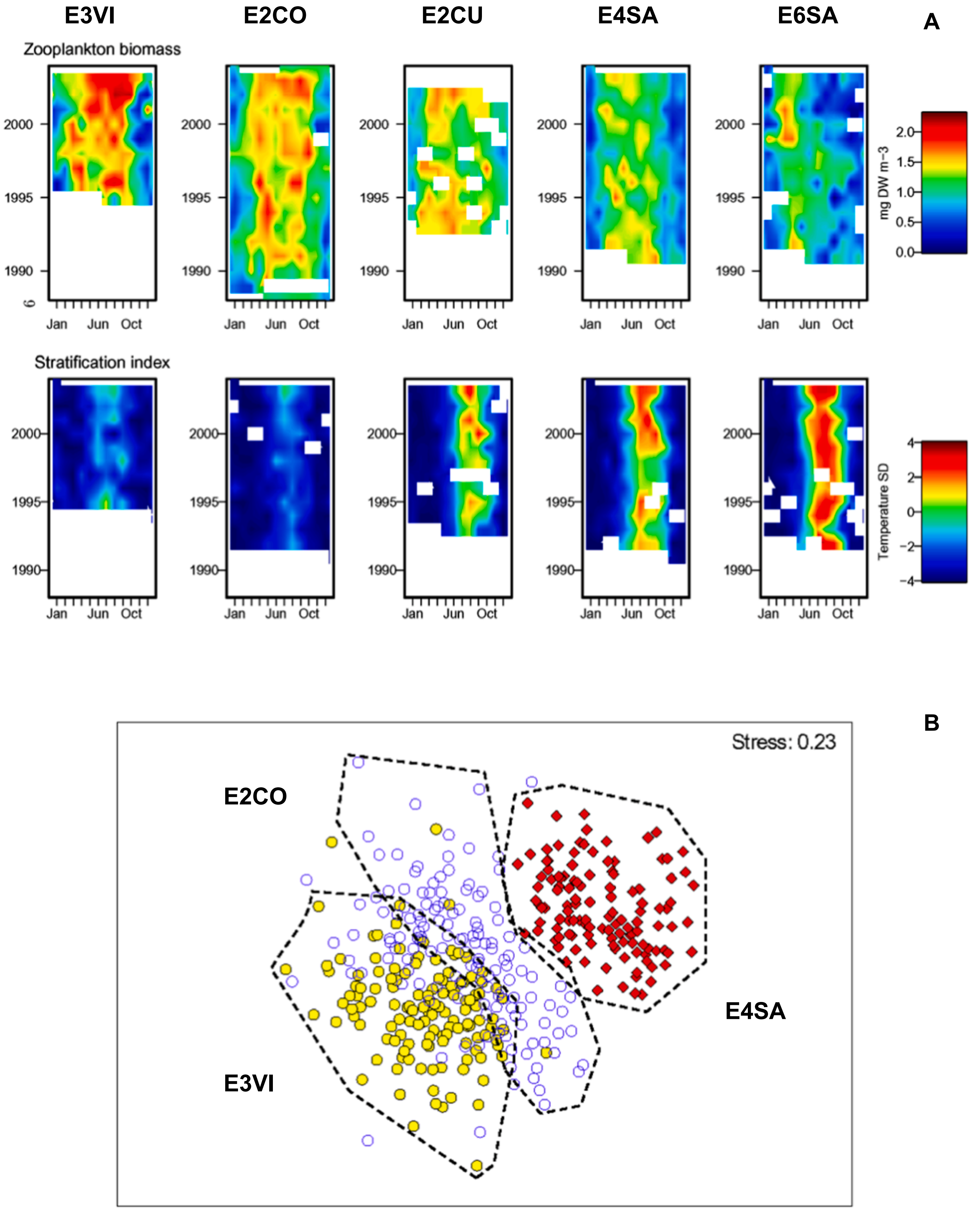

Fig. 4. Comparative analysis. (A) Zooplankton biomass (mg m^{-3}) and stratification index (temperature sd, °C) for mid shelf stations in each transect and for the most oceanic station off Santander (modified from Valdés et al., 2007). (B) Multidimensional scaling plot of copepod biomass time-series for shelf break stations (modified from Bode et al., 2012a).

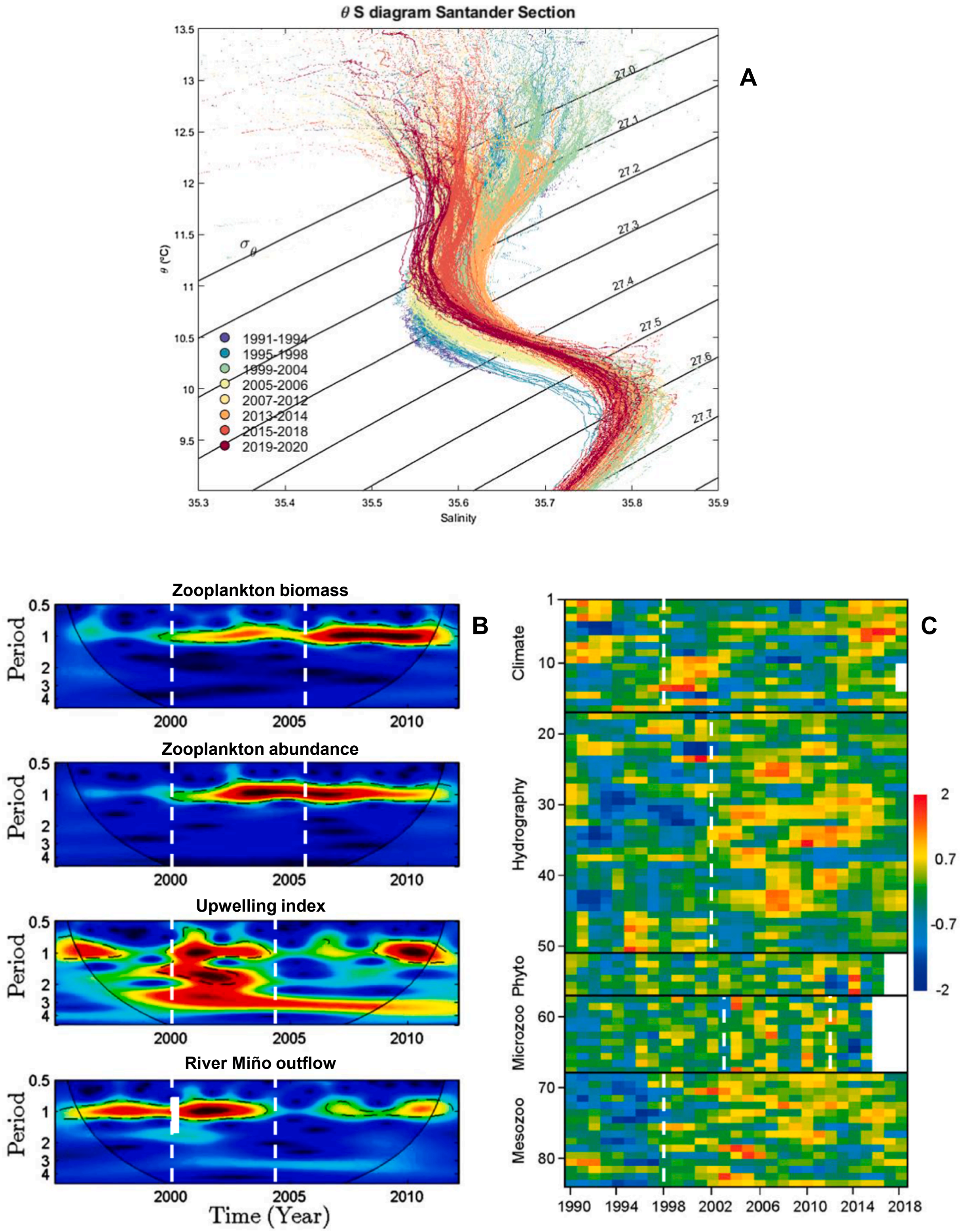

Fig. 5. Multidecadal analysis. (A) Diagram of θ/S for the deepest station of the Santander standard section during the whole time series with some isopycnals superimposed in the graphic (the different periods are shown by different colours as indicated in the colour scale). (B) Wavelet decomposition of zooplankton and environmental time series for Station E1VI off Vigo between 1994 and 2011. Color code for power values is graded from blue (low values) to dark red (high values), and the black line defines the cone of influence below which the information is affected by edge effect (modified from Buttay et al., 2017). (C) Distribution of standardized anomalies from the overall mean for climate, hydrography and plankton series for Station E2CO off A Coruña between 1989 and 2018 (Bode et al., 2020). The dashed vertical lines separate the main regimes identified.

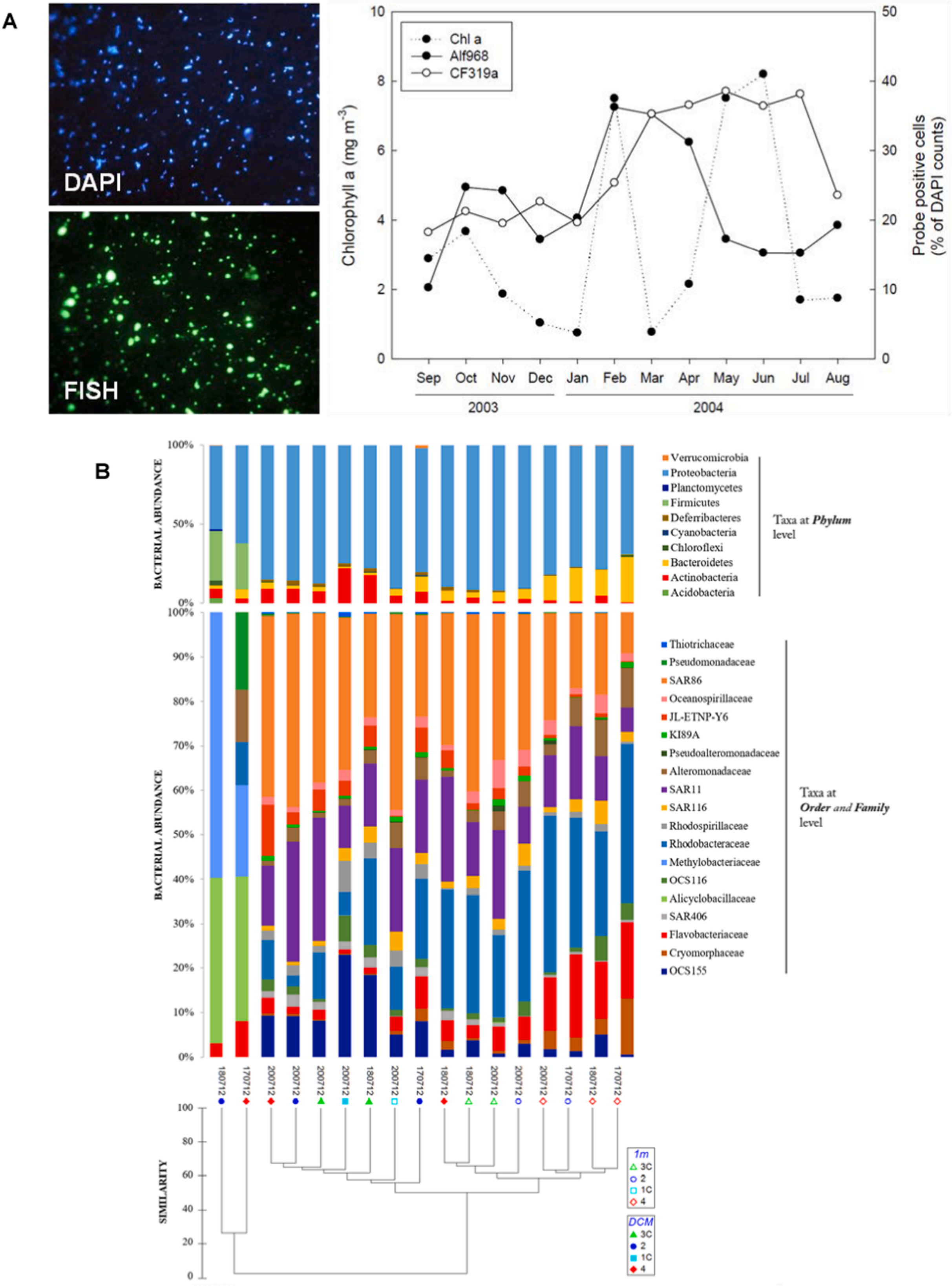

Fig. 6. Unknown component of bacterioplankton diversity. (A) Epifluorescence micrograph of prokaryotes in a seawater sample stained with DAPI and/or with Alexa-488-labelled-fluorescence in situ hybridization (FISH) probes showing the alternance of *Alpha-proteobacteria* and *Bacteriodetes* groups in the deep-chlorophyll *a* maximum over the seasonal cycle in the upwelling system off A Coruña (B) Cluster analysis of bacterial diversity determined by 454-pyrosequencing among different samples collected in the shelf waters in front of A Coruña (modified from Montes et al. 2020).

sampling (Gijón transect). Currently the RADIALES project focuses its activity on the Spanish North Atlantic coast from the 5 transects from Vigo to Santander (Fig. 2). The project continues the sampling and dissemination of results and promoting the establishment of synergies between the project and other research initiatives to optimize the use of resources and benefit from synergies to bridge the gap between the science and policy (i.e. position paper Marine Board, Glockner et al. (2012)) other structural projects from IEO, as the Santander reference station SATS (Santander Atlantic Time-Series), which is currently listed as an ocean reference station of OceanSITES (http://www.oceansites.org/). SATS includes (i) the AGL buoy, sited at the outer slope and equipped with meteorological, oceanographic and biogeochemical sensors, and (ii) the deepest station (2500 m depth) of the RADIALES section off Santander. A synthesis of the results obtained in the first 16 years of the project has been collected in the book “Climate change and Oceanography in the North Atlantic of Spain” (Bode et al., 2012b), and comparative analysis among the different transects sampled were published as research articles in international journals (see section 2.3).

2.2. Objective, logistics and methods

RADIALES is a multidisciplinary project whose main objective is to “*Understand and parameterize the ecosystem response to the various sources of temporal variability, both in its oceanographic characteristics and in planktonic populations, and especially in those factors and processes that influence biological production and can alter the ecosystem.*”

The RADIALES project builds time series of oceanographic data based on the systematic and continuous sampling of the ocean carrying out multidisciplinary observations (physics, chemistry, biology) covering oceanographic events in all seasons of the year and in successive years, that is, it allows discriminating between different sources of temporal variability (Fig. 1).

The choice of transects and sampling stations was made taking into account the following considerations:

- o Sampling is carried out in a systematic and regular way with a frequency that allows identifying the variability factors that govern the ocean climate, the ecosystem dynamics and resolving their periodicity.
- o The location of the sampling sites avoids as much as possible the influence of major continental inputs and other local factors overlapping and veiling the natural dynamics.
- o The sampling stations in each transect include coastal, shelf and slope stations in sections perpendicular to the shoreline following the steepest slope in bathymetry.
- o The sampling area is representative of the region in which it is located and not only of local conditions.
- o In addition, local availability of the boats and crews is guaranteed for the sampling.

The RADIALES project sampling is carried out following common working protocols and the collection of results is stored in databases, from where they are accessible to all researchers in the program and supplied to a wide variety of users under demand. The project obtains information on basic variables for the knowledge of oceanographic conditions (temperature and salinity profiles, dissolved oxygen and nutrients) and planktonic communities (biomass of phyto- and zooplankton), being supplemented in some stations, when the availability of specialized personnel and resources allow it, with other measures such as biomass, abundance and diversity of bacterioplankton, composition of phyto- and zooplankton species, primary and heterotrophic production, sediment material, pCO_2, etc. (Table 1).

Throughout its first 30 years of life, the project has embraced the collaboration of numerous specialists from different disciplines. In 2021 the IEO’ staff participating in the RADIALES project includes 32 researchers, 32 technicians and 3 pre-doctoral students, in addition to the crews of the 3 coastal oceanographic vessels that allow sampling at sea (Table 2).

The structural activities of the RADIALES project (monthly samplings, analysis of EOVs) are supported by own funds from the Spanish Institute of Oceanography. Furthermore, these activities have included numerous complementary measures in research and advisory short-term projects sustained with additional external funding provided by foundations (Fundación Pro-Vigo, Fundación Marcelino Botín), regional agencies (Xunta de Galicia, Principado de Asturias, Government of Cantabria), and competitive calls from national (Spanish R + D + i Plan) and international (European R + D + i programmes) (Supplementary Figure S1).

As early as 1998, the RADIALES project began to incorporate autonomous and remote observation equipment (observations from buoys and remote sensing) in order to complete the series of observations based on samples to be able to analyze to incorporate short-term scales of variability that are not resolved with the project’s sampling frequency. These activities are carried out in close collaboration with IEO initiatives such as the Satellite Image Reception Station in Santander, in operation since 1998 (www.ieo-santander.net/teledeteccion/) or the Oceano-Meteorological Buoy Augusto González Linares (AGL buoy), deployed in 2007 in oceanic waters off the coast of Santander (www.boya-agl.st.ieo.es/boya_agl/en/index.php). The observations of the RADIALES project in coastal waters are complemented by those carried out in deep waters as part of the VACLAN/RADPROF project (Climate Variability in the North Atlantic), which performs samples at least once a year in the oceanic waters of the Spanish northwest region since 2003 (Prieto et al., 2015). More recently, RADIALES observations are integrated into ocean observation and prediction systems that include sampling, remote observations and numerical models. An example on a regional scale is the Observatorio da Marxe Ibérica RAIA, an initiative of research centers, universities and agencies in Galicia and Portugal (www.observatorioraia.org/).

2.3. RADIALES’ products: From new scientific knowledge to ecosystem management and advice

The ‘pay check’ you receive from consistent long-term ship based

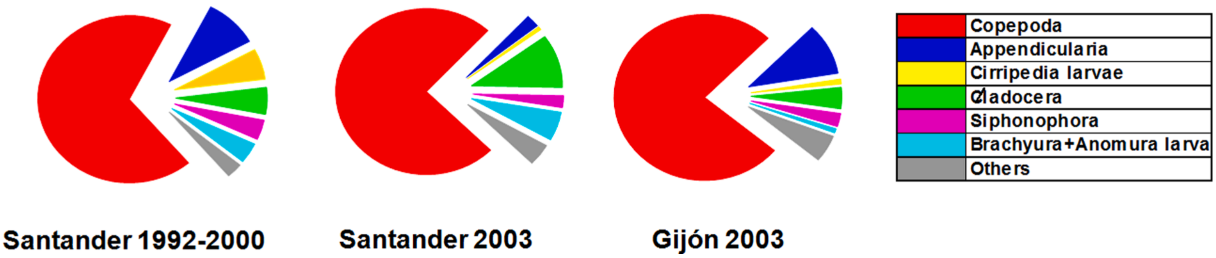

Fig. 7. Taxonomic composition of mesozooplankton in the Santander and Gijón transects. The percentages of the most important taxonomic groups identified in station 4 of the Santander transect during the months of January-May of the period 1992–2000 are represented and compared with the results obtained in the months of January-May and January-March-April, at the mid-shelf stations of the Santander and Gijón transects respectively.

marine time series is not regular, but many times it is surprising, as demonstrated by recent discoveries, e.g., proof of ocean acidification, ecosystem changes, exploration of the deep sea, which illustrate that sustained multi-decadal observations are ecological and economical important research investments for future generations (Ducklow et al., 2009; Henson, 2014).

The project has yielded scientifically important results. It has allowed establishing ranges and patterns of variability of numerous environmental and biological variables, including the estimation of local and regional rates and trends in hydrographic and biological variables, circulation changes superimposed to the low frequency variability at ocean-basin scales, and the determination of baselines to assess the magnitude of environmental disturbances and to estimate recovery times. Furthermore, observations from some of the RADIALES stations have been incorporated into regular ICES Reports on Ocean Climate (IROC, González-Pola et al., 2020), on Zooplankton Status (O'Brien et al. (2013)), and on Phytoplankton and Microbial Plankton Status (O'Brien et al. (2012)).

The results are disseminated mainly through articles in national and international scientific journals, books, monographs and reports. To date the project has produced 500 written publications, including 164 articles in international journals, 35 book chapters and monographs, 29 Doctoral Theses, 57 reports, and more than 200 contributions to scientific meetings (Supplementary Figure S2). It also has its own website: www.seriestemporales-ieo.net.

The project supplies data to various international scientific organizations, and their scientists participate actively in various working groups, especially ICES, on hydrography and plankton, among others. In addition, the results of the project constituted an important part of the national contribution to programs of the IGBP such as GLOBEC and IMBER, as well as to GOOS. Currently the RADIALES project is one of the most active promoters of the European Marine and Observation Data Network (EMODnet). SATS ocean reference station provides calibrated data of the AGL buoy and its oceanographic station to OceanSITES Global Data Assembly Centers (GDAC) in IFREMER and US NDBC (http://tds0.ifremer.fr/thredds/catalog/CORIOLIS-OCEANSITES-GDAC-OBS/DATA/catalog.html). Finally, within the national context, the data collections of the project have been used on multiple occasions responding to requests from the administration in the preparation of reports and evaluations on environmental disturbances (especially in cases of oil spills) and climate change studies.

RADIALES' scientific activity is a unique framework to train new marine researchers and technicians. Since its inception, the project allows for close collaboration with vocational training centers and with Universities, participating in doctorate and master courses (Universities of A Coruña, Oviedo, Santiago de Compostela, Vigo, Cantabria, Basque Country, Barcelona, Balearic Islands, etc.). Every year, students who carry out specialization practices in the observation, measurement and analysis of the sea and its organisms join part of their activities.

In addition, thanks to the RADIALES project it is possible to have a collection of plankton samples that allow retrospective studies of variables and characteristics not initially observed as part of the basic study of the series. This collection constitutes a valuable heritage for future generations of scientists by making available not only biological collections and material (i.e. DNA) that would otherwise have been lost, but also basic environmental information collected simultaneously for

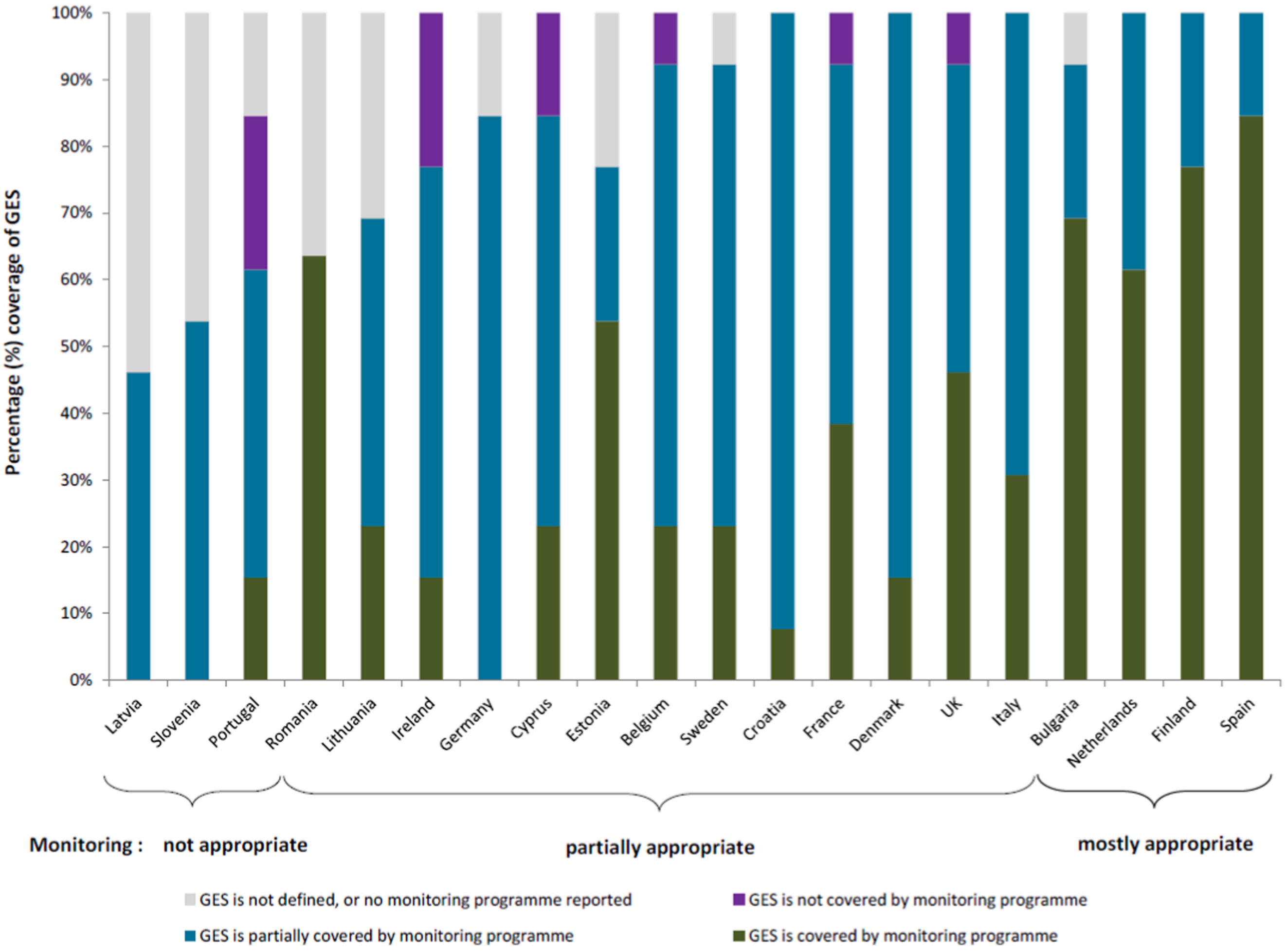

Fig. 8. Coverage of good environmental status by MSFD monitoring programmes based on technical assessment. Source: European Commission (2017b).

reference.

The RADIALES time series results evolved in four phases, following the progressive accumulation of data in the series and the emergence of new techniques: 1) discovery phase, focused on the description of seasonality and morphological species identification 2) comparative analysis, stressing the similitude and differences among the series, mostly in the spatial domain but also between years, 3) multi-decadal analysis, revealing long-term trends and shifts connected to regional climate and oceanography, and 4) introduction of emerging techniques, particularly genomics applied to the study of plankton diversity. This sequence can be also recognized in similar time-series through the world (Steinberg et al., 2001; Karl, 2010; Karl and Church, 2019; Muller-Karger et al., 2019). A full list of RADIALES publications can be downloaded from the project web page (www.seriestemporales-ieo.net/). In the following sections we summarize some of the relevant results of RADIALES in each phase. In addition, the application of these results to the assessment of specific environmental perturbations is summarized in Section 2.3.5.

2.3.1. *Discovery phase*

Seasonality is the dominant source of temporal variability in the RADIALES series, as they are representative of mid-latitude temperate ecosystems (Bode et al., 2012b). Oceanographic studies prior to 1990 highlighted the marked differences in hydrographic, biogeochemical and planktonic variables along the annual cycle in this region, particularly those related to the alternation of upwelling and relaxation conditions in coastal waters off Galicia (e.g. Margalef et al., 1955; Fraga, 1981; Tenore et al., 1995), and to the seasonal warming and cooling of the surface layer in the Cantabrian Sea (e.g. Estrada, 1982; Bode and Fernández, 1992). Therefore, the first studies of RADIALES data were, and still are, focussed in documenting this seasonality, its underlying causes, and the modifications imposed by climatic and local factors.

The first examples of seasonal cycles captured by the RADIALES project are descriptions of the seasonal dominance of mesozooplankton (Valdés, 1993), large-sized phytoplankton (Varela, 1996; Casas et al., 1997), and of bacterial biomass and production (Varela et al., 2006a, 2006b; Calvo-Díaz et al., 2014; Teira et al., 2015) (Fig. 3). This seasonality is more marked and predictable in the eastern series while it is greatly modified in the western series by the influence of the wind-driven upwelling. Upwelling, more frequent between March and October, causes a re-initiation of the planktonic succession by distorting the seasonal stratification by the warming of the surface and providing new nutrients for phytoplankton growth.

Consequently, chain-forming and large diatoms produce a series of blooms during most of the spring and summer in Galicia (Fig. 3A). The dissolved organic carbon released during these blooms supports a significant heterotrophic bacterial activity, which in turn is largely dependent on the intensity of the upwelling. As an example, the phytoplankton-bacteria coupling is stronger in Vigo than in A Coruña because of the higher intensity of the upwelling in the former favours the release of labile dissolved substrates by actively growing phytoplankton (Fig. 3B). These patterns were recurrent in other variables and components of the ecosystem. For instance, the changes in zooplankton abundance and biomass close followed those of phytoplankton (Valdés et al., 1991; Bode et al., 2003) while the microbial biomass increased after the accumulation of dissolved organic matter, generally in late summer (Teira et al., 2003; Calvo-Díaz and Morán, 2006). Rate measurements, as primary production (Bode et al., 2011; Morán and Scharek, 2015), respiration (Serret et al., 1999; Teira et al., 2003; 2015), zooplankton grazing (Bode et al., 2003; López-Urrutia et al., 2003) or bacterial activity (Varela et al., 2006a, 2006b; Calvo-Díaz et al., 2014; Teira et al., 2015) also followed these patterns. The recognition of seasonal patterns was the first step for the definition of ecosystem baselines for quantifying the effects of perturbations (see section 2.3.5). However, as the series grew longer, marked year-to-year changes in this seasonality were soon evident.

2.3.2. *Comparative analysis*

In contrast with other programs focused in single stations (Table 1), RADIALES allowed for the study of regional variations by comparing the series from the different transects. For instance, a study of zooplankton biomass (Valdés et al., 2007) showed an inverse relationship with the strength of summer stratification, and a positive relationship with the intensity of upwelling (Fig. 4A). Sites with marked stratification have much lower zooplankton biomass during the stratified period, thus restricting the biomass peak to the spring period. The spatial gradient in upwelling also conditioned the species composition of communities, as shown by studies on zooplankton (Bode et al., 2012a; Chust et al., 2016). Copepod species identity and biomass patterns were consistent within locations but showed also clear spatial patterns (Fig. 4B). Regional homogeneity was maintained by species as *Calanus helgolandicus* and *Acartia clausi*, while the local variability was provided by other species as *Paracalanus parvus* and *Clausocalanus* spp.

Interestingly, the series in the Cantabrian Sea revealed the increase in warming-tolerant species and the decrease in those species typical of upwelling. Local variability was also found with other ecosystem components as bacteria (Hernando-Morales et al., 2018; Otero-Ferrer et al., 2018) affecting their coupling with phytoplankton (Teira et al., 2015). Bacterial production was closely coupled to the release of dissolved organic carbon by phytoplankton at sites where the strong upwelling favoured large blooms but decoupled at sites with weaker upwelling and small blooms. The differences in primary production along the upwelling gradient were quantified by the sustained measurements at sites representative of eutrophic and mesotrophic conditions (Bode et al., 2011).

Other examples of spatial variability where provided by the changes associated to the distance to the coast and the depth of the water column sampled in RADIALES. Coastal stations showed in general higher planktonic biomass per unit of volume than shelf stations and also higher values in the number and magnitude of seasonal maxima (Casas et al., 1997; Valdés and Moral, 1998; Calvo-Díaz et al., 2014). Such temporal heterogeneity favoured the accumulation of a surplus of organic matter produced during blooms that maintained heterotrophy during periods of low primary production, as in summer in the Cantabrian Sea, and offshore (Serret et al., 1999).

In addition to spatial comparisons, RADIALES series showed year-to-year changes in hydrography (González-Pola et al., 2005; Somavilla et al., 2009; Gago et al., 2011), and in nutrients and plankton (Llope et al., 2006, 2007; Valdés et al., 2007; Bode et al., 2009, 2011, 2012a, b, 2013). Some of these changes were attributed to occasional events, as the exceptional cooling of the winter of 2005 that caused an intense mixing of the water column (Somavilla et al., 2009) or the typical

Table 3
What are marine ecological time series telling us. Ten assessments from IGMETS (as in O'Brien, et al., 2017).

Observations which are not made today are lost forever!
Existing observations are lost if are not made accessible.
The collective value of data sets is far greater than its dispersed value.
No substitute exists for adequate observations.
The value of time-series observations is positively correlated to the duration of continuous measurements. Measurements covering a time span of several decades, allows identification of seasonal, inter-annual, and decadal patterns.
The analysis of multiple datasets from different time-series stations allows the separation of stressors, and evaluation of connected ecosystem responses.
During the past decades science and technology evolved along with time-series observations. Anticipated development of new techniques will allow streamlining the measurements and will improve the geographical coverage.
Advanced analysis, including global assessments and improved computation, using existing data, creates new science.
Models will evolve and improve, but, without data, will be untestable – projections and forecasting need a big variety of in-situ data.
Today's climate models will likely prove of little interest in 100 years. But adequately sampled, carefully quality controlled and archived data for key elements of the climate system will be useful indefinitely

predominance of winter upwelling events in Galicia in 2012, triggering blooms of harmful algae (Díaz et al., 2013). However, there were trends unequivocally related to regional and global alterations of climate and oceanography, as the progressive warming of sub-surface and intermediate water masses since the early 1990 s (González-Pola et al., 2005). It is noteworthy to remark that since 2014 the trend has reversed and the cooling signal captured in RADIALES has been regularly reported to IROC (González-Pola et al., 2020).

2.3.3. Multidecadal analysis

After 2010, with most series spanning two or three decades, sustained trends and abrupt changes were revealed. While earlier analysis focused in the identification of trends spanning several years (e.g. Valdés and Moral, 1998; González-Pola et al., 2005), more recent studies suggested more complex changes. Thus, the monthly frequency of the sampling of the deepest station of the RADIALES section in Santander reaching 2500 m depth and covering intermediate water mass levels (Fig. 5A) have provided detailed observational evidence of recent conspicuous changes occurred in the mid-latitudes of the Eastern North Atlantic (ENA) with implications at ocean-basin scales (Somavilla et al. 2016; Sullivan, 2016). Extraordinary convective mixing events in the mid-2000 s transferred upper ocean heat to deeper layers. As a result, ENA modal waters were saltier, warmer, and denser than in previous years. The changes in density affected the circulation patterns by reversing the southward regional flow and enhancing the input of saltier waters to higher latitudes. Since the mid-2010 s, saltening and warming trends reversed and accelerated freshening and cooling in the upper ocean has been observed first in the subpolar North Atlantic, but now it is widespread and has reached the mid-latitudes of the ENA being observable in the outermost station of the RADIALES section in Santander (González-Pola et al. 2020). During these years, the monthly hydrographic profiles obtained at this location have also evidenced the occurrence of deeper mixed layers concurrent with surface warming trends, a finding with important implications for biogeochemistry that RADIALES data in combination with other data sets have also enabled to characterize in detail (Somavilla et al. 2017).

Other examples of trends spanning several years are those of zooplankton off Vigo (Buttay et al., 2017) where biomass increased continuously while abundance increased between 1994 and 2006 but decreased thereafter (Fig. 5B). These trends were strongly associated to the dynamics of upwelling and river outflow, as these environmental drivers regulated the accumulation of zooplankton near the coast and the synchrony in the seasonal cycles between the different species. Similarly, the abundance of individual phytoplankton species off A Coruña showed a variety of non linear trends across two decades (Bode et al., 2015). Interestingly, in this case the trends were not associated to diatoms, dinoflagellates or to other groups of phytoplankton, as described for other regions of the North Atlantic (Leterme et al., 2005), but suggested the rapid adaptation to frequent disturbances of the Galician phytoplankton communities because of the upwelling. These findings also suggested a higher resilience of plankton in upwelling ecosystems compared to plankton in ecosystems characterized by short productive periods.

In addition to trends in individual variables, the application of multivariate analysis to annual series over several decades allowed to the identification of regime shifts. These shifts represented the alternation of different states of the ecosystem, involving many variables and often driven by climatic oscillations (Conversi et al., 2015). Off A Coruña, regime shifts were detected using multiple series (Bode et al., 2020). One major shift occurred between 1997 and 1998 and was related to a change from cold and dry to warm and wet climate conditions, affecting the abundance of zooplanktonic groups and phytoplankton species assemblages (Fig. 5C). Another shift between 2001 and 2002 was more related to local changes in hydrography and nutrients, indicating recent increases in remineralisation, and was associated to changes in zooplankton groups and species assemblages.

The sequence of these shifts suggests the existence of complementarily effects and interactions within the food web. In this way, phytoplankton diversity was the best predictor of resource use efficiency across trophic levels and therefore important for maintaining the planktonic biomass production in this upwelling environment (Otero et al., 2020). In a regional context, all these shifts were related to similar changes observed in the North Atlantic near the turn of the century (Beaugrand et al., 2015; Alheit et al., 2019). While the exact timing of the shifts varied between locations or ecosystem component analysed due to lagged biological responses, there are indications of a

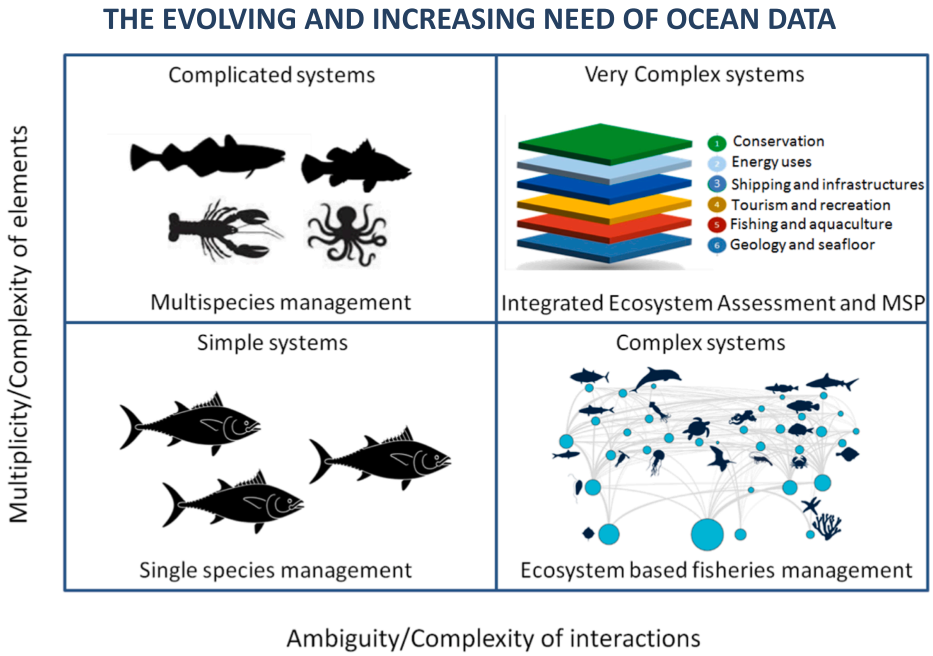

Fig. 9. Diagram showing the evolving and increasing need for ocean observations to fulfill the demand of ocean data needed for ecosystem management as we gain in complexity of elements and interactions. Source: Valdés et al. (2021).

synchronous response of the marine ecosystems to the rapid temperature increase in the region, prompting for more studies analyzing teleconnections and regime shifts at large scales (Kröncke et al., 2019). However, these studies require multidisciplinary time series spanning several decades, as those collected by RADIALES.

2.3.4. *Introduction of emerging techniques: The case of bacterioplankton*

First analysis on RADIALES time series bacterioplankton compartment only measure bulk properties such as bacterial abundance, biomass and heterotrophic activity (Valencia et al., 2003; Varela et al., 2006a, 2006b; Calvo-Díaz and Morán, 2006), and marine bacteria were usually considered as a "black box". After 2000, concurrent to an increasing recognition of the importance of microbes and the analysis on the identity of dominant oceanic bacteria opening the door to a new view of ocean bacterioplankton, RADIALES time-series monitoring of bacterial communities with genetic methods emerged as a powerful approach for the study of bacterioplankton (Teira et al. 2017, Hernando-Morales et al. 2018, Montes et al. 2020).

Early studies based on Fluorescence in situ hybridization (FISH) probes (Fig. 6A) evidenced a succession among the dominant groups Alphaproteobacteria and Bacteriodetes, with Alphaproteobacteria peaking during the water mixing period (winter and early spring) while Bacteriodetes clearly associated with changes in the concentration of chlorophyll-a dominating during the phytoplankton bloom (Varela et al. 2008). Later studies have demonstrated that some of these seasonal changes in the bacterioplankton community structure are related to a high ambient availability of polymers associated to algal cell lysis, which, in turn weakens the short term coupling between phytoplankton release and bacterial production (Teira et al. 2017).

After these FISH-based studies, a variety of 16S rRNA gene approaches become available including DNA fingerprinting analysis, clone library studies or high-throughput sequencing. The most noticeable biogeographic patterns observed were seasonality (Alonso-Sáez et al. 2015) and also horizontal homogeneity and spatial synchrony in bacterial diversity and community structure related with regional upwelling-downwelling dynamics (Hernando-Morales et al. 2018). Further analysis allow us to identificate the phylogenetic bacterial identities through 16S rDNA clone libraries, showing a variety of clusters of bacteria that tend to co-occur, including populations belonging to different phylogenetic groups, and thus suggesting adaptation to similar niches or ecological interdependence of distantly related phylogenetic populations. Recently, we have also incorporated high-throughput sequencing (HTS) to the study of bacterioplankton (Montes et al. 2020).

The higher taxonomic resolution of HTS methods have discovered a previously unseen fine vertical variability, with Rhodobacteraceae (under class Alphaproteobacteria) and Bacteriodetes dominating the surface waters and decreasing during the upwelling pulse, whereas SAR 86 (under class Gammaproteobacteria), Actinobacteria and SAR11 clade increasing their relative abundance at the deep chlorophyll maximum with upwelling relaxation (Montes et al. 2020) (Fig. 6B). Other very recent examples included evidences of functional diversity, such as the presence of a diverse and temporally variable diazotrophic community driven by hydrodynamic forcing in an upwelling system (Moreira-Coello et al. 2019).). Complementary analysis to quantify (by real-time PCR targeting the *nifH* gene) the main diazotrophs in the region under contrasting hydrographic regimes revealed the highest abundances of two sublineages of *Candidatus* Atelocyanobacterium thalassa or UCYN-A (UCYN-A1 and UCYN-A2), mainly at surface waters during upwelling and relaxation conditions, and of Gammaproteobacteria γ-24774A11 at deep waters during downwelling (Moreira-Coello et al. 2017).

2.3.5. *Applied research for ecosystem management and advice*

The use of RADIALES data from the hydrographical casts, nutrients, biogeochemistry and planktonic communities extends beyond pure scientific knowledge, as the expertise gathered within the programme has been applied to solve multiple environmental issues, from fisheries and pollution to global change and were used for instance for environmental assessment (e.g. the Prestige oil spill) and into policy advice (e.g., implementation of European directives and policies).

2.3.5.1. *The Prestige oil spill" (November 2002).*

More than 70% of the total oil consumed in the EU is moved by shipping through the Finisterre pass directly towards the English Channel and then to the final destination in different European harbors. In recent years several oil spills have occurred in the Bay of Biscay, for example 5 supertankers carrying more than 50 000 t have been wrecked since 1976, and the last 3 in an interval of just a decade (1992 Aegean Sea; 1999 Erika; 2002 Prestige), which has made this region the most severely affected by this kind of accident in the world. The Prestige oil spill in November 2002 covered an area extending from northern Portugal to the southern French coast, almost overlapping the area covered by the RADIALES project.

The Prestige oil-tanker spilt out a total of 60 000 t of oil, which was dispersed by the dominant currents in a wide region inside the Bay of Biscay, affecting beaches, cliffs, fishing grounds, marine protected areas, etc. More than 40 000 t of fuel were removed from the sea and beaches after the spill, but another 10 000 t were dispersed along the coast or deposited on the bottom. Experts and resources were mobilized in order to surveillance the entire north Spanish coast, waters and marine sediments on the shelf. Shellfish and benthic fisheries were closed in Galicia and some other regions in the north of Spain for several months and economic losses were enormous.

The environmental information obtained after the accident, up to the year 2003, was compared with the historical data available in the RADIALES project, which served as baseline for the purpose of answering the following questions: Have there been any changes in plankton biomass? Has the primary production changed? Have we observed any changes in the main taxonomic groups? Has there been a shift in the dominance of the characteristic plankton species?

The results were not only useful for the administration authorities and policy makers but also for scientific purposes and were published in technical reports and in the scientific literature (Valdés et al., 2003; Varela et al., 2006a, 2006b).

Despite the fact that zooplankton copepods were found to be contaminated with oil—externally as well as internally—no harmful effects were observed to cause changes in the biomass or community structure (Fig. 7). In fact, no relevant effects on the pelagic system were observed in the study area, other than the expected enhanced bacterial heterotrophic activity short after the spill (e.g. Bode et al., 2006). There were not any noticeable changes in phytoplankton primary production and no alterations in either phytoplankton or zooplankton biomasses were detected as compared to previous years. The phytoplankton and zooplankton community structure did not exhibit any significant differences before and after the spill. No evidence of oil transfer through the food web was observed. The abundance distribution of sardine eggs showed the same coastal pattern as in previous years (Valdés et al., 2003; Varela et al., 2006a, 2006b).

Oil spills are a real risk in the Bay of Biscay. The events monitored during the Aegean Sea, the Erika and the Prestige events can be used as a basis for comparison and for a better understanding of ecosystem response to these perturbations, as well as for preparing adequate action plans. In this regard, a good knowledge of the range of the natural variability of plankton is essential for a correct evaluation of the impact caused by oil spills or any other environmental disturbance and monitoring projects such as RADIALES has proven to be irreplaceable.

2.3.5.2. *Policy advice.*

The EU Marine Strategy Framework Directive (MSFD) provides a framework in which Member States must take the necessary measures to achieve or maintain 'good environmental status' in all of the EU's marine waters. Achieving this objective means that the EU's seas are clean, healthy and productive and the use of the marine environment is sustainable. The MSFD includes eleven qualitative "descriptors" describing what the environment should look like when good environmental status has been achieved. Commission Decision 2010/477/EU and further developments in Decision 2017/848/EU on criteria and methodological standards on good environmental status of marine waters guides Member States on how this objective is to be achieved (European Commission, 2010, 2017a).

According to the MSFD, EU Member States must establish monitoring programmes for the ongoing assessment of the environmental status of their marine waters on the basis of an indicative list of elements. Monitoring data is required to support suitable indicators for the assessment of the achievement and maintanance of good environmental status. Therefore, several key principles were agreed to ensure that monitoring programmes were adequate, coordinated, coherent and adaptive. Furthermore, these programmes should produce interoperable data, link with assessments, take into account risk considerations, apply the precautionary principle, and acknowledge differences in scientific understanding.

Overall, on the basis of the technical assessment, the European Commission (2017b) considered that four Member States' monitoring programmes could be considered as mostly appropriate (being Spain at the top of the rank, Fig. 8), thirteen others were qualified as partially appropriate and three Member States' monitoring programmes were considered not appropriate (Fig. 8). The current goal is to adapt monitoring programmes to take into account future MSFD obligations, including updated to Member States' determination of good environmental status. This means that in addition to current monitoring (e.g. for eutrophication, contaminants, inputs, discharges, human activities etc.), future monitoring programmes are intended to cover additional parameters relating for example the measurement of pH, total alkalinity, dissolved inorganic carbon and pCO2 to assess the progression of ocean acidification, and the measurement of microplastics.

The IEO RADIALES programme is already conducting the measurement of many of the MSFD descriptors required for mandatory evaluations on the North Spanish coast (Ministerio de Agricultura Pesca Alimentación y Medio Ambiente, 2012a, 2012b). In fact, data collected in the framework of the RADIALES structure has been the core of the initial assessment in the N and NW Spain and the key element for the identification of environmental objectives were incorporated into international databases such as SeaDataNet or EMODnet, and developing web based viewers maintained in permanent servers and services. In the pursuit of giving visibility to the IEO sampling network, as well as the activities of this group, a data viewer has been developed within the RADIALES dedicated web site (www.seriestemporales-ieo.net/). This effort will result in a better reuse of data and information obtained and benefits a wide community of final users (Tel et al., 2016).

2.3.5.3. Climate change. Over the last 30 years, ecosystems in the North Atlantic, as well as in all oceans and seas, have changed substantially, in large part due to warming sea temperature linked to climate variability and change. The changes are reflected in the shifts of distribution, seasonal timing and loss of biodiversity, with many appearing to accelerate (Thomas et al., 2012; Beaugrand and Kirby, 2018; Masson-Delmotte et al., 2018). The prognosis is for continuing change as temperatures rise, with likely significant detrimental effects on biogeochemical cycles and living marine resources (Whitehead and Crossman, 2012; Schickele et al., 2021). Time series programmes are instrumental to establish a solid scientific research base in relation to the role of the ocean in the Earth's Climate system and (i) understand the functioning of marine ecosystems under the pressure of climate change and ocean acidification, (ii) determine the impacts of climate change on marine ecosystems, (iii) develop and evaluate options for mitigation and sustainable use of marine ecosystems, and (iv) provide information to the public that will also assist policy-makers and other stakeholders in their decisions.

No less than 25% of the scientific literature produced by RADIALES is related with climate change in one way or another, which is a substantial portion of the total written production. In fact, the RADIALES project has published and contributed as authors or reviewers of several global (IPCC, WOA), regional (ICES, see for example https://ocean.ices.dk/core/iroc) and national (Spanish) reports on climate change reports and synthesis on the effects and impacts of climate change as a contribution to debates on climate policy (Pérez and Boscolo, 2010; Reid and Valdés, 2011; Bode et al., 2012b; Kersting 2016; Malone et al., 2017; González-Pola et al., 2020). In Spain, preliminary evaluations of the effects of climate change on the ocean have also been carried out considering the entire Bay of Biscay coastline (Anadón et al., 2005; Bode et al., 2012b) or regions such as Galicia (Xunta de Galicia, 2009) or Asturias (Anadón and Roqeñi (2009)). These syntheses represent a contribution of the RADIALES scientists' to build a corpus of technical knowledge on the effects and impacts of climate change in the North Atlantic and as a contribution to debates on climate policy.

The available and published data proves that in this region, the rise in sea level and the warming of the waters have occurred at a speed significantly higher than the global average, especially until the early 2010 s following the broad freshening and cooling reversal observed in the remaining North Atlantic (González-Pola et al., 2020). Partially due to the rapid Greenland Ice Sheet melting, these oscillations are part of low frequency variability while the general warming trends persist. In addition, the influence of the upwelling, which seasonally fertilizes coastal waters, has undergone recent changes in correspondence with the variability in climate, changes that have affected the contribution of nutrients and the biomass, production and composition of plankton. Although the length of the series of records is still short to determine the causes and mechanisms by which the climate affects the pelagic ecosystem of this region, it is likely that in the coming decades the biomass and composition of plankton will be different from the current one. According to current warming trends in the region, the response of ocean phytoplankton community structure evolve towards increasing number of typical warm water species, with a smaller body size than the current ones and lower biomass values. It is noteworthy that the fate of upwelling regions is particularly uncertain at the present time, with climate models forecasting poleward displacement of coastal upwelling cells in the mid-term (Rykaczewski et al. (2015)). If this pattern is confirmed plankton communities will respond accordingly, affecting specially the Cantabrian Sea where upwelling is inherently much weaker than in west Iberia and background climatic warming has manifested more clearly so far.

There is no longer any doubt that global warming and ocean acidification are real and that the climate of the Earth has entered a period of rapid change, with potential negative consequences for the oceans, their ecosystems and living marine resources (Valdés et al., 2009; Bindoff et al., 2019; IPCC, 2019). Warming, de-oxygenation and acidification already have, and will continue to have, significant ecological and economic consequences. This is taken into account by proposed indicators for the UN Sustainable Development Goal 14. Reliable detection of anthropogenic impacts on the marine ecosystems will require increasing the number of sustained observations at a high temporal and spatial resolution, including physical, chemical and biological measurements.

Most of these reports go beyond the pure scientific knowledge and also include thoughtful discussions about the future scientific challenges facing climate change research in both the North Atlantic and in other oceans and seas, as well as highlighting future research needs and priorities. Its conclusions support the development of an international coordinated research strategy that addresses these priorities, the maintenance of a sustained climate change monitoring network for the oceans that includes a biological component, improvements in modelling, and the development of indicators.

Knowledge gaps are also highlighted in the hope that continuing research efforts will fill these gaps and thus improve the ability to predict, adapt to, and mitigate the effects of climate change. The immense area of the open ocean and the modest extent of our knowledge severely limit predictions of how ocean systems will respond to climate change. The successful management and conservation of marine species, habitats, living marine resources, and ecosystem services require a considerable improvement in observational capabilities and predictive power.

3. Discussion & challenges

3.1. New light for time series

Ship-based biogeochemical and ecological time series are one of the most valuable tools to characterize and quantify ocean climate (González-Pola et al., 2020; Benway et al., 2019) and ecosystem dynamics (GLOBEC, 1992, 1993). These programmes remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column and continuously provide major breakthroughs in understanding ecosystem variability, allowing for quantification of the ocean carbon cycle, and help to understand the processes that link biodiversity, food webs, and changes in services that benefit human societies (www.go-ship.org). Some ecological time series are maintained for more than 50 years (O'Brien et al., 2017), providing the information needed for climate models whose outputs are used in various marine science assessments (e.g. by the IPCC or ICES reports).

The importance of continued sampling by existing marine time series is now highlighted by the UN Decade of Ocean Science for Sustainable Development (2021–2030). A quantum jump in regional and global ocean ecosystem science can be gained by aggregating observations from individual time series that are distributed across different oceans and which are managed by different countries. In fact, essential research priorities like climate change and ecosystem functioning depend on the development and implementation of global networks of multidisciplinary capabilities. The collective value of these data is greater than that provided by each time series individually, as was highlighted very recently by a group of international experts on marine ecological time series (O'Brien et al., 2017) (Table 3).

Attention has been shifting increasingly toward multidisciplinary "observatories," a clear advance from the traditional physical and atmospheric measurements collected largely by moorings and other in situ platforms. Both technological advances and the recognition that human activities are inducing major changes to Earth's climate system and ecosystems drove this shift. The new challenge—to understand the influence of climate on ecosystem functioning and biogeochemistry—will require an interdisciplinary approach that simultaneously captures all aspects of physical, biological, and chemical forcing mechanisms. Deployment of a robust and global ecological observing system that could describe the actual state of the marine ecosystem and key processes will fundamentally change society's view of the ocean environment.

This ideal observing network will require extensive infrastructure, including: (1) in situ observatories in the ocean, on the seafloor, and across the land–water interface; (2) shore-based laboratory facilities for sample analysis and experimental manipulation; and (3) a wide range of survey capabilities together with observing-system maintenance procedures. In that context, marine laboratories around the world have great potential as infrastructures dedicated to the development of research, training, and education, as well as conservation of marine biodiversity (Valdés et al., 2010). This network may also offer crucial support to global scientific programs in which ocean data and routine observations contribute to regular reports on the state of the marine environment as requested by the UN General Assembly and the EU MSFD. For instance, data series and expertise derived from RADIALES were incorporated in the First Global Integrated Marine Assessment: World Ocean Assessment (Malone et al., 2017). But probably the single most important aspect of the network is the development of the user community that is essential for assuring the long-term maintenance of the observations.

Recent findings reported by IPCC (Masson-Delmotte et al., 2018) show that the climate system is moving toward a more unstable state, which could speed the sea level rise and global temperature, among other effects. Therefore, detecting climate variation should be regarded as the highest priority. The proposed network would provide the information necessary to improve our ability to predict and monitor these trends and variations in climate. Analysis of these observations will allow the development of more effective adaptation and mitigation strategies, which may help to reduce the consequences of climate change.

3.2. The need for continued sampling

In a growing effort to distinguish between natural and human-induced earth system variability, sustained ocean time-series measurements have taken on a renewed importance. However, the value of time series measurements is still not fully appreciated, and very often programs face severe funding difficulties and few survive beyond a few years (Duarte et al., 1992). Some could not sustain measurements with the same sampling frequency in time, resulting in temporal gaps of observations, and financial resources even ceased and no alternatives could be obtained (Frost et al., 2006). However, some others survived and gained international prestige (e.g.: CalCOFI, HOT, BATS, CARIACO, ESTOC, Plymouth L4, Helgoland Roads, RADIALES) in particular for providing the reference baselines for different variables at local–regional scales and in different ocean biogeographical provinces.

Time series projects and programmes require a commitment by the science community and sponsor agencies (Michaels, 1995; Karl and Lukas, 1996; Ohman and Venrick, 2003; Greve et al., 2004; Harris, 2010). In this sense, RADIALES has been a pioneering and successful project which is still possible thanks to the vision and institutional and financial support of the IEO. RADIALES represents an important contribution to the advancement of environmental research in the marine environment and exemplifies the importance of basic research as a fundamental premise for a correct management of environmental resources.

While the need for marine monitoring is well established, there are increasing societal demands for answers on how much the marine ecosystems are changing (Neuer et al., 2017; Benway et al., 2019). Human intervention and global warming are two sources of variability whose long-term impact on the ecosystem is not known, and add a high degree of uncertainty to the proper management of marine resources and uses of coastal areas. The diagram in Fig. 9 is based on a matrix of structural differences between systems complexity of elements vs. complexity of interactions as formulated in economic theory by Ulrich and Probst (1988) and adapted to marine ecology by Valdés et al (2021), and shows very visually the transition from the different management stages (from single species management to a multi-species management and to the Ecosystem Based Management (EBM) approach and ultimately the Marine Spatial Planning (MSP). The development of a more coherent and comprehensive understanding of how these processes interact with physics and biology of marine ecosystems is a major challenge for coming years which can only be satisfactorily dealt with if collections of data with a suitable temporal perspective are obtained now. In this regard, understanding past changes may help to advance changes in the future. For this reason, EU member states currently spend several millions a year in observing the ocean, some of which is funded by the EU and some by the countries to meet the EU legislation. Pursue for a Directive aiming for Member States to bring all public bodies responsible for ocean with EU funding to support observations of common benefit is currently a debate open for public consultation (European Commission, 2020).

In a time of increasing pressures on the marine environment, time series are central to understanding past, current and future alterations in ocean biology and to monitoring future responses to climate change (Valdés et al., 2010; Karl, 2014). With many time series having now accumulated sufficient data to quantify variability and trends, it would be foolish to allow reductions in sampling or long gaps to occur, and replacing the ship based long term series with autonomous platforms should not be the ultimate path to follow (González-Pola et al., 2019). While these tools provide high quality and high frequency data for certain, generally physical and geochemical, parameters, ship-based time series are unique in their multidisciplinarity: physical, chemical and biological parameters can be measured at the same time. Many ecosystem processes and functions (e.g., primary production, phytoplankton composition, utilization of specific nutrients) cannot be directly obtained from these autonomous sensors and only some can be derived through proxy measurements. Furthermore, regular and consistent calibration of independent sensors, moorings and remote sensing techniques can only be assured with standardized in-situ measurements. Operational procedures and support activities are required to advance and reinforce the sampling network and to obtain a better yield in the exploitation of results. Satisfaction of both demands would result in a reinforcing of the structure of the project and would be the best guarantee of continuity in long-term programmes to resolve long-term scales of variability in a way that is impossible for standard process-oriented studies.

On the other hand, because continuation of long-term monitoring programmes is often heavily dependent on the personal effort and dedication of individual scientists, and because, by the nature of long-term monitoring programmes, they are not competitive when evaluated by their short-term scientific yield, the challenge in the near future is to maintain operative the structure of collaborations among institutions, co-funding of co-ordinated projects, integration of network of sampling into a pan-European one, etc. For instance, the papers with the highest scientific impact from individual programmes are those based on data spanning more than 20 years. An additional attraction for scientists to work in long term programmes appears if data sets are pooled together among institutions, as opposed to the isolation of present practices, thereby comparing observations from distant locations collaborative effort of many scientists led to the increasing use of data and products from repositories (e.g. PANGAEA) and data portals (e.g. EMODnet, SeaDataNet). On the other hand, detection of broad-scale changes, and distinguishing them from local imbalances, is possible only when data from distant locations are compared; this comparative approach will enhance the potential to detect risks and forecast them.

Author contributions

All authors have contributed to the work. LV as leading author organized data, paper writing and the structure of the manuscript, AB assisted in the structure of the manuscript as well as paper writing and ML, EN, RS, MV, CGP, GC contributed to analyze and describe the results section and assisted paper writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pocean.2021.102671.

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