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RESEARCH ARTICLE

INTEGRATED MACARONESIA MARINE MONITORING NETWORK (R3M)

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ABSTRACT

Although ocean monitoring technology has improved significantly over the last twenty years, there are still many deficits in terms of data quality, reliability, efficiency and sustainability. Macaronesia is a vast area of key interest for the marine and maritime sectors. However, logistics and support to develop and maintain a useful and sustainable monitoring strategy programme still fall short of the needs. There is now a multi-disciplinary group of companies and institutions that have come together as a result of working on common initiatives for many years, for the purpose of consolidating a regional ocean observation strategy entitled R3M (Macaronesia Marine Monitoring Network). This network gathers data from several meteorological and oceanographic devices, such as buoys, underwater vehicles and weather stations, all integrated to a data portal where the data is managed and displayed according to end-users needs.

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INTRODUCTION

In-situ ocean monitoring remains difficult and costly for a large number of reasons, despite current advances in key marine technology fields. Oceans have a complex 3D-structure and their behaviour is governed by a wide variety of processes. Their long-term monitoring also poses substantial technical and logistic challenges. The World's oceans are constantly shifting in ways that impact every aspect of our society. To keep open-ocean and coastal communities, economies, and ecosystems healthy, key physical, chemical, and biological parameters have to be monitored in order to assess how these areas are changing (offshore and coastal, from surface to seafloor) so that the right decisions can be taken, both for them and for the environment (Lampitt *et al*., 2010). From a global and multidisciplinary perspective, it is now possible to link databases holding information from in-situ ocean observation with modelling tools and to use them for supporting forecasted ocean states according to end-user needs (Bahurel, 2009; de La Beaujardiere, 2008).

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Conflicts between trade, leisure, research and development, environmental protection and the management of living resources are increasing. The social and economic costs of inadequately informed decisions are growing accordingly. A global integrated system of ocean observations and analysis is still needed to provide the information (data products) required by society to fill the key gaps that continue to exist in this context.

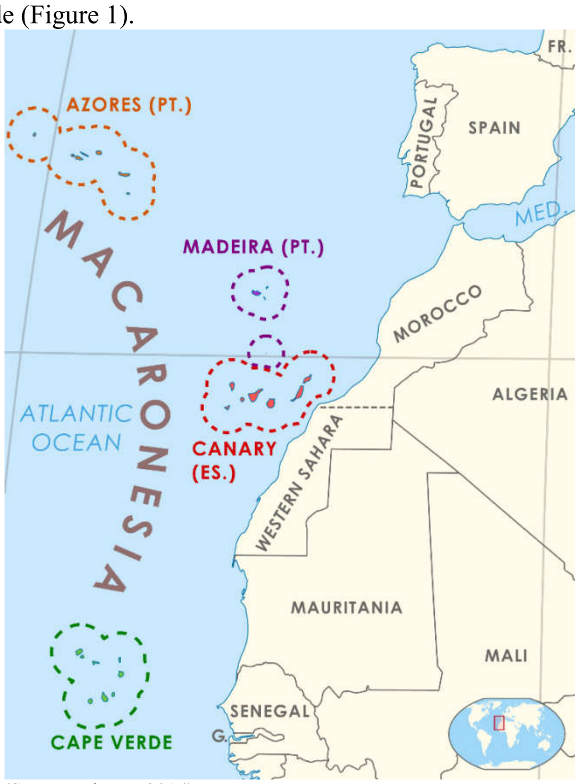
World Ocean Observation Strategy

The Group on Earth Observations, GEO, is coordinating efforts to build a Global Earth Observation System of Systems, or GEOSS. GEO was launched in response to calls for action by the 2002 World Summit on Sustainable Development and by the G8 (Group of Eight) leading industrialised countries. These high-level meetings recognised that international collaboration is essential for exploiting the growing potential of Earth observations to support decision making in an increasingly complex and environmentally stressed world. GEO is a voluntary partnership of governments and international organisations. It provides a framework within which partners can develop new projects and coordinate their strategies and investments. As of March 2012, GEO's Members included 88 governments and the European Commission.

In addition, 64 intergovernmental, international, and regional organisations with a mandate on Earth observation or related issues have been recognised as Participating Organisations (Commission & others, 2005; GEOSS, 2005; UNESCO, 2015). GEO is constructing GEOSS on the basis of a 10-Year Implementation Plan for the period 2005 to 2015 in order to define a vision statement for GEOSS, its purpose and scope, expected benefits, and the nine "Societal Benefit Areas" of disasters, health, energy, climate, water, weather, ecosystems, agriculture and biodiversity. GOOS (Global Ocean Observing System) is the oceanographic component of GEOSS (Dexter & Summerhayes, 2010; Kullenberg & Rebert, 1997). GOOS, sponsored by WMO, IOC of UNESCO, UNEP, and ICSU are designed to provide sustained observations from the global ocean and related analysis in support of operational oceanography and climate change applications by in situ and satellite observations. It is not solely operational, but includes work to convert research understanding into operational tools. It is designed to produce products useful to a wide range of users.

Area of Work: Macaronesia

The region of Macaronesia is an area located in the East-Central North Atlantic encompassing over 30 million km^2, only 0.05% of which is land, containing four main archipelagos: Azores, Madeira, Canary Islands and Cape Verde (Figure 1).



(Source: Platon, 2014)

Figure 1. The Macaronesia region location

All of them clearly show a common volcanic (hotspot) origin which gives them similarities with respect to biodiversity, although there are climate differences due to their respective positions in the sub-tropical North Atlantic gyre and their terrain. The status of outermost region, the fragmentation of each archipelago into islands as bounded units and external dependence are structural features that have conditioned and decisively influenced the development of human activities and the availability of resources.

Despite this, Macaronesia has a clear and strategic international interest for all major socio-economic sectors within the marine maritime fields, which require an efficient and continuous flow of information as the product of observations of the marine environment.

Macaronesia Marine and Maritime Network: R3M

R3M (Macaronesia Marine and Maritime Network) is a regional initiative (linked globally) aimed at increasing the quantity and quality of marine environmental observations, in order to understand and predict both the phenomena that take place in it and the related environmental and socio-economic impacts. R3M is an integrative and synergic tool, offering compatibility with and access to all marine environmental observations [time series observations gathered by different "in-situ" and remote sensing platforms from cutting-edge and conventional methodologies] for all potential end-users (commercial and recreational navigation, harbours, safety & security, oil & gas, aquaculture, waste-water, tourism, marine research, water sports, ocean energies, protected areas, weather agencies, national and regional governments, etc.), irrespective of the institution or company that makes them. The initiative includes technological developments for all types of instruments and tools required, with a view to making them more accessible from both a technical and a financial point of view (Sosa-Cabrera *et al*, 2012). R3M has been built "from the bottom up", starting with the specific end-users and moving towards general users, while keeping in mind the goals and rules established by national and international agencies, such as the Global Ocean Observing System (GOOS). R3M is one of the results arising from more than 15 years of partnership work carried out through regional and international projects, mainly funded by the EU-INTERREG and EU-Framework programs (C. Barrera *et al*., 2006, 2007 and 2009), as detailed in Table 1.

At the same time, there are other networks joining the R3M initiative in accordance with their needs and capabilities. These are managed and funded by national government bodies like the Instituto Hidrografico (Lisbon) and State Ports (Puertos de Estado, Madrid) as reference initiatives covering the whole national ocean space for Portugal and Spain respectively. The R3M initiative is led by a core group of institutions from Portugal (IH, UAC, APRAM, OOM), Cape Verde (INDP and ENAPOR) and Spain (ULPGC, ICCM, PLOCAN, AEMET, IEO, Puertos del Estado), with the support of partners from other European countries (mainly France, Germany and the UK).

Data and methods

Network of Meteo-Oceanographic Observation systems and devices

R3M now integrates a large number of different, independent technological platforms across the Macaronesia region (Figure 2) aimed at monitoring the maximum number of environmental, meteorological and oceanographic parameters, in accordance with their capabilities and needs (Fer & Peddie, 2012; Neuer *et al*., 2007; Rudnick *et al*., 2004). The existing devices (Table 2) are managed and supported by local, regional and national governmental bodies, agencies or research groups, through individual or joint actions as networks or single platforms.

Table 1. List of projects that have funded the Integrated Macaronesia Marine Monitoring Network (R3M)

ACRONYM	PROJECT NAME	PROGRAMME	OUTERMOST REGIONS INVOLVED	TIME RANGE
RED ACOMAR	Red Acomar Canarias, Monitorización en tiempo real para la alerta, control y observación marina de Canarias / Real Time Monitoring to alert, control and marine observation at Canary Islands	Canary Islands Government	Canary Islands	1999-2009
ANIMATE	Atlantic Network of Interdisciplinary Moorings and Time-series for Europe	V Framework Programme	Madeira, Canary Islands, Azores	2001-2004
PREVIMAR	Previsión de Circulación del Espacio Marino-Maceronésico / Forecast currency at Marine-Macaronesian Space	Interreg III B 2000-2006	Madeira, Canary Islands, Azores	2002-2004
ALERMAC	Red Integrada de Monitorización, alerta y gestión de riesgos de vertidos contaminantes e incidentes catastróficos en la zona Marítima Macaronésica /Monitoring network to alert and risk management at Marine – Macaronesian region	Interreg III B 2000-2006	Madeira, Canary Islands, Azores	2004-2007
MERSEA	Marine Environment and security for the European area	VI Framework Programme	Madeira, Canary Islands, Azores	2004-2008
CLIMARCOST	Clima Marítimo costero – Sistema de Monitorización de datos meteo-oceanográficos / Monitoring system for weather-oceanographic data	Interreg III B IV Call	Madeira, Canary Islands, Azores	2005-2007
AMASS	Autonomous Maritime Surveillance System	VII Framework Programme	Madeira, Canary Islands, Azores	2008-2011
EUROSITES	Integration and enhancement of key existing european deep-ocean observatories	VII Framework Programme	Madeira, Canary Islands, Azores	2008-2011
MACSIMAR	Incorporación del sistema integrado de monitorización meteorológica y oceanográfica de la Macaronesia en la Estrategia de investigación marino-marítima europea integrada / Incorporation to weather-oceanographix integrate system monitoring at Macaronesian region to Marine-Maritime european integrated strategy	Transnational Cooperation Programme MAC 2007-2013	Madeira, Canary Islands, Azores	2009-2012
ESTRAMAR	Estrategia Marino-Marítima de I+D+i en la Macaronesia /Marine-Maritime R&I Strategy at Macaronesian Region	Transnational Cooperation Programme MAC 2007-2013	Madeira, Canary Islands, Azores, Cape Verde	2012-2015
FIX03	Fixed Point Open Ocean Observatory Network	VII Framework Programme	Madeira, Canary Islands, Azores	2013-2017

Figure 2. A weather-oceanographic Dolan buoy (left), water sampling rosette (centre), autonomous underwater vehicle glider (right)

Table 2. Total number and type of buoys installed in each area of Macaronesia within R3M

REGION	METEOROLOGICAL STATION	HC-BUOY	WAVE BUOY	OCEAN BUOY
AZORES	1 (2015)	1 (2014)	1 (2015)	3 (2008, 2010, 2014)
MADEIRA	1 (2014)	2 (2013, 2014)	2 (2014, 2015)	1 (2013)
CANARY ISLANDS	4 (2012, 2013, 2014)	1 (2013)	-	1 (2013)
CAPE VERDE	1 (2014)	1 (2013)	-	1 (2013)

The most important ones are the following:

Drifters and gliders are Lagrangian devices and the difference in the latter is their capacity to change direction and, therefore, to be able to follow a course over their run (Carlos Barrera *et al*., 2013). Moorings and fixed buoys like hydro-carbon buoys (HC) or meteo-oceanographic buoys (like the ODAS buoys) are Eulerian devices anchored at a fixed point. They all transmit the data they gathered by satellite, enabling them to gather data throughout the Macaronesia region simultaneously in real time. We have data sets from most of these devices that cover over 15 years (Araña *et al*., 2005). Additionally, these autonomous and cutting-edge observation technologies are supported by more conventional systems and devices (ship-based sensors and instruments) also designed for ocean monitoring, as well as remote sensing tools or even “customised” turtles carrying on-board sensors and satellite modems for real-time telemetry.

The leading R3M projects include the network of buoys for detecting hydrocarbons (SeaMon-HC), the autonomous underwater vehicle base and their periodic launch in the Macaronesia area, the area network of drifters and the European Station for Time-Series in the ocean (ESTOC) (Vega-Moreno *et al*., 2011).

Hydro-carbon control network

Checking for the presence of hydro-carbons in port regions is especially important in outermost regions like Macaronesia, where tourism is a leading industry, as is the case of the 4 main archipelagos the comprise the region. That is why hydro-carbon detection buoys have been installed in the main ports of the 4 archipelagos as part of R3M, as shown in Table 2 (Llerandi *et al*., 2011).

Gliders

Gliders are autonomous, un-manned underwater vehicles, driven only by differences in water density that can collect ocean data over extended periods of time with minimum energy consumption. Gliders can remain at sea for up to 9 months and cover 7000 km without having to change batteries. Devices of this kind make ocean research far more economical, reducing costs between 50 and 100-fold in comparison with using oceanographic vessels. A glider can do 4 1000m-deep profiles a day, obtaining 40,000 data per day for each parameter (M. Marqués *et al*, 2013).

Depending on how the vehicle is set up, the oceanographic parameters measured by gliders can be temperature, salinity, chlorophyll concentration and an approximation of the amount of biomass in the environment, dissolved oxygen concentration in sea water. Less frequently, and depending on which sensors are installed, it can also measure ocean currents, CO2 concentration or the concentration of hydro-carbons in sea water. But also an increasing range of payloads are being developed by gliders (Palmer *et al*., 2015). A fleet of gliders suited by the main commercial buoyancy driven (Slocum, Seaglider and Spray) and ASV (Waveglider and Sailbuoy) technologies is currently managed from the PLOCAN gliderport facility in a synergetic way with the rest of existing autonomous and ship-based technologies, aiming to increase ocean observations in a sustainable manner. Gliders provides the opportunity to monitor remote open ocean areas, approaching in some way the archipelagos in the Macaronesia all together in a wider framework as it is the North Atlantic basin. Several missions have been performed until now, with different scopes and applications. Some examples are listed as follows: The Silbo buoyancy-driven Slocum G2 glider set an historic milestone between 2011 and 2015. In an attempt to emulate the 1872 Challenger mission, it circumnavigated the Atlantic Ocean, from North to South and from East to West. Setting out from Iceland, it covered all of Macaronesia and finally reached Brazil (Figure 3).

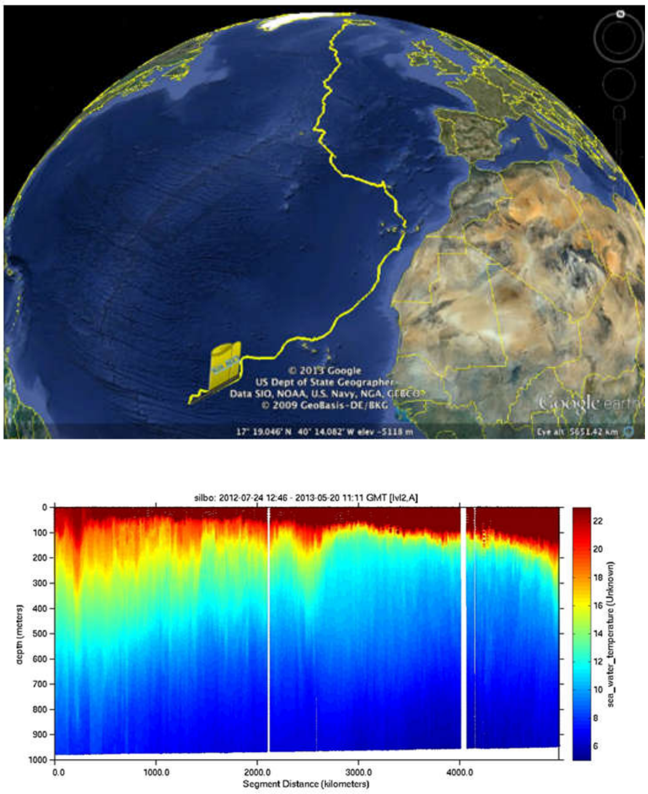


Figure 3. Course of the Silbo glider (left) and vertical temperature profile measured by the glider (right)

A seasonal buoyancy-driven glider mission of three weeks duration is conducted from Gran Canaria to ESTOC site (round trip) since 2011. The glider is suited by a basic payload sensor configuration that includes CTD, dissolved oxygen, turbidity and chlorophyll. Gathered data are provided in NRT through PLOCAN glider portal. http://gliders.plocan.eu/
With Hermes wave-glider SV2 was conducted in June 2012 a challenging four-week mission in the surrounding waters of an active submarine volcano in El Hierro Island, with a dedicated payload met-ocean sensor configuration in order to monitor and characterize in a safe and sustainable manner the effects of this unusual natural event in Canarian waters. Deployment and recovery was performed in Gran Canaria and the round trip was remotely piloted by PLOCAN in cooperation with Liquid Robotics Inc. Same approach was performed with a Seaglider unit in order to monitor the water column in the closer area of the active volcano. With the ASV Sailbuoy several missions have been also performed up to now across the Macaronesia and Morocco coast (Dakhla Bay, ESTOC, etc.) in cooperation with partners interested in some specific areas and monitoring studies

Drifters

Over 500 drifters have been launched in the Macaronesia area as a characteristic example of Lagrangian devices as part of the

R3M (Cardona *et al*., 2011). These drifters can provide us with information including sea surface temperature, barometric pressure, salinity wind speed and direction, to predict seasonal or inter-annual variations. This makes it possible to construct predictive oceanic and meteorological models, observe the variability of certain regional systems and even apply this information to study global climate change. The information is transmitted and received by satellite, and also enables us to calibrate surface temperature satellite images with the data measured in-situ.

The results of the annual surface circulation in the archipelagos of Macaronesia obtained from drifters have provided an in-depth understanding of the system of surface currents in the area. They confirm the variability in the direction of the current as an indicator of the trend of the gyres and the generation of mesoscale structures such as eddies due to the fact that the Archipelagos of Cape Verde and the Azores act as an obstacle in the way of the surface and sub-surface currents, apart from their possible interactions with coastal up-wellings. The data base used over the years has a total of 519 drifters in the Macaronesia region.

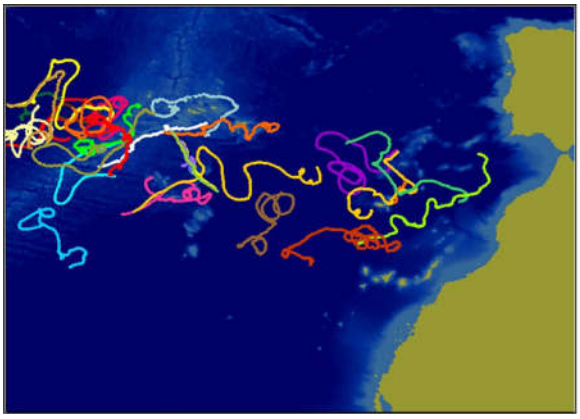


Figure 4. Tracks of the drifters in the Macaronesia region in 2010

Long-term Observations - European Station for Time-Series in the Ocean (ESTOC)

ESTOC (European Station for Time-Series in the Ocean, Canary Islands) represents a benchmark for monitoring and controlling physical, chemical and biological parameters over time in the ocean measured at a fixed point. ESTOC started operations in February 1994 sponsored by four European institutions (the Universities of Bremen and Kiel, Germany, and in Spain by the Oceanography Institute and the Canary Institute for Marine Sciences) and was initially funded by several observation programmes: the German JGOFS (Joint Global Ocean Flux Study), and national and local funding in Spain (Neuer *et al*., 2007). From 2002 to 2007, ESTOC was involved in two European projects: ANIMATE and MERSEA. One of the purposes of these projects was to improve the time-resolution of the bio-geo-chemical measurements at the deep Atlantic Ocean observatories. Recently, the EuroSITES and FixO3 projects are integrating as part of European open-ocean fixed point observatories with a view to harmonising the observatories and providing access to these key facilities for the broader community. Additionally, ESTOC belongs to the Marine-Maritime observation network of the Macaronesia region, which has been supported by the European overseas territories programmes since 2009. This network aims to increase the quantity and quality of marine environmental observations.

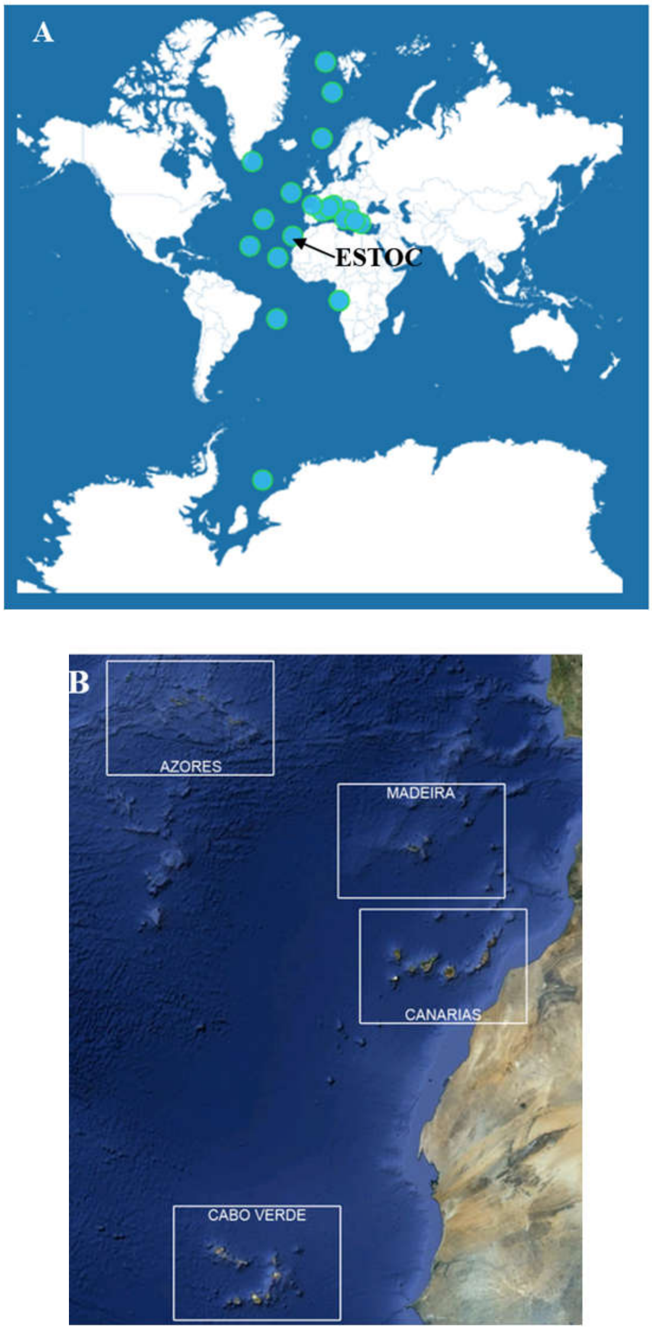


Figure 5A. Map of the observatory locations within FixO3 project. 5B. Overseas territories within the Marine-Maritime network of the Macaronesia region

ESTOC is currently the oceanic reference point in the eastern central North Atlantic according to physical and biogeochemical marine measurements. The comparative studies between BATS (Bermuda Atlantic Time-series Study) and ESTOC have found similarities and differences in time variability at both western and eastern boundaries of the sub-tropical North Atlantic gyre. Comparisons include those made in studies of the carbon export (Neuer, 2002), the in situ nutrient budgets (Cianca *et al*., 2007), the variability in the carbon system (Bates *et al*., 2014; Santana-Casiano, 2007) and chlorophyll and oxygen dynamics (A. Cianca *et al*., 2012, 2013). A total of 47 studies have been published that refer to the ESTOC site in some of the main international oceanography journals (Table 3).

Table 3. Summary of the main observations made at ESTOC site

TYPE OF OBSERVATION	PROGRAM NAME	PARAMETERS	INSTITUTIONS INVOLVED	TIME RANGE
Ship- based	ESTOC time-series	T, S, DO, Chl. a, DIN, DIP, DIS, Alcalinity, pH, total CO_2, PCO_2, DIC and Pigments	ICCM, ULPGC, IEO and PLOCAN	1994- present (Carbon parameters from 1996 and pigments from 2008)
	Oceanographic cruises and process studies	T, S, DO, Chl. a, DIN, DIP, DIS, Alcalinity, pH, total CO_2, PCO_2, DIC, Pigments and others	Diverse	Variable since 1994
Surface buoy and mooring	Canary Islands Sediment traps	PON, POC and sinking particle flux	Bremen University	1995- 1999 and 1991- 2007
	Hydrography (current and transport)	T, S and currents	IFM Kiel	1994- 2000
	Weather, Hydrography and biogeochemistry (ANIMATE, MERSEA, EuroSITES and $FixO_3$)	T, S, DO, Chl. a, Nitrate, pH, PCO_2	ICCM, IFMK, UB, NOCS, ULPGC and PLOCAN	2002 -present
Drifters	Canary Islands surface circulation	T and current	ICCM, PLOCAN and NOAA	1997- present
XBT launching	ESTOC section	T	ICCM	1996- 2004
ARGO float	Canary Islands region	CTD	IEO	2012- present
Glider	ESTOC section	CTD, DO, Chl. a, turbidity and current	PLOCAN	2012- present

The ESTOC observatory currently offers real-time / near real-time meteorological observations of atmospheric pressure, relative humidity, air temperature, wind speed and direction, as well as observations of surface oceanographic variables such as temperature, salinity, dissolved oxygen, chlorophyll a, pH, pCO2 and turbidity. All data mentioned above is being quality automatically controlled following the recommendations for in situ data near real time quality control (EuroGOOS DATA-MEQ working group, 2010) and manually from oceanographic experts. The data dissemination is through the THREDDS (http://data.plocan.eu/thredds/catalog/aggregate/public/ESTOC InSitu/FixO3/surfacebuoy/Realtime/catalog.html).

Additionally, surface (once the buoy is recovered and data quality controlled) and subsurface monitoring in delayed mode, which includes physical (temperature, salinity) and biogeochemical observations either at 100m and 150m (dissolved oxygen, current, Chlorophyll a, turbidity and nutrients) are distributed through http://data.plocan.eu/thredds/catalog/aggregate/public/ESTOCInSitu/FixO3/surfacebuoy/Delayed-mode-data/ catalog.html. Ship-based data (Historical ESTOC time-series), taken by CTD/ water sampler and analysed following the protocols described in Neuer *et al*., 2007, are stored and distributed by request in the email observatory@plocan.eu. Supplementary to the buoy monitoring, seasonal glider missions, for measurements in the surrounding waters, are annually carried out. Related data sets are available through THREDDS and graphs which show the variability of the parameters (temperature, salinity, dissolved oxygen, chlorophyll and turbidity) during the mission, are available at http://data.plocan.eu/thredds/catalog/aggregate/public/ESTOCInSitu/FixO3/GliderCampaigns/catalog.html.

R3M Data Portal

Over the last two years, R3M has undergone significant upgrades with a set of independent but compatible applications to process, store and disseminate information gathered through different oceanographic platforms (Cornillon, Gallagher, & Sgouros, 2003). These applications have been implemented using open standards, such as HTML and CSS, and open source software, like Python as programming language and Django as framework web. In some cases, the upgrades have been developed to well-known international standards and protocols (SeaDataNET, GROOM and OceanSites). All details can be checked through the following website: http://r3m.estramar.eu/

Conclusion

The need, importance and specific difficulty of monitoring ocean regions like Macaronesia in a coordinated, efficient and sustainable way is reflected in the development and current status of R3M, after more than fifteen years of co-operation among a wide and multi-disciplinary group of both public entities and private institutions in the marine and maritime sectors. This path has made it possible to share common and specific needs and experiences based on their activities in both the in-shore and off-shore ocean environment, and it is one of the most important for developing a common data portal (R3M) to display and manage useful information. However, despite significant advances in terms of technology and co-operation, there are still gaps to be adequately covered based on both current and future end-user needs.

Acknowledgement

The authors are truly grateful to the EU-INTERREG and EU-Framework programmes for funding a large number of projects and specific actions over the last fifteen years (and still) at a regional and international level, enabling us to set up, improve and keep the R3M initiative going in a sustainable fashion. We would like to make special mention to all our partners and associates from different socio-economic sectors (universities, governments, agencies, port authorities, private companies, etc.) in the marine and maritime fields, for their direct or indirect support they have provided in this challenging and useful initiative for the Macaronesia region.

Nomenclature

AEMET – Spanish Meteorological Agency

APRAM - Administraçao dos Portos da Regiao Autonoma da Madeira, S.A
BATS - Bermuda Atlantic Time-series Study
ENAPOR - Empresa Nacional de Administração dos Portos de Cabo Verde
ESTOC - European Station for Time-Series in the ocean
GEO - Group on Earth Observations
GEOSS - Global Earth Observation System of Systems
GOOS - Global Ocean Observing System
ICCM - Canary Institute of Marine Science
ICSU – International Council for Science
IH- Hydrographic Institue
INDP - Instituto Nacional do Desenvolvimento das Pescas
IOC – Intergovernmental Oceanographic Commission of UNESCO
ODAS – Ocean Data Adquision System Buoys
OOM - Observatorio Oceanico da Madeira
PLOCAN – Oceanic Platform of the Canary Islands
R3M - Macaronesia Marine Monitoring Network
SeaMon- HC – Hydrocarbons Buoys
UAC - Universidade Dos Açores
ULPGC - University of Las Palmas de Gran Canaria
UNEP – United Nations Environment Programme
UNESCO – United Nations Educational, Scientific and Cultural Organization
WMO- World Meteorological Organization

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