“Marine Autonomous Observing Systems: Scientific Requirements and Technological Opportunities” Workshop

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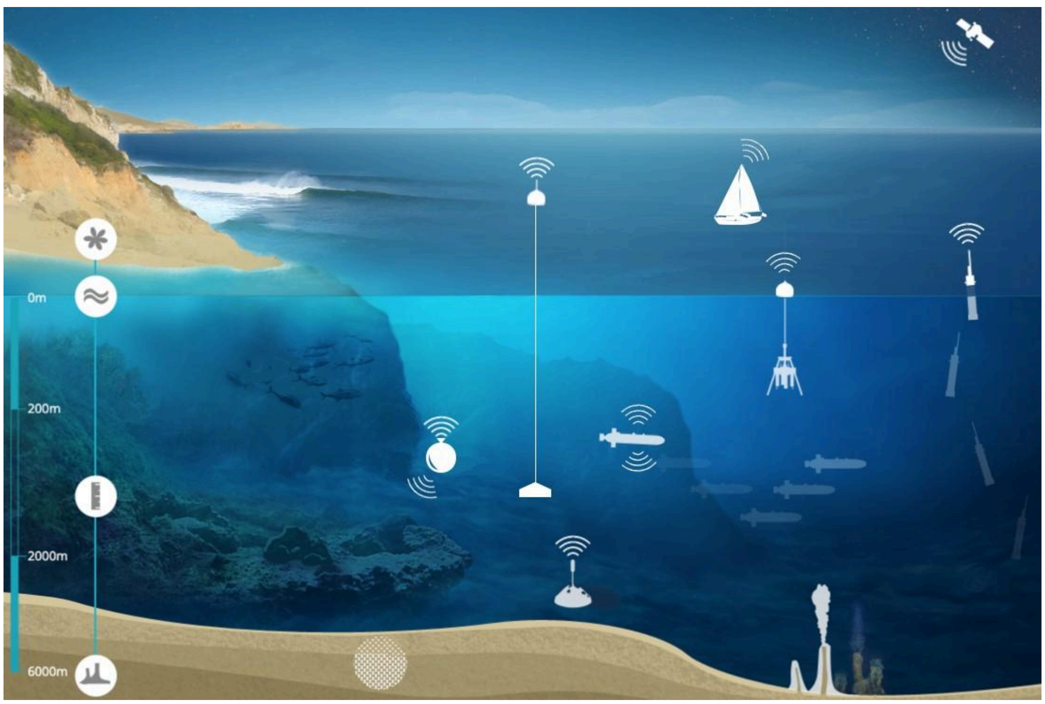
White Paper - Physical Oceanography



Guidelines:

- **Coordinators / contacts: Gilles Reverdin / Aurélien Ponte**
  Please send email to coordinators to notify your interest for this section
- **Length (soft limit)**: 6-8 pages
- **Structure**: each subsection should adopt the following structure:
  - Scientific context and questions
  - Observational challenges
  - Perspectives
- **Table:** fill the sheet entitled "scientific need" in the following spreadsheet:
  - https://docs.google.com/spreadsheets/d/1aIDtzbTsZqSEzydYGZsivjrf-04ci0UOyyGddkv6e_M/edit?usp=sharing
  - The data will be used to assemble pie charts synthesizing each subsubsection
- **List contributors**
- **References:** provide landmark papers or pointers/links toward relevant projects and efforts
- **Keywords:** a list of keywords related to either scientific questions and/either in situ observational challenges
- **Potentially overlooked topics :** air-sea interactions, other?

discussion / general comments:
(please identify yourself)

Actions restantes:

1. Réintégrer les références aux citations orange dans le corps du texte
2. Trouver ou créer une illustration pertinente: celle-ci doit résumer un ou des besoins du moment

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1. Scientific questions and experimental requirement

1.1. Physical Oceanography

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The main scientific questions tend to evolve both with questions of large time and space scales, on which the global arrays of autonomous instruments (Argo floats, drifters, gliders, mooring arrays…) of GOOS play a key role, and with issues of the dynamics at small scales, presently poorly sampled, except during process and dedicated experiments. These dynamic processes also require dedicated, often autonomous instrumentation.

1.1.1. Climatic variability and tracer distributions

Prediction at the seasonal to decadal and longer (Climate change) time scales

Context. The ocean plays a key role in climate change, both due to heat and carbon storage and changes in ocean surface conditions and transports. Climate forecasting at seasonal to decadal timescales have key economic and societal values and is of paramount importance for ensuring sustainable ecosystem and human services. The upper ocean plays a major role in controlling the climate variability on those time scales.

Observational challenge. A key challenge of climate forecasting at different time scales is to determine how and with which observational data forecasting models need to be initialized and what controls their evolution. Separating natural variability from anthropogenically induced variability (in particular through changes in greenhouse gases and anthropogenic aerosols) and initializing it, forecasting at decadal and multi-decadal scales are nowadays outstanding challenges. This requires **robust and long-lasting (at least 10 years) monitoring**, in particular, of ocean temperature and salinity. Ocean current monitoring is also important, in particular near the equator and in western boundary currents, as it will help validate model simulations and disentangle processes.

Perspectives.

- Understanding the ocean circulation so as to anticipate its vulnerability to external stresses and global warming
- Development of robust modelling and knowledge of model needs, and performances and uncertainties.
- Development a business plan to maintain and extend existing networks
- Methodological developments for the positioning of instruments and observation networks (example of the key role played by equatorial mooring array of T/S/currents for seasonal climate forecasts)

Ocean temperature (T), salinity (S), Oxygen (O2), Carbon (C), pH distributions and integrated contents

Context. The ocean heat, steric content, oxygen content, ocean carbon, and pH have largely changed during the last 50 years, with varying spatial patterns partially related to patterns of air-sea exchanges, ocean circulation, and ventilation/upwelling changes, and, with most of the changes in the top 1500 to 2000m. The heat budget and steric ocean budgets have actually been rather well constrained over the last 15 years thanks to Argo float data in a large part, and help reduce uncertainties on the evolution of the different components of the climate system. Uncertainties are still large for ocean carbon (and pH), estimated largely from ocean inventories and surveys (combined with statistical tools of ranging complexities and importance) for the exchanges with the atmosphere which are done at a low time resolution. Both O2, ocean carbon, and pH levels constrain marine life and biogeochemical cycles, in particular in regions of high surface productivity, such as in the Eastern Boundary Upwelling Systems or in near coastal waters. Dissolved oxygen is a powerful integrator of both physical and biogeochemical processes and a useful indicator of water mass transport and ocean ventilation. Oxygen levels have been decreasing since the 50s, leading to wide-scale expansion of Oxygen Minimum Zones (OMZ), and ocean carbon increasing, leading to pH decrease which can affect calcification processes.

Observational challenges. The role of the deep ocean in the different budgets is increasing while this region remains less sampled. An important issue for the future is to quantify the penetration of anthropogenically-induced signals and be able to diagnose how the vertical ocean circulation evolves and how this will affect penetration of (T increase, S decrease at high latitudes, anthropogenic carbon, oxygen...) to the deep ocean.
There also are specific issues with dissolved oxygen and ocean carbon, related to the monitoring of large changes that are expected in the surface layers, in particular in areas of upwelling and ocean ventilation, changes in ocean productivity, and to the surveying (for ocean carbon) of air-sea exchanges. The latter will require dedicated observational networks. It is critical to enlarge our observing capacities for the tropical thermocline since presently no model is able to realistically represent the oxygen decreasing trend in the oceanic tropical band.

Autonomous instrumentation plays a key role here via first the ARGO network. This network needs to be maintained and extended to the deep ocean, which represents an important challenge, with high accuracy requirements for T, P, S, O2, and pH measurements over long duration. Extending arrays of autonomous observations for O2, pH, and pCO2 is a key challenge in itself, but this will require using different arrays of autonomous platforms and instrumentations, such as a for monitoring surface or near-surface property change (such as from gliders, moorings, surface autonomous vehicles, or animal Borne Ocean Sensors networks). For example, T or sound speed near sea bottom would also be interesting contributors.

Perspectives.

- Incoming project supporting deep observations and more biogeochemical observations, in particular the oxygen EOV.
- Leads for novel (high accuracy, and/or low-cost) sensors
- Development of Unmanned Surface Vehicles (USV) , but also deep sea robots
- Development of a global ocean oxygen database and atlas for assessing and predicting deoxygenation and ocean health in the open and coastal ocean

1.1.2. Key components of ocean circulation and process regions: high latitudes and basin scale circulation

Context. Uncertainty remains today about ongoing changes in several key regions: Arctic oceans and other high latitude seas such as the Antarctic boundary in the Southern Ocean. Changes of the circulation either basin-wide, e.g. associated with the Atlantic Meridional Overturning Circulation (AMOC), or more locally, for example through exchange transports at sills are not known well enough. All play key roles in the ocean system, and are expected to change in the next decades. Understanding why these changes occur and whether they will be enhanced in the future remains a priority, along with the monitoring of key components of the changes involved (heat and freshwater changes, sea ice changes, melt of nearby ice-sheets and ice shelves (for both Antarctica and Greenland). The impact of these changes for carbon and O_2 export/transports, ocean productivity and biogeochemical cycles is another important task. The connection between AMOC as currently measured at mid and low latitudes and higher latitude processes is not fully understood at all relevant time scales currently. The connection between AMOC, the Antarctic Circumpolar Current (ACC) and Southern Ocean ventilation, in particular near the eddying ACC, are potentially important but not fully monitored.

Observational challenges.
Autonomous measurements are expected to play a major role in the future to bridge the gaps both for process studies and for monitoring the changes. Autonomous vehicles, acoustic measurements, use of marine mammals, ice-permitting floats with dedicated tracking/data transmission will be required.
Observations are needed both at the fine scale for selected boundary currents and sills, but also at the large scales across basins, and on rather long-time scales of years to decades. In the Arctic and high latitudes, there is the added difficulty to carry ocean observations in the presence of sea ice. Also, air-sea exchanges through the changing sea ice and circulation near sea-ice edges need to be better monitored and integrated.
Long-term measurements of currents (combined with other components of the observing system measuring density profiles) are required in some key regions of the Atlantic, both at high and lower latitudes. Although on interannual time scales these measurements are not very coherent, models indicate that on decadal time scales, they should become more coherent, thus enabling the monitoring through a fairly loose set of instrumented cross-oceanic sections (moorings, but with other autonomous instrumentation involved: gliders, AUV, cables…), and observations of western boundary currents. The challenge is thus here to design, build and maintain observational networks in coordination with international partners.

Perspectives.

- Adaptive networks thanks to coupling with modeling/assimilating systems
- Robust instruments that operate with ice cover, and the integrations of the different observing systems for the Arctic seas and in the southern part of the Southern Ocean.
- Development of acoustic-based transmission in order to make measurements under sea ice.
- Development of new algorithms to retrieve information on the ocean in ice-covered regions from satellites.
- Development of autonomous platforms able to monitor sea ice conditions and its interface with both the ocean and the atmosphere.
- Integrated approaches (moorings, autonomous vehicles, cruises, sea level data, floats...) to monitor AMOC in selected key locations/sections, in particular across sills that separate different seas, ocean basins, and are easier to monitor.

1.1.3. Surface currents and small scale variability

Surface currents

Context. Near-surface currents are strongly implicated in local sea state/swell through current-wave-swell interactions, they control the drifts of pollutants, what becomes of the micro (and macro)-plastics, sargassum…, and are deemed important (together with waves) in air-sea momentum, heat and other fluxes exchanged with the lower atmosphere.

Observational challenge. The challenge is to extend coverage from current low temporal and large scales (inherited from satellite altimetry products), local measurements from moorings, or Lagrangian drifts of floats and drifters, often drogued at 15-m depth [Villa Boas et al. 2019]. A large part of the ocean energy near the surface, in particular, is not well sensed, either at higher frequency, at smaller horizontal scales, or at smaller vertical scales. Autonomous instruments will play a key role in providing data for validation of space observations, process studies and data to be assimilated in models.

Perspectives.

- Perspectives are strongly constrained by incoming innovative satellite missions and projects: SWOT and STREAM or equivalent efforts
- Low cost instruments integrating drift, wave, oceanographic, meteorological parameters.
- Combinations between these data sources (drifters, altimetry, direct satellite estimate, ship,moorings, tagged animals, gliders, wave spectra) , i.e. methodology effort

Mesoscale and submesoscale variability

Mesoscale (horizontal scales around 100 km) and submesoscale (horizontal scales around 1 km) ocean variability present their specific challenges that are addressed experimentally often through a combination of satellite monitoring and imagery, in situ dedicated instrumentation and regional and/or high resolution ocean modelling.

Mesoscales. Mesoscales have long been shown to be ubiquitous in ocean observations in large parts of the world ocean, and key contributors to large scale transports and mixing as well as for biogeochemical processes [McWilliams 2008, Omand et al. 2015, Busecke and Abernathey 2019, Gnanadesikan et al. 2015, Uchida et al. 2019]. Numerical models are required to resolve mesoscales motions in order to realistically reproduce the ocean circulation for climate or now-cast purposes. Their observations rely largely on satellite observations which only partially resolve associated currents on the time and space scale required. Near the equator, observations rely on a sparser density of satellite observations and a loose array of equatorial moorings that has been difficult to maintain lately. [Sea Ice challenge with citation]

Submesoscales. The dynamics shifts substantially at submesoscales such that associated eddies, front and filaments lead to relatively strong exchanges between the surface and the ocean interior and modulations of the upper ocean stratification [Ferrari 2011, McWilliams 2016]. These motions have been more routinely resolved numerically over the last decade thanks to highly resolved simulations which enabled us to grasp the relevance of these processes for the functioning of the ocean in a broad sense. Submesoscale motions are for example expected to be key players for marine life-cycles via modulations of ecological interactions [Lévy et al. 2018, Mahadevan 2016]. Submesoscales motions are also produced as boundary currents and along-slope flows of convective water interact with ocean bathymetric features (valleys, canyons, ridges…) and downstream of sills and expected to modulate vertical mixing and sediment transport/dynamics. Observation based validations of the numerical results obtained is an outstanding issue and an important step prior to the development of the necessary parametrizations of submesoscale effects in climate models.

Observational challenges. Mesoscale and submesoscale motions are small compared to the resolution of both in situ networks (Argo, GDP) and most satellite observations and their observation require thus dedicated field campaigns or moored observatories [Yu et al. 2019]. The campaigns involve targeting structures of interest thanks to remote sensing (e.g. altimetry, infrared sea surface temperature, optical images) and combining ship-operated and autonomous instruments [Shcherbina et al. 2015]. The challenge arises from the swift evolution of these structures (exacerbated at submesoscales) and the necessity to follow them which motivated the development of water-following (“Lagrangian”) strategies [Doglioli et al. 2013].
Reaching the level of synopticity sufficient to the description of these structures is a difficult challenge to meet. When met, e.g. by the development of swarm deployment of low-cost instruments [Novelli et al. 2017], efforts have been shown to pay off as illustrated by the discovery of the “Zipper effect” which recently highlighted the concentrating ability of submesoscale currents at the surface [D’Asaro et al. 2018].

Perspectives.

- New generation satellite missions are being developed (SWOT / STREAM) and could change our vision and knowledge of mesoscale variability thanks to more high resolved data or newly measured variables (currents for example with STREAM). This will require validation data sets to understand and interpret the satellite data, possibly over the next 10 years roughly that will largely rely on dedicated autonomous instrumentation.
- The satellite context is a strong incentive to improve our ability to sample the ocean in situ from the surface. The on-going development of Unmanned Surface Vehicles (USV, see section X and X) as well as of low-cost drifting platforms and multi-instrumented drifting platforms (e.g. FLAME).
- Swarm deployments of autonomous instruments have shown their value at the surface but equivalent efforts at depth will require the development of low-cost propelled (AUV) and freely drifting platforms as well as longer range geolocation systems.
- Novel strategies are needed for deployments and for the optimal combination of the information provided by the different platforms. These strategies could potentially be adaptative and relying on data assimilation.

1.1.4. Coastal processes

Context

The coastal ocean circulation is triggered by the amplification of tidal currents over most of the shelves, the wind forcing and air-sea fluxes, river freshwater inputs, and the general circulation from the open ocean. The coastline shape and the bathymetry contribute to add fine scales in both horizontal and vertical dimension (e.g., bottom boundary layer).
Existing measurement platforms provide a good knowledge of the main physical processes variability in the coastal zone. Their temporal variability has been studied for a long time using fixed coastal stations measuring physical and biogeochemical parameters (e.g. SNO COAST-HF/IR ILICO coastal network of coastal buoys). These systems provide information on the influence of river input on coastal circulation and hydrology under the influence of extreme events (Pairaud et al., 2016, Poppeschi et al., 2021). Spatial coverage has more recently been ensured by HF radars measurements, as well as the use of drifting buoys or gliders. Recent advances in the development of autonomous vehicles (e.g. gliders, USV, AUVs), used as platforms for ADCPs and CTDs, provide more details on the water column current and hydrology structure, even during storms (Gentil et al., 2020). Miniaturisation of sensors and emerging low-cost systems (like MASTODON thermistor mooring lines, Lazure et al., 2015) further give access to the submesoscale variability in the coastal zone by increasing both the temporal and spatial coverage of sampling.

Observational challenges

Yet, the river-sea continuum in shallow areas, and associated frontal structures, or the coastal-deep water continuum through slopes and canyons, remain to be investigated. And the long term influence of extreme events (storms, low salinity events, heat waves) still require to be better characterized.

A focus should be made on the observation of processes at the interfaces in the first meters above the bottom layer or below the surface and in the pycnocline to ensure their correct representation in oceanic models. It is thus crucial to cover all the water column with autonomous systems, and to be able to perform measurements even in poor conditions at sea and in crowded areas where there is a constant risk of collision or vandalism.

Perspectives

- Development of low cost instrumentation is foreseen in order to get a synoptic view of coastal oceanic processes and to overcome the risk of material loss without dramatically altering the scientific objectives. Investigation of frontal structures and of the influence of extreme events in the coastal zone, including very shallow areas, will benefit from the development of low-cost micro-AUVs platforms.
- Novel strategies and development of new algorithms will be necessary to get information from an optimal combination of a big quantity of data provided by the different platforms, as a step toward the production of schematic pictures of coastal processes and coastal ocean response to the various forcings at short to long timescales.

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