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Assessing economic impacts of environmental research infrastructures: overview of methodological tools

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Abstract. The data generated by environmental research infrastructures (ENV RIs) are key material to forecast the environmental conditions of these activities' growth: in a context marked by emerging risks from global warming, atmosphere and ocean monitoring is taking up critical importance for environment sensitive industries.

The objective of this paper is to review the main tools used to assess the performance of ENV RIs via their economic impacts. Three impact categories are considered: 1) upstream impacts on equipment suppliers; 2) downstream impacts on observation and forecast performance; 3) feedback impacts on environment in terms of damage mitigation and risk avoidance. For each category, the main impact assessment methods are described against their application scope and limits.

An ocean-related case study serves as a practical example: Argo, a global in-situ ocean observing system, helps to gain a better grasp of the chain of primary and processed data flows for ocean monitoring and forecast, and of its functioning. It highlights the issues involved in assessing the different categories of impacts.

Keywords: Argo; benefit; cost; economy; environment; forecast; impact; indicator; ocean; observation; research infrastructure.

1 Introduction: objectives and impacts of ENV RIs

Environmental research infrastructures (ENV RIs) have become critical information providers for the management of environment sensitive economic activities such as farming, fisheries, offshore oil platforms, air transport, shipping and tourism. The decision over how much to invest in an ENV RI development project depends on its present and expected economic value. This value can be assessed in terms of the costs and benefits generated by the development project on the economy: for instance, RI development costs benefit to equipment supply and maintenance services; and environmental forecast, as supplied by ENV RIs, benefit to forecast product users if their business is environment sensitive.

This paper focuses on the mechanism through which economic value is generated by ENV RI development projects and presents an overview of the main assessment methods used to analyse their economic impacts, exemplified by an ocean-related case study.

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The economic impacts considered herein can be classified into three categories:

- Upstream impacts from ENV RI development on facility and equipment supply;
- Downstream impacts on the performance of ENV RIs' observing and forecast services;
- Feedback impacts of improved forecast services on environment sensitive activities in terms of damage mitigation and risk avoidance.

Upstream impacts are related to the commercial relationships between ENV RI facility and equipment suppliers (including design, manufacture and trade) on the one hand and ENV RI developers and operators on the other. As illustrated by the double arrows in Figure 1, upstream impacts include a "demand-pull" effect whereby suppliers' performance is boosted by ENV RIs' demand and a "supply-push" effect whereby equipment supply contributes to improving RIs' performance. This paper does not distinguish between these two effects and considers the methods used to assess correlations between the related supply and demand. The economic impacts on suppliers are usually assessed in terms of turnover, employment, compensations, innovation and exports.

Downstream impacts are related to the supply of environment observation and forecast data. Suppliers are usually research centres and government funded entities working in co-operation with ENV RIs and using their primary data. Further downstream, the next step includes customized data products and value-added services usually produced and supplied by ENV RIs' customers. At stake is the performance of observation and forecast data and their impacts on data demand from end users or value-added services.

Feedback impacts, or response impacts, involve the response to man-made and natural risks threatening environment sensitive activities. The development of ENV RIs is mainly motivated by environmental risks and the need for improved observations and efficient forecast. Feedback impacts involve not only ENV RIs but also the supply chain from upstream equipment suppliers to the diversity of downstream value-added services (Figure 3).

2 A case study: Argo

2.1 Argo's role in the ocean data acquisition chain

2.1.1 Observation instruments and parameters

Argo (Figure 4) is an in-situ ocean observing system providing real-time and delayed mode observations at global scale. It develops an array of free-drifting profiling floats measuring marine parameters on a periodical basis.

- The generated data series are mainly relating to temperature and salinity as functions of depth from sea surface to -2,000 m.
- Bio-Argo floats measure a range of biogeochemical parameters including dissolved oxygen, chlorophyll, turbidity, CDOM (coloured dissolved organic matter), nitrates and pH.

- The initial objective of 3,000 profiling floats was met in November 2007. The current number of floats is increasing by about 150-200 floats/year. Euro-Argo is Europe's contribution to Argo with about 600 active floats. Each Argo float has a lifetime of 4 to 5 years.

Sea waters are analysed as playing a major part in the development of climate conditions. Since the 1990s operational oceanography has benefitted from the development of in situ and satellite global observing systems. The use of Argo is now key to operational oceanography and climate research.

Argo brings a major contribution to the Global Ocean Observing System (GOOS) but cannot be analysed as a separate entity. It works in association with:

- sea surface and temperature observations from satellite sensors;
- other sets of in situ platforms and profilers: ship based CTDs (Conductivity-Temperature-Depth profilers), XBTs (expendable bathythermographs, for temperature and depth), ferry box systems (for physical, chemical and biological parameters), moorings (for a range of parameters including current), sea mammal born instruments, gliders and drifting buoys;
- Assimilation of satellite and in-situ data into ocean circulation models, enabling to develop ocean forecast.
- Floats transmit observation data to satellites during the time slot where they are at surface level.

The strong complementarity between in-situ platforms and satellites must be emphasized:

- Platforms measure certain types of parameters that satellite profilers do not capture: sea subsurface temperature and salinity, and most bio-parameters.
- Satellite profilers provide parameters which are either impossible to get from floats (altimetry/sea level and waves, current, ocean colour, sea ice and winds) or complementing in situ data.
- The parameters provided by satellites are key for ocean circulation models and assimilation techniques. Experiments have shown (see below: 2.2.2) that assimilating both satellite and in-situ data significantly improves sea surface temperature and salinity forecast.

2.1.2 Data acquisition, processing and supply chain

Argo is part of a supply chain including several segments from primary data collection to processed data distribution and, further downstream, to value-added marine services for environment monitoring and security (Figure 5). Downstream from in-situ platforms, the data acquisition chain of Argo, after satellite re-transmission, includes a data assembly segment:

- Eleven national Data Acquisition Centres (DACs) collect, quality-control, standardize, archive and distribute real- and delayed-time biological, chemical, physical and geophysical ocean profiles from Argo floats and other types of profilers, and convert observation data into standard exchange format.
- These data, together with associated metadata, are provided to the Global Telecommunication System (GTS) of the World Meteorological Organisation (WMO) and the two Global Data Assembly Centres (GDACs) in charge of collecting Argo data: FNMOC, USA, and Coriolis, France. Coriolis provides real time in situ data to the Copernicus

Marine Environment Monitoring Service (CMEMS) and to ocean and climate scientists. Observation data are made publicly available from the GDACs via the internet.

Marine services are developed using a variety of processed marine data. In Europe, CMEMS is key: its in-situ component is the CMEMS In-Situ Thematic Assembly Centre, includes Monitoring and Forecasting Centres (which develop ocean models) and Assembly Centres (which collect in-situ and satellite ocean data); it collects, quality-controls and validates Argo and non-Argo observation data, and supplies the former with near-real time datasets for assimilation into ocean models; it also supplies both the former and other downstream users with delayed mode data products for model assimilation and ocean reanalysis i.e. historical observations and climate studies. At regional level, Argo Regional Centres (ARCs) provide expertise on specific ocean regions using Argo and non-Argo observations. The data generated by the Argo system are made freely available to the public within hours after collection.

Standardized marine services include observation data compliant with the EU INSPIRE Directive 2007/2/EC in terms of data interoperability. For instance, the network of organisations EMODnet (European Marine Observation and Data Network), as a major component of the EU marine data supply strategy, publishes interoperable data products and geographical information system (GIS) maps on bathymetry, geology, seabed habitats, chemistry, biology, physics and human activities. These marine data products are provided to end-users such as maritime transport (shipping, cruise lines), offshore mining (oil rigs, dredging), etc., but also commercial consultancies. The latter are active further downstream, on customized service markets based on local forecast and specific coastal management services.

Future Argo development projects include:

- Extension of Deep Argo, with a new design of the Argo array including -4,000 to -6,000 m observations;
- Extension of Bio-Argo, with more observations on acidification, oxygen and carbon, notably in targeting critical spots.

Remarks:

- The present marine data market is recent and narrow: governmental influence remains important. Most data and service suppliers are either government-owned, or government- and EC- funded entities; these have a strong impact on the types of services and products delivered by downstream consultancies. Likewise, upstream equipment manufacturers and suppliers largely depend on government orders. Overall, the role of the states is major in the supply chain as summarized in Figure 5.
- The US-originating strategy of free-of-charge marine observation data products – to boost the competitiveness of downstream value-added services – is superseding alternative business models outside the US, notably in Europe (see Groupe interministeriel, 1995). On the narrow market of marine data products, the free-of-charge option reinforces the role of public funding in the supply chain.

2.2 Cost of Argo

The AtlantOS "Optimizing and Enhancing the Integrated Atlantic Ocean Observing System" project (H2020, 2015-2019) issued a report (Reilly et al., 2018) providing the estimated costs of a selection of ocean observing networks in the Atlantic, among which the costs of the Atlantic Argo array (Euro- and US-Argo floats). Data gaps are recognised by the report as a limiting factor; pending a better data coverage, the costing exercise is thus a first step toward consistent accounts of Atlantic ocean observing networks. But as it stands, it provides valuable information on the costs of in-situ observing networks over the 2012-2016 observation period, with a focus on the chain from in-situ operations to data collection and transmission. Data management and downstream operations such as the development of data products are outside its scope.

The report estimates the costs for the Argo floats of the AtlantOS area (Table 1), deployed by Euro-Argo ERIC members (Bulgaria, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Norway, Poland, Spain, UK), Brazil, Canada and the US.

Certain cost components would require further scrutinizing:

- Staff costs have been excluded from the accounting and remain to be analysed. The difficulty is to have a common definition of the activities involved in Argo operations. The report indicates differences between member states in this respect. Harmonization between countries in terms of staff categories is a prerequisite. Accounting for staff costs would modify the appraisal of costs without radically changing their order of magnitude. E.g. Table 1 indicates an annual workforce of 23 FTEs for Euro-Argo, which would amount to staff costs of the order of EUR 1.5m, as compared to capital and running costs estimated at about EUR 8.5m per annum.
- The costs of research vessel services and those of ships of opportunity have also been excluded though data were possible to collect for some countries. Cost harmonization remains to be extended also in this area.

3 Approach to the valuation of economic impacts

Following the classification presented above, this section outlines the approach to the valuation of upstream, downstream and feedback impacts.

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3.1 Valuation of upstream impacts

The focus is on the development and running of ENV RI development projects and on their requirements for equipment supply. This generally includes, e.g. the manufacture and trade of remote sensing and in-situ measurement instruments, of airborne or waterborne platforms, of data transmission means, but also the development of data collection and processing units. Attention is given to the valuation of upstream impacts in terms of business indicators such as turnover, value added and job creation.

3.1.1 Analysis of suppliers: direct assessment

In the favourable situation where suppliers are clearly identified and accept to provide economic information on their businesses, a direct assessment of upstream economic impacts is feasible.

A case study proposed by Barrow et al. (2005) on “marine science and technology industry” (MST) in New England (group of five US states) illustrates the approach. The paper analyses MST employment, sales and number of establishments per type of activity, for each state of New England.

The methodology of the case study uses a master database of 481 MST companies and organizations sourced from universities, public agencies and a commercial consultancy’s database, and supplemented by web searches and targeted interviews. However, the companies listed in the master database are totally or partially involved in MST. To characterize this total or partial involvement, their employment and sales figures have been weighted at 100%, 40% or 10% if they pertain to the core, partial core or second tier respectively, of MST. This operation has led to a set of adjusted indicators (Table 2) for MST in New England. Companies are classified into five subsets analysed in terms of sales and employment. The “Marine Instrumentation and Equipment” (MIE) and “Marine Research and Education” (MRE) subsets are relevant to our approach; they include respectively: 1) cutting edge measuring instrument producers for oceanography, geophysics, acoustics, electronics for marine instruments, platforms and marine navigation; 2) marine education, industry and technology and transfer groups, and all areas of oceanography including fisheries research. The other subsets are less directly usable: “marine services” include consultancies and engineering; “marine materials and supplies” includes marine equipment (paints, engines, machinery, etc.); “shipbuilding and design” includes civil and defence shipbuilding operations.

Barrow’s approach points to a feasible way to assess the upstream segment of EU Ocean Observing RIs, based on targeted inquiries on jobs and sales of a delimited set of businesses. However, Barrow’s objective is to describe the industry of a given geographical area using a simple economic metrics, but not to assess the upstream impacts from ENV RIs on the supply industry which may be active beyond the geographical delimitation of New England.

A master database of MST companies such as the one used by Barrow would be worth developing for the EU. An option would be then to define a set of activities equivalent to MST for the EU countries and collect economic information through ad-hoc business inquiries.

3.1.2 Analysis of suppliers: indirect assessment

In less favourable but more frequent situations where suppliers are identified but do not provide commercial information, the impacts of ENV RI's operational and investment costs can be estimated using the standard classification of activities serving as a basis for national statistics. The EU statistical framework is based on the NACE[1], from which each member state derives its own national classification. In that case, the best option is not to rely on the official data as sourced from businesses:

- Enterprises are classified into NACE classes: one class per enterprise, based on its core business.
- "Structural Business Statistics" (SBS) are updated, using annual business inquiries, by the National Statistical Institutes (NSIs) of EU countries. They provide financial and non-financial indicators (turnover, purchases, gross value added, number of employees, personnel compensation, etc.) per NACE subdivision, and are used to develop National Accounts.

SBS are readily available and provide series of annual economic indicators per NACE class. If the classes including the targeted businesses (ENV RI suppliers) can be identified, it is feasible to estimate the impacts from ENV RIs' operational and investment costs in terms of turnover and employment, using SBS economic indicators as average estimates of suppliers' economic data.

There are two limits to this option. First, SBS series are developed without time consistency objective. Time consistency is ensured by national accounts after the processing of SBS for developing branch accounts. Second, though class is the finest level of the NACE, many classes include a diversity of activities, which does not allow for an accurate assessment of a small set of RI suppliers.

For instance, NACE class 26.51 "Manufacture of instruments and appliances for measuring, testing and navigation" includes the manufacture of aircraft engine instruments, radars, medical laboratory instruments, etc. The manufacture of ocean measuring instruments is only a modest part of this set. Likewise, the wholesale trade involved in the upstream segment of ocean RIs account for a small part of NACE class 46.69 "Wholesale of other machinery and equipment".

Consequently, estimates will be required to value the upstream impacts from ENV RI development, using SBS and complementary indicators such as yearly development costs.

3.1.3 Analysis of ENV RI purchases

When information on suppliers is missing, a consistent option is to collect the available data on ENV RIs' equipment and service purchases, either directly through ENV RI purchase records or indirectly through inventories and stock variations.

A standard statistical tool permits to classify the different types of products and services: the hierarchical "Classification of products by activity" (CPA), in force in the EU, classifies products by physical characteristics as goods or services and by

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[1] The "Classification of Economic Activities in the European Community" (referred to by its French acronym: NACE) is a hierarchical classification of EU economic activities into 21 sections, 88 divisions, 272 groups and 615 "classes". Member states' National Statistical Institutes develop national versions of the NACE adapted to their respective economies.

originating activity as defined in the NACE. CPA classes are strictly consistent with NACE classes: each CPA product corresponds to a specific NACE class. Like the NACE, each member state adapts the CPA to its national economy.

National accounts then permit to quantify the impacts of demand, as classified in terms of products, on the production branches that (equipment) products belong to. Demand impacts are translated in terms of value added and workforce increase per NACE class, based on branch accounts: the latter permit to assess the direct impacts of a marginal demand increase on supply. Indirect impacts, generated by suppliers' spending, raise other economic issues and are not considered at this stage.

An example of ENV RI purchase data is given by INSU (Oceanography division of the French National Centre of Science Research). INSU publishes an inventory of its open ocean instruments, available online, including every type of material with technical specifications, purchase value, origin and number of instruments. The periodical flows of INSU purchases provide the data that would be necessary for assessing demand: flows can be inferred from stock variations based on successive inventory updates.

Table 3 is a short summary of INSU's inventory, limited to the amounts of purchase costs by supply originating country. It points out the high degree of competition on EU marine research equipment markets and the diversity of INSU's suppliers. More than half of the equipment value originates from North America, and more than a third from the US alone. This shows by the way that a detailed assessment of the upstream impacts of European ocean RIs must take account of imports, especially from North America.

Though consistent in accounting terms, this method only delivers a general valuation of impacts on branch accounts but not on specific supply businesses. In addition, branch accounts have to be available preferably at class level: lower resolution levels of the NACE – branch accounts are often available at division level – do not allow an accurate enough quantification of ENV RI demand on a limited group of specialized suppliers.

3.1.4 Summary: upstream impact assessment

Each of the options examined above has its area of validity and its limits. Validity is determined by the practical conditions of data collection, depending on how much relevant information can be available from businesses or official statistics. Limits are methodological: ad-hoc inquiries are time consuming and require much input from respondents; SBS are useful proxies for suppliers' business data but must be used with care as inter-annual comparison is impossible; in the absence of information on suppliers and if ENV RI purchases are detailed, branch accounts are the most consistent tool to obtain an accurate valuation of upstream impacts in general terms, provided information is available at class level.

Practically, the selection of the most appropriate tools will depend on their capacity to analyse a diversity of very specialized equipment suppliers. Estimates are inevitable if business information is not available from the latter; in that case, the resolution power of the available information is critical to appraise the quality of the resulting estimates.

3.2 Assessment of downstream impacts

The performance of ENV RIs in terms of observation data collection, analysis and forecast, has downstream impacts on the performance of customized forecast and monitoring services, and consequently on demand for observation data. The assessment of downstream impacts requires valuing the performance of observation data products and that of primary data analysis and forecast (cf. Figure 5). With regard to ocean RIs, the focus is on data products supplied by operational oceanography, i.e. observation data after first stage processing, and ocean analysis and forecast.

The difficulty is that the activity has not reached the commercial stage: it is limited to scientific, state-funded organisations in a context of free-of-charge data supply (cf. remarks above: 2.1). Therefore performance cannot be valued through commercial or accounting indicators; it must be based on specific indicators to be defined for each of the two stages shown in Figure 5:

a) Primary data collection, with a first stage processing (quality control and archiving);
b) Primary data processing, analysis and forecast, from in-situ and satellite observations.

The objective would then be to correlate performance indicators with either users' performance itself or with their demand for environmental observation and forecast products.

3.2.1 Data collection quality: the role of key performance indicators

DACs and GDACs are key players at the stage of observation data collection, archiving and quality control. GDACs publish information on data performance using a set of key performance indicators (KPIs).

The KPIs used by Coriolis and other assembly centres shape a metrics of ocean observation data quality used by CMEMS for performance monitoring; they include:

- delay (e.g. share of delayed data per time interval),
- Types and number of platforms (by type of sensors and by measured parameter),
- Accuracy of measurement (for temperature and salinity),
- Number of downloads and number of users.

As quality control is relatively recent, certain KPI series do not go back many years in time and cannot characterize long term progress in equipment generations. However, the number of platforms per type or per parameter is monitored since 2014 by Coriolis, which is enough to give indications on the trend; likewise, several other monthly, weekly or daily KPIs generate sizeable time series with short-term monitoring purposes (Figure 6 shows a "number of platforms" KPI from the CMEMS In Situ Thematic Assembly Centre). In the future, longer series will enable to analyse correlations between data supply and demand, i.e. between data quality KPIs and the number of downloads.

Complementary sources of KPIs are available, e.g. from the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM), an intergovernmental body in charge of, inter alia, co-ordinating the WMO Marine Meteorology and Oceanography Programmes. JCOMM's "in-situ Observation Programme Support Centre" (JCOMMOPS) monitors, and provides metrics for, a range of in-situ observing networks including Argo. Indicators on the array (activity, density, intensity), data flows (delivery, sensor metadata quality, timeliness) and national diversity are made available to the public on the JCOMMOPS website (https://www.jcommops.org/board). Some series started in 2000, which secures a correct historical background. Observing float arrays monitored by Coriolis and JCOMMOPS overlap; some measurement differences may arise between the two sets of floats.

3.2.2 Data analysis and forecast: the role of observation experiments

Atmosphere and ocean analysis and forecast rest on real time observations provided by different components of global systems. To value forecast accuracy and errors, observing system experiments (OSEs) have become a frequent tool. The most common method consists in withholding a subset of past observations assimilated in a forecast model and measuring the resulting forecast error on real observations: this allows quantifying the impact of assimilating the subset of information withheld, for a given global ocean forecast model with the associated assimilation technique. To supplement OSEs, the impacts of new assimilation techniques and new generations of observation instruments are quantified by Observing system simulation experiments (OSSEs). OSSEs are carried out using simulated observations from a model generating a “nature run”. Forecast is the outcome of simulations being assimilated in the forecast model; system experiments are performed by comparing forecast to nature runs.

Among the various experiments performed so far, it is useful to mention OSEs recently carried out for global ocean models in the framework of two research projects: the GODAE OceanView program (GOV), and E-AIMS (2013-2015).

- GOV was to promote and co-ordinate operational ocean observing at global scale. The OSEs carried out by GOV were related: 1) to GOOS components, including satellite altimetry, Argo and non-Argo floats (Oke et al., 2015a); 2) to regional observing systems, developed to provide the GOOS with additional constraints for initialising ocean forecast models, and to resolve regional and local processes (Oke et al., 2015b).
- E-AIMS (Euro-Argo Improvements for the GMES Marine Service) focused on the impacts of Euro-Argo and its capacity to meet the requirements of GMES/Copernicus Marine Services. It made recommendations to further develop Euro-Argo and deploy new floats. To assess the impacts on the performance of ocean forecast, a range of contributions using OSEs and OSSEs are summarized in Rémy and Le Traon (2015).
- Both projects include a component dedicated to the study of Euro-Argo’s impacts on the ocean forecast model developed by Mercator Ocean; these impacts are detailed in Turpin et al. (2016).

Most OSEs presented in these papers calculate the root mean square of the difference (RMSD) between forecast and real-time observations to measure the impacts of a specific set of observations. Turpin et al. (2016) assesses the impacts of Argo data assimilation on the short-term real-time analysis and forecast of sea surface temperature and salinity. The paper summarizes OSEs conducted over 2012 using the “Mercator Ocean 0.25°” global ocean analysis and forecasting system. These OSEs include the assimilation of observations from satellites, from all other-than-Argo in situ instruments and from a share of the Argo array, with three options for this share: 100%, 50% and 0%, starting from the same initial conditions of the

Mercator Ocean model. RMSD and mean statistics of differences between forecast resulting from the above options are calculated in 2°x2° spatial boxes and for 0 to 300m and 700 to 2000m depth layers. The results show that the impacts of Argo profiles on RMS for temperature and salinity are significant from sea surface to -2000 m: the use of Argo data can lead to a 20 to 50% decrease in RMS for temperature on the 700-2000 m depth layer, and 30 to 65% for salinity.

The findings from Turpin et al. (2016), Oke et al. (2015a and 2015b) and Rémy-Le Traon (2015) include the following points:

- The use of Argo profiles has positive impacts on real time ocean analysis and forecast in a wide range of cases including short- and long-term analyses, ocean properties up to 2000 m depth, and sea level analysis.
- Regarding sea level analysis, Argo observations on sea water properties are critical to complement satellite altimetry and constrain ocean state analysis.
- The above remarks must be qualified as the results may vary depending on sea water parameters and the state of deployment of Argo. For certain parameters and certain ocean regions, non-Argo observation networks are as important as Argo, e.g. moored buoy arrays deployed in the Atlantic, Pacific and Indian oceans to analyse tropical atmosphere ocean properties.
- The results obtained from OSEs and other experiments depend on the details of the model and assimilation system used, as emphasized by Oke et al. (2015b).
- If RMSD is used as key statistics for forecast assessment, it does not exclude other relevant metrics. Alternative OSEs and metrics are considered, and examples are described. One of these examples is the range of OSEs made in 2011 using near-real time observations (data are made available a few hours after observation) and the UK Met Office's ocean forecasting system (Oke et al., 2015a). Monthly OSEs are carried out in excluding different specific subsets of observations, e.g. XBTs, Jason altimetry, Tropical Pacific buoys, Argo, etc. Forecast RMSDs are then assessed and compared. Results evidence the complementary between the different subsets in terms of forecast performance: this goes beyond an Argo vs non-Argo comparison. Regional assessments (Oke et al., 2015b) are of comparable interest. Such approach is therefore an important step toward assessing the impacts from the gradual development of the GOOS in terms of forecast performance, through new generations of instruments.

3.2.3 Summary: downstream impact assessment

The above summarizes two complementary approaches to assessing the performance of ocean observing systems' downstream segment.

- KPIs, as applied to in-situ observations, provide combined information on observation data quality, number of platforms and demand (number of downloads).
- OSEs assess observation analysis and forecast. They prove useful for assessing the impacts of Argo on ocean forecast, as they would for new components of Argo.

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KPIs and OSEs have different scopes of application. Combined together, they would constitute a relevant metrics for ocean RIs' downstream impacts. To confirm this assumption, prior steps are required:

- Longer time series would help to gain more experience on KPIs and observation experiments. On the other hand, regular performance monitoring through routine OSEs would be essential to assess the value of the GOOS at its present and future stages (cf. Oke et al., 2015a; Rémy and Le Traon, 2015; GOV Science Team, 2014).
- Further insight is required on correlations between performance indicators and demand for observation and forecast products, whether they are supplied by private or public entities. The difficulty is that demand is not systematically monitored and remains to be analysed through long time series.

3.3 Assessment of feedback impacts

Feedback impacts (Figure 3) involve the entire chain of activities upstream and downstream of ENV RIs as a response to environmental risks and uncertainty. In the case study considered above, they involve the Argo array and other ocean observing networks including non-Argo platforms and satellite observations, with the common goal of delivering services for managing coastal zones, maritime activities (shipping, offshore energy, etc.), and mitigating impacts from risks such as hurricanes, oil spills and floods.

The analysis of the impacts of the environment analysis and forecast chain from observation data to value-added services involves the valuation of costs and benefits from improved forecast. Benefits include the value of having more secure environment sensitive activities, based on the avoided costs arising from risk avoidance, as compared to investment and running costs. Cost-benefit analysis (CBA) is a classic tool for valuing feedback impacts. Most CBAs on ocean and climate forecast include a scenario based on advanced ocean services (monitoring and forecast) compared to a baseline scenario.

3.3.1 Examples of CBAs on ocean forecast

Since the 1990s, several CBAs have assessed the expected economic (feedback) impacts from the GOOS to highlight the potential significance of ocean observation. Three of the examples described below pertain to this category: they concern a class of problems which includes the feedback impacts from Argo. The fourth example of CBA was applied to a pilot project of the GMES: a case also comparable to Argo.

- Sassone and Weiher (1997) focus on forecast related to the El Niño Southern Oscillation (ENSO) phenomenon and its impacts on US agriculture.
- Solow et al. (1998) analyse the value of improved ENSO forecast to US agriculture with a focus on cropping strategies.
- Kite-Powell and Colgan (2001) consider Gulf of Maine local activities which could use and benefit from available marine data: maritime transport, commercial fishing, recreational fishing and boating, SAR, pollution and oil spill management.

- Cedre[2] and Ifremer (2009) analyse the potential impact of GMES monitoring and forecasting services on the prevention and mitigation of a past oil spill event

Though based on a common approach, these CBAs exhibit some methodological differences.

Sassone and Weiher (1997) build on progress in improved ENSO forecast and the findings of the Tropical Ocean Global Atmosphere (TOGA) project (1984-1995), a research program studying coupled tropical ocean-atmosphere modelling. For further development, a research program was considered, combining an extension of TOGA and an ENSO Observing System (EOS) to make routine ENSO forecast. The relevance of public support to this proposal is analysed in this paper. A CBA assesses the development of TOGA-EOS vs a baseline scenario. Projected costs are based on past TOGA costs and government's expectations for EOS costs; projected benefits are those to the US Agriculture sector. The overall benefits to agriculture are the sum of farmers' profit and consumers' surplus, farmers being assumed to gradually accept, and adapt their strategy to, forecast: gradual adaptation is translated in quantitative terms. Annual costs and benefits to the agriculture sector are estimated for 10-year and 20-year periods (assumed to be "reasonable" with respect to evolving forecast techniques) from 1995, which allows calculating an internal rate of return (IRR)[3].

Solow et al. (1998) focus on farmers' cropping strategies: 1) Impacts from improved ENSO forecast on temperature and precipitation forecast are simulated for a set of US locations, using a meteorological model. 2) Predictions of crop yield using a plant growth model are inferred, and farmers' cropping strategies are optimized following predictions. 3) Using an economic model of the agriculture sector, changes in prices and quantities of crop products and in farmers' profit and consumers' surplus are estimated. Since ENSO forecasts are expressed as long-range averages, expected profit estimates are averages and do not exclude local losses in the future.

Kite-Powell and Colgan (2001) review maritime activities in the Gulf of Maine: shipping, fisheries, fish farming, boating, leisure fishing, search and rescue, pollution prevention (e.g. oil spill prevention). Ocean observations are generated by the observing system of the Gulf of Maine (GoMOOS). Potential impacts from additional ocean information being available to businesses, are expressed in terms of avoided operating costs, value-added increase, higher consumers' willingness to pay, and lower mitigation costs due to damage prevention efficiency increase. These impacts have been broadly estimated, based on general information available. But this preliminary study opens the way toward a comprehensive coverage of benefits from additional ocean observing capacity.

In a deliverable of the FP6 InterRisk project, Cedre and Ifremer (2009) present an oil spill related case study. It relies on experience gained by Cedre in oil spill response management. Cedre, as an operational agency during the wreckage of Erika oil tanker in the Bay of Biscaye (December 1999; 40,000 tonnes oil spill), has got information on damage and response costs

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[2] Cedre: French state agency created in 1978 after the oil spill from Amoco-Cadiz oil tanker. Cedre provides technical advice and expertise to French and foreign authorities and businesses in charge of responses to marine accidental pollution, particularly oil spills.

[3] IRR: discount rate at which a project, given its yearly costs and benefits, has a net present value of cumulated cash flows of zero at the end of a given time period. If the real discount rate is expected to be less than IRR over a period to come, real benefits are expected to exceed real costs at the end of the period.

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depending on the size of spills, and on the sensitiveness of marine and coastal activities to similar incidents. The impacts of InterRisk, a pilot project of GMES services, are assessed as if it was operational during the Erika oil spill. To do this: 1/ Marine and coastal activities' costs and losses from Erika are estimated. They include: public response to oil spill, fisheries, aquaculture, salt production, coastal private and natural assets, coastal hotels, tourist visits, equipment and material supply to fisheries and aquaculture, seafood processing, local tourism supply. 2/ The potential mitigation of the spill is quantified in tonnage, as a result of more ocean data being available to the state response scheme. 3/ Mitigation is translated into avoided losses for coastal businesses. For steps 2 and 3, changes are estimated in percentage.

3.3.2 Conditions of validity of CBAs

The common feature of the CBAs examined above is that projected benefits from additional ocean observations are high as compared to costs (Table 4). Improved ocean observation and forecast is therefore considered beneficial. The limits to this conclusion is that the scenarios analysed by the CBAs are related to extreme events; results are difficult to extend to business-as-usual periods.

The validity of the results is also based on major assumptions, including:

- Improved ocean forecast is expected to be fully exploited by future users and translated into optimal consumption and production strategies. In this respect, the assumption that users gradually accept to modify their behaviour based on forecast (Sassone and Weiher, 1997), is important: its applicability must be checked on a case by case basis.
- Over the time periods under analysis, ENV RI costs and social benefits are supposed to remain constant despite the technical progress that ENV RIs are likely to incorporate, with inevitable change in investment and running costs as well as in ENV RI users' demand. CBAs are therefore more appropriate if the time frame is short, like in the case of Cedre-Ifremer, 2009.

The problem is that the two above conditions lead to opposite requirements in the case of ENV RIs. The former requires learning time for users to exploit forecast. The latter suggests that the CBAs are designed to meet punctual needs for taking decisions, given an initial state of observing systems. It is therefore preferable to regard those CBAs as indicative of orders of magnitude of costs and benefits and of the process through which costs and benefits are generated.

4 Conclusion

This methodological overview of upstream, downstream and feedback impacts outlines the main categories of tools used to analyze the performance of ENV RIs. A focus on a case study, namely the ocean RI Argo, is helpful to frame the approach.

ENV RIs present different characteristics, as they incorporate: a) science and research activities, whose products and services are rarely marketable; b) operational monitoring systems combining in-situ and satellite observation techniques, whose products – observation and forecast data – are generally made available to the public free of charge and where state support is critical; c) development strategies requiring equipment and material supplied on competitive markets; d) and downstream of this core business, value-added services generated from the processing of observation and forecast data, are supplied on competitive markets. ENV RIs develop in an economic and technological environment where commercial and non-commercial activities are associated.

This has an implication on the assessment of ENV RIs: upstream, downstream and feedback impacts necessarily combine monetary and non-monetary indicators as shown by the above examples. This diversity is largely explained by the approach herein adopted, whereby the assessment metrics has been adapted to the structure and the segmentation of the supply chain as highlighted by our case study. This diversity is nevertheless limited by the common features of several ENV RIs in terms of in-situ observation, data collection, assembly and processing, and by the limited range of relevant and reliable categories of supply chain performance indicators.

Regarding the future development of ENV RI impact assessment, further study is required on the statistical correlations between performance indicators to achieve a greater coherence of the assessment. This concerns correlations between observation and forecast data performance and the amount of demand for data as estimated by data flows; with such complex metrics as the valuation of observation and forecast performance, correlations between indicators will remain qualitative. This also concerns correlations between forecast performance of RIs and business performance indicators on upstream equipment suppliers; such information would be useful tool for better adapting ENV RI investment to monitoring and forecast data demand. Finally, this concerns the study of correlations between ENV RIs' forecast performance and risk avoidance capability as expressed via environment sensitive activities' avoided costs: more knowledge on such correlations is necessary to better adapt ENV RI performance and investments to the needs of end users.

References

Barrow, C., Loveland, R., Terkla, D., Flanagan, T., and Proshina A.: The marine science and technology industry in New England. Haldey, USA: University of Massachusetts, Donahue Institute, 24 pages, 2005.

Carval, T., Coatanoan, C., and Cancouet, R.: Argo data management report 2018, Coriolis DAC & GDAC, Ifremer/IRSI/ISI-DTI/RAP-18-102, 41 pages, doi: 10.13155/58109, 2018.

Cedre and Ifremer: INTERRISK. Estimation of avoided consequences of the crisis linked to the setup of project tools. D6-4, WP 600, Task 5, 14 pages, Brussels, 2009.

GODAE OceanView Science Team: Strategic Plan 2015-2020. Exeter, UK: GODAE OceanView Project Office, 54 pages, 2014.

Groupe interministériel sur la politique de diffusion des données d'observation de la Terre à partir de l'espace: Politique de diffusion des données d'observation de la Terre à partir de l'espace. Paris: Ministère de l'Industrie, des Postes et Télécommunications et du Commerce extérieur, 78 pages, 1995.

Kite-Powell, H.L. and Colgan, C.S.: The potential economic benefits of coastal ocean observing systems: The Gulf of Maine. Washington: National Oceanic and Atmospheric Administration, Office of Naval Research, Woods Hole Oceanographic Institution, 13 pages, 2001.

Ministère de l'Education nationale, de l'Enseignement supérieur et de la Recherche: Politique de diffusion des données d'observation de la Terre. Paris: MENESR, 78 pages, 2004.

Oke, P.R., Larnicol, G., Fujii, Y., Smith, G.C., Lea, D.J., Guinehut, S., Remy, E., Alfonso Balmaseda, M., Rykova, T., Surcel-Colan, D., Martin, M.J., Sellar, A.A., Mulet, S., and Turpin, V.: Assessing the impact of observations on ocean forecasts and reanalyses: Part 1, Global studies, Journal of Operational Oceanography, 8: sup1, s49-s62, doi: 10.1080/1755876X.2015.1022067, 2015a.

Oke, P.R., Larnicol, G., Jones, E.M., Kourafalou, V., Sperrevik, A.K., Carse, F., Tanajura, C.A.S., Mourre, B., Tonani, M., Brassington, G.B., Le Henaff, M., Halliwell Jr., G.R., Atlas, R., Moore, A.M., Edwards, C.A., Martin, M.J., Sellar, A.A., Alvarez, A., De Mey, P., and Iskandarani, M.: Assessing the impact of observations on ocean forecasts and reanalyses: Part 2, Regional applications, Journal of Operational Oceanography, 8:sup1, s63-s79, doi: 10.1080/1755876X.2015.1022080, 2015b.

Reilly, K., Cusack, C., Fernández, V., Buch, E., and Ott, M.: Atlantic Ocean Observing Networks: cost and feasibility study, AtlantOs project-633211, D1.4. Galway: Marine Institute, 84 pages, 2018.

Rémy, E. and Le Traon, P.-Y.: Final synthesis report, E-AIMS, D3.341. Brest: Ifremer, 9 pages, 2015.

Sassone, P.G. and Weiher, R.F.: Cost benefit analysis of TOGA and the ENSO observing system, In: Operational oceanography: the challenge for European co-operation. Proceedings of the First International Conference on EuroGOOS, The Hague, 7–11 October 1996, Stel, J.H., Behrens, H.W.A., Borst, J.C., Droppert, L.J. and van der Meulen, J.P. ed., Elsevier Oceanography Series, 62: 36-50, 1997.

Solow, A.R., Adams, R.F., Bryant, K.J., Legler, D.M., O'Brien, J.J., McCarl, B.A., Nayda, W., and Weiher, R.: The Value of improved ENSO prediction to US Agriculture. Climatic Change, 39: 47-60, 1998.

Turpin, V., Rémy, E., and Le Traon, P.-Y.: How essential are Argo observations to constrain a global ocean data assimilation system? Ocean Science, 12, 257-274, DOI: 10.5194/os-12-257-2016, 2016.

Weiher, R.F. ed.: Improving El Niño forecasting: the potential economic benefits, Washington: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of Policy and Strategic Planning, 63 pages, 1998.

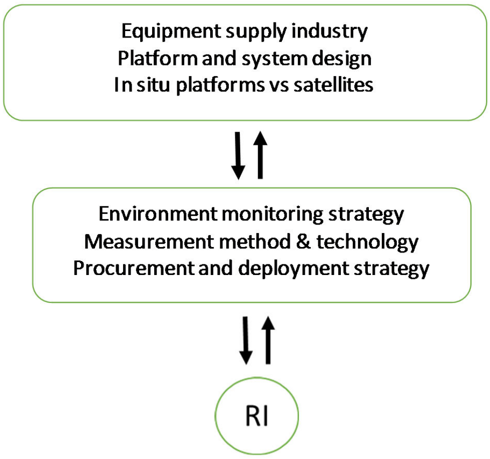

Figure 1: Upstream impacts.

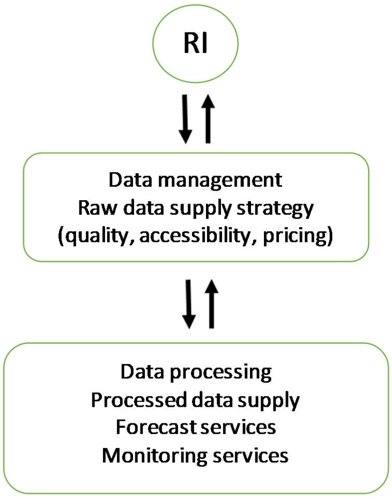

Figure 2: Downstream impacts.

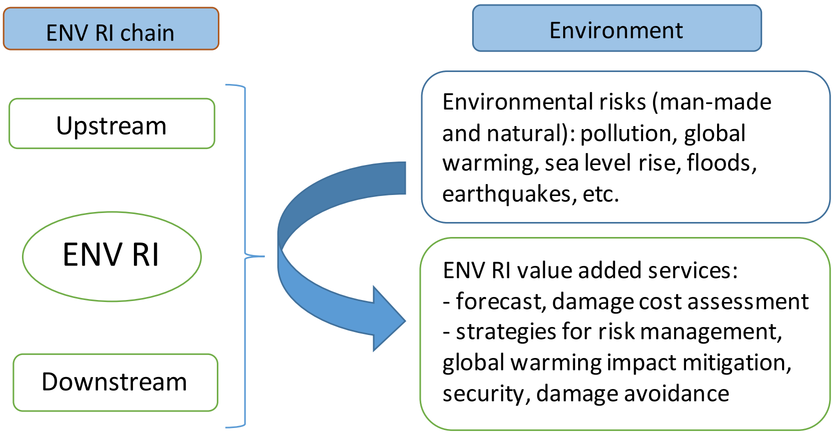

Figure 3: Feedback impacts.

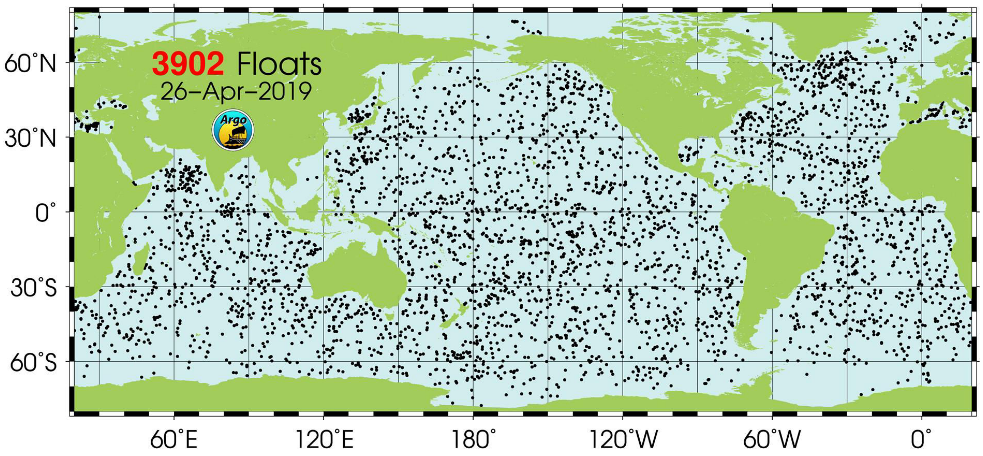

Figure 4: Argo global array of profiling floats: position of floats having delivered data within the last 30 days until 26 April 2019.
Source: © Argo Program http://www.argo.ucsd.edu

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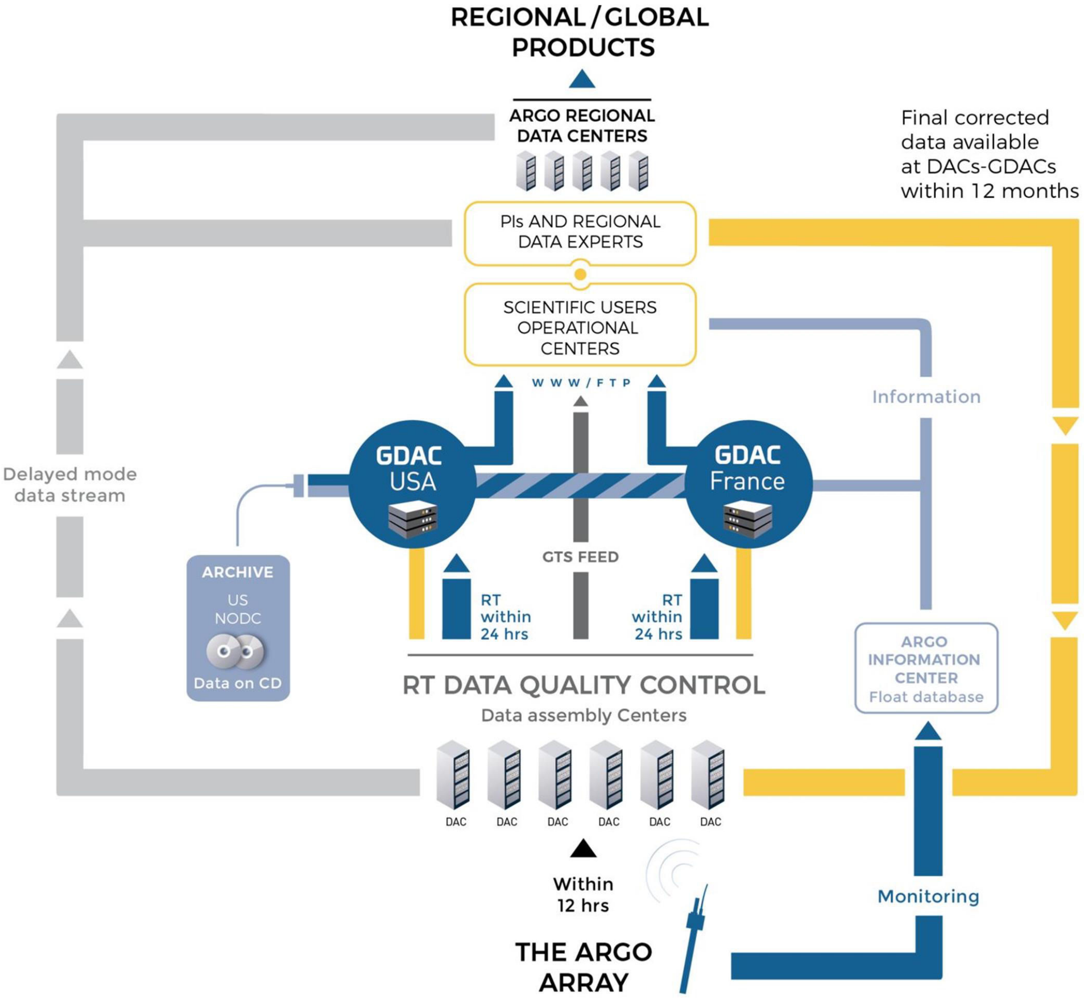


Figure 5: Scheme data flows 2017.
DAC: Data Assembly Centre.
GDAC: Global Data Assembly Centre.
5 **GTS: Global Telecommunication System.**
RT: real time.
Source: © Euro-Argo ERIC https://www.euro-argo.eu/Activities/Data-Management/Argo-Data-System

	Euro Argo			AtlantOS area		US
	Core Euro-Argo (T&S)	Deep Argo*	BGC	Core Argo (T&S)	All Argo	
Number of floats deployed per annum, 2012-2016**		35	38	229		
Unit purchase cost (€)	14 280	30 000	85 000	15 890		17 500
Additional unit costs/year						
Testing and calibration (€)		300	300	300		
Logistics (€)		400	600	400		
Transmission (€)		1 920	1 440	1 440		
Total cost per annum (€)		1 124 900	3 337 160	4 128 870	8 590 930	
Workforce (FTE/year)***	22.63					

Table 1: Cost of Argo.
T&S: temperature and salinity profiler
BGC: biogeochemical profiler
***Arvor Deep Argo floats only. Apex floats excluded.**
****Target annual deployment for Deep Argo and BGC floats.**
*****France includes co-ordination and management staff.**
Source: Reilly et al. (2018).

	MIE	MRE	MST
Employment*	12496	1457	38906
Sales ($ million)	1966,3	6,8	4868,9
Establishments	175	:	481

Table 2: Marine Science and Technology industry adjusted figures for New England, 2004.
: not reported
***number of persons employed**
MIE: Marine Instrumentation and Equipment
MRE: Marine Research and Education
MST: Marine Science and Technology industry
Source: Barrow et al. (2005)

Originating country of supply (1)	Value of material (2) ('000 EUR)	Market shares
US	1416.7	37.0%
UK	115.6	3.0%
Canada	599.3	15.7%
Norway	449.2	11.7%
France	917.4	24.0%
Germany	61.5	1.6%
Italy	18.5	0.5%
Not specified (3)	246.1	6.4%
TOTAL	3824.3	100.0%

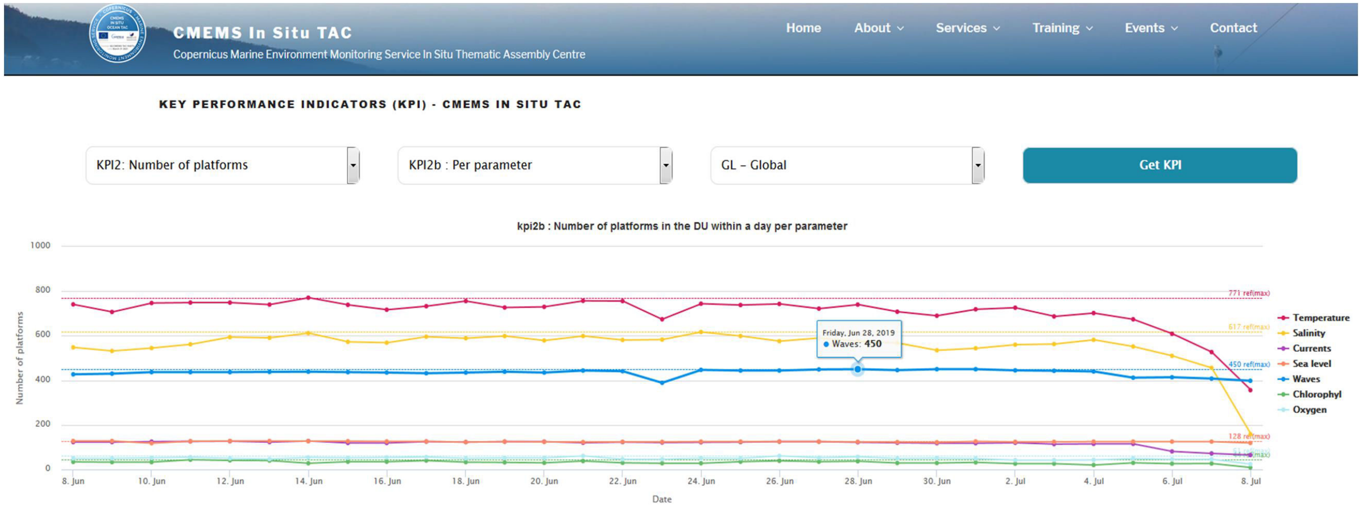
Table 3. Open ocean equipment, INSU Brest Centre

(1) Country of supplier's head office. Does not indicate country of manufacture.

(2) Purchase value for INSU.

(3) Material listed without details about suppliers.

Source: INSU.



CMEMS In Situ TAC
Copernicus Marine Environment Monitoring Service In Situ Thematic Assembly Centre

KEY PERFORMANCE INDICATORS (KPI) - CMEMS IN SITU TAC

KPI2: Number of platforms
KPI2b : Per parameter
GL - Global

kpi2b : Number of platforms in the DU within a day per parameter

Friday, Jun 28, 2019
Waves: 450

Figure 6. Example of KPI: number of platforms per day per parameter
DU: Distribution Unit (i.e. the CMEMS In-Situ Thematic Assembly Centre)
5 **Source: © CMEMS In Situ Thematic Assembly Centre** http://www.marineinsitu.eu/monitoring/

Study	Topic	Methodology	Results
Sassone, Weiher, 1997	Costs and benefits from TOGA project and ENSO observing system (EOS)	Impacts on US agriculture over 1995-2015. Sensitivity analysis using: -producers' and consumers' skill level (capacity for adapting to forecast), -future time horizon, -rate of acceptance of ENSO forecast, -annual future costs of EOS.	IRR = 13 to 26% Depends on assumptions on sensitivity of parameters.
Solow et al., 1998	Benefits from better ENSO forecast on US agriculture through more efficient cropping.	Based on simulation: -meteorology model for simulating ENSO forecast on temperature and precipitations -plant growth model for optimization of crops -economic model for impacts from crop strategies on crop product markets.	Expected producers' and consumers' annual surplus: $240 to 323 m as compared to ENSO forecast costs ~ $12.3m/year.
Kite-Powell, Colgan, 2001	Benefits from GoMOOS on marine activities in the Gulf of Maine	Review of commercial and non-commercial uses of GoM waters: -Key indicators per activity: operating costs/day, value added/day, willingness to pay for leisure, oil spill cost reduction. -Assumptions on avoided costs per activity from using ocean forecast and improving business management.	Annual potential benefits = sum of avoided costs per activity. Estimate of sum: $33 m Lower bound: missing data for several terms.
Cedre, Ifremer, 2009	Benefits from pilot tool for GMES. Case study: oil spill on France's Atlantic coast, December 1999	Review of coastal and marine activities affected by the oil spill. -Estimated turnovers of commercial activities. -Estimates of avoided costs from more efficient mitigation of damages. -Estimated cost of response to oil spill.	Sum of avoided costs per activity. Avoided costs: €49 m (conservative estimate) as compared to total oil spill cost estimate: €450 m.

Table 4. Four examples of CBAs on ocean forecast impacts

5

Annex

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Competing interests: the author declares that he has no conflict of interest.

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