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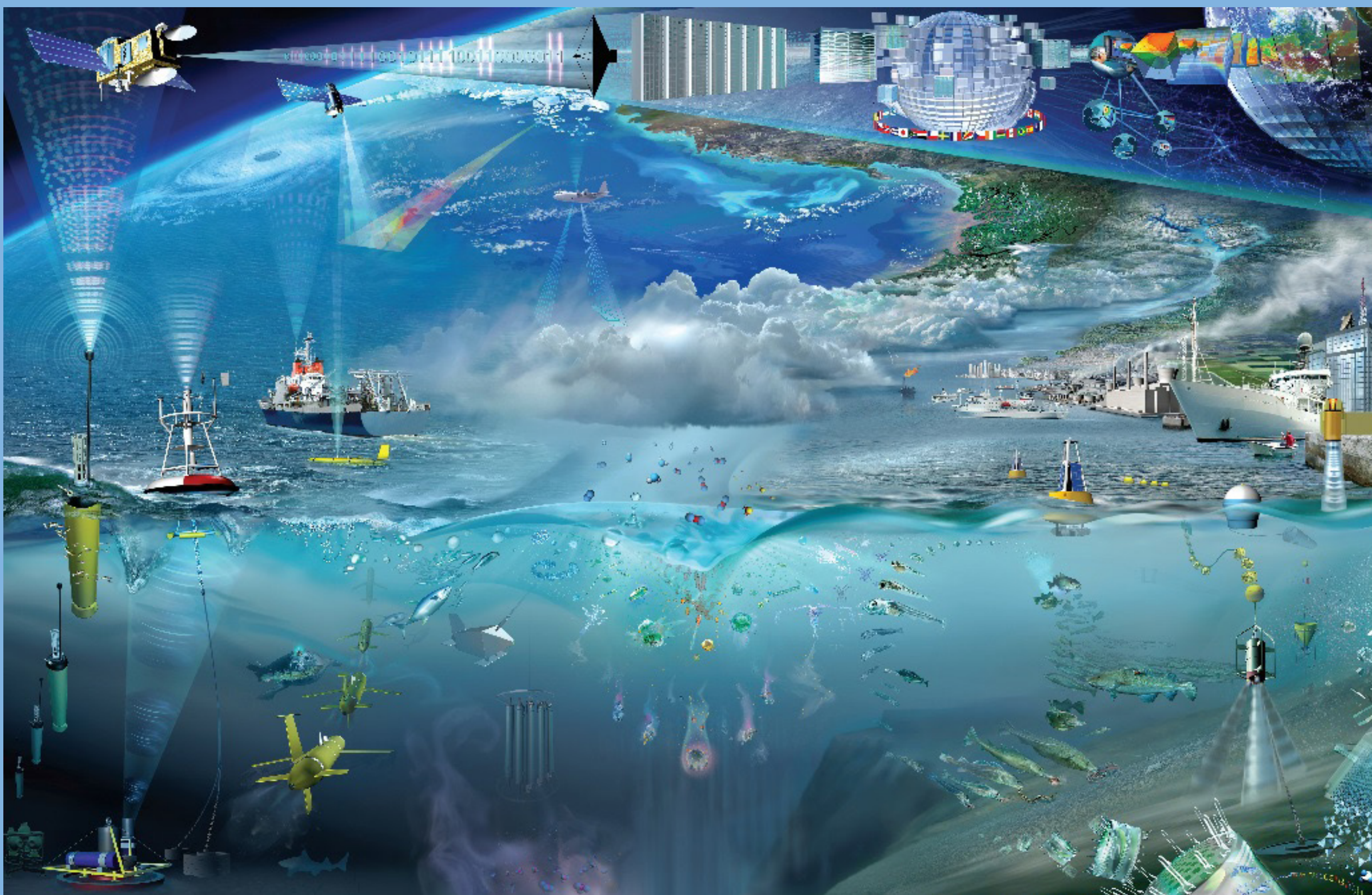

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Ocean Reanalyses in the context of GODAE OceanView

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Introduction

Ocean reanalyses involve the combination of ocean observations with numerical models to yield an estimate of the three-dimensional, time-varying ocean circulation. Facilitated by progress in ocean modelling and data assimilation methods, increased supercomputing capacity and, most importantly, enhanced, routine and sustained in-situ and remotely-sensed ocean observations, the last 15 years saw the development and operational implementation of mesoscale ("eddy-resolving") short-range ocean forecasting and reanalysis capabilities in an increasing number of oceanographic centres. Building and maintaining operational[1] ocean forecasting systems requires extensive expertise. Founded as an experiment in the late 1990s as the Global Ocean Data Assimilation Experiment (GODAE), its successor GODAE OceanView (GOV) coordinates multi-agency efforts to coordinate the research, development and operational implementation of physical and biogeochemical ocean forecasting and reanalyses systems through its science team (www.godae-oceanview.org). GOV continues the legacy of GODAE (GOV Science Team, 2014) with its collaborators from more than 50 academic and national agencies world-wide with a research focus to improve short- to medium-range (days to weeks) operational ocean forecasting systems, and to enhance and sustain their development and routine operations.

The forecast and reanalyses systems provide timely information about the marine environment including ocean physical and biological states. This information benefits marine, ecosystem, cryosphere and numerical weather prediction and associated applications such as marine industries (e.g. commercial fishing, shipping, oil and gas, renewable energy, tourism), governments (e.g. search and rescue, defence, coastal management, environmental protection) and other stakeholders (recreation, artisanal and sport fishing, yacht racing).

The objectives of the GOV Science Team are aligned with those of the World Weather Research Program (WWRP), the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), the Committee on Earth Observation Satellites (CEOS) and the

[1] "operational" is used here "whenever the processing is done in a routine pre-determined systematic approach with consistent accuracy and constant monitoring. With this terminology, regular re-analyses may be considered as operational systems, as well as organized analyses and assessment of climate data".

Blue Planet initiative of the intergovernmental Group on Earth Observations (GEO). In this context, GOV contributes to the prioritisation, advocacy, implementation and exploitation of the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS). Akin to numerical weather prediction, GOV operational ocean forecasting systems must be sustained, as well as evolve and improve, to remain relevant and have broad utility. This necessitates an ongoing, coordinated research activity. The core ocean forecasting disciplines of ocean modelling, data assimilation, forecast verification and observing system evaluation are routinely applied to associated reanalyses systems. These systems often underpin operational forecasting systems and assimilate quality-controlled in-situ and remotely-sensed observations. Consequently, reanalyses represent the "best case scenario" in terms of skill to be expected from an operational forecast system that have the additional challenge of near-real-time quality control of observations (due to the short time window from data sampling to data assimilation) and forecast surface fluxes (compared to reanalysed surface fluxes for reanalyses).

There exists a diverse range of four-dimensional reanalyses of the ocean state at global to regional scales - based on the common modelling and assimilation infrastructure used for ocean forecasting. Horizontal grid resolution of ocean models has been steadily increasing over the last two decades accompanied by increases in forecast skill (Tonani et. al., 2015) with horizontal spatial resolutions for global systems of typically 1/4° to 1/12°. Similarly, ocean data assimilation systems used in operational ocean forecasting and reanalyses use ensemble optimal interpolation (EnOI) (e.g. Oke et al., 2008; Ferry et al., 2010), adjoint tools (e.g. Lee et al., 2009) and Ensemble Kalman Filter (EnKF) methods (e.g. Sakov et al., 2012).

The GOV reanalysis systems are similar (in some cases, identical) to those used by the climate community (e.g. CLIVAR GSOP – Global Ocean Synthesis Panel, see Caltabiano et al, this issue) with the exception that operational considerations have been taken into account in the design of the reanalyses modelling and data assimilation systems (Schiller et al., 2013). The term "reanalyses" is used here to denote retrospective analyses that combine observed and modelled fields to reconstruct the ocean state. As our observing systems, data assimilation, and modelling capabilities improve over time it is often useful to repeat reanalyses with enhanced observations, thus providing improved model-based estimates of the ocean circulation.

GOV Reanalysis Systems: Applications for Climate Research

Even though high-resolution reanalysis systems have been originally developed to improve the analytical and forecasting capabilities for shorter time scales (days to weeks), the results of studies based on these systems improve our understanding of regional dynamics that is also important in climate research. The ocean is turbulent and dominated by mesoscale variability (Chelton et al., 2011). Hence, high-resolution ocean reanalyses can provide important first-order insights into basin-scale ocean current systems (e.g., Maximenko et al., 2008; Divakaran and Brassington, 2011). Furthermore, reanalysis products associated with operational forecast systems can contribute to better understanding of ocean dynamics at mesoscale resolution and can lead to new scientific findings in climate research. There is an increasing synergy between ocean reanalyses, championed by GODAE OceanView, and and those championed by CLIVAR - particularly as high-resolution reanalyses performed under GOV are performed to cover longer periods ("1990's to present reanalyses are typical, and provide consistent performance; however reanalyses back to the 1950's and 1970's are emerging). Some short-term ocean forecast and seasonal-to-decadal assimilation systems now share much of the data assimilation methodology and infrastructure. For example, the ongoing French Global Ocean Reanalysis and Simulation (GLORYS) project adopted the assimilation scheme developed for the French Mercator Océan forecasting system (Ferry et al., 2010). Similarly, the data assimilation component of the Australian seasonal prediction system POAMA (Yin et al., 2011) is based on the same data assimilation system used for short-range prediction (Oke et al. 2005; 2008; 2013). The relatively high-resolution nature of the ocean analysis and forecasting systems benefits studies of regional ocean dynamics and climate (including regional sea level change). Some examples are described below.

The goals of the Australian BLUElink effort include the development of eddy-permitting, data-assimilating, ocean forecast and reanalysis systems. The post-1991 assimilation product of BLUElink has been shown to realistically reproduce the mesoscale circulation in the Asian-Australian region (Schiller et al., 2008). Accurate representation of mesoscale eddy and circulation behaviour provides important information needed to realistically estimate mass and heat transport and to elucidate processes associated with water mass formation in conjunction with climate variability. For instance, Schiller et al. (2010) demonstrated the utility of the Bluelink assimilation product to represent the observations collected by the INSTANT program and to study the dynamics of intraseasonal variability associated with the complicated pathways of the Indonesian throughflow. More recently, Divakaran and Brassington (2011) have discovered ocean zonal mean currents in the southeast Indian Ocean by using similar BLUElink products.

In parallel to the development of the Global Ocean forecasting system, supported by the European MyOcean project, the Mercator Océan Agency has produce different versions of GLORYS spanning the 1992–2013 time period. Based on the NEMO Ocean and Sea Ice model, with the use of ERA-Interim air sea fluxes and a data assimilation system based on Ensemble Optimal Interpolation (sometimes referred to as an extended Kalman Filter, based on the SEEK approach), altimetry, SST, in-situ (e.g. Argo, XBT, TAO, sea-mammals) and sea ice concentration data are assimilated to provide a deterministic estimate of the ocean state (Figure 1; Lellouche et al, 2013). This reanalysis provides boundary conditions to regional ocean reanalyses all along the European shelves at higher resolution and to produce long-term simulation of the PISCES biological model (Aumont et al., 2015).

In the context of the European Copernicus programme (2015-2021), Mercator Océan will become the leader of the Marine Service and will update the operational global ocean forecasting system as well as reanalysis by improving the NEMO ocean / sea-ice model, increasing the resolution of the deterministic simulation (1/12°, 1/24°) and to develop an ensemble-based data assimilation system at lower resolution (300 members, 1/4°).

The Norwegian TOPAZ4 forecasting and reanalysis system is a coupled ocean-sea ice data assimilation system for the North Atlantic Ocean and Arctic (Sakov et al., 2012). It is currently the only operational, large-scale ocean data assimilation system that uses the EnKF (specifically, the Deterministic EnKF; Sakov and Oke 2008). TOPAZ4 therefore features a time-evolving, state-dependent estimate of the background error covariance and includes covariances between ocean

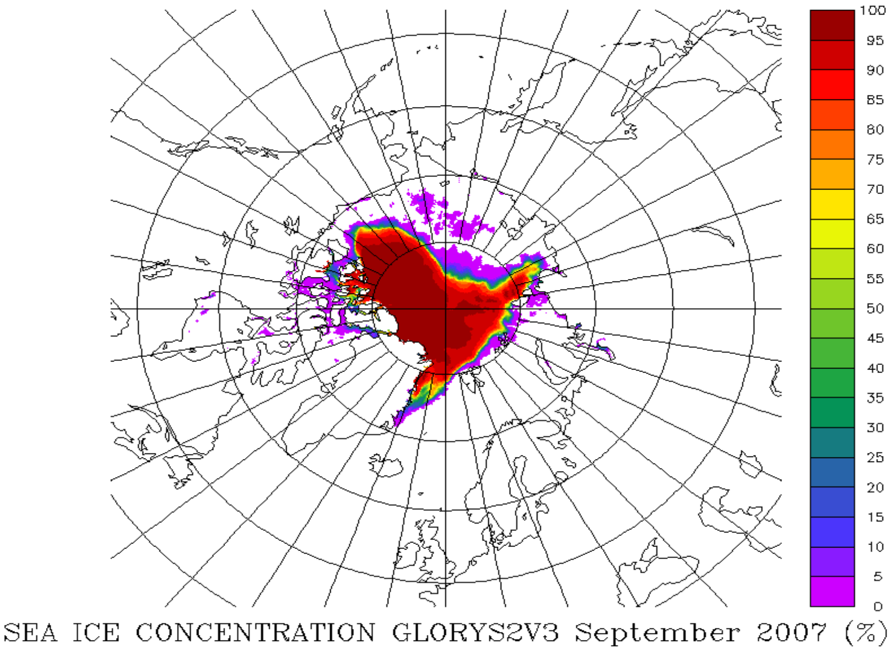

Figure 1: Monthly sea ice concentration based on GLORYS reanalysis for September 2007, showing the percentage of coverage.

variables and sea-ice variables, through the ensemble statistics – that is unique to ensemble-based data assimilation systems. TOPAZ4 produces a realistic estimate of the ocean circulation in the North Atlantic and the sea-ice variability in the Arctic.

The US Naval Research Laboratory (NRL) has run a 32-layer 1/12° global HYbrid Coordinate Ocean Model (HYCOM) ocean reanalysis that is the same basic configuration as the US Navy's operational Global Ocean Forecast System 3.0 (Metzger et al., 2014). It assimilates surface and subsurface observations using the Navy Coupled Ocean Data Assimilation system (Cummings and Smedstad, 2013) and is forced with National Centers for Environmental Prediction 1-hourly Climate Forecast System Reanalysis products (Saha et al., 2010). The time period spans October 1992 to December 2012. The ocean output have been interpolated to a constant 0.08° latitude/longitude grid (HYCOM's native grid is on a tri-pole configuration) and have been remapped in the vertical to 40 z-levels. A snapshot of sea surface height is shown in Figure 2. These output are served at: http://hycom.org/dataserver/glb-reanalysis.

Outlook

The development of data assimilation methods, mesoscale-resolving ocean reanalyses and their application to a wider range of problems will likely proceed as a result of their proven utility in ocean climate research. Data assimilation for oceanic biogeochemical and ecological modeling is of interest because of the possible application of such models to sustainable management of marine resources. However, there are many issues to be addressed in data assimilation for such complex systems. In particular, there remains uncertainty in a variety of oceanic biogeochemical and ecosystem model parameters, largely due to inaccurate 3-dimensional advection as one of the key processes determining the distributions of nutrients and plankton (e.g., Anderson and Robinson, 2001). At present, ocean color measurement from satellites seems to be the most suitable observation type to constrain biogeochemical and ecosystem models. However, the expansion of oxygen sensors on Argo floats promises to offer an important compliment to satellite observations.

A suite of ocean synthesis products have been produced in the past decade for various purposes. Few products provide uncertainty estimates for inferred quantities (e.g., global ocean heat content and sea level change). There is an increasing need to understand the consistency and uncertainty of these products. This is a very challenging task because of the large number of factors that can contribute to the differences among these products. Among these factors are the differences in model (including the configuration, parameterization, resolution, etc.), in forcing, in assimilation or estimation methods (including the way they are implemented; e.g. the treatment of error estimates), and in the observational data being assimilated (e.g., data types, data sources). Decadal and longer variability and temporal inhomogneity of observations could also contribute to the differences among different products. These challenges are not unique to ocean products, and are also known in atmospsheric analysis and reanalysis products.

Understanding the consistency and uncertainty of ocean synthesis products requires international coordination among ocean synthesis groups such as the ongoing evaluation effort coordinated by CLIVAR GSOP and GOV. A close collaboration among the ocean reanalyses, modeling, and observational communities becomes increasingly important. Moreover, the ocean and atmopsheric reanalysis communities need to work together to tackle over-arching issues such as the estimation of air-sea fluxes. Similarly, as capabilities in biogeochemical modelling improve, the community needs to consider methods for coupling the physics and biology for mutual benefit. As new capabilities in ocean forecasting emerge with countries like Canada, Brazil, India and China, it is likely that researchers in these countries, and elsewhere, will soon contribute to the international efforts in ocean reanalyses.

An important future challenge is the development of seamless systems that will enable scientists to fully investigate multi-scale interactions (i.e., between short- and long-term, between small- and large-scale phenomena, and across interfaces, such as ocean-atmosphere). This development is important because high-frequency and small-scale features may rectify low-frequency and large-scale phenomena, and large-scale climate signals may compound with synoptic variability (e.g., storm surge) to affect regional changes (e.g., for regional sea level).In this context it will be important to provide analyses of the coastal zone to better understand land-ocean exchange processes that are relevant to climate change, for instance, in conjunction with the distribution and fluxes of freshwater. However, application of the data assimilation approach to coastal oceanography involves many complications (e.g., De Mey et al., 2009). High-resolution models are required to represent nearshore phenomena on relatively fine temporal and spatial scales. Such models often produce strong currents that reduce controllability during the assimilation procedure because of inherent nonlinearities (Köhl and Willebrand, 2002). Further development of data assimilation techniques and improved model implementations will inevitably require sustained observations of the finer structure of water properties and precise topographic information to improve model representations of near-shore phenomena.

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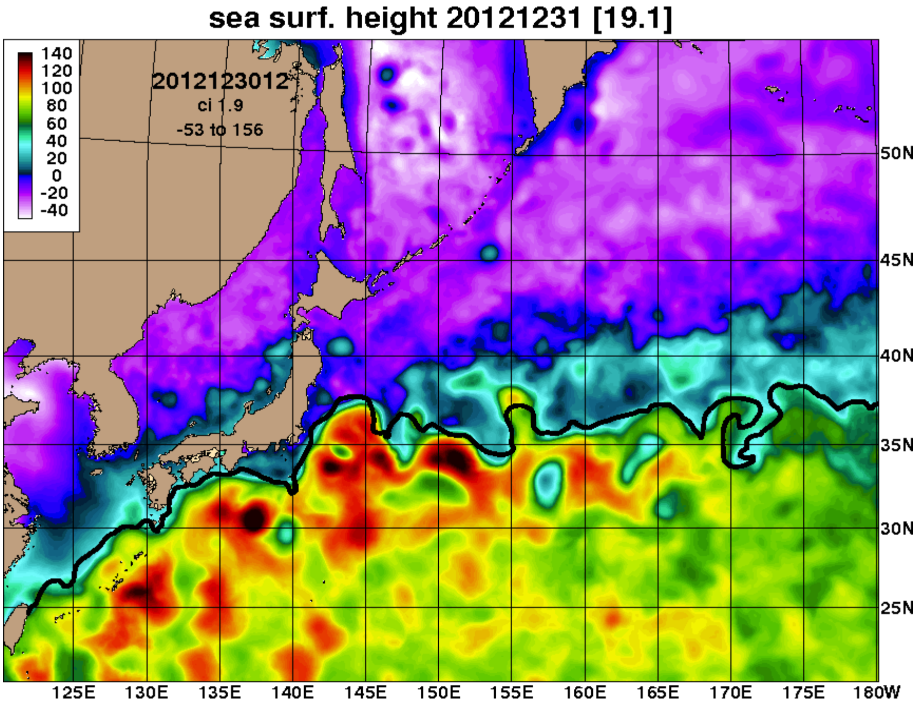

Figure 2: Snapshot (31 December 2012) of sea surface height in the Kuroshio Extension region from the HYCOM reanalysis. Units of the colour bar are in cm and the black line denotes an independent infrared frontal analysis that depicts the north wall of the Kuroshio.

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Animal-Borne Platforms for Ocean Observing

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Introduction

Marine vertebrates play important roles in ocean ecosystems, and as such, are an ideal platform for sampling the ocean environment. Because direct observation of these animals is difficult, and because of the rapid advances in low energy electronics and computation it is hardly surprising that the use of telemetry and autonomous data loggers to study them has rapidly increased. The combination of new positioning technologies, small, low power sensors and the variety of data recovery options provide a tremendous capacity to investigate how aquatic animals use their three-dimensional world, and to quantify important physical and biological aspects of their environments. The benefit of improvements to our understanding of animal movement and behavior can be seen in a wide range of applications, including those providing scientific information for marine fisheries and protected species management, and for evaluating the potential effects of anthropogenic disturbances. The data the animals have collected has also been used for improving coupled ocean-atmosphere observation and forecasting models.

Biological applications

Tag data can be used to inform and improve population censuses and stock assessment activities. For example, tag-derived movement data helped to improve management of Atlantic bluefin tuna through delineation of stock structure and demonstration of movement patterns (Taylor et al. 2011). Leatherback sea turtles have been observed to use corridors shaped by persistent oceanographic features such as the southern edge of the Costa Rica Dome and the highly energetic currents of the equatorial Pacific (Shillinger et al. 2008), and these findings led to an International Union for Conservation of Nature resolution to conserve leatherback sea turtles in the open seas. Habitat utilization patterns of marine mammals revealed by animal telemetry have helped identify, avoid or mitigate conflicts with oil, gas and alternative energy development, dredging and military activities (Tyack et al. 2011). By establishing times when tagged animals are not in close proximity to proposed human development operational windows for construction, dredging, pile driving, and military activities have been delineated, avoiding or minimizing disturbance. Distribution and migration data from a variety of taxa have been overlaid on oceanographic data to develop predictive mapping tools that help Central Pacific longline fishers minimize bycatch of protected loggerhead sea turtles (Howell et al. 2008). From the perspective of biological study of the animals themselves, most often these