A GLOBAL OCEAN EDDYING FORECASTING SYSTEM AT 1/16°

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Abstract

The Global Ocean Forecast System GOFS16 is an operational global ocean analysis and forecast system that runs daily at the Euro-Mediterranean Center on Climate Change (CMCC) since early 2017. GOFS16 produces 7-day forecasts of the state of the global ocean and sea ice (three-dimensional ocean temperature, salinity and currents, as well as sea ice thickness, concentration and drift). The system is based on a NEMO platform configured in a global eddying ocean at 1/16° horizontal resolution. To compute the initial conditions for the ocean forecasting, *in situ* observations of temperature, salinity, altimeter data, satellite sea surface temperature and sea ice concentration are jointly assimilated each day over a 1-day observation window using a 3DVar data assimilation scheme which has been recently parallelized to deal with the global high-resolution grid at 1/16°. Statistics of the differences between the model forecasts and observations are routinely produced. This paper introduces the first version of the GOFS16 system and details all its components. A validation procedure, including online web service, has been developed and here described.

Keywords: global ocean forecasting, eddy-resolving models, data assimilation

1. Introduction

The unique capability of satellite altimetry to observe the global ocean in near-real-time at high resolution and the deployment of Argo buoys were essential to the development of global operational oceanography. Such an integrated approach (satellite and *in situ* observations) has been fundamental and fostered a series of major achievements in oceanography since the 1990s. At the same time, the ocean modelling community started to deal with the challenges that the need to resolve complex mesoscale dynamics poses. Thanks to recent advances in computational resources, in the recent years, the ocean forecast community is investing a growing effort towards the prediction of mesoscale processes and day-by-day variability at global and regional scales using eddy-permitting and eddy-resolving modelling capabilities. New high-resolution global and regional simulations are able to resolve mesoscale structures in large parts of the domains. However, despite the significant improvements in modelling and computational capacity, and the increased availability of observations during the last two decades, one among the initial plans of the global operational community has not been reached yet, that is the eddy-resolving capacity in the continental shelf regions and at high polar latitudes. Furthermore, a realistic representation of mesoscale variability is triggered by the capability of the assimilation schemes to efficiently ingest the increasing number of observations available. In order to realistically represent the full dynamics and life cycle of baroclinic eddies in the majority of the global ocean, at CMCC we developed GOFS16, a global eddying configuration of the ocean and sea ice system which operates on a daily basis since mid 2017. Every day, terabytes of data are produced, manipulated and validated, with highly parallelized software designed at CMCC, to provide the three-dimensional state of the global ocean circulation at a pioneering resolution of roughly 6 km. In January 2021, GOFS16 joined the OceanPredict intercomparison project (ex GODAE OceanView) that gathers and compares different global prediction systems at different resolutions. The 6-day forecast products of GOFS16 have hourly/daily frequency for the ocean temperature, salinity, sea surface height and meridional/zonal velocities, together with sea ice concentration and thickness. The chain consists of daily production of a 6-day-long forecast, initialized by a former (daily) analysis. Each daily production (say production of day T) starts with a first integration of the sole model between T-48h and T-24h. Corrections are then calculated by the DA system and applied to a second model integration of the same day. This leads to the best initial conditions at T-24h that are used to generate the nowcast (T-24,T) and a 6-day-long forecast. Maps of GOFS16 forecasts are available from the following webpage http://gofs.cmcc.it/ in almost near-real-time (daily update). A validation tool of the analysis fields is also available online at http://evalid.cmcc.it/evaluation/gofs/, where *in situ* temperature and salinity profiles from Copernicus Marine Environment Monitoring Service (CMEMS) catalogue are compared with model equivalent values. In Section 2, we present the GOFS16 in its three components (model, data assimilation and assimilated observations), while Section 3 illustrates the validation matrix used to monitor the forecast skills of the system and a synthesis of the same skills.

2. GOFS16 Description

The global ocean forecasting system includes:

a. The NEMO ocean model, configured in a global configuration at about 1/16° horizontal resolution, 98 vertical levels and coupled to the LIM2 sea ice model;

b. A three-dimensional variational (3DVar) data assimilation scheme that assimilates in situ Temperature and Salinity and satellite Sea Level Anomaly (SLA) and Sea Surface Temperature (SST) observations;

c. a nudging scheme that uses space-borne sea surface temperature observations and sea ice concentration (Reynolds *et al.*, 2007) supplied by NOAA, and sea surface salinity (Good *et al.*, 2013).

The GOFS16 analysis and forecasting numerical core is based on NEMO ocean/ice model (version 3.4, Madec and the NEMO team, 2012). The configuration (described in Iovino *et al.*, 2016) is a global, eddying configuration of the ocean and sea ice system with a horizontal resolution of 1/16° at the Equator, corresponding to 6.9 km, that increases poleward as cosine of latitude, leading to 5762 × 3963 grid points horizontally, and roughly 3 km in the polar regions. Ocean and sea ice are on the same horizontal mesh, a non-uniform tripolar grid, computed at CMCC following the semi-analytical method of Madec and Imbard (1996). The vertical coordinate system is based on fixed depth levels and consists of 98 vertical levels with a grid spacing increasing from approximately 1 m near the surface to 160 m in the deep ocean. The bathymetry is generated from three distinct topographic products: ETOPO2 (US Department of Commerce, 2006) is used for the deep ocean, GEBCO (IOC, IHO and BODC, 2003) for the continental shelves shallower than 300 m, and Bedmap2 (Fretwell *et al.*, 2013) for the Antarctic region, south of 60° S. The ocean component OPA is a finite difference, hydrostatic, primitive equation ocean general circulation model, with a free sea surface. The NEMO code solves the primitive equations using as prognostic variables: 3D temperature, salinity, meridional and zonal velocities and 2D sea-surface height. In the current version a linearized free-surface formulation is used (Roullet and Madec, 2000) and a free-slip lateral friction condition is applied at the lateral boundaries. Tracer advection follows a total variance dissipation (TVD) scheme, while vertical mixing is achieved using the turbulent kinetic energy (TKE) closure scheme (Blanke and Delecluse, 1993). The model interactively computes air-surface fluxes of momentum, mass, and heat. Forcing fields are provided by the NOAA operational system with 0.25° spatial resolution. The surface boundary conditions are computed using the bulk formulation by Large and Yeager (2004). The turbulent variables are applied at a 6 hourly frequency and radiative and freshwater fluxes are daily fields. The water balance is computed as evaporation minus precipitation and runoff. The evaporation is derived from the latent heat flux, precipitation is provided by NCEP as daily averages, while the river runoff is added at the surface along the land mask as a monthly climatology (Dai and Trenberth 2009). The ocean component is coupled to the sea ice module LIM2 that includes the representation of both the thermodynamic and dynamic processes. The ice dynamics are calculated according to external forcing from wind stress, ocean stress, and sea surface tilt and internal ice stresses using C grid formulation. The elastic–viscous–plastic formulation of the sea ice rheology is used.

OceanVar is a three-dimensional variational (3Dvar) data assimilation scheme originally developed for the Mediterranean Sea (Dobricic and Pinardi, 2008), later extended to the global ocean (Storto *et al.*, 2011) and recently massively parallelized in a hybrid MPI-OpenMP environment to deal with global high-resolution grid (Cipollone *et al.*, 2020). The background-error covariance matrix accounts for vertical covariances (modeled through the use of multivariate EOFs) and horizontal correlations (through the application of recursive filters). Horizontal correlation length-scales have been scaled to the 1/16° mesh from the reference 1/4° resolution configuration to maximise the impact of dense satellite datasets such as SLA and SST, improving the ocean initial condition for the short-term forecast. Observation processing includes background quality checks, thinning of dense datasets, spatial (statistical) unbiased for SLA and the removal of diurnal SST retrievals. In addition to the 3Dvar assimilation, GOFS16 uses a nudging scheme for surface temperature, salinity and sea ice concentration. The assimilated data includes: near-real-time SLA L3 observations (from Jason3, Sentinel 3a, Sentinel 3b and Altika satellites) provided by CMEMS; near-real-time *in situ* observations coming from moorings, Argo floats, Expand-able Bathy Termographs (XBTs), and Conductivity-Temperature-Depth (CTDs) gathered together in the CMEMS catalog; near real time SST data: Advanced Very High-Resolution Radiometer (AVHRR) from NOAA and Advanced Microwave Scanning Radiometer 2 (AMSR2) from NASA. The analysis of GOFS16 includes a nudging scheme to correct the heat and freshwater surface fluxes using gridded SST analyses provided by NOAA (Reynolds *et al.*, 2007) and the sea-surface salinity objective analyses from the UK MetOffice EN4 (v4.2.1), respectively. As an important step forward for the prediction of sea and sea-ice states at high latitudes, GOFS16 implements a data assimilation scheme to ingest sea-ice concentration observations from satellites. The sea-ice analysis uses in particular data from the SSM-I instruments on board the DMSP constellation (F-15 and F-17) processed by NCEP and the assimilation scheme consists of nudging to the sea-ice analysis with an 8-hour relaxation time-scale.

The GOF16 assimilation system is designed to share the same grid of the model at 1/16° resolution at any step. This brought several benefits starting from a direct ingestion of corrections into the model run without the need of extra interpolation that could lead to additional errors. Moreover, it helps the system to maximize the amount of information coming from high-resolution observational networks and to reduce the spatial correlation among observations inevitably introduced at the length scale of grid spacing. The benefits of using this approach which implies that the minimization is performed on the same grid of the ocean, versus the alternative one in which the ocean output was interpolated onto 1/4° horizontal resolution grid as first guess fields for 3Dvar has been shown in Cipollone *et al.*, 2020.

3. GOFS16 Skills

The forecast skill of the model is routinely monitored by calculating different types of statistics for the global domain as well as numerous sub-regions of the world ocean. The Validation/Verification process of GOFS16 is provided at different time scales and is performed using semi-independent analysis. The metrics refer to the 'misfits' that are calculated by the data assimilation system as differences between observations and model outputs transformed at the location and time of the observations, and include:

- Root Mean Square Errors (RMSE) and BIAS of 3D temperature and salinity using misfits with ARGO-CTD and XBT (only for temperature) collected from CMEMS INS TAC. An interactive validation webpage is available online for the analysis of vertical profiles and time series at selected depth (http://evalid.cmcc.it/evaluation/gofs/) (see two examples in Figure 1);
- RMSE and BIAS of SLA using misfits with satellite along track sea level anomalies from CMEMS SL TAC;
- RMSE and BIAS of SST using AVHRR and AMRS2 retrievals or AVHRR-OI;
- Daily RMSE/BIAS time series and spatial RMSE/BIAS maps for SST and SLA are also calculated for the first 6 days of the forecasts;
- Anomaly correlation coefficients (GDPFS WMO, 2010) to measure the correlation between observations and model forecast/analysis, out of the seasonal trend.

The validation also includes the assessment of the near-surface current (at 15 m depth) compared to the trajectories of Lagrangian drifting buoys distributed by the AOML's Drifting Buoy Data Assembly Center (https://www.aoml.noaa.gov/phod/gdp/) in several subdomains in non-operational mode.

Recently, a reprocessed dataset from OceanPredict has been included in the validation system for a CLASS4 semi-independent comparison. Such a dataset provides a first quality-controlled version of near-real time satellite and *in situ* data, aggregated with others that are late-coming (up to 5 days), plus measurements coming from other sources (such as drifters). The SLA and SST RMSE/bias time series for the last three months show values which fall within the range of the OceanPredict global systems at coarser resolution (Figure 2 upper panels, see Figures 2 and 3 of Ryan *et al.*, 2015 for comparison). The T and S RMSE/bias as a function of depth (Figure 2 bottom panels, see Figures 4 and 5 of Ryan *et al.*, 2015 for comparison) are also in agreement with the performance of the other global systems with the notable exception of a larger upper ocean T bias in our system which seems to come from some specific regions (not shown) and which is currently under investigation.

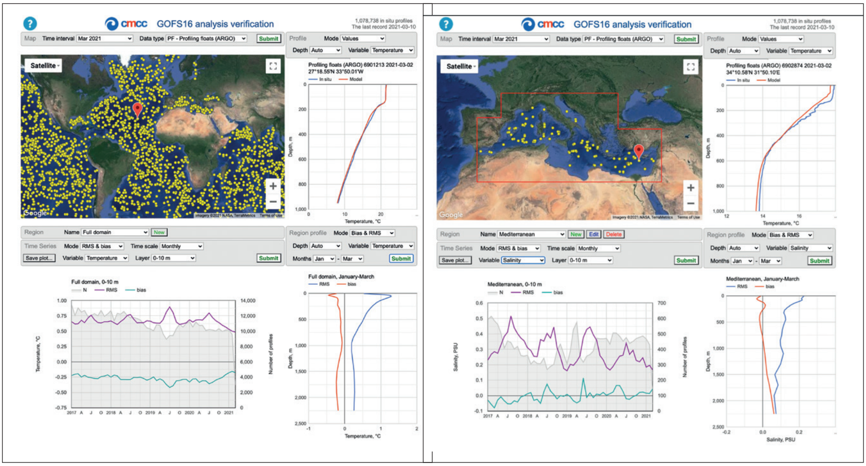

Fig.1. Two examples from the validation webpage of the analysis (http://evalid.cmcc.it/evaluation/gofs/) for the temperature in the global ocean (left panel) and the salinity in the Mediterranean Sea (right panel). Upper panels show the locations of available observations (yellow dots) in a selected time frame and the vertical profiles of ocean variables for one of those. Lower panels show the time series of RMSE and bias for a depth range and the time/space mean vertical profiles of RMSE and bias.

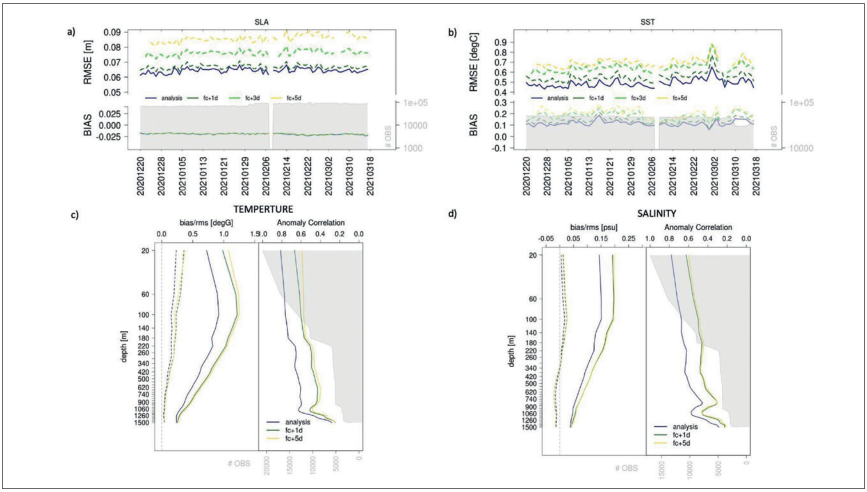

Fig. 2. RMSE/bias time series of analysis, 24h, 36h and 120h forecasts for global mean SLA (a) and SST (b). RMSE/bias and anomaly correlation as a function of depth of analysis, 24h, and 120h forecasts for global mean T (c) and S (d). The background grey represents the number of observations per day. The validation is done using the OceanPredict reference observation data set.

4. Conclusions

The Global Ocean Forecast System GOFS16 is an operational ocean analysis and forecast system at 1/16° horizontal resolution that runs daily at the Euro-Mediterranean Center on Climate Change since early 2017. The system is based on a global eddying ocean combined with a state-of-the-art variational data assimilation system that has been massively parallelized and is capable of assimilating space-borne and conventional observing networks, including hydrographic profiles and several satellite data. In this work we presented the different components of the systems and a preliminary assessment of GOFS16 forecast skills by means of conventional error and bias analyses. Since January 2021 GOFS16 has joined the OceanPredict inter-comparison project that gathers and compares different global prediction systems at different resolutions. The routinely evaluation of the current system skills, which has gone through some bug fixing and continuous improvements since its birth, is encouraging and seems to confirm the capacity of GOFS16 to perform within the range of the other global systems. The intercomparison will help to assess its current skills with respect to more mature but coarser resolution global forecasting systems, identify its main weaknesses, and inspire possible future refinements/developments to further improve its quality.

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