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Short Communication

Oceanic data assimilation study in northern Chile: use of a 3DVAR method

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ABSTRACT. We report the use of a 3-dimensional variational (3DVAR) data assimilation method as part of a numerical model off northern Chile. The numerical model is part of an ocean forecasting project that aims to understand the impact of environmental variability on the distribution of biological species in the area. We assimilated data from a simulated ocean observing system to recover a known state, obtaining a significantly smaller error when compared to a numerical run with no assimilation. Our results validate the computational implementation of the code, and allow us to evaluate the impact of the choice of data in the assimilation process: the assimilation of sea surface height being particularly important. We note that the assimilation of surface data propagates properly to greater depths and reduces the error with reference to the known state. This was possible by using covariance error matrices calculated previously for the California coastal area. The implementation of the data assimilation module is relatively simple and permits its use in operational forecasting systems, and for the design and evaluation of future ocean observational systems.

Keywords: ocean forecast, observational system simulation, data assimilation, northern Chile.

Asimilación de datos oceánicos en el norte de Chile: uso de un método 3DVAR

RESUMEN. Se presenta el uso de un método variacional en tres dimensiones (3DVAR) como parte de un modelo numérico en el norte de Chile. El modelo numérico es parte de un proyecto de pronóstico del océano que busca entender el impacto de la variabilidad ambiental en la distribución de especies biológicas en el área. Se han asimilado los datos de un sistema de observación del océano simulado para recuperar un estado conocido, logrando obtener un error significativamente menor en comparación a una simulación sin asimilación. Los resultados validan la implementación computacional del código y permite evaluar la elección de los datos en el proceso de asimilación: la asimilación de la altura del nivel del mar fue particularmente importante. Se observa que la asimilación de los datos de superficie se propaga correctamente a mayores profundidades y se reduce el error calculado con referencia al estado conocido. Esto fue posible por el uso de matrices de covarianza de errores que fueron anteriormente calculadas para la zona costera de California. La configuración del código implementado es simple y permitirá su uso en sistemas de pronóstico operacional, así como para el diseño y evaluación de futuros sistemas observacionales del océano.

Palabras clave: pronóstico oceánico, simulación de sistemas observacionales, asimilación de datos, norte de Chile.

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The objective of this work is to improve one of the few Chilean projects in operational coastal oceanography, devoted to forecast ocean circulation in the north of Chile (15°-35°S, http://www.sipo-costachile.cl/), using the regional model ROMS (Shchepetkin & McWilliams, 2005) in its AGRIF version (Penven *et al*., 2007; Debreu *et al*., 2012) with a spatial resolution of 9 km and 32 vertical levels. Fig. 1 illustrates the forecasting system domain. This forecast is part of an integrated program of marine, biological and atmospheric forecast that, along with in situ monitoring efforts, aims to relate the oceanic environmental variability with that of the biological species of ecological and commercial interest in the region. For this, the use of a 3DVAR data assimilation module will help reducing existing errors in the current operational forecasting system. The forecasting system is based on results from a

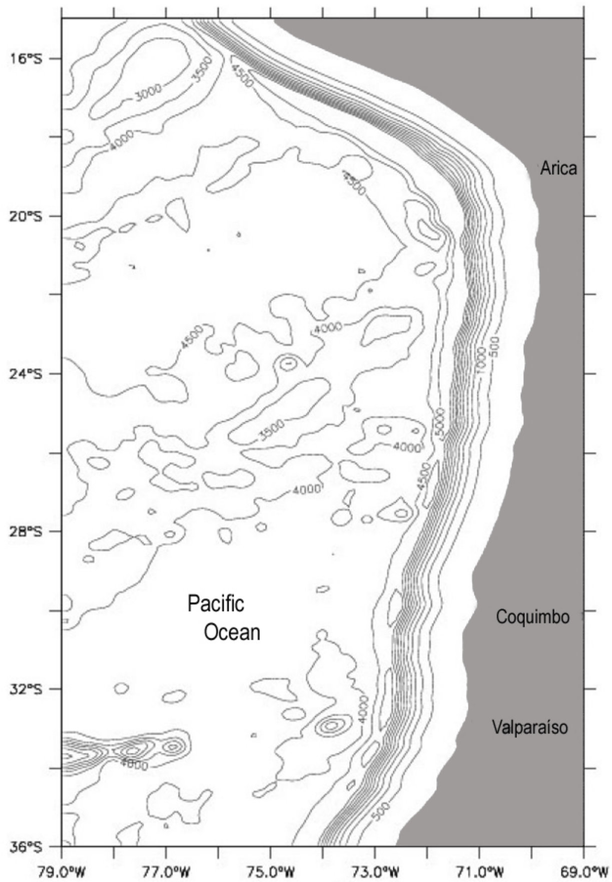

Figure 1. Map of simulated area, center-north area of Chile. Contour lines represent bathymetry (m).

monitoring and forecasting oceanic and atmospheric project in New Caledonia that has shown interesting capabilities, given its simplicity and portability (Marchesiello *et al.*, 2008). The oceanic part of this system uses a numerical approach for downscaling the global MERCATOR operational products (Drévillon *et al.*, 2008), based on ROMS, with atmospheric forcing from the Global Forecasting System (NCEP, 2003). The MERCATOR assimilated solution provides a regional representation of the circulation that is smoothly projected in the ROMS solution by a nudging technique. The results are positive in terms of mesoscale predictability, but improvement in forecasting smaller space and time scales requires the implementation of local data assimilation. We therefore considered the implementation of a 3DVAR data assimilation method developed for ROMS (Li *et al.*, 2008a; Chao *et al.*, 2009). This approach is suitable for sigma coordinate models, and for the nesting technique that is part of ROMS_AGRIF (Penven *et al.*, 2007; Debreu *et al.*, 2012). A similar system is currently used for southern California and the Gulf of Alaska (http://ourocean.jpl.nasa.gov), and its portability and computational efficiency makes it a very attractive option for other coastal applications. Here, we describe preliminary results on the Chilean coast from an Observing System Simulation Experiment (OSSE). This first step is needed in order to verify the correct implementation of the code and the impact of such an addition to forecasting the Chilean coastal circulation.

The method used to develop ROMS-3DVAR is based on the idea of flow decomposition in slow and fast components, representing ocean and coastal areas respectively. The slow component is in geostrophic balance and it is dependent only on the steric part of horizontal pressure, which is deduced from the temperature (T) and salinity (S) fields, which are the control variables of the system. The fast components (ageostrophic currents and non-steric sea level) are introduced as dynamic control variables in ROMS-3DVAR, which amounts to constraining the slow dynamical equilibrium. This method allows the non-steric and ageostrophic effects, often dominant in the coastal areas, to be represented. It also avoids the necessity to calculate the multivariate covariance between η (total), T and S. This allows compliance with a crucial principle of efficiency in data assimilation (Weaver *et al.*, 2005): transformation of the model space (where the variables are highly correlated) to control space (where variables are weakly correlated). Thus, any inconsistencies between density measurements (T, S) and altimetry assimilation only have a negligible effect.

The algorithm of ROMS-3DVAR provides a weak constraint to the flow dynamics (Parrish & Derber, 1992), which is appropriate for fine prediction. Notice that in fine vortical structures, where the centrifugal force becomes important, the gradient wind balance (between pressure gradient, Coriolis and centrifugal forces) could advantageously replace the geostrophic balance for constraining slow modes. However, the gradient wind relation is more difficult to apply in practice, and will require some work for its implementation. What is certain is that a significant portion of ageostrophy in submesoscale eddies is only due to the centrifugal force (Capet *et al.*, 2008). Using fine-scale observations (*e.g.*, HF radar) to correct the effect of this force would be ineffective and counter-productive.

Another originality of the method is its multi-scale approach. In this approach, large and small scales are treated in several stages (two at least, or more, when considering intermediate scales). This separation method has been used to eliminate biases (artifacts of vortices in this case) from inconsistency between observations at different scales (Li *et al.*,

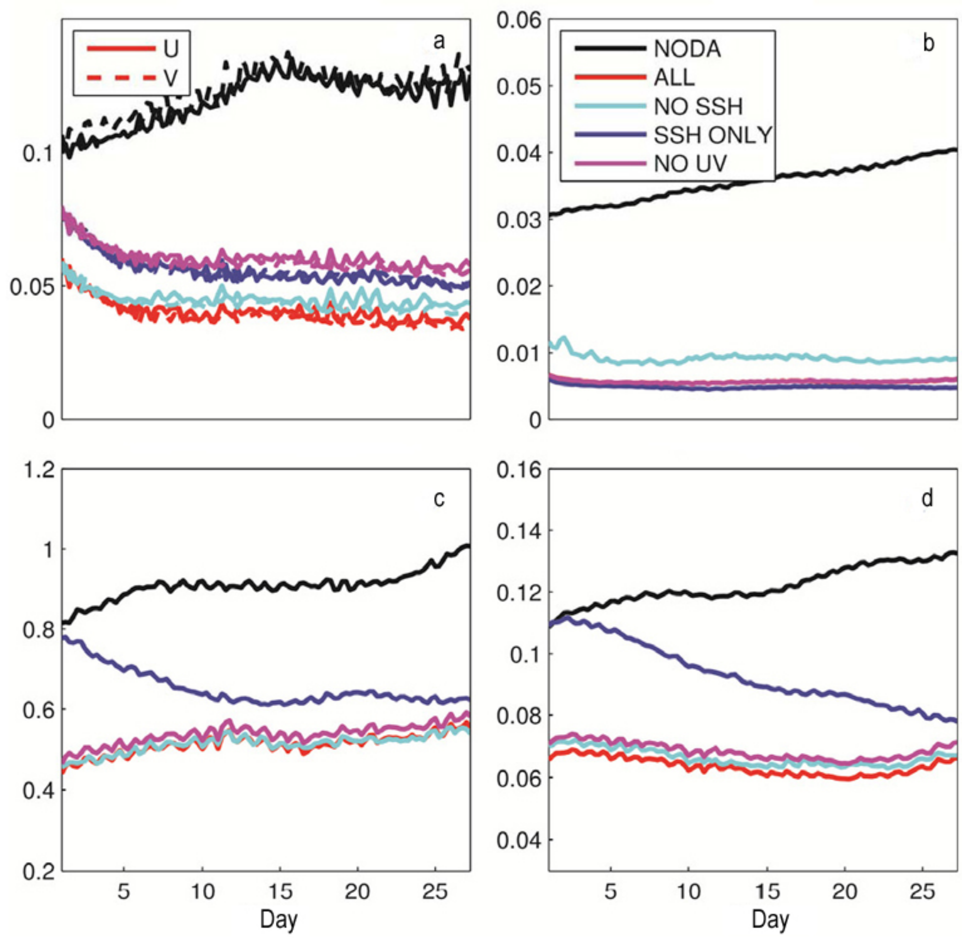

Figure 2. Time series of mean error in a) velocity (m s^{-1}), b) sea level (m), c) temperature (°C) and d) salinity at 20 m depth. Black line represents the case were in which no information is assimilated and initial condition is perturbed. Red line represents the assimilation of all the information available. Green line represents the case in which everything except sea level is assimilated. Blue line represents the case were only sea level is assimilated.

2008b). This is important, given that upwelling systems are particularly rich in fine scales associated with various processes of frontogenesis, production of turbulence and interaction with the coastline and bottom topography.

The performance of a 3DVAR scheme hinges on forecast error covariance. ROMS-3DVAR incorporates a unique Kronecker product formulation to construct forecast error covariance. One important capability of this formulation is the representation of 3D inhomogeneous and anisotropic error covariance. The inhomogeneity and anisotropy are often significant in coastal oceans due to two physical boundaries: the sea surface and the coastline. In particular, the atmosphere drives the ocean at its surface; therefore more dynamic processes occur near the ocean surface than in deep water. Vertical difference in the dynamics leads to complex vertical structures in forecast errors. Since most of oceanic observations are limited to the surface, this 3D inhomogeneous and anisotropic error covariance allows the representation of complex vertical structures and consequently effectively propagates the observed information from the surface to the deep ocean.

Furthermore, the computation related to the background error covariance is highly demanding and imposes a great challenge on the use of high-resolution coastal ocean models. The Kronecker product formulation greatly reduces the computational and memory requirements, so that coastal implementations become manageable on present-day computers. Another important step in computational efficiency is the Cholesky factorizations of 3D covariance matrices. They are used to precondition the minimization problem, improving computational reliability and efficiency, and guarantee that the error covariance is positive definite. Our application uses

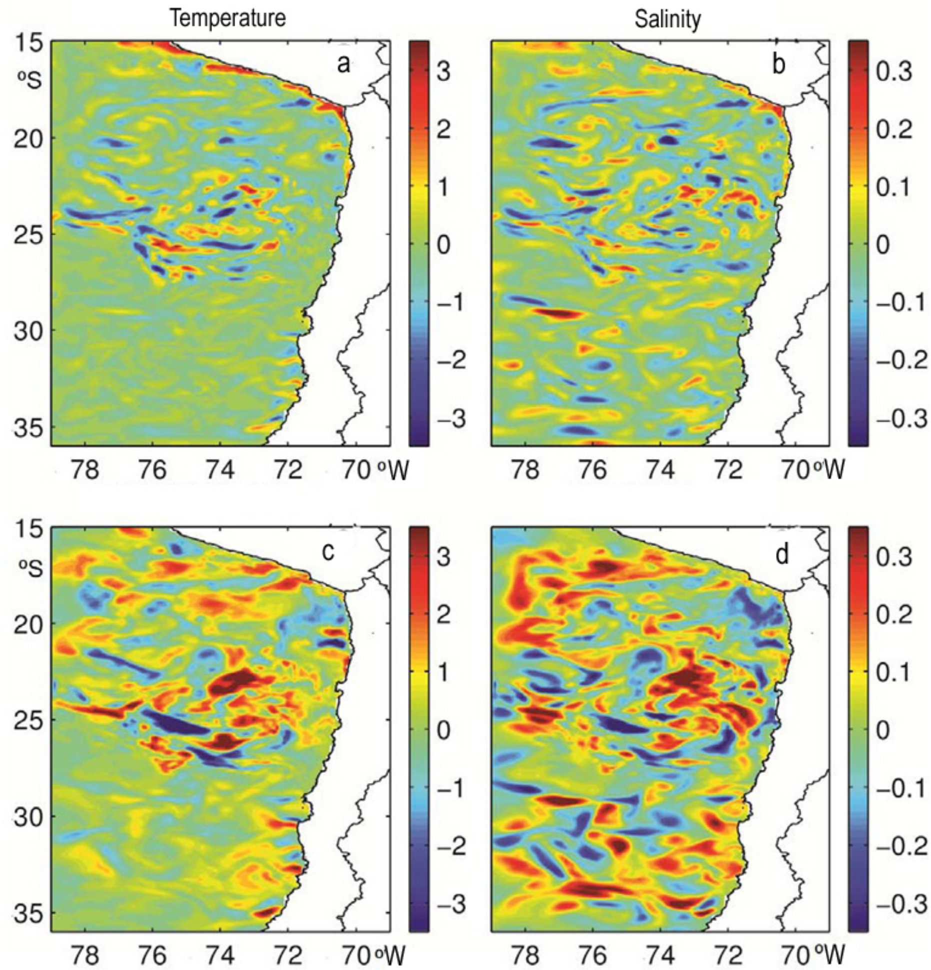

Figure 3. Spatial distribution of the error (assimilation minus simulation) for temperature and salinity at 20 m depth. a, b) represent the case with data assimilation, and c, d) without data assimilation. It is clear that the error is large in the latter case.

the covariance error matrices from the California coastal area, calculated by Li *et al.* (2008b).

An OSSE is an approach that provides a diagnostic of the assimilation system and a quantitative assessment of the impact of observing systems on forecast, thus acting as a guide to the design of observing systems. The idea is to create a proxy of the real ocean, so-called Nature Run, obtained through a free simulation of the model, *i.e.*, without data assimilation. The Nature Run is used as the true state of the ocean for error calculation. A subsample is then extracted and used as the data to be assimilated in another simulation with a perturbed initial condition. The aim of the assimilation scheme is to correct the error introduced by the perturbed initial condition and bring the solution closer to the Nature Run. For our application, the assimilated variables, our observation system, consisted of a subsample of T, S, profiles at 24 depths, from 0 to 1200 m at intervals of 0.3° in longitude and 0.8° in latitude, SSH (sea surface height), SST (sea surface temperature) and surface currents on zonal sections spaced at intervals of 0.2° in longitude and 0.16° in latitude. These data are considered either separately or combined, to test the role of each type of measurement. The various data involved in the assimilation represent observations that can be obtained using various sensors, such as HF radar, fixed and drifting buoys, gliders, and satellites, in both inshore and offshore areas, where the equilibrium dynamics are different. Assimilation on short time windows is used to avoid the excessive production of adjustment waves.

All assimilation experiments appear to significantly improve the predictability of the system variables (Figs. 2a, 2d) compared to a simulation without assimilation (NODA) where the area averaged initial error logically tends to increase in time. Moreover, the simultaneous assimilation of all variables (ALL) gives the best results, indicating an absence of conflict. For surface velocities (Fig. 2a), the assimilation of SSH allows a very significant decrease of the error, which can be further decreased by the assimilation of surface velocities. The result is similar for SSH error (Fig. 2b); the sole assimilation of SSH has a positive effect, and the assimilation of other variables improves furthermore the result. Error correction on the temperature and salinity fields (Figs. 2c, 2d) is significant in the first analysis in which these variables are directly assimilated. The assimilation of SSH only provides a correction to T, S errors, although a period of adjustment is needed in this case (10 days for temperature and 25 days for salinity). This correction results from the effect of hydrostatic constraint. The spatial structure of the errors (Fig. 3) is also improved by means of data assimilation. At 20 m depth the range and extension of temperature errors decrease when all data are assimilated (Fig. 3a), compared with no assimilation at all (Fig. 3c). The same can be observed with salinity (Figs. 3b, 3c) for both coastal and oceanic areas.

Data assimilation is essentially dealing with Lyapunov instability (sensitivity to initial conditions) and forcing errors, but improvements must also rely on modifications of the model physics and numerical accuracy. In the future, for example, it will be essential to consider the impact of waves and wave-current interactions on ocean dynamics, both of which represent a huge challenge for coastal operations. In this sense, the development of ROMS-3DVAR for the coast of Chile is a study of scientific interest as a well as a test of portability, and its application will extend one of the first Chilean projects in operational coastal oceanography.

In the next step, ROMS-3DVAR will be used to assimilate available Argo floats and satellite data operationally, namely the SST and SSH anomalies, as these are datasets that are available in near real time and could be used on a daily basis to improve the results of an oceanic forecast. This will be a common choice for an area where very few datasets are easily available. ROMS-3DVAR will be used to test the impact of assimilating a local and very dense data set available for November 2009 in the area near Tongoy: it includes HR marine radar deployed in the region of Coquimbo, five buoys, tide gauges, CTD sections, and gliders, which were deployed in a coordinated effort from several scientific projects. This would constitute a realistic best scenario, were resources from different projects are focused to study a limited area for a short time to provide insight on the design of future coordinated experiments.

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