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Short communication

A reanalysis of the Chilean ocean circulation: preliminary results for the region between 20ºS to 40ºS

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ABSTRACT. The development and initial results from a reanalysis, or best estimate, of the historical state of central Chile's coastal ocean are presented. The Chilean Ocean State Estimate (COSE) covers the western coast of South America southwards of 20ºS and for the period 1993 to 2012. The reanalysis is being performed using the 4DVAR driver of the Regional Ocean Modeling System (ROMS). The ROMS solution is constrained to reconcile satellite sea surface temperature and altimetry data with prior estimates of the initial state and boundary conditions derived from the HYCOM (Hybrid Coordinate Ocean Model) global reanalysis. Here we present preliminary results from COSE for central Chile and the year 2008. The regional reanalysis reduces the model-observations mismatch of the global HYCOM solution by 38 and 27%, for sea surface temperature and height respectively, and corrects a spurious on-shore surface current present in the HYCOM reanalysis. Inspection of the assimilation increments suggests that ROMS simulations forced by satellite winds overestimate coastal upwelling.

Keywords: coastal ocean circulation, data assimilation, reanalysis, Chilean coast, southeastern Pacific.

Our relatively short, sporadic, and spatially unstructured observational record limits our ability to understand and interpret Chile's coastal ocean. The utility of reconstructing the unobserved component of the historical ocean state is patent, and so-called reanalyses of the ocean and atmosphere that provide a gridded, gap-free and dynamically consistent estimate of the historical system state, have found extremely broad use across the sciences (*e.g.*, the NCEP reanalysis; Kalnay *et al.*, 1996). In fact, such reanalysis products are commonly treated on a par with observations, despite the fact that they are in reality data constrained numerical simulations.

In the following we briefly outline the development and preliminary results of a new reanalysis of the historical state of Chile's coastal ocean, named the Chilean Ocean State Estimate (COSE). The region covered by COSE is shown in Figure 1. While various global ocean state estimates now exist (*e.g.*, SODA, Carton & Giese, 2008; ECCO Forget *et al.*, 2015; GODAS Behringer 1998; HYCOM, Chassignet *et al.*, 2006), their resolution is, in most cases too coarse to represent coastal zone processes well. And although new eddy resolving reanalysis products are available (*e.g.*, HYCOM, the Operational Mercator Global Ocean Analysis and Forecast system (Lellouche & Regnier, 2016) the global focus necessarily rests developers' attention from regional details. For example, the 1/12º resolution HYCOM reanalysis uniquely provides a 20 year record that resolves well the upwelling and instability processes that dominate mesoscale variability in central Chile, but suffers from an occasional spurious surface intensified onshore flow at 30ºS resulting from a numerical artifact of the atmospheric model used to provide the wind field (Alan Wallcraft, *pers. comm.*) (Fig. 2). Such a localized error may be acceptable at the global scale of HYCOM, but obviously it may compromise the utility of the HYCOM reanalysis for applications in central Chile. The COSE regional reanalysis presented here was intended to correct such limitations of global reanalyses, providing a state estimate that improves the representation of the coastal zone, but with the aim of nesting smoothly within the global HYCOM reanalysis.

Estimating the state of a system by combining observations and models, commonly referred to as data assimilation (Wunch, 2006), is an example of a control problem - how should the control variables of the model (*i.e.*, surface fluxes, boundary and initial conditions) be set so that the trajectory of the model passes within the

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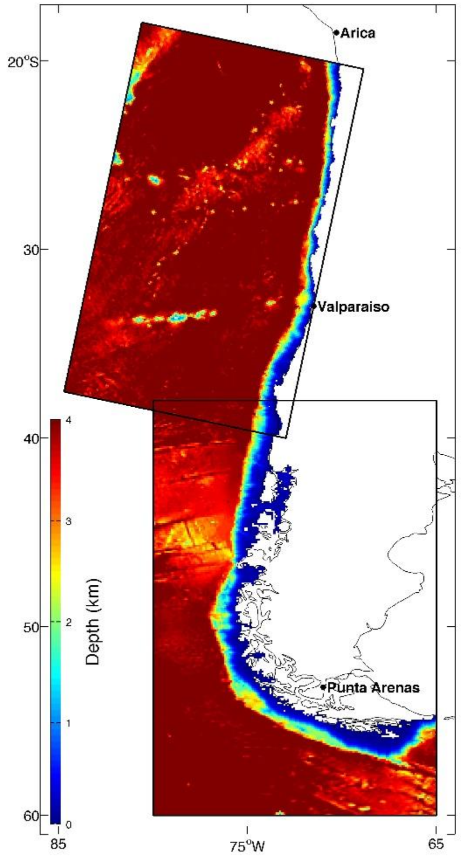

Figure 1. The two domains comprising the Chilean Ocean State Estimate (COSE). This study presents results from the northern domain only.

confidence intervals of the observations? Solving the problem amounts to minimizing a quadratic cost function that penalizes the model-observation misfit and departures from the prior estimate of the system variables, subject to the constraint that the solution must remain physically consistent. In COSE, the observations used are satellite ocean surface temperature and height; prior estimates of the system state are taken form the HYCOM reanalysis; and the Rutgers version of the Regional Ocean Modelling System (ROMS; Shchepetkin & McWilliams, 2005) imposes physical correctness of the solution. Besides being widely used for coastal ocean simulations, the existence of tangent linear and adjoint versions of ROMS permits implementation of the computationally efficient “Lagrange multiplier" or “4DVAR" method (Wunsch, 2006). Unlike common data assimilation schemes such as Optimal Interpolation or 3DVAR, the 4DVAR scheme retains the desirable quality of allowing error statistics to evolve, as in the optimal full Kalman filter, without the need to update error covariance matrices. (In COSE the error covariance’s are estimated from the variance in the HYCOM reanalysis). This efficiency means that 4DVAR can allow tractable near optimal data assimilation in the full space of the model. The Ensemble Kalman Filter (EnKF) shares similar properties (Lorenc, 2003). In the ROMS implementation of 4DVAR (Moore *et al.*, 2004, 2011), nonlinearity of the underlying physics is dealt with by incrementally minimizing a linearized cost function via the Kalman gain. 4DVAR ROMS remains computationally demanding, even for moderately sized problems. Each 3 day analysis window of COSE took approximately 2.5 h walltime to run on eight threads of a 2.3 GHz Intel i7.

The ROMS configuration used in COSE is typical of those employed in other eastern boundary current systems. For computational efficiency the region is divided into two domains (Fig. 1). Here results from the northern domain only are presented. Both domains employ a horizontal resolution of 1/12° and 30 vertical levels. Surface heat and momentum fluxes are determined through the ROMS “bulk flux” option, fed by NCEP heat flux (Kalnay *et al.*, 1996) and CCMP winds (Atlas *et al.,* 2011). NCEP reanalysis data were obtained from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. At the open boundaries standard Flather and Chapman conditions are respectively applied to barotropic velocity and surface elevation, while the baroclinic velocity component is clamped to the corresponding values from the HYCOM reanalysis. The time step for the baroclinic mode was 15 min.

Boundary conditions are typically troublesome in regional ocean models due to the unavoidable mismatch between the calculated internal and imposed external fields. Such boundary artifacts can influence the internal solution and are undesirable here as we wish the COSE circulation to merge smoothly into the HYCOM reanalysis. This problem is dealt with to some extent through the inclusion of a 10 grid cell wide sponge layer on each open boundary, in which the eddy viscosity is raised linearly towards the open boundaries. In addition, by including boundary values in the control vector, and hence allowing them to be adjusted *a posteriori*, the assimilation should also tend to suppress boundary artifacts. To aid in this, velocities within the sponge layer were constrained with the HYCOM reanalysis. In effect this forces the assimilation to attempt to match the COSE and HYCOM solutions close to the open boundaries. An example of the reduction of rim currents in COSE is shown in Figure 3. This method is conceptually similar to direct nudging, but with the great advantage of preserving the physical consistency of the solution.

The observational products used to constrain the state estimate are daily 1/12° sea surface temperature

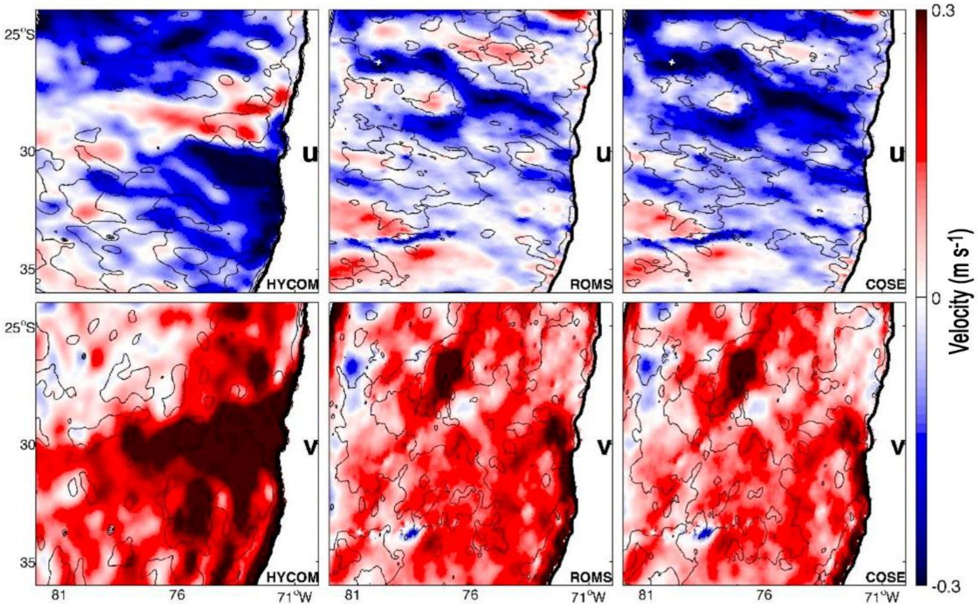

Figure 2. Correction of the spurious velocity structure found at 30°S in the HYCOM reanalysis in unconstrained ROMS and COSE. The panels show the mean for the year 2008 in eastwards (u, upper row) and northwards (v, lower row) surface velocity. Contours of the standard deviation in each velocity component are overlaid.

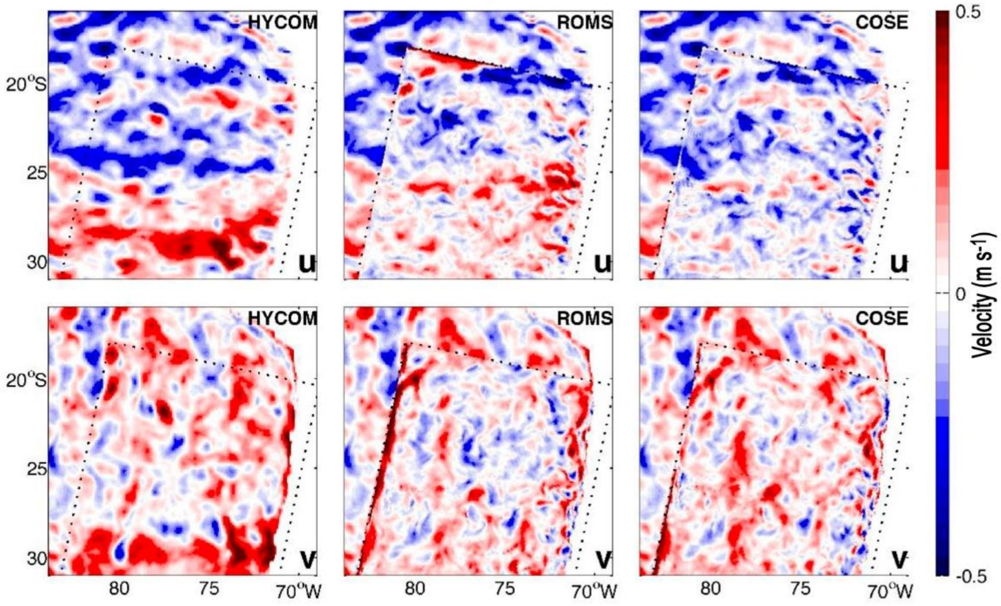

Figure 3. An example of the partial suppression of boundary artifacts by the assimilation. The surface northwards (v) and eastwards (u) velocity from the unconstrained ROMS prior estimate (central column) and COSE (right column) is superimposed upon the HYCOM reanalysis (left column) that contributes the boundary conditions in each case.

(SST) from GHRSST (Merchant *et al.*, 2014) and 5-daily absolute sea surface height (SSH) mapped to a 1/4º grid from AVISO (http://www.aviso.altimetry.fr/). Additional sources of observations such as hydrographic casts are being assimilated in an updated reanalysis that is presently in development.

The assimilation significantly reduces the mismatch to the observations, relative to both the unconstrained ROMS simulation and the HYCOM reanalyzes (Fig. 4). The median RMS errors in the COSE reanalysis for the year 2008 are 0.33 and 0.36 for SST and SSH, respectively, compared to 0.56 and 0.48 for the HYCOM reanalysis, and to 0.49 and 0.48 for the unconstrained ROMS simulation. It may be appreciated in figure 4 that some examples exist, predominantly during summer, where both COSE and ROMS perform

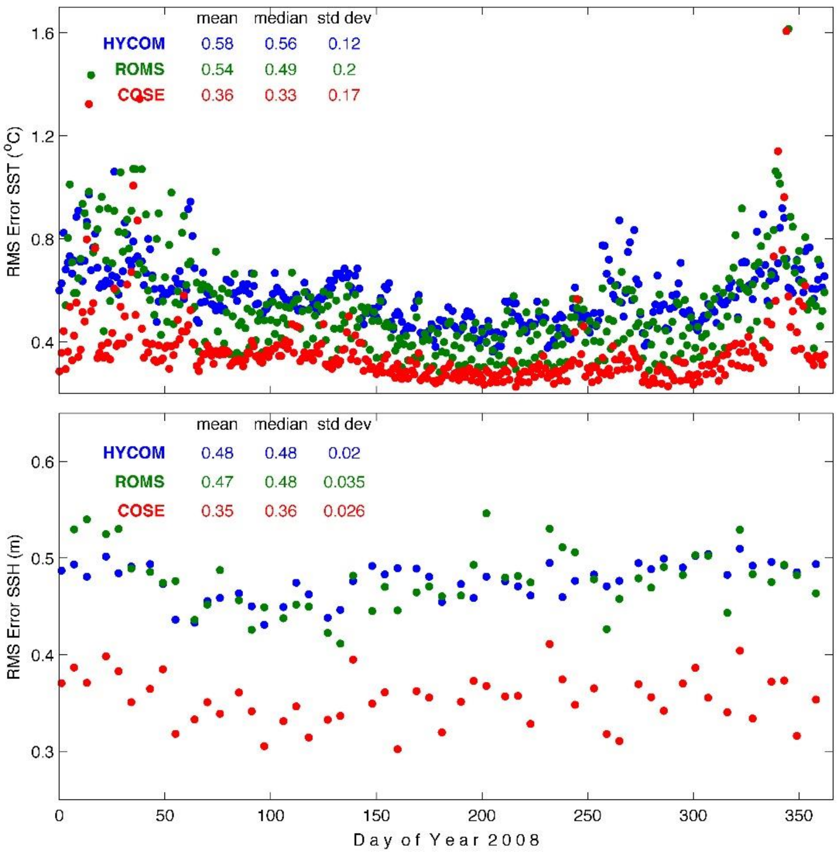

Figure 4. RMS error in surface temperature (above) and sea surface elevation (below) of the HYCOM reanalysis (blue), the ROMS prior estimate (green) and COSE (red) for the year 2008. The mean, median and standard deviations are given in the upper right of each panel.

worse than HYCOM. These cases correspond to the development of boundary artifacts towards the end of some assimilation cycles. As a result, the standard deviation in the hindcast error is substantially lower The errors do not overly influence the internal solution, but nonetheless it is hoped that the second generation reanalysis will reduce such errors.

It may be appreciated that COSE completely removes the spurious a geostrophic current present in HYCOM at 30°S (Fig. 2). However, the artificial current is also absent from the unconstrained ROMS simulation, consistent with the origin being the Gibbs phenomenon in the wind product used in HYCOM, and hence is not due to the assimilation. The added value of the assimilation is that it provide a solution that is consistent with the observations and reduces inconsistencies at the open boundaries.

Because only surface observations were assimilated, vertical structure differs little between COSE and unconstrained ROMS. Both, however, differ significantly from HYCOM. A cross-shore transect at 26°S (Fig. 5) illustrates that COSE and unconstrained ROMS sustain a more intense and coastal Poleward Undercurrent (PUC) and a deeper mixed layer than HYCOM. Figure 6 displays the mean correction made by COSE to the unconstrained ROMS solution in the surface velocity and temperature. The effect of the assimilation of SST and SSH observations can be seen to, in general, reduce the off-shore temperature gradient associated with coastal upwelling and weaken the mean northwards and off-shore surface flow. This suggests that the unconstrained ROMS model overestimates the intensity of the coastal upwelling circulation. The inadequately resolved wind field near to shore of satellite wind products such as CCMP, is likely to be the cause of this persistent error in the unconstrained ROMS simulation (Capet *et al*., 2004). Given the essential similarity of the majority of ROMS simulations of the south east Pacific ROMS, the overestimation of coastal upwelling may be a systematic deficiency in these simulations. Most variance in the corrections to velocity occur close to the open boundaries, owing to assimilation's attempts to constrain boundary currents. The entire COSE for both domains and the period 1993-2012 will be available for use by all interested users.

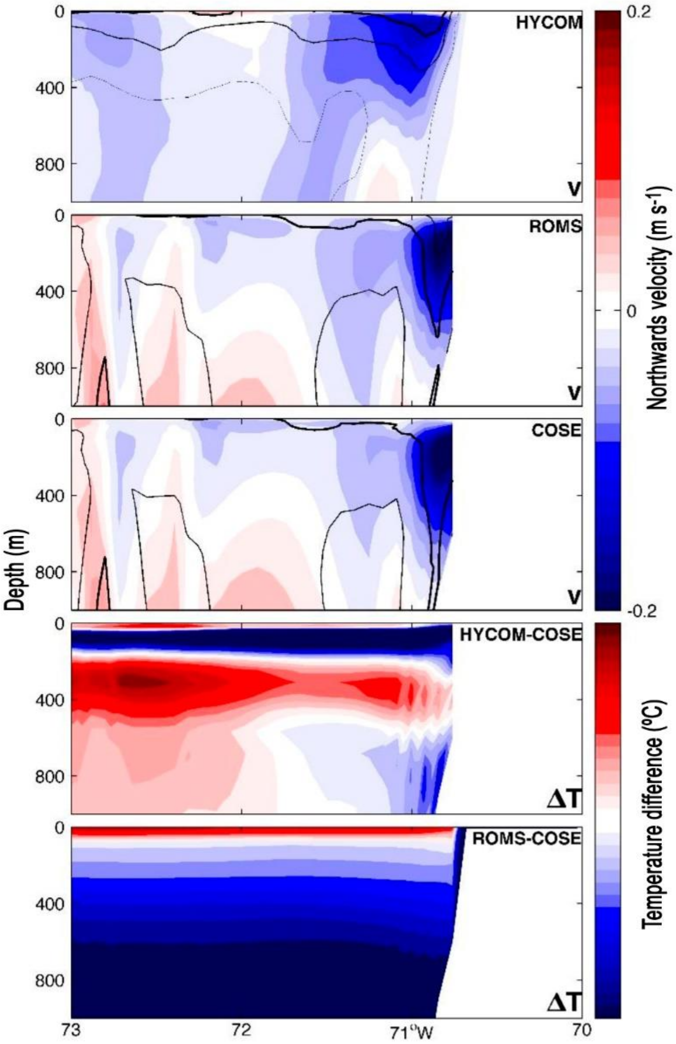

Figure 5. Cross-shore transects at 26°S of, from top to bottom, northwards velocity in HYCOM, in unconstrained ROMS and in COSE, and of the temperature difference to COSE of HYCOM and of ROMS.

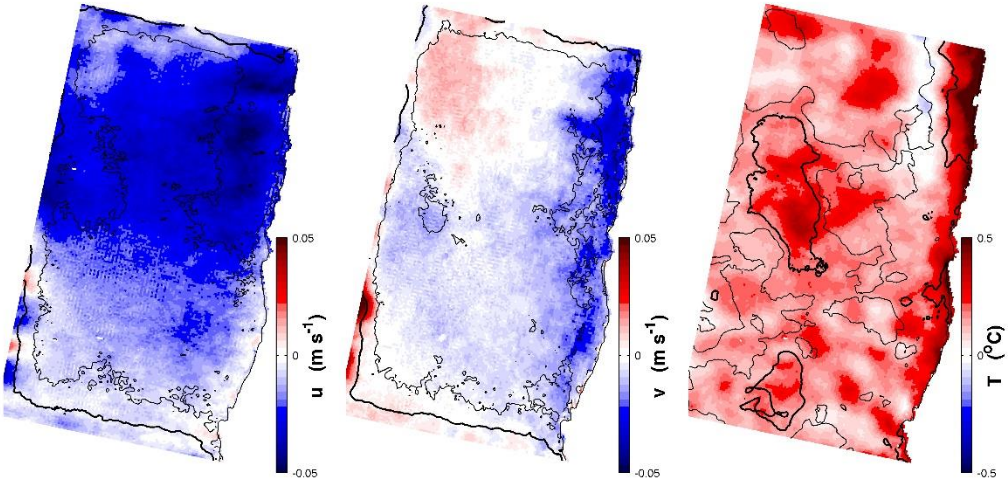

Figure 6. Mean (shaded) and standard deviation (contours) of the correction to the unconstrained ROMS solution for surface velocity and temperature in COSE.

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