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Short communication

Prediction of currents and sea surface elevation in the Gulf of California from tidal to seasonal scales☆

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ABSTRACT

A web tool that provides currents and/or sea surface elevation in the Gulf of California is presented. The above variables are reconstructed from harmonic constants obtained from harmonic analyses of time series produced by a 3D baroclinic numerical model of the Gulf. The numerical model was forced (1) at the Gulf's mouth by the tides and the hydrographic variability of the Pacific Ocean (at semiannual and annual frequencies), and (2) at the Gulf's surface by winds, heat and fresh water fluxes (also at the semiannual and annual frequencies). The response to these forcings results in motions with time scales limited to semidiurnal and diurnal, fortnightly and monthly (due to nonlinear interactions of the tidal components), and semiannual and annual frequencies (due to the nontidal forcing).

1. Introduction

The objective of this article is to present a web page developed to visualize predictions of currents and/or sea level based on results obtained from a numerical model of the Gulf of California (GC hereafter) located in the northwest of Mexico. Prediction must be understood as the calculation of currents and sea surface elevation from a given initial time – not present time necessarily – to a selected final time. In this sense "prediction" means also "hindcast" in this work.

The variability and evolution of sea level and ocean currents are a very important research topic in oceanography as to the moment we still don't know in detail how they evolve, as the different forcings, shape of the basins, nonlinear interactions, etc. all are complicated. However, at some particular scales, our capacities to reproduce and predict the sea level and currents have increased considerably. This is due to both the availability of observations (sea level time series, seasonal climatologies) and to the improvements of numerical models. In particular, tides and tidal currents can be predicted very accurately, given their specific frequencies.

There are many Internet sites devoted to tidal prediction for scientific, navigational or recreational purposes, most of them are limited to the prediction of the sea surface elevation and tidal currents based on the knowledge of the harmonic constants in specific points along the coast (see for example: http://easytide.ukho.gov.uk/EasyTide/EasyTide/index.aspx, http://www.shom.fr/ann_marees/cgi-bin/predit_ext/choixp, and http://tbone.biol.sc.edu/tide/sites_allcurrent.html). Prediction of tidal elevation and associated currents along the coastline and to the interior of a specific basin where there are no observations require the implementation of numerical models; to our knowledge there are no free access pages on the Internet with this kind of information for any place. The same situation is true in the GC, at the moment there is not a product which gives an idea of the currents at any selected place and time. The actual knowledge of the Gulf's circulation is still at basic research level by means of some measurements and numerical models. In the GC, as in any many places, there is a pressure to know the currents for both, scientific and practical reasons. Fisheries studies require information of the currents to explain some aspects of the distribution of larvae, eggs, etc. The same is true for pollution problems. Here we explain how to use a web page to obtain sea level and currents predictions at any time and location in the GC from the results of a numerical model. The users would have the option to obtain sea level and currents within time scales ranging from semidiurnal and diurnal bands, those resulting from their nonlinear interactions (fortnightly and monthly bands) and the seasonal produced by the imposed atmospheric and hydrographic forcings.

The rest of the paper is organized as follows: Section 2 presents the model from which time series of sea level and currents were

☆ Software availability: http://gulfcal.cicese.mx

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obtained and the analysis done to make the predictions, Section 3 gives some model validations, and Section 4 explains how to use the web page. Section 5 presents the conclusions.

A warning: the current predictions are exclusively qualitatively and the accuracy is not precisely known. Therefore, they should not be used for navigation or as an authoritative piece of information for making decisions. We welcome your evaluations, opinions and suggestions. Please send comments, questions or request for more detailed results to marinone@cicese.mx, ignaci@cicese.mx or figuer@cicese.mx.

2. Analysis and model

The numerical model used in this study is the layerwise vertically integrated Hamburg Shelf Ocean Model (HAMSOM) developed by Backhaus (1983, 1985) and adapted to the GC by Marinone (2003). The model is forced by the tides, the Pacific Ocean, the winds, and the heat and fresh water fluxes. The model equations are a set of vertically averaged equations for each layer. For momentum,

$$\partial u/\partial t = -h^{-1}\nabla_H(\underline{v}uh) - uH^{-1}\Delta(w) - fv - \rho_0^{-1}\partial P/\partial x + H^{-1}\Delta(\tau_x) + \nu\nabla_H^2 u,$$

$$\partial v/\partial t = -h^{-1}\nabla_H(\underline{v}vh) - vH^{-1}\Delta(w) + fu - \rho_0^{-1}\partial P/\partial y + H^{-1}\Delta(\tau_y) + \nu\nabla_H^2 v,$$

for continuity,

$$w_{zd} = \partial(uH)/\partial x + \partial(vH)/\partial y + w_{zu},$$

for temperature and salinity,

$$\partial(T,S)/\partial t = -\nabla_H[\underline{v}(T,S)] - h^{-1}\Delta[(T,S)w] + K_h\nabla_H^2(T,S) + \partial(T,S)/\partial z K_v,$$

the hydrostatic equation is,

$$\partial P/\partial z = -\rho g,$$

and the overall continuity equation is,

$$\partial\eta/\partial t = -\nabla(\underline{V})$$

In these equations, $\underline{v} = (u,v)$ is the horizontal velocity, w is the vertical velocity, $\underline{V} = (U,V)$ is the transport for each layer, f is the Coriolis parameter, $\rho = \rho(S,T,P)$ is the density field, (S, T, P) are salinity, temperature and pressure, g is the gravity's acceleration, $P = (\eta - z)\rho_0 g + p(x,y,t)$ is the total pressure, p is the baroclinic pressure, ρ_0 is the reference density, h is the layer thickness which is equal to H (the nominal thickness), except in the first and last layers where it accommodates the surface elevation, η, and the topography, respectively. (x,y,z) are the northward, eastward and upward coordinates. The operator $\Delta(\ldots)$ is the difference of $(\ldots)$ taken between the upper (zu) and lower (zd) surfaces of the layer, $\nabla = (\nabla_H \partial/\partial z,)$, and $\nabla_H = (\partial/\partial x, \partial/\partial y)$.

The vertical stresses are $\underline{\tau} = A_v(\partial\underline{v}/\partial z)$ where A_v is the vertical eddy coefficient, defined as (Kochergin, 1987)

$$A_v = \alpha|\partial\underline{v}/\partial z|/(1 + \beta\mathrm{Ri}),$$

where Ri is the Richardson number, $\alpha = 10\ \mathrm{m}^2$ and $\beta = 10$. The surface and bottom stress boundary conditions are

$$\underline{\tau}_s = C_{da}\underline{V}_w\left(U_w^2 + V_w^2\right)^{1/2} \quad \text{and} \quad \underline{\tau}_b = C_{db}\underline{v}\left(u^2 + v^2\right)^{1/2},$$

respectively, where $\underline{V}_w = (U_w, V_w)$ is the wind velocity, C_{da} and C_{db} are drag coefficients for the air/water interface and for the sea bottom, respectively. The values used for C_{da} and C_{db} were 0.002 and 0.004, respectively. Finally, K_h and K_v are the horizontal and vertical eddy diffusion coefficient for scalar quantities, which in the model are equal to ν and A_v, the horizontal and vertical eddy viscosities. ν is constant ($100\ \mathrm{m}^2\,\mathrm{s}^{-1}$) and its selection obeys to numerical stability only, sea level and currents do not change significatively with variations of ν. On the other hand, A_v varies from 0 to $\sim 0.3\ \mathrm{m}^2\,\mathrm{s}^{-1}$ with temporal and spatial average of $0.013\ \mathrm{m}^2\,\mathrm{s}^{-1}$.

The model domain has a mesh size of 2.5' × 2.5' (3.9 km × 4.6 km). The number of layers depends on the local depth, but 12 nominal layers are used in the vertical, with lower levels at 10, 20, 30, 60, 100, 150, 200, 250, 350, 600, 1000 y 4000 m.

The tidal forcing includes the seven most important semidiurnal and diurnal tidal constituents, namely M2, S2, N2, K2, K1, O1, and P1, plus the semiannual (Ssa) and annual (Sa) components. The harmonic constants were estimated from several years of observations in Mazatlán, in the mainland side of the Gulf entrance, and in Cabo San Lucas, at the tip of the Baja California península. From these points, the sea surface elevation was obtained at each time step and then interpolated along the open boundary. It is also forced with climatological hydrography at the Gulf's mouth, and climatological heat and fresh water fluxes at the air–sea interface. The temperature and salinity fields were obtained from data of 41 cruises during the period of 1939–1995. From these data, the fields were interpolated at each grid point along the open boundary. Then the data were least square fitted to the annual and semiannual harmonics. Similarly, the meteorological parameters to calculate the heat and fresh water fluxes were fitted to semiannual and annual functions from seven meteorological stations around the Gulf and then interpolated to the rest of the model domain (Marinone, 2003). For wind forcing a simple up- and down-Gulf annual sinusoid was used; the source of this seasonal wind is justified following Ripa (1997). Comparison of the results with this spatially homogeneous wind and a data set derived from QuickScat (fitted to semiannual and annual functions) produced basically the same results in the time scales limited to those of this study (Jiménez et al., 2005).

The model becomes periodically stable after 3 years and the results of this study were obtained from the fourth and fifth year of the model run. The time series of surface elevation and currents were subjected to harmonic analysis, to obtain amplitude and phase values for 14 harmonics (listed in Table 1). [Note that the variability at the annual and semiannual harmonics results from the forcing of the tides at these scales (Ssa and Sa components), the seasonal variation of the (T,S) fields at the open boundary, and the seasonal variation of the atmospheric forcing. For this reason they are labeled Semiannual and Annual in Table 1.] This is done for

Table 1
Constituents used for harmonic analysis

Name	Frequency ω (cycles/hour)	Period (days)
M2	0.0805114	0.52
S2	0.0833333	0.50
K1	0.0417807	1.00
O1	0.0387306	1.08
N2	0.0789992	0.53
P1	0.0415526	1.00
K2	0.0835615	0.50
N2S2	0.0043341	9.61
Mf	0.0030500	13.66
Msf	0.0028219	14.77
Mm-	0.0015122	27.55
Msm	0.0013099	31.81
Semiannual	0.0002281	182.67
Annual	0.0001141	365.18

every grid point of the model. For the predictions in the web page, the currents and sea level are reconstructed as

$$\varphi = \Sigma_i A_i \cos(\omega_i t - \phi_i),$$

ϕ being the sea surface elevation, the eastward or the northward velocity components. For each variable, (A_i,φ_i) are the amplitude and phase of the ith constituent, of frequency ω_i. The explained variance with these constituents resulted in more than 95% and up to 99% of the model currents and sea level, respectively.

3. Model validation

The tidal currents, both barotropic and baroclinic, produced by the model have been compared against observations by Marinone and Lavín (2005), who find good overall agreement for the different tidal constituents: the best agreement is for the semidiurnal components, while the diurnal components are a little underestimated. Briefly, they compared the harmonics from 124 time series (of different length) in 62 stations with those of the model at the same grid point. Both, data and model show large spatial variability. Comparisons of the means of the major and minor axis of the current tidal ellipses obtained by the model and the data for the whole Gulf, and by areas (northern, central, southern Gulf) by means of the Wilcoxon test of means gave in most cases that the means are equal. The sea level, on the other hand, is predicted with a high degree of accuracy (see web page for examples of comparison with observations).

On seasonal scales, the gyres in the northern region of the Gulf observed by Lavín et al. (1997), and the overall heat balance are also

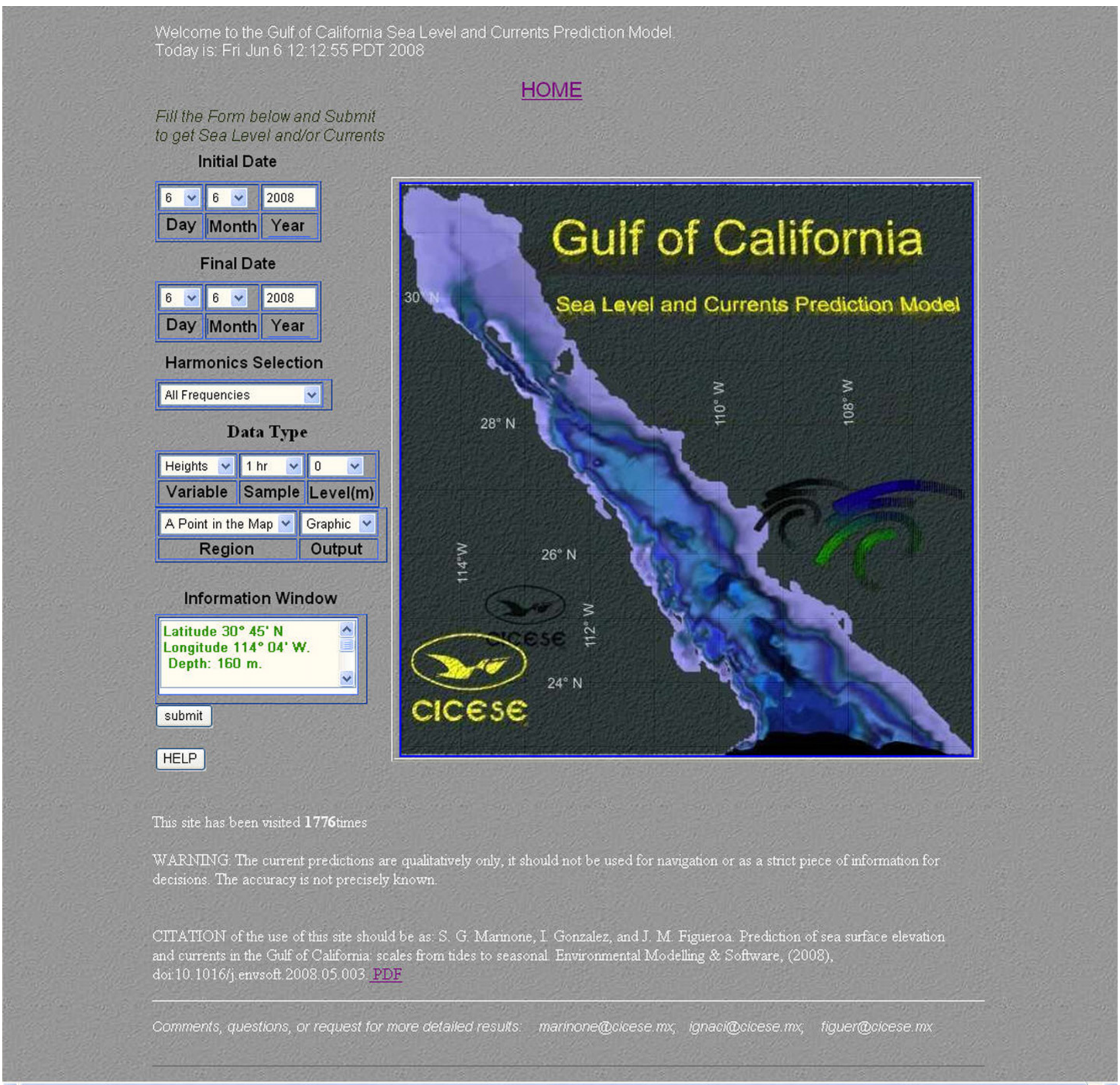

Fig. 1. The Interactive Interface (http://gulfcal.cicese.mx/map.php) showing the filling editable windows for the different options and the interactive map.

reasonably well reproduced, as reported by Marinone (2003). Actual work to improve the model performance has been initiated with a finer bathymetry (we have some initial trials with a 1/3 of the resolution used for this work), the use of QuickScat data for winds in real time, and the use of (T,S) fields at the open boundary from a general circulation model of the Pacific.

Instead of showing comparisons with observations here, a link in the "Main" web page to figures comparing observations with the predictions of the site is available. In general the agreement among model and observations is acceptable, and we feel that the predictions do provide a qualitative idea of how the currents are in a given time and place inside the Gulf.

4. The web site

The web site can provide predictions of the sea level, the currents or both. For clarity purposes of the web site output, only one of every four data points are shown; this also speeds up the calculations and the transmission of the files. The web site is hosted in an Apache V2.055 server running on Pentium D with Windows XP operative system. For the development of the site we used Matlab V7.01, Matlab Compiler V 4.1, Visual C++ V7.0, PHP 5, javascript V1.5, and HTML code. The site is intended to work with the most common web servers: it was developed in Internet Explorer V6.0 and tested in Netscape V8.0, Mozilla V5.0 and Opera V8.54.

The "Main" page (http://gulfcal.cicese.mx/) welcomes the user and offers five options: (1) "The interactive interface" (http://gulfcal.cicese.mx/map.php) which sends the user to the filling-form page where the selections are made (Fig. 1), (2) "Help" a document where definitions and limitations are explained, (3) "The Document" which links to this article, (4) "Comparison between model and observations" where some figures comparing observations and model predictions are included, and (5) "Links" which sends the user to other related WebPages, including one where articles related to the model in the GC are available.

4.1. The interactive interface

This is the working/predictive part of the page (Fig. 1) where the user selects:

- Initial and Final dates of the prediction.
- The group of harmonics to include in making the prediction (semidiurnal, diurnal, semidiurnal and diurnal, seasonal, and all of them). Note that the selection "seasonal" would produce the general circulation.
- The variables: surface elevation, currents or both. Here the user also chooses the sampling rate (from minutes to months) and the depth for the currents.
- The type of output: the user selects one of "A Point in the Map", "North Gulf", "Central Gulf", "South Gulf" or "Full Gulf". When "A point in the map" is selected, the user must click with the "mouse" the desired location. Different options for the output are selected (data or graphics), depending on the case. For a "A Point in the Map" the user can retrieve data or a time series plot. When areas are chosen the user has different options: if surface elevation is selected the animation is in a two- or three-dimensional projection, "Graphic" or "3D View", respectively. If currents or both are selected the animation is only in "Graphic" mode. When movies are obtained, a window pops-up showing its last frame, and the user must "click" on it in order to start the animation or to retrieve the file to its personal computer. This part depends completely on the user system, sometimes a double click animates the movie, in other cases the file is transferred and opened with the user's default movie program.

Below these options there is an "Information Window" summarizing the selections or alerting the user that some rules have been violated. Below it, there is a link to a help document where some "Rules" are explained. Once the decisions are made, the user "submits" the information to the server and waits for the output.

5. Conclusion

A web interface that predicts sea surface elevations and/or currents for the GC was developed using the output of a three-dimensional baroclinic model which was forced at the open boundary by the tides and seasonal temperature and salinity fields and at the sea surface with seasonal winds, heat and fresh water fluxes. With the model's output, harmonic analyses were performed and the prediction is made with the harmonic constants obtained. The results of these predictions should be taken with care, even though the model has been shown to work well in a qualitative sense, the results of these predictions should be taken with caution and should not be taken as a substitute for observations or more realistic modeling. However, with this caveat, the predictions provided by the web site should provide the user an useful idea of what the surface elevation and currents will be (or were) in a given area and time.

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