Available online at www.sciencedirect.com

ScienceDirect

Continental Shelf Research 27 (2007) 1303–1316

CONTINENTAL SHELF
RESEARCH

www.elsevier.com/locate/csr

# Suppressing bias and drift of coastal circulation models through the assimilation of seasonal climatologies of temperature and salinity

Keith R. Thompson*, Kyoko Ohashi, Jinyu Sheng, Josko Bobanovic, Jie Ou

*Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada*

Received 22 March 2006; received in revised form 25 October 2006; accepted 30 October 2006
Available online 20 February 2007

## Abstract

Recently Thompson et al. (2006. A simple method for reducing seasonal bias and drift in eddy resolving ocean models. Ocean Modelling 13, 109–125.) proposed a new method for suppressing the bias and drift of ocean circulation models. The basic idea is to nudge the model toward gridded climatologies of observed temperature and salinity in prescribed frequency–wavenumber bands; outside of these bands the model's dynamics are not directly affected by the nudging and the model state can evolve prognostically. Given the restriction of the nudging to certain frequency–wavenumber bands, the method is termed spectral nudging. The frequency–wavenumber bands are chosen to capture the information in the climatology and thus are centered on the climatological frequencies of zero, one cycle per year and its harmonics, and also low wavenumbers (reflecting the smooth nature of gridded climatologies). The new method is applied in this study to a fully nonlinear, 3D baroclinic circulation model of the continental shelves and inland seas of Atlantic Canada and the northeast US. It is shown that the scheme can suppress drift and bias in a nine month integration (February–October, 2002) while still allowing realistic evolution of tides, surges and wind and tide-driven coastal upwelling. It is also shown that density stratification can affect significantly tidal elevations in some regions. The implications for ocean hindcasting and short-term forecasting are discussed.

*Keywords:* Physical oceanography; Coastal circulation; Numerical models; Data assimilation; Tides; Northwest Atlantic

## 1. Introduction

Bias and drift of water temperature and salinity are common problems in coastal models (e.g. Chu et al., 1999; Ezer and Mellor, 2000; Kurapov et al., 2005; Oey et al., 2005). They can cause the realism of a model's time-averaged state to fade with time and this can negatively impact the model's usefulness in terms of both short-term forecasting and multi-year hindcasting.

Many factors can contribute to bias and drift including inadequate model resolution, poor parameterizations of subgrid scale processes, and inaccurate surface and lateral boundary conditions. Recently, Thompson et al. (2006) proposed a simple, statistically-based method for suppressing the bias and drift of basin-scale ocean circulation

---

*Corresponding author.
*E-mail address:* keith.thompson@dal.ca (K.R. Thompson).

0278-4343/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2006.10.011

models and illustrated the technique using an eddy permitting model of the North Atlantic forced with realistic surface fluxes for the period 1991–2002. The objective of the present study is to show that the new method can also be used to carry out hindcasts, and also short-term forecasts of physical conditions on continental shelves.

The method is based on the simple idea of nudging the model toward seasonal climatologies of ocean observations in specified frequency and wavenumber bands; outside of these bands the model is unconstrained. To describe the method, and relate it to other approaches, we follow Thompson et al. (2006) and let $x_{t+1} = f_t(x_t, w_t)$ represent a nonlinear dynamic model that describes how the discretized ocean state vector, $x_t$, is advanced forward one time-step. In this study, $f_t$ defines a single time-step of the Princeton Ocean Model (Mellor, 2004). Uncertainty in the forecast is reflected by the inclusion of the model error vector $w_t$. The relationship between $x_t$ and the contemporaneous vector of observations, $y_t$, is modelled by $y_t = h_t(x_t, v_t)$ where $h_t$ is the observation operator and $v_t$ defines the observation error (e.g. Daley, 1994). If all errors are mutually independent, and $Y_t$ denotes all available observations up to and including time $t$, then routine application of Bayes' Rule allows the probability distribution of $x_t$ given $Y_t$ to be updated sequentially using $p(x_t|Y_t) \propto p(y_t|x_t) \int p(x_t|x_{t-1}) p(x_{t-1}|Y_{t-1})\, \mathrm{d}x_{t-1}$ (e.g. Jazwinski, 1970). This conditional density contains all information on $x_t$ given $Y_t$; quantities like the conditional mean of $x_t$, its variance and higher order moments can all be obtained from this density.

Unfortunately this updating equation can only be solved by direct integration for low dimensional problems (e.g. Kitagawa, 1998) and so approximate schemes must be developed for use with high-dimensional ocean models. If $f_t$ and $h_t$ are linear operators, and $w_t$ and $v_t$ are normally distributed with zero mean, the linear Kalman filter (e.g. Jazwinski, 1970) provides an elegant way of sequentially updating the conditional mean and variance of $x_t$ given $Y_t$. For nonlinear problems the situation is less clear-cut and a number of sub-optimal schemes have been proposed including the extended Kalman filter, the singular evolutive Kalman filter (Pham et al., 1998) and the ensemble Kalman filter (Evensen, 1994).

All forms of Kalman filter correspond to "nudging" the ocean state toward the observations using an equation of the form $x_t = x_t^f + K_t(y_t - h_t(x_t^f))$ where $x_t^f$ is the one-step-ahead-forecast, and $K_t$ contains the nudging coefficients organized in the Kalman gain matrix. The differences amongst the various filters affect only the calculation of $K_t$. A simplified approach is to prescribe $K_t$. If $K_t$ is diagonal then the nudging takes the conventional form $\gamma(y_t - x_t^f)$ at observation points where $\gamma^{-1}$ corresponds to a relaxation time in model time-steps. Sarmiento and Bryan (1982) used this form of nudging to assimilate observations of temperature and salinity into a realistic ocean model. Their technique has proved very useful over the years and is usually referred to as the robust diagnostic method. If $\gamma = 1$ the nudged ocean state is replaced by observed values, a procedure known as direct insertion. The main advantage of these simplified forms of nudging is that they are easy to implement, and can keep the model arbitrarily close to the observations. Unfortunately, they suppress variability and distort the dynamical response of the model (e.g. Thompson et al. (2006) and references therein).

Thompson et al. (2006) outline a straightforward way of ensuring a model's climatology does not stray too far from an observed climatology, thereby suppressing bias and drift. The basic idea is to nudge the model in frequency and wavenumber bands that cover only the frequencies and wavenumbers resolved by the climatology. For this reason Thompson et al. (2006) called the technique "spectral nudging", in accord with a method developed earlier by Von Storch et al. (2000) to downscale large-scale atmospheric states using high resolution regional atmospheric models. Outside of these frequency–wavenumber bands the nudging is effectively zero and the model can evolve prognostically, regardless of the strength of the nudging (i.e. $\gamma$). This contrasts sharply to more conventional nudging schemes which suppress variability more strongly as $\gamma$ increases. In the next section, we use a highly idealized model to illustrate some of the methods used in coastal modelling to suppress drift and bias, including conventional nudging and diffusion toward climatology (e.g. Ezer and Mellor, 2000), and compare their performance to that of spectral nudging.

Recently, Sheng et al. (2001) proposed the "semi-prognostic" method as a way of eliminating systematic errors in ocean models. The method involves correcting the pressure gradient term in the model's horizontal momentum equations by an