Ocean Modelling 106 (2016) 74–89

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod

Virtual Special Issue
Coastal ocean modelling

Description of surface transport in the region of the Belizean Barrier Reef based on observations and alternative high-resolution models

D. Lindo-Atichati[a,b,c,*], M. Curcic[d], C.B. Paris[d], P.M. Buston[e]

[a] City University of New York, College of Staten Island, Department of Engineering Science and Physics, Staten Island, NY 10314, USA
[b] Graduate Center of the City University of New York, Doctoral Program in Earth and Environmental Sciences, New York, NY 10016, USA
[c] Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA USA
[d] University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, FL 33149, USA
[e] Boston University, Department of Biology and Marine Program, Boston, MA 02215, USA

ARTICLE INFO

Article history:
Received 5 June 2015
Revised 16 September 2016
Accepted 17 September 2016
Available online 20 September 2016

Keywords:
Ocean–atmosphere model
Lagrangian drifters
High-resolution
Coral reefs
Belize

ABSTRACT

The gains from implementing high-resolution versus less costly low-resolution models to describe coastal circulation are not always clear, often lacking statistical evaluation. Here we construct a hierarchy of ocean–atmosphere models operating at multiple scales within a $1 \times 1°$ domain of the Belizean Barrier Reef (BBR). The various components of the atmosphere–ocean models are evaluated with in situ observations of surface drifters, wind and sea surface temperature. First, we compare the dispersion and velocity of 55 surface drifters released in the field in summer 2013 to the dispersion and velocity of simulated drifters under alternative model configurations. Increasing the resolution of the ocean model (from 1/12° to 1/100°, from 1 day to 1 h) and atmosphere model forcing (from 1/2° to 1/100°, from 6 h to 1 h), and incorporating tidal forcing incrementally reduces discrepancy between simulated and observed velocities and dispersion. Next, in trying to understand why the high-resolution models improve prediction, we find that resolving both the diurnal sea-breeze and semi-diurnal tides is key to improving the Lagrangian statistics and transport predictions along the BBR. Notably, the model with the highest ocean–atmosphere resolution and with tidal forcing generates a higher number of looping trajectories and sub-mesoscale coherent structures that are otherwise unresolved. Finally, simulations conducted with this model from June to August of 2013 show an intensification of the velocity fields throughout the summer and reveal a mesoscale anticyclonic circulation around Glovers Reef, and sub-mesoscale cyclonic eddies formed in the vicinity of Columbus Island. This study provides a general framework to assess the best surface transport prediction from alternative ocean–atmosphere models using metrics derived from high frequency drifters' data and meteorological stations.

1. Introduction

The coastal ocean is receiving significant attention due to an increasing exploitation of its resources worldwide (Pauly et al., 2013). Knowledge of the coastal circulation is useful for many applications, from assessment of pollution risk to management of nearshore fisheries. For example, transport in the coastal ocean drives the exchange of larval fish among populations and influences the population dynamics and genetic structure of marine species (Paris et al., 2007; D'Aloia et al., 2013; D'Aloia et al., 2014). Consequently, it is important to predict patterns of dispersal and population connectivity to manage fisheries and design effective networks of reserves (Sala et al., 2002; Fogarty and Botsford, 2007; Almany et al., 2009). Although management strategies might benefit from considering coastal circulation, observations of currents and coastal circulation models are scarce for most reef ecosystems.

Development of ocean circulation models has proceeded rapidly over the last 25 years. Progress has been made in three key areas. First, the number and spatial extent of models has increased: models now predict transport at coastal, basin, and global scales (Hurlburt and Hogan, 2000). Second, the horizontal resolution of models has increased: models with fine resolutions are now able

---

[*] Corresponding author at: City University of New York, College of Staten Island, Department of Engineering Science and Physics, Staten Island, NY 10314, USA.
E-mail addresses: david.lindo@csi.cuny.edu, dlindo@whoi.edu (D. Lindo-Atichati).

http://dx.doi.org/10.1016/j.ocemod.2016.09.010

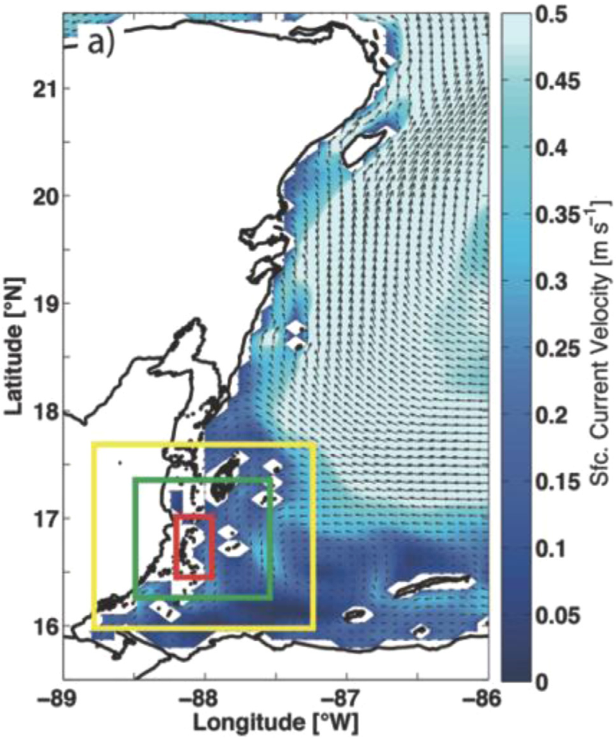

Fig. 1. Map showing the Belizean Barrier Reef System and the rest of the Meso-American Barrier Reef System, with surface ocean currents from GLB-HYCOM on 12 November 2012 showing the Caribbean Current in light blue, domain of the atmospheric (yellow square) and ocean (green square) models, and the 40 km stretch where drifters are deployed (red rectangle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to resolve eddies and instabilities in the ocean (Luettich et al., 1992; Shchepetkin and McWilliams, 2005). Third, the vertical resolution of models has increased: models can use uniform depth levels (z-level models) (Griffies et al., 2005), density as a vertical coordinate (Bleck, 2002), or terrain-following (sigma or s-coordinate) structure (Ezer et al., 2002). Curiously, despite these advances, the gains made by increasing the resolution of the models are not well understood because i) the predictive skill of alternative models with different spatio-temporal resolution is rarely compared and ii) the mechanistic cause of the difference in predictive skill is rarely investigated.

One reef ecosystem that is experiencing increased utilization of its resources is the Belizean Barrier Reef System (BBRS) (Fig. 1). The BBRS stretches from Honduras through Belize to Mexico, and it is the longest (ca. 1000 km) barrier reef in the Western Hemisphere. The BBRS separates the coastal domain in two different regions: a) a shallow lagoon located shoreward of the reef, between the reef and the coastline, to the west; and b) a region of steep walls and oceanic waters seaward of the reef, to the east. Thirteen marine protected areas have been established on the Belizean portions of the BBRS (Cho, 2005) and offshore oil exploration is currently being considered (Cisneros-Montemayor et al., 2013). A coastal circulation model would facilitate management of this ecologically and economically important region (Cooper et al., 2009).

The main mesoscale circulation features in the region of the BBRS are the Caribbean Current and a cyclonic circulation in the Gulf of Honduras (Fig. 1). In situ hydrographic measurements suggest that the BBRS circulation can be divided into two distinct regimes, a northern BBRS region that acts as a boundary between the northward-flowing Yucatan Current and the rest of the BBRS, and a southern BBRS region with weaker southward coastal currents and the presence of the Honduras Gyre (Carrillo et al., 2015). Satellite observations of ocean color suggest that there are significant land-reef connections in the BBRS (Soto et al., 2009), and in situ observations suggest that the strength of currents are controlled partially by tidal forcing at the northern and southern end of atolls in Belize (McClanahan and Karnauskas, 2011). Existing models suggest that when cyclonic eddies are present near the BBRS they cause a reinforced cyclonic circulation and flow is predominantly southward along the reef (Ezer et al., 2005; Chérubin et al., 2008); conversely, when anticyclonic eddies are present near the BBRS they cause a weakened cyclonic circulation and flow is predominantly westward across the reef (Ezer et al., 2005; Chérubin et al., 2008).

In contrast to what is known about mesoscale circulation features, little is known about the sub-mesoscale ocean features in the region. Sub-mesoscale features are characterized by horizontal scale smaller than internal Rossby radius of deformation. The averaged first-baroclinic Rossby radius of deformation R_1 within the BBRS is approximately 65 km (Chelton et al., 1998). Capturing the sub-mesoscale dynamics requires horizontal resolutions in the ocean models to be at least an order of magnitude smaller than the first-baroclinic Rossby radius of deformation. Our understanding of the coastal circulation in the region of the BBRS would be advanced by implementing a high-resolution ocean–atmosphere model that accounts for: a) sub-mesoscales where the flow departs from geostrophic balance; b) non-linear flow-topography interactions (Ezer et al., 2012); and c) tidal fluctuations.

The main aim of the present work is to prescribe an ocean–atmosphere model for the BBRS. For this purpose, we implement alternative models with various resolutions and forcing, and evaluate them by their ability to predict initial surface transport of drifters along the BBR. The performance of the alternative models is further assessed using surface wind, sea surface temperature from meteorological stations, and satellite derived sea surface temperature. The discrepancies among the models are investigated in more detail to understand the processes that need to be resolved for accurate predictions. Finally, we use the best model configuration to describe the surface flow of the region during the summer of 2013 when the observations were made.

2. Methods: in situ observations and modeling

2.1. In situ drifters, flow description, and meteorological stations

The primary dataset used in this work is from surface drifters provided by the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE, http://carthe.org). The drifters are drogued at 40 cm and designed to sample the near-surface current while minimizing windage. They are tracked using Global Positioning System (GPS) every second with 5 m accuracy. The GT-31 GPS receivers are set in a waterproof housing attached to the drifter (MacMahan et al., 2009).

From May 30 to July 2 of 2013, 55 drifter deployments were made at 1–5 km off a 40 km stretch of the BBR centered on South Water Caye (16.82°N, 87.97°W) (Fig. 2b and c, red rectangles). This deployment region of about 400 km^2 was chosen to describe the circulation near the coral reefs for subsequent integration with larval dispersal data (D'Aloia et al., 2015). Thirty five percent of the drifters were deployed shoreward of the reef and 65% seaward of the reef at isobaths deeper than 50 m where the circulation can differ from that in the lagoon. The drifter deployments targeted different tidal phases with 27 drifters deployed on flood, 13 drifters on ebb, and 15 drifters on slack tidal phases. Most of the deployments involved clusters of 2 drifters at a single location, with initial separation of less than 500 m, to calculate dispersion. The mean duration of each deployment was 2.4 ± 0.8 h. The time series of drifter positions is used to derive the four following metrics