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An operational version of the Navy Layered Ocean Model is used to study the generation of a coastally trapped wave forced by a strong and intermittent wind event at the Northern Bight of Panama. This study identifies the winds at the Northern Bight of Panama as a new source for the generation of coastally trapped waves along the west coast of the North American continent. The results indicate that after its generation. The wave propagated poleward increasing the sea level> 10 cm, producing surface currents> 5O cm/S, and traveling> 1200 km. The generation and existence of the coastally trapped wave and the model results are validated with sea surface height coastal tide gauge observations.

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A note on coastally trapped waves generated by the wind at the Northern Bight of Panamá

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RESUMEN

Con el propósito de estudiar la formación de una onda atrapada a la costa, generada por un evento de viento en la parte norte de la Bahía de Panamá, se analizan resultados de una versión operacional del modelo Navy Layered Ocean Model. Los resultados indican que después de su generación la onda se propaga más de 1200 km a lo largo de la costa incrementando el nivel del mar en más de 10 cm y generando, a su paso, corrientes costeras superficiales de más de 50 cm/s. La ocurrencia de la onda atrapada a la costa es validada con observaciones costeras de nivel del mar.

ABSTRACT

An operational version of the Navy Layered Ocean Model is used to study the generation of a coastally trapped wave forced by a strong and intermittent wind event at the Northern Bight of Panamá. This study identifies the winds at the Northern Bight of Panamá as a new source for the generation of coastally trapped waves along the west coast of the North American continent. The results indicate that after its generation, the wave propagated poleward increasing the sea level > 10 cm, producing surface currents > 50 cm/s, and traveling > 1200 km. The generation and existence of the coastally trapped wave and the model results are validated with sea surface height coastal tide gauge observations.

1. Introduction

Although the winds in the gulfs of Tehuantepec and Papagayo can reach gusts of 35 m/s (Romero-Centeno *et al*., 2003; Zamudio *et al*., 2006) they are not able to force coastally trapped waves (CTW) because they lack a significant directional component parallel to the coast (Crépon and Richez, 1982; McCreary *et al*., 1989; Trasviña *et al*., 1995; Bourassa *et al*., 1999). However, the Navy Operational Global Atmospheric Prediction System (NOGAPS) from the Fleet Numerical Meteorology and Oceanography Center (Rosmond *et al*., 2002) wind products show events blowing along the coast at the Northern Bight of Panamá (81-77° W, 6 - 9° N), which are able to force CTW (Fig. 1). The present note documents, for the first time, the generation of a CTW by a wind event at the Northern Bight of Panamá.

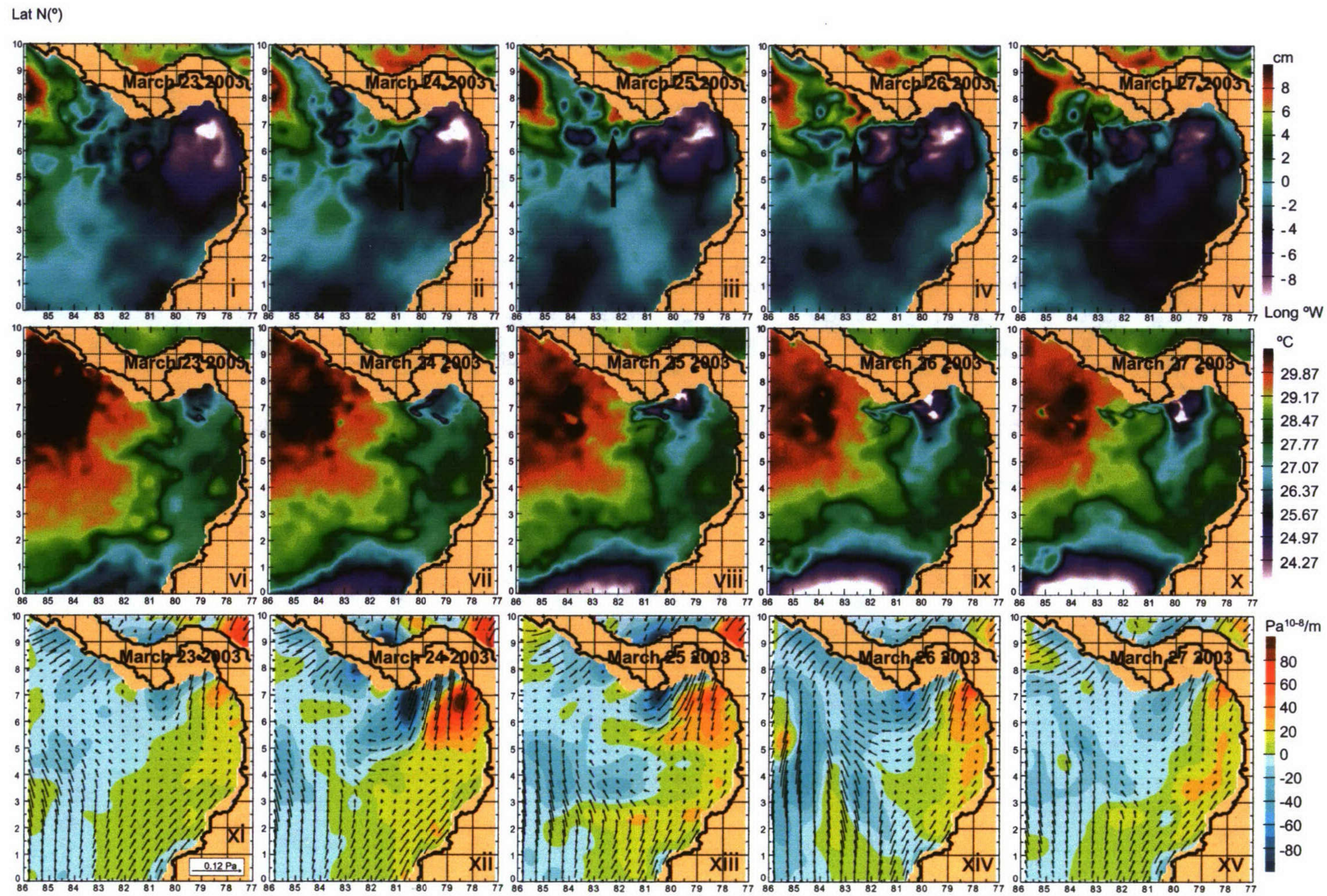

Fig. 1. (i)-(v) Sea surface height anomaly (color contours in cm), (vi)-(x) sea surface temperature (color contours in °C) for five different dates in March 2003 as simulated by 1/16° operational NLOM, and (xi)-(xv) wind stress curl (color contours in 1×10^{-8} Pa/m) and wind stress (vectors) as determined by NOGAPS. The reference wind stress vector (0.12 Pascals) is in the lower right corner of panel (xi). The white arrow in panels (ii)-(v) indicates the position of the coastally trapped wave.

2. The model

The operational Navy Layered Ocean Model (NLOM) has been extensively documented by Rhodes *et al.* (2002), Smestad *et al.* (2003), Wallcraft *et al.* (2003), and references therein. The version used in this study is a real-time eddy-resolving (1/16°) nearly global (72° S to 65° N) ocean model, which is run operationally by the Naval Oceanographic Office (NAVOCEANO). The model is forced with 3 hourly winds and daily averaged heat fluxes from NOGAPS. It consists of 7-layers (including the mixed layer) and includes a free surface, isopycnal outcropping and realistic bottom topography. The coastline is determined by the 200-meter isobath. It includes nonlinearity, thermodynamics, and incorporates assimilation of sea surface temperature and real-time TOPEX/Poseidon, Geosat Follow On, and European Remote Sensing 2 altimeter sea surface height anomalies available via NAVOCEANO's Altimeter Data Fusion Center. Maps and animations, from operational NLOM, are available at the NRL public web site (http://www7320.nrlssc.navy.mil/global_nlom).

3. Results and discussion

A sequence of snapshots showing the wind field around the Bight of Panamá and its oceanic effects in sea surface height (SSH) and sea surface temperature (SST) is presented in Figure 1. On March 23, 2003 the SSH anomaly is characterized by a coastal low, which extends from 81 to 78° W and 4 to 7.8° N; it includes a local minimum < –8 cm, and the low is basically located to the south of the Gulf of Panamá (Fig. 1i). Also, the SSH anomaly field contains a high, which extends from 86 to 84° W and 7 to 9.5° N and it contains a local maximum >8 cm. Co-located with the SSH maximum and minimum are the SST maximum and minimum of the region that are characterized by temperatures > 30.5 and < 24.5 °C, respectively (Fig. 1vi), but no CTW can be recognized in the SSH and SST fields at this time. A day later (March 24), the SSH (SST) includes evidence of the formation of a maximum (minimum) along the model coast of the Northern Bight of Panamá (Figs. 1ii and 1vii). However, on March 25 the SST field indicates a cold tongue, which reaches a minimum < 22 °C, that originates at the entrance of the Gulf of Panamá and extends west-southwestward along the model coast (Fig. 1viii). At the same time, positive SSH anomaly of ~6 cm develops along the coast extending from 83 to 81° W and from 6.6 to 8° N (Fig. 1iii) that is the first evidence of the formation of a new CTW along the Central American west coast. During March 26 the coastal SST cold tongue increased in area (Fig. 1ix) and the positive SSH anomaly increased its amplitude to >10 cm and propagated poleward along the coast as a CTW (Fig. 1iv). The CTW continues its poleward propagation reaching 9° N and the extension of the cold tongue starts to decrease on March 27 (Figs. 1v and 1x). The CTW propagated with a phase speed of ~1.5 m/s that agrees with the phase speed range of values reported in the articles reviewed by Brink (1991). The CTW was characterized by alongshore and cross-shore scales of ~200, and ~65 km, respectively. In particular, the cross-shore scale is the intrinsic trapping scale of the wave, which is similar to the first baroclinic radius of deformation of the region. After the wave traveled >1200 km it was measured by the closest available poleward coastal tide gauge at Manzanillo, México (104.3° W, 19° N) (Fig. 2). Throughout its poleward propagation the wave was not affected by any wind event at the gulfs of Papagayo (with center close to 85.5° W, 10.5° N), and/or Tehuantepec (with center close 94.5° W, 15.5° N). What then was the generation mechanism for this CTW?

According to the SSH snapshots of Figure 1, the CTW does not have an equatorial origin as is common for many CTW in this region. That can be corroborated by analyzing the SSH snapshots, which neither include any positive SSH anomaly along the equator nor along the coast from 0 to ~6.5° N during the period March 23-27 (Figs. 1i-1v). To provide some insight about the geographical origin of this CTW, and consequently the potential forcing mechanism, we examine SSH along the model coast that clearly shows positive SSH anomalies propagating poleward during March-April 2003 (Fig. 3). It is important to mention that since Figure 3 is a SSH anomaly field, the SSH contribution of the Costa Rica Coastal Current (Wyrtki, 1966; Kessler, 2006) and the Mexican Current (Zamudio *et al.*, 2001; Lavín *et al.*, 2006; Zamudio *et al.*, 2007; Zamudio *et al.*, 2008) has been removed. Of particular interest for this study is the positive SSH anomaly >10 cm, which originated on March 25 at ~7.7° N and can be tracked to the north to ~20° N, though no evidence of this signal can be tracked south of ~7.7° N (Fig. 3). This confirms the Central America west coast as the genesis area for this CTW.

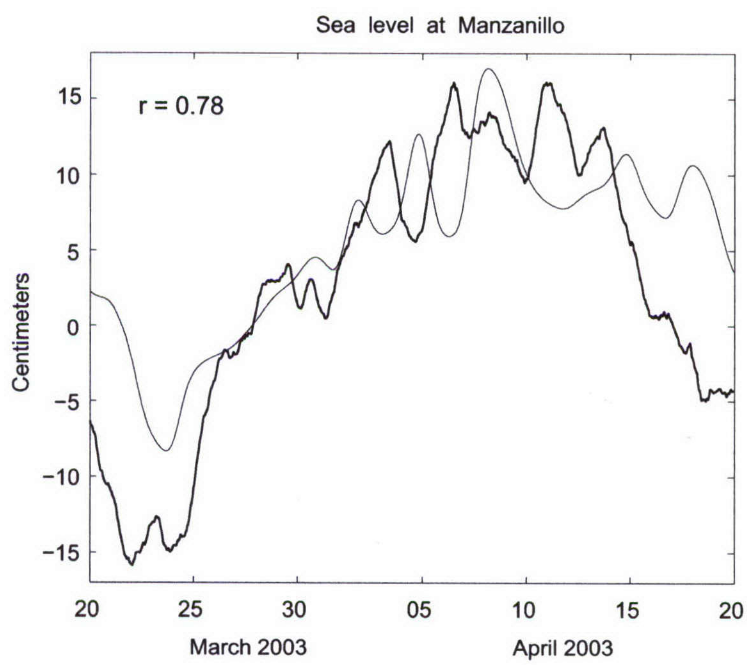

Fig. 2. Time series of observed (thick line) and simulated (thin line) sea surface height at Manzanillo, México (104.3° W, 19° N). The observed data have been de-tided, corrected for atmospheric pressure load effect and a 1-day running mean filter has been applied. The correlation coefficient (r) between the observed and simulated time series is 0.78.

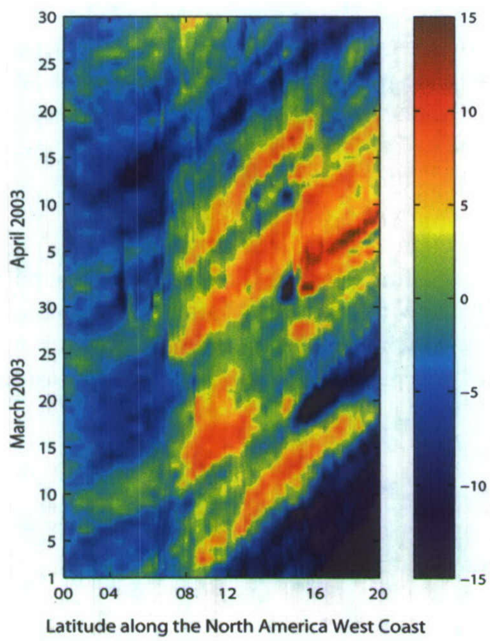

Fig. 3. Sea surface height anomaly (relative to the 1993-1999 mean) time series simulated by 1/16° operational NLOM along the model west coast of Central America from 0 to 20° N.

The wave was forced by the strong and intermittent wind event, which arrived at the Northern Bight of Panamá during March 24 (Fig. 1xii). In general, during the period March 23-27, the wind stress curl was characterized by an anticyclone (cyclone) on the western (eastern) side of the Bight of Panamá (Figs. 1xi-1xv). This wind feature is consistent with the wind characteristics reported by Rodríguez-Rubio *et al.* (2003) throughout this time of the year (early spring). During March 23 the cyclone and anticyclone pattern is weak but well defined (Fig. 1xi). However, on March 24 both the cyclonic and anticyclonic wind stress curl strengthened considerably and injected large amounts of energy into the Northern Bight of Panamá waters. In addition, the wind induced negative (positive) relative vorticity on the western (eastern) side of the Northern Bight of Panamá via Ekman pumping (suction). In the process a strong convergent (divergent) Ekman transport increased (decreased) the oceanic pressure on the western (eastern) side of the Northern Bight of Panamá. The convergence dropped the thermocline ~40 m (not shown) and raised the SSH ~6 cm generating the baroclinic downwelling CTW (Figs. 1ii-1iii), which induced poleward surface currents >50 cm/s (not shown). During the following days the CTW propagated poleward (Figs. 1ii-1v, 2, and 3) and the wind event weakened (Figs. 1xii-1xv).

4. Summary and concluding remarks

Current oceanographic literature postulates that equatorial winds (Chelton and Davis, 1982; Enfield and Allen, 1980; Spillane *et al.*, 1987; Ramp *et al.*, 1997; Zamudio *et al.*, 2001; Melsom *et al.*, 2003; Zamudio *et al.*, 2006) and eastern North Pacific tropical cyclones winds (Christensen *et al.*, 1983; Enfield and Allen, 1983; Merrifield, 1992; Gjevick and Merrifield, 1993; Zamudio *et al.*, 2002) act as generators of the CTW that propagate along the west coasts of Central America and México. However, to the best of our knowledge, no study has reported any other wind forcing as a CTW generator along these coasts of the North American Continent. In this study we show the generation of a CTW by a wind event at the Northern Bight of Panamá (Fig. 1) that subsequently propagated poleward (Fig. 3) without being affected by the winds in the gulfs of Tehuantepec and Papagayo. Thus, the CTW was observed by the sea level tide gauge at Manzanillo, México (Fig. 2). These new CTW are partially responsible for the high frequency SSH variability occurring along the coasts of Central America and México during late winter and early spring, and they may be propagating as far north as the Gulf of California, in which they might be responsible for the sea level and current variability (in high frequency bands) reported by López *et al.* (2005) inside this semi-enclosed sea.

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