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On the evolution of coastally trapped waves generated by Hurricane Juliette along the Mexican West Coast

Luis Zamudio
Center for Ocean-Atmospheric Prediction Studies, Florida State University, Tallahassee, Florida, USA

Harley E. Hurlburt and E. Joseph Metzger
Naval Research Laboratory, Stennis Space Center, Mississippi, USA

Ole Martin Smedstad
Planning Systems Incorporated, Stennis Space Center, Mississippi, USA

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[1] An operational real-time eddy-resolving (1/16°) global ocean nowcast/forecast system is used to study the evolution of two coastally trapped waves generated by Hurricane Juliette along the Mexican West Coast. Results indicate that the first wave was generated along mainland Mexico and it propagated poleward as a free coastally trapped wave; it also generated anticyclonic eddies near Cabo Corrientes and the María Islands. Upon entering the Gulf of California the wave weakened cyclonic eddies and after reaching the shelf break north of Guaymas, it reversed direction and propagated southward along the east coast of the Baja California Peninsula (BCP). Next, the wave generated an anticyclonic eddy at Cabo San Lucas. Finally, the wave weakened while exiting the gulf and propagated northward along the BCP West Coast. The second coastally trapped wave was generated by Juliette's poleward winds along the BCP West Coast, but was subsequently greatly weakened by Juliette's equatorward winds. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4544 Oceanography: Physical: Internal and inertial waves; 4504 Oceanography: Physical: Air/sea interactions (0312); 4255 Oceanography: General: Numerical modeling. **Citation:** Zamudio, L., H. E. Hurlburt, E. J. Metzger, and O. M. Smedstad, On the evolution of coastally trapped waves generated by Hurricane Juliette along the Mexican West Coast, *Geophys. Res. Lett.*, *29*(23), 2141, doi:10.1029/2002GL014769, 2002.

1. Introduction

[2] From May to November the west coast of Mexico is exposed to the action of Eastern North Pacific Tropical Cyclones (ENPTC). Normally those cyclones produce beneficial rainfall over Mexico. The tropical cyclones also cause substantial sea surface height (SSH) variability along the Mexican West Coast (Plate 1). Previous studies have used sea level records (among other data), theoretical models and idealistic numerical models to report the existence of ENPTC-induced coastally trapped waves along the coast of mainland Mexico [*Christensen et al.*, 1983; *Enfield and Allen*, 1983; *Merrifield*, 1992; *Gjevik and Merrifield*, 1993]. However, no study has reported: 1) the complete life cycle (birth, evolution and decay) of those coastally trapped waves, or 2) the ENPTC-generation of coastally trapped waves along the Pacific Coast of the BCP.

[3] The present note documents the evolution of two coastally trapped waves induced by Hurricane Juliette. One of them was generated along the coast of mainland Mexico and the other along the Pacific Coast of the BCP. The direct ENPTC-generation of coastally trapped waves along the Pacific Coast of the BCP is being reported for the first time.

2. The Operational NLOM System

[4] Our approach is based on the analysis of results from a real-time eddy-resolving (1/16°) nearly global (72°S to 65°N) ocean nowcast/forecast system run operationally by the Naval Oceanographic Office (NAVOCEANO). The system uses a 7-layer version of the Naval Research Laboratory (NRL) Layered Ocean Model (NLOM). The model is forced with 3 hourly winds and daily averaged heat fluxes from the Fleet Numerical Meteorology and Oceanography Center's Navy Operational Global Atmospheric Prediction System (NOGAPS) [*Rosmond et al.*, 2002] and uses the 200 meter isobath as a land-sea boundary. The model includes assimilation of sea surface temperature (SST) and real-time TOPEX/Poseidon, Geosat Follow On and European Remote Sensing 2 altimeter SSH data available via NAVOCEANO's Altimeter Data Fusion Center. The ability of a data-assimilative ocean model to track observed ocean features by dynamically interpolating the data is an important advantage in this study, especially for rapidly propagating features like coastally trapped waves. In the case of Hurricane Juliette, the atmospheric forcing, which included the hurricane, was also essential because of its large, rapid impact. The atmospheric model (NOGAPS) used to force the ocean model includes assimilation of scatterometer data. That data incorporate cyclones from their early stages [*Katsaros et al.*, 2001; *Sharp et al.*, 2002]. In addition, NOGAPS is one of the hurricane prediction models used by the National Hurricane Center. Details of the NLOM system can be found in *Rhodes et al.* [2002] and *Smedstad et al.* [2002] and references therein. Operational NLOM results, maps and animations,

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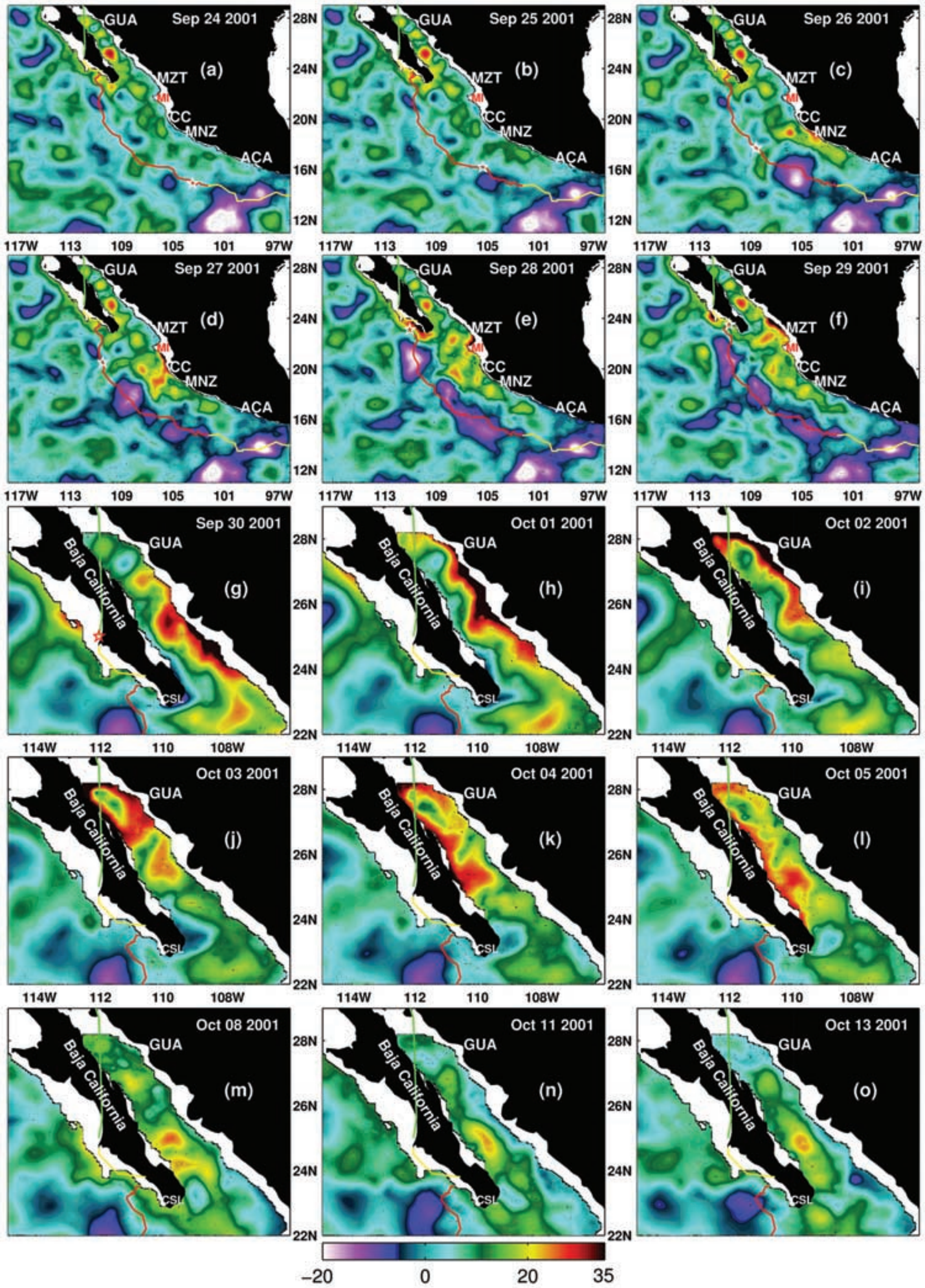

Plate 1. Sea surface height anomaly (color contours in cm) for fifteen different dates in September–October 2001 as determined from operational NLOM. Juliette's center is indicated with a white or red star in panels a–g. Juliette's path is represented with yellow, red and green lines for tropical storm, hurricane and tropical depression, respectively. The positions of Acapulco (ACA), Manzanillo (MNZ), Cabo Corrientes (CC), María Islands (MI), Mazatlán (MZT) Guaymas (GUA) and Cabo San Lucas (CSL) at the tip of the Baja California Peninsula are indicated.

are available at the NRL public web site (http://www.ocean.nrlssc.navy.mil/global_nlom).

3. Juliette's Pathway and the Dynamical Ocean Response

3.1. Juliette's Path

[5] The tropical cyclone that became Juliette was named as a tropical storm on 21 September 2001 with the center located near 13.4°N–94°W and maximum sustained winds of ~24 m/s. During the subsequent days, Juliette followed a route approximately parallel to the southwest coast of mainland Mexico and within ~400 km of the coast (Plate 1). Juliette strengthened, reaching ~64 m/s on 24 September 2001, a category four hurricane on the Saffir/Simpson hurricane scale (http://www.nhc.noaa.gov/).

[6] Juliette was upgraded to a hurricane on September 23, 2001. Nevertheless, it was not conclusively recognized in

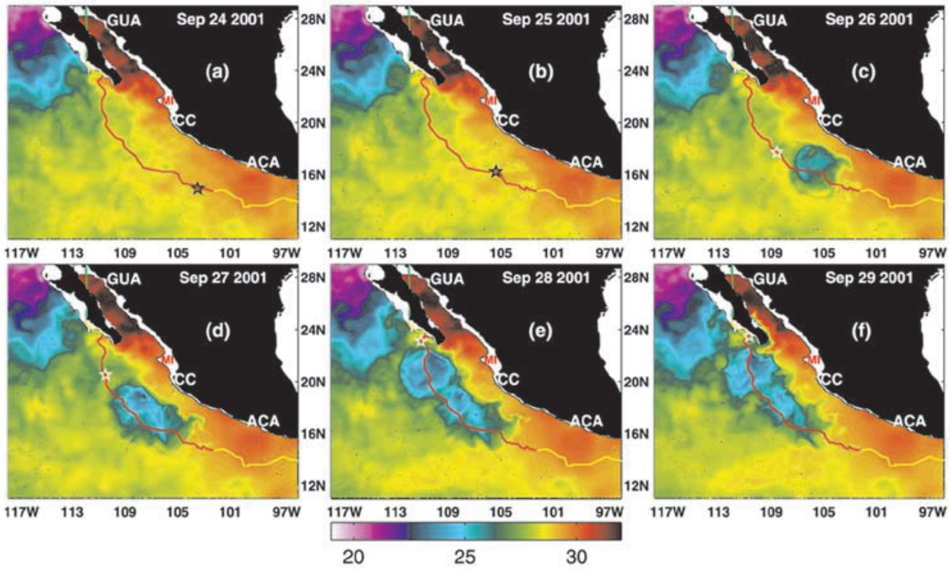

Plate 2. Sea surface temperature snapshots (color contours in °C) for six different dates in September 2001 as determined from operational NLOM. Juliette's center is indicated with a black or white star in all the panels. Juliette's path is represented with yellow, red and green lines for tropical storm, hurricane and tropical depression, respectively.

the model SSH and SST fields until September 26 (Plates 1 and 2). Juliette's traveling speed and the inertia of oceanic motions, which are approximately two orders of magnitude slower than their atmospheric counterparts, could be critical issues in the ~2 day lagged oceanic response. During its early stages Juliette traveled too fast, ~8.3 m/s, to allow strong upwelling and vertical mixing in response to Juliette's winds. In contrast, after Juliette's traveling speed decreased to ~2.8 m/s large oceanic responses are evident (Plates 1c–1f and 2c–2f). A characteristic feature of the SST field (Plate 2) is the "warm pool" off Acapulco. Juliette was upgraded to a hurricane just after passing over this warm pool. Details about the existence of the Mexican warm pool have been discussed by *Magaña et al.* [1999].

3.2. The Mainland Coastally Trapped Wave

[7] The strong cyclonic surface wind of Juliette generated Ekman suction that raised the thermocline ~25 m in the model, dropped the SSH ~20 cm (Plate 1) and lowered the SST ~5° C (Plate 2). Furthermore, Juliette winds stimulated oceanic mixing producing a dramatic increase in the mixed layer depth, which changed from ~10 m to ~80 m (not shown). On the coast, Juliette's poleward winds drove an oceanic onshore Ekman transport and generated a strong coastal convergence. The convergence dropped the thermocline ~40 m and raised the SSH ~28 cm generating a baroclinic coastally trapped wave (CTW) between Acapulco and Cabo Corrientes, which is clearly recognized in both model results and sea level measurements (Plates 1a–1c and Plate 3a). Similar wind forcing prevailed through 27 September 2001 favoring coastal convergence and a strengthening of the mainland CTW during its poleward propagation (Plate 1d). The alongshore and cross-shore scales of the CTW were ~700 km and ~58 km, respectively. The wave phase speed was ~2.7 m/s and it generated currents >1 m/s.

[8] By the time it passed the latitude of Cabo Corrientes, Juliette was located farther from mainland Mexico than during its earlier positions to the southeast (Plates 1a–1f). Therefore, Juliette's poleward coastal winds that generated and forced the mainland CTW decreased allowing free northward propagation of the wave (Plates 1e–1i). While passing Cabo Corrientes and the María Islands the wave generated and reinforced anticyclonic eddies (Plates 1c–1f). After that the wave continued its northward journey along the mainland coast of the Gulf of California until it arrived at the shelf break north of Guaymas. Since the

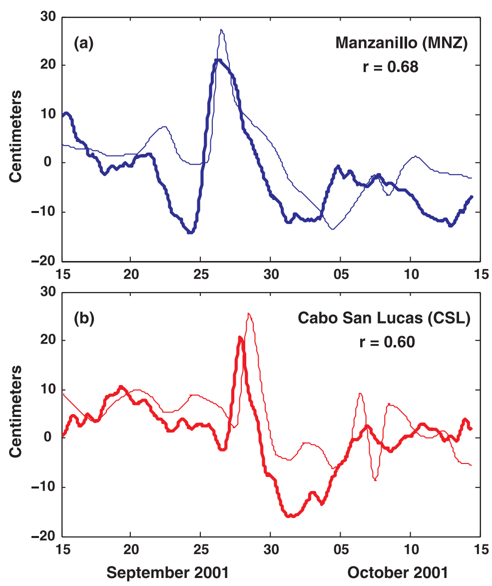

Plate 3. Time series of measured (thick line) and modeled (thin line) sea level at Manzanillo (a) and Cabo San Lucas (b). The measured data have been de-tided, corrected for atmospheric pressure load effect and a 1-day running mean filter has been applied. The correlation coefficient between the measured and modeled time series is indicated for each of the two locations. The geographical positions of Manzanillo and Cabo San Lucas are indicated in Plate 1.

continental shelf break is the waveguide of this wave, it then reversed direction and next propagated southward along the east coast of the BCP (Plates 1g–1m). Note the weakening of the cyclonic eddy off Guaymas and how the CTW starts to decay after turning southward. However, this CTW decayed most rapidly in rounding the southern tip of the BCP where it excited inertial-gravity waves and generated a weak anticyclonic eddy at the tip off Cabo San Lucas (Plates 1m–1o). The eddy formation mechanism is flow around a cape as discussed by *Cenedese and Whitehead* [2000]. Later, this Cabo San Lucas eddy fused with the María Islands and the Cabo Corrientes eddies. Finally, a weak CTW, which was characterized by SSH of a few centimeters, turned northward after rounding the tip of the peninsula and continued its propagation along the Pacific Coast of the BCP (not shown). Remnants of this wave were observed traveling northward in the model around 34°N. As pointed out by one of the reviewers, the preceding CTW documentation is another example of the Gulf of California acting as a trap for coastally trapped waves with this longshore length and duration.

3.3. The Baja California Coastally Trapped Wave

[9] By 28 September 2001 Juliette's maximum sustained winds had decreased to ~36 m/s and its center had moved to about 130 km west of Cabo San Lucas. The cyclonic open ocean response was located to the southwest of Cabo San Lucas (Plate 1e). The coastal ocean response along the southern part of the BCP West Coast was characterized by a baroclinic CTW that raised the SSH ~25 cm in the model and ~35 cm in the sea level measurements (Plates 1e and 3b). It is interesting to notice that during its northward propagation this wave decays rapidly (Plates 1e–1h). Juliette's path could be a key factor in the CTW fast decay processes. On September 29 and 30 Juliette was downgraded to a tropical storm and then a tropical depression and CTW propagation began to dominate over amplification (Plate 1f). On September 30 (Plate 1g) Juliette made landfall on the BCP and the CTW was located northwest of the storm center where an equatorward wind component drove an oceanic offshore Ekman transport component. This generated a coastal divergence, raised the thermocline, dropped the SSH and contributed to rapid decay of the CTW generated on September 28 (Plate 1e). However, remnants of the CTW can be seen propagating northward in Plates 1g–1h.

4. Summary and Concluding Remarks

[10] Formation, propagation and decay of two coastally trapped waves generated by Hurricane Juliette along the Mexican West Coast are documented using an operational ocean nowcast/forecast system. The existence of the numerically modeled coastally trapped waves is validated with coastal sea level observations. Results show that Juliette's poleward winds forced an oceanic onshore Ekman transport generating a strong coastal convergence from the north of Acapulco to Cabo Corrientes. The convergence raised the sea surface height >25 cm, generating a baroclinic coastally trapped wave (Plates 1c and 3a). After that, the wave propagated poleward, produced and reinforced anticyclonic eddies near Cabo Corrientes and the María Islands, passed by Mazatlán as a well developed coastally trapped wave (Plate 1f), and entered into the Gulf of California. While inside of the gulf the wave weakened a cyclonic eddy near Guaymas and after reaching the shelf break north of Guaymas, it reversed direction and propagated southward along the east coast of the Baja California Peninsula. Next, the wave generated an anticyclonic eddy at Cabo San Lucas, which later merged with the Cabo Corrientes and the María Islands eddies.

[11] Juliette was a significant cyclone, not only because its sustained winds reached ~64 m/s, but also because its poleward winds generated a second coastally trapped wave along the Pacific Coast of the Baja California Peninsula (Plates 1e and 3b) that was later weakened by Juliette's equatorward winds. However, remnants of this wave were observed traveling northward in the model as far north as the California Bight.

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H. E. Hurlburt, E. J. Metzger, O. M. Smedstad, and L. Zamudio, Naval Research Laboratory, Stennis Space Center, Mississippi, 39529, USA. (hurlburt@nrlssc.navy.mil; metzger@nrlssc.navy.mil; smedstad@nrlssc.navy.mil; zamudio@nrlssc.navy.mil)