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REPORT TITLE: Ultra-Deep Circulation Processes in the Gulf of Mexico

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BACKGROUND: Deep circulation (approximately 1000 m below the free surface) in the Gulf of Mexico is poorly known and its dynamics is not well-understood. Observations at the present time give incomplete and sometimes confusing and misleading picture of the circulation – hence often misinterpretations of the related dynamics. Models are simpler but also often give misleading conclusions if not carefully analyzed. Moreover, models are imperfect and have errors due to their numerics (e.g. truncation errors), forcing, and incomplete physics. This work therefore first attempts to identify these imperfections in the models, and then conducts a series of carefully controlled model experiments that do not crucially depend on the detailed (hence imperfect) model physics. These experiments are analyzed to identify essential physics that govern the deep circulation in the Gulf of Mexico and how they are forced by and are coupled to the Loop Current and eddies in the upper layer.

OBJECTIVES: (1) To compare model simulation against deep observations in the Gulf of Mexico. Then to use models (2) to describe and explain the deep mean circulation; (3) to identify and explain regions of deep, high eddy kinetic energy; and (4) to describe and explain the coupling between the Loop Current and rings with the deep flows.

DESCRIPTION: Despite advances in numerical models and increased observations in the Gulf of Mexico, how the deep circulation in the Gulf of Mexico is produced is very poorly known. We first check our circulation model for the Caribbean Sea and the Gulf of Mexico that is based on the Princeton Ocean Model against deep observations in central Gulf of Mexico. We then conduct a series of carefully designed experiments and theoretical analyses to understand both the deep eddy-kinetic-energy (EKE) as well as the mean circulation. We then relate these processes to upper-layer forcing by the Loop Current and rings, and also to the ring-separation process itself.

We show that topographic Rossby waves (TRW's), which previously have been identified to contribute to the largest portion of EKE in the deep Gulf, can focus in regions of closed contours of $N|\nabla H|$ (N = buoyancy frequency and H is bottom topographic depth below the mean surface) which we dubbed as "topocaustics" where deep EKE can accumulate, leading to intense bottom currents. Such intense currents are shown to occur in the Sigsbee escarpment for example. The TRW (energy) rays are shown to follow the same rule as internal-wave rays in (simpler) two-dimensional xz-plane, but topocaustics are uniquely TRW's because these low-frequency rotational waves have preferential propagation direction with shallow depths on the right in the northern hemisphere, leading to energy accumulation in the western side of closed contours of $N|\nabla H|$ for H that shallows northward.

We then analyze mass balances in a special 'box' defined over the deep eastern Gulf of Mexico (EG) bounded by 90W to the west, the Gulf's bottom at the lower boundary, the z=-1000m planar surface at the upper boundary, the sill wall of the Straits of Florida at the east, the northern Gulf's continental slope topography at the north, and the Yucatan channel in the south. There are only 3 openings: 90W, z=-1000m plane, and the deep Yucatan channel. By calculating transport balances in this box (across the 3 openings) over repeating Loop Current shedding cycles, we are able to explain the coupling between stages of Loop Current Cycle: intrusion and formation, incipient shedding, eddy-propagation, and the deep flows in *both* the eastern and western Gulf of Mexico.

We show that previously widely believed correlation between Loop expansion and Yucatan deep flows is weak at best and, more importantly, is based on a physically incorrect misconception of the upper-lower coupling that neglects the deep interaction between the eastern and western Gulf of Mexico. We show that this deep interaction results in what we call the Gulf of Mexico Oscillator, in which the western Gulf thermocline at z=-1000m rises while that at the eastern Gulf falls and vice versa over the Loop Current shedding cycle. We show that the net vertical transport in the eastern Gulf is downward across the z=-1000m and deeper through z=-2000m because the Loop spends more time "reforming" (i.e. accumulating its mass) than shedding eddies. As a result, since the deep Gulf is closed below the sill depth of the Yucatan Channel at z≈-2000m, the net circulation is zero and the eastern Gulf's downwelling results in anticyclonic mean circulation in the east and cyclonic circulation in the west. To the best of our knowledge, this is the first time that the cause for the deep cyclonic circulation in the western Gulf of Mexico has been robustly explained without resorting to complicated arguments involving, for example, TRW's. Moreover, since the deep western cyclonic gyre necessitates an influx of deep water from eastern to western Gulf, it results in upwelling across the z=-2000m plane in the western Gulf, which together with downwelling across the z=-1000m plane, results in convergence and eastward transport in the middle layer across 90W from west to east. Since the upper layer (0 to -

1000m) transport is westward due to eddies carrying mass westward, the circulation across 90W is of a 3-layer structure: westward from surface to z=-1000m, from z=-2000m to bottom, and eastward in between from z=-1000m to z=-2000m.

We show that the Yucatan deep flow is towards the south throughout the Loop Current Cycle. However, at incipient shedding, the Yucatan deep flow is very weak, so that deep perturbation in the channel at this stage can significantly affect the timing of eddy separation from the Loop Current.

Finally, as we pointed out previously in a related study [Chang and Oey, 2010a] that changes in flow condition in the Straits of Florida may affect shedding of eddies, our results (and previous modeling works) show that this downstream condition is not necessary. We point out then that a recently published claim of observed downstream-triggered mechanism to eddy-shedding is misleading.

SIGNIFICANT CONCLUSIONS: This project has advanced our basic understanding of deep eddy energy, the upper-lower layer coupled dynamics, and the deep mean circulation in the Gulf of Mexico – the first time such knowledge has been carefully documented and demonstrated in peer-reviewed publications. The shedding of Loop Current eddies is shown to depend not only on transport (hence also momentum) balances between the Gulf and the Caribbean Sea, but also on the coupled responses between the eastern and western Gulf of Mexico – i.e., on conditions within the Gulf.

STUDY RESULTS: This study developed ocean models and mathematical analyses to explain the dynamics that govern deep flows in the Gulf of Mexico, and how these deep currents are driven by and coupled to the Loop Current and rings.

STUDY PRODUCTS: Oey, L.-Y. and P. Hamilton, 2012. Ultra-deepwater circulation processes in the Gulf of Mexico. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study BOEM 2012-004. 82 pp.

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