

Tides, Internal Waves, and Mixing in the Northern Gulf of Eilat

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Scientific Background

A major challenge facing oceanographers is, and has consistently been, the observation, understanding, and modeling of ocean mixing. Ocean mixing processes greatly influence the physics, chemistry, and biology of the ocean on all length and time scales of interest to oceanographers. For instance, mixing over millimeters to centimeters may seem insignificant but can greatly affect the dispersion of eggs and sperm during spawning events and the subsequent recruitment/settlement of larvae. On the other end of the spectrum, large-scale ocean mixing processes affect the oceanic distributions of heat and carbon dioxide, for example, and, therefore, profoundly impact Earth's climate system.

Recent advances in satellite remote sensing and numerical modeling have increased our understanding of large-scale mixing processes. Small-scale mixing processes, however, often cannot be measured from space (i.e. deep ocean mixing) and cannot be resolved in global general circulation models (typical resolutions of 10s of km). Recent research has revealed that small-scale phenomena, such as mixing barriers, are important features that can greatly affect small scale dispersion, particularly the fate of larvae and pollutants. Small-scale vertical mixing in the deep ocean significantly affects the cycling of carbon and other biologically important nutrients, such as nitrogen and phosphate, controlling to some extent the amount of carbon dioxide in the atmosphere and the oceanic ecosystem.

Roughly half of the energy required to mix the deep ocean is thought to be supplied by tidal motions, specifically internal waves of tidal frequency, or internal tides. Thus, tidal energy reaches the deep ocean through internal waves that can become unstable, break, and mix the deep ocean. This deep vertical mixing is an essential part of the climate system, but remains poorly understood.

The northern Gulf of Eilat (hereafter referred to as 'the Gulf') is an ideal natural laboratory for observing small-scale mixing processes in deep water because of its small dimensions (6 km x 10 km), great depth (a depth of 400 m is found a mere 1 km from the shore), lack of freshwater input, seasonally varying stratification, and important oceanic processes (i.e., tidally forced internal waves, deep water formation, and small-scale mixing processes). The Gulf of Eilat is also of interest because it hosts a unique ecosystem that has attracted the attention of biologists for decades. However, relatively few physical studies of the Gulf have been conducted and little is known about the complex circulation in the Gulf. Specifically, transport of larvae and population connectivity is a relevant, open question. Due to lack of observations, larval transport is often crudely estimated from single-point measurements using progressive vector diagrams (PVDs) that assume spatially uniform flow. Thus, our observations and numerical studies are important for understanding the interplay between physics and biology in this biologically diverse ecosystem.

Objectives

- Assess the accuracy of the progressive vector diagram (PVD) for estimating transport pathways
- Produce an estimate of the maximal small scale (<10 km) horizontal ocean mixing
- Estimate the amount of vertical mixing driven by breaking internal waves

Methods

We use a combination of direct observations, analytical models, and numerical general circulation models to study the dynamics in the northern Gulf. The Gulf can be observed and modeled at high resolution because of its small lateral dimensions. We use a high frequency (HF) radar network to make high resolution measurements of surface currents in the Gulf. Surface currents are observed at grid points spaced 300 m apart and maps of the surface current vectors are produced every 30 min. Additionally, vertical profiles of currents are measured with moored acoustic Doppler current profilers (ADCPs) and a recently-acquired profiling mooring. The profiling mooring collects water velocity and temperature data while traveling up and down a mooring wire. High resolution numerical simulations of the entire Gulf, from the northern tip near the cities of Eilat and Aqaba to its southern terminus at the Straits of Tiran, provide insight into the connections between the northern Gulf and the rest of the basin, and with the larger Red Sea system.

Results

HF radar current data were used to estimate the accuracy of transport estimates produced by PVDs. The PVD assumes that current measurements at one location can be used to represent the currents over a large area. The HF radar surface currents in Figure 1 show that this assumption is invalid for the northern Gulf. Additionally, the spatial variability of the currents cannot be predicted. Therefore, the accuracy of the PVD was assessed by computing the trajectories of passive virtual particles released at over 500 locations in the Gulf. The PVD was computed using only the currents from the release location. The PVDs were compared to trajectories computed using the full spatially varying current data. In order to account for possible seasonal differences the comparisons were performed over 13 months, from September 2005 to September 2006. The average times required for a given PVD/trajectory particle pair to separate by 500 m and 1000 m are approximately five and seven hours, respectively. For more, see Carlson et al (2010a).

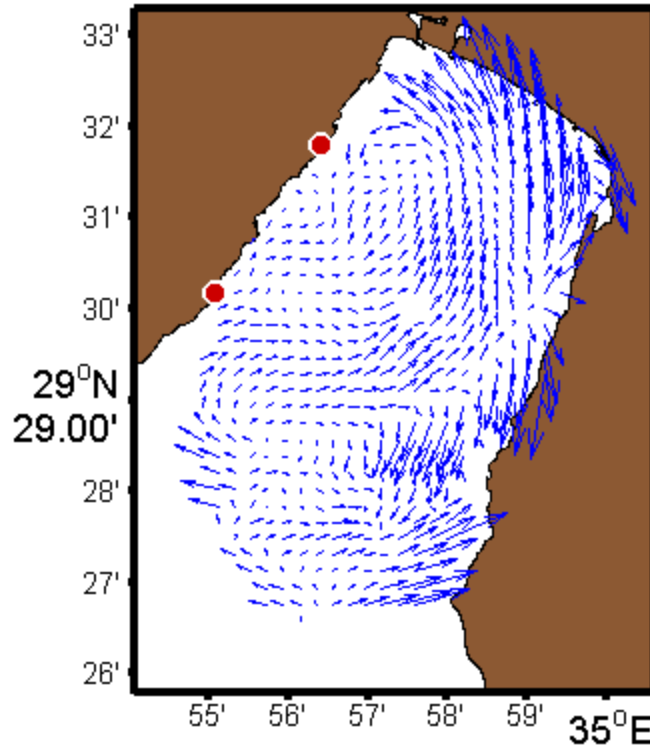


Figure 1. A map of the surface currents measured by two HF radar antennae on 2 February 2009 at 14:30 shows considerable variability in the surface circulation. The two red circles indicate the locations of the HF radar antennae.

The upper limit of small-scale horizontal ocean mixing was estimated using particle trajectories computed from observed or modeled velocities in the vicinity of a known mixing barrier. A mixing barrier is not a physical barrier but instead signifies a line that separates two regions in the ocean with markedly different circulation patterns. Thus, a particle in one region will not cross the mixing barrier into the other region. The particle trajectories were also subject to random movements whose magnitude was related to a parameter known as the ‘eddy diffusivity’. The eddy diffusivity is used to represent unresolved mixing by small-scale turbulent motions. It is not something that is directly measured, but instead is inferred from a particular flow field. With the addition of the random movements caused by the eddy diffusivity particles were able to move from one region to the other. We hypothesized that the mixing barrier would disappear at maximal horizontal mixing (i.e. maximal eddy diffusivity). Thus, the value at which the mixing barrier disappeared provided an estimate of the upper bound of the eddy diffusivity. For more, see Carlson et al (2010b).

The role of tides in mixing the deep ocean is being investigated using moored ADCP and temperature measurements and vertical profiles collected by the profiling mooring. The contribution of tidally forced internal waves to deep ocean mixing cannot be addressed without first understanding the deep tidal circulation. Previous tidal studies in the Gulf took place in shallow coastal environments that are more heavily influenced by winds, surface waves, and atmospheric heating and cooling. Thus, the deep tidal circulation in the northern Gulf has been

investigated using a series of deep moorings. One long-term mooring collected current profiles from near-surface to ~230 m from October 2008 to July 2009 show that the semi-diurnal tidal currents were present throughout the deployment period. Coastal current data collected during the same time show more seasonal sensitivity.

These measurements have also been used to determine the basic properties of the internal wave field in the northern Gulf. Fixed-depth temperature time series and repeated vertical profiles of temperature show that the internal waves have maximal vertical amplitudes of approximately 50 m. Maximal vertical amplitude was observed during February. Data collected by the profiling mooring during June 2011 show large amplitude internal waves of semi-diurnal frequency that are modulated by the spring-neap cycle.

Future Work

The tide and internal wave studies are being prepared for publication. A vertical microstructure profiler was recently purchased and will be put to use soon. The microstructure profiler falls freely and collects high resolution velocity, temperature, and salinity data that are used to estimate the amount of turbulent diffusivity (a proxy for mixing). We intend to use this device to quantify the amount of mixing generated by breaking internal waves in the deep northern Gulf.

Publications

Carlson, D.F., P.A. Muscarella, H. Gildor, B.L. Lipphardt, and E. Fredj (2010a) How useful are progressive vector diagrams for studying coastal ocean transport? *Limnology and Oceanography Methods*. **8**:98-106.

Carlson, D.F., E. Fredj, H. Gildor, and V. Rom-Kedar (2010b) Deducing an upper bound to the horizontal eddy diffusivity using a stochastic Lagrangian model. *Environmental Fluid Mechanics*. doi:10.1007/s10652-010-9181-0

Available online at <http://www.earth.huji.ac.il/data/File/gildor/publications1.html>