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The annual cycle of vertical mixing and restratification in the Northern Gulf of Eilat/Aqaba (Red Sea) based on high temporal and vertical resolution observations

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ABSTRACT

The stratification in the Northern Gulf of Eilat/Aqaba follows a well-known annual cycle of well-mixed conditions in winter, surface warming in spring and summer, maximum vertical temperature gradient in late summer, and erosion of stratification in fall. The strength and structure of the stratification influences the diverse coral reef ecosystem and also affects the strength of the semi-diurnal tidal currents. Long-term (13 months) moored thermistor data, combined with high temporal and vertical resolution density profiles in deep water, show that transitions from summer to fall and winter to spring/summer occur in unpredictable, pulses and are not slow and gradual, as previously deduced from monthly hydrographic measurements and numerical simulations forced by monthly climatologies. The cooling and deepening of the surface layer in fall is marked by a transition to large amplitude, semi-diurnal isotherm displacements in the stratified intermediate layer. Stratification is rebuilt in spring and summer by intermittent pulses of warm, buoyant water that can increase the upper 100–150 m by 2 °C that force surface waters down 100–150 m over a matter of days. The stratification also varies in response to short-lived eddies and diurnal motions during winter. Thus, the variability in the stratification exhibits strong depth and seasonal dependence and occurs over range of timescales: from tidal to seasonal. We show that monthly or weekly single-cast hydrographic data under-samples the variability of the stratification in the Gulf and we estimate the error associated with single-cast assessments of the stratification.

1. Introduction

The Gulf of Eilat/Aqaba (hereinafter ‘the Gulf’) is the north-eastern arm of the Red Sea and hosts a diverse tropical coral reef ecosystem that is under significant anthropogenic stress (Bahartan et al., 2010; Lazar et al., 2008). This paper presents the first long-term (13 months), continuous high temporal resolution temperature measurements in deep water in the Northern Gulf. A moored profiling carrier (MPC) also collected the first high-frequency temperature profiles in deep water in the Northern Gulf. These data show that the stratification exhibits considerable variability over a range of periods and that seasonal transitions are often dramatic, not slow and gradual, as previously deduced from monthly hydrographic data (Paldor and Anati, 1979; Wolf-Vecht et al., 1992; Ben-Sasson et al., 2009) and numerical simulations (Biton and Gildor, 2011a, 2011b, 2011c). These dramatic changes can be explained only partially by atmospheric forcing, with the rest likely due to the internal ocean dynamics. The onset of stratification in spring is marked by episodic pulses of warm water that can increase the temperature by approximately 2° in a matter of days. Additionally, the semi-diurnal internal tide can generate large amplitude (30–50 m) isotherm displacements in the stratified upper 200 m during summer. In addition to advected heat and internal tides, these data show that the stratification varies in response to inertial motions, convective mixing, and eddies.

The seasonality of the stratification in the Gulf has been shown to have significant impacts on both the dynamics and the ecosystem. Seasonal changes in the stratification affect the exchange flow with the Red Sea (Biton and Gildor, 2011c), have been correlated with the magnitude of the semi-diurnal tidal currents (Carlson et al., 2012; Genin and Paldor, 1998; Monismith and Genin, 2004), and also affect the magnitude of the wind-driven circulation (Berman et al., 2000). Additionally, deep winter mixing ventilates the deep waters and mixes nutrients into the photic zone (Badran et al., 2005; Cornils et al., 2007; Häse et al., 2006; Genin et al., 1995; Lazar et al., 2008;

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Silverman and Gildor, 2008). Nutrient enrichment of surface waters by deep winter convective mixing triggers blooms of phytoplankton (Genin et al., 1995; Lindell and Post, 1995) and zooplankton (Cornils et al., 2007; Farstey et al., 2002) that peak at the beginning of the restratification phase.

Till date, however, very few detailed studies of the stratification have been published, with most relying on monthly, weekly, or irregularly spaced vertical profiles of temperature and salinity (Paldor and Anati, 1979; Wolf-Vecht et al., 1992; Lindell and Post, 1995; Cornils et al., 2007; Ben-Sasson et al., 2009). The few high-frequency measurements of stratification in the Northern Gulf (Dunckley et al., 2012; Meeder et al., 2012; Steinbuck et al., 2011; Steinbuck et al., 2010) were either of limited duration or conducted in shallow depths. Additionally, many numerical studies (Berman et al., 2003; Biton and Gildor, 2011a, b, c) employed monthly climatological surface forcing and, therefore, could not reproduce higher frequency variability in the stratification.

Here we compile recent moored observations in the Northern Gulf to investigate the full range of variability in the stratification. In addition, this paper shows that estimates of the mixed layer depth (MLD) from single vertical profiles are prone to errors of several tens of meters. Methods to quantify this error are suggested and the impacts of such errors on previous findings are discussed.

1.1. Study area

The Gulf is a long (180 km), narrow (5–25 km), and deep (maximum depth >1800 m; average depth ~ 800 m) sub-tropical marginal sea (Manasrah et al., 2007). The prevailing climate is arid, winds are primarily northerly (Afargan and Gildor, in preparation; Ashkenazy and Gildor, 2009; Berman et al., 2000; Manasrah et al., 2007), evaporation is high (1–2 m yr^{-1}), and precipitation and runoff are negligible (Wolf-Vecht et al., 1992; Ben-Sasson et al., 2009). The Gulf is connected to the Red Sea via the shallow (252 m) Straits of Tiran (Fig. 1) and the Red Sea, in turn, is connected to the Indian Ocean through a shallow (137 m) sill near Bab el Mandab (Genin, 2008; Siddall et al., 2002; Smeed 2004). These shallow sills prevent cold, dense, deep water from penetrating into the Red Sea and the Gulf (Wolf-Vecht et al., 1992; Genin et al., 1995; Genin, 2008). The limited exchange and large evaporation rate make the Gulf warm (>20 °C) and hypersaline (>40 psu) at all depths (Paldor and Anati, 1979; Genin et al., 1995; Genin, 2008; Ben-Sasson et al., 2009). Furthermore, the observed annual ranges of temperature and salinity variability are only 6–7 °C and ~ 0.5 psu, respectively (Paldor and Anati, 1979; Cornils et al., 2007; Silverman and Gildor, 2008). This range of warm temperatures permits tropical coral reef to exist at sub-tropical latitudes (Genin, 2008).

Temperature has been used as an indicator for density in the Gulf as the relatively warm water makes the seawater density more sensitive to changes in temperature than to changes in salinity (Genin et al., 1995; Farstey et al., 2002; Biton and Gildor, 2011a; Carlson et al., 2012). The vertical structure of the Gulf, therefore, is more sensitive to the net heat flux than other subtropical seas and the stratification exhibits strong seasonality (Lindell and Post, 1995; Cornils et al., 2007; Genin, 2008; Ben-Sasson et al., 2009; Biton and Gildor, 2011a, b). The annual cycle of the stratification in the Gulf can be divided into the restratification phase (April–August) and the mixing phase (September–March; Biton and Gildor, 2011b).

During the mixing phase, surface heat loss to the atmosphere drives deep (>400 m) convective mixing that usually peaks in mid-March and in extreme years can exceed 800 m (Genin, 2008; Genin et al., 1995; Biton and Gildor, 2011a), though considerable interannual variability in the depth of the wintertime convective mixing has been observed (Wolf-Vecht et al., 2002; Lazar et al., 2008; Silverman and Gildor, 2008; Carlson et al., 2012). Deep water forms throughout the entire Gulf by shelf and open water convection and is an important contributor to the intermediate and deep water of the Red Sea (Wolf-Vecht et al., 1992; Plähn et al., 2002; Niemann et al., 2004; Cornils et al., 2007; Genin, 2008; Biton et al., 2008; Silverman and Gildor, 2008; Biton and Gildor, 2011a).

The restratification phase usually begins in March or April as advected heat from the Northern Red Sea rapidly warms the upper layer of the Gulf (Biton and Gildor, 2011b). The warmer water from the Northern Red Sea increases the volume of the surface layer of

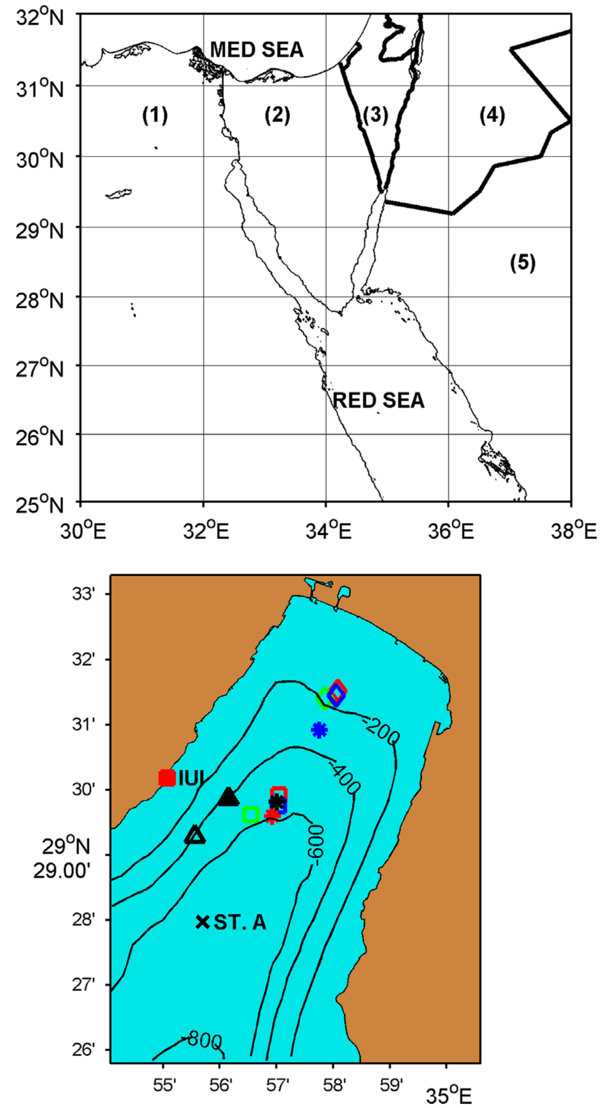

Fig. 1. Top: The Northern Red Sea and surroundings: (1) Mainland Egypt; (2) Egyptian Sinai; (3) Israel; (4) Jordan; (5) Saudi Arabia. The Gulf of Eilat/Aqaba is the northeastern extension of the Red Sea, with the Sinai Peninsula to the west, Israel and Jordan to the north, and Saudi Arabia to the east. The Gulf of Eilat/Aqaba is surrounded by the Sinai Peninsula to the west, Israel and Jordan to the north, and Saudi Arabia to the east. The study area is located in the Northern Gulf at the southern tip of Israel (3). Bottom: The northern Gulf of Eilat/Aqaba is shown along with mooring locations and selected isobaths (in meters). The long-term, fixed depth moorings DM1 and DM2 are indicated by open and filled triangles, respectively. The short-term, fixed depth moorings deployed near the 200 m and 500 m isobaths are denoted by diamonds and squares, respectively. The summer 2010, fall 2010, and winter 2010 deployments are indicated by red, green, and blue coloring, respectively. The February 2011, June 2011, and March 2012 profiler deployment locations are shown by red, blue, and black asterisks. The location of the InterUniversity Institute (IUI) for Marine Sciences is represented by a red square on the west coast. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)