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Rapid Subsurface Ocean Warming in the Bay of Fundy as Measured by Free-Swimming Basking Sharks

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It is widely recognized that the western North Atlantic has recently warmed very rapidly. Sea surface temperatures (SST) in 2012 were measured to be 1–3°C higher than the 1982–2011 average (Mills et al., 2013). In particular, in continental shelf regions, such as the Gulf of Maine (GoM), there was pronounced warming, with SSTs > 2°C higher than normal, to almost 20°C, during this "ocean heat wave." Although the specific cause of this warming trend is still being debated, it may have implications for local fauna; concurrent shifts in the distributions of marine organisms associated with local climate changes have already been reported (Nye et al., 2009; Pinsky et al., 2013). Ocean warming trends are usually discussed in terms of SST changes, with few studies considering events in benthic habitats. The GoM (Figure 1) is monitored by the Northeastern Regional Association of Coastal and Ocean Observing Systems (NERACOOS, http://www.neracoos.org) buoy system that uses remote buoys with probes to 200 m, though only in a few fixed locations. The goal of this study was to determine whether the 2012 warming trend extended into subsurface habitats in the northern reaches of the GoM and adjacent Bay of Fundy (BoF). This highly productive body of water is located in the northern corner of the GoM, but has different oceanographic patterns due to its enormous tides (changing by 6–12 m twice daily). Whether BoF water column temperature profiles mirror those of the central GoM has been unclear, as there are no oceanographic sensing buoys present.

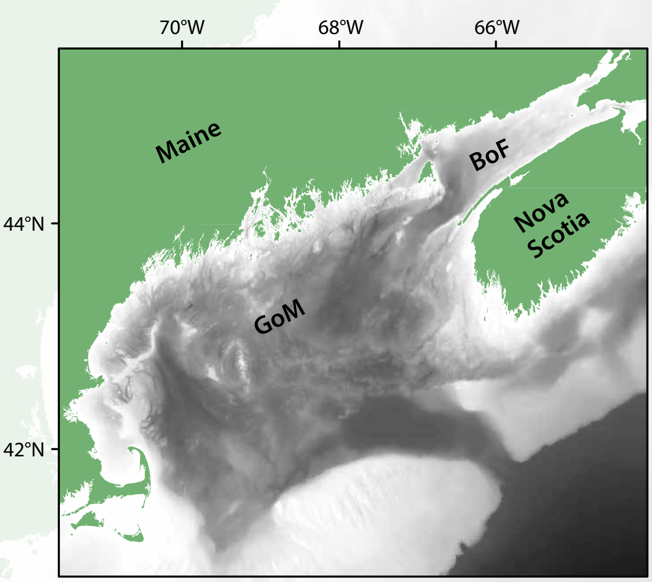
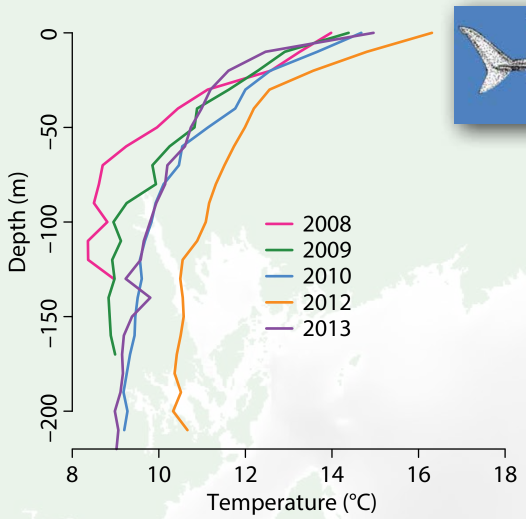


Figure 1. Regional map showing the Gulf of Maine (GoM) and Bay of Fundy (BoF) study area.

We used a novel means to collect water temperature profiles while studying the diving behavior of basking sharks (*Cetorhinus maximus*). We deployed 11 electronic archival tags on sharks in the BoF during August and September from 2008 to 2013 (except 2011). Tags recorded depth, temperature, and speed every second for four to five days. From the temperature-depth data, we created temperature profiles of the water column, integrated over the five-day deployment period. Sharks moved throughout the BoF, and diving data revealed that they use the entire water column (the deepest part of the BoF is ~ 230 m). Data from these tags revealed a dramatic increase in water temperatures from 2008 to 2012 (Figure 2). Most surprising was the fact that this increase occurred not just at the surface (where SST is measured remotely) but throughout the entire water column. From 2008 to 2012, we measured an SST increase from 13.1°C to > 16°C during late summer, and temperatures rose from 8.3°C to 10.8°C below 100 m. In the BoF, 2012 was indeed much warmer than previous years, as it was in the GoM, but in addition, bottom temperatures had been steadily increasing by ~ 0.6°C per year since 2008. The year 2013 (Figure 2) more closely resembled 2010.

Unfortunately, there are few comparative data on water column temperatures



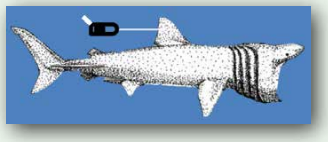


Figure 2. Average water temperature profiles from the surface to the bottom of the Bay of Fundy, as recorded by tags deployed on basking sharks during August and September 2008–2013. Depth-specific temperature data for all sharks from each year were pooled to construct each profile.

in the BoF, especially in the 100–230 m depth range. Templeman (1936) measured temperatures of 10.5–11.4°C in shallow waters (4–8 m) in August 1932. Hachey (1949) reported that summer surface temperatures "do not reach much above 12.2°C" while those on the bottom (to 90 m) "may" reach 10.0°C. For the period from 1921 to 1978, Trites and Garrett (1983) described SST of 11°C and bottom temperatures (< 100 m depth) at 10°C for August 1958, and maximum SST of 15°C in August 1976. More recently, Petrie and Jordan (1993) described mean water temperatures (< 12 m depth) of 11–12°C during August and September 1979–1990. Finally, monthly conductivity-temperature-depth (CTD) casts from 2000 to 2012 at the Prince 5 station (44.93°N 66.85°W) yielded bottom temperatures between 80 m and 99 m ranging from 7.7–11.2°C in August (highest value, 2012), and 9.4–12.2°C in September (highest value, 2012) (accessed via http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/hydro/index-eng.html). The only deepwater data available (Michaud and Taggart, 2007) show temperatures of 9–10°C from 100–200 m water depth during August and September 2002. These previous data indicate that 2012 was a very warm year at the surface of the BoF; however, the lack of data below 100 m makes deeper water trends more difficult to evaluate. The 3.7°C SST increase over 2008–2012 was not unexpected, as adjoining water bodies also exhibited higher SSTs. The 2.5°C increase throughout the deeper part of the water column was much more profound, given the enormous thermal input required to heat this well mixed, tidally driven system.

It is clear that subsurface water temperatures in the BoF differ from those in the adjoining GoM (Figure 3). Mean temperatures from NERACOOS buoy N01 (150 nm SSE of our study area) at 150 m from the same time frame as our tag deployments (August 13 to September 12) were warmer (by 0.5–1.0°C) than those of the BoF below 100 m, with the exception of 2012, when temperatures agreed. Thus, BoF waters warmed to a relatively greater degree from 2010 to 2012 than the GoM, and while BoF temperatures in 2013 declined slightly, those in the GoM did not. The differences between the two regions was not consistent (range 0.01–1.1°C), indicating that GoM temperatures cannot predict those in the BoF, and a separate, independent monitoring system is needed to measure subsurface temperatures in the BoF.

Tracking changes below the surface is likely more important than SST data for many species that use deeper waters for foraging, such as the calanoid copepods that are the critical base of the BoF food web and are primary prey for North Atlantic right whales and basking sharks, species of conservation concern. Another benthic animal of considerable ecological and economical interest is the American lobster. Along with increased temperatures, we have documented a significant decrease ($P < 0.001$) in fecundity in female lobsters over the period 2008–2013 in the BoF, at the rate of 10% per year. Accompanying the decrease in reproductive output was a steady increase in local lobster landings (DFO, 2013). Although at this point we cannot tease apart density-dependent effects from those of temperature on decreased

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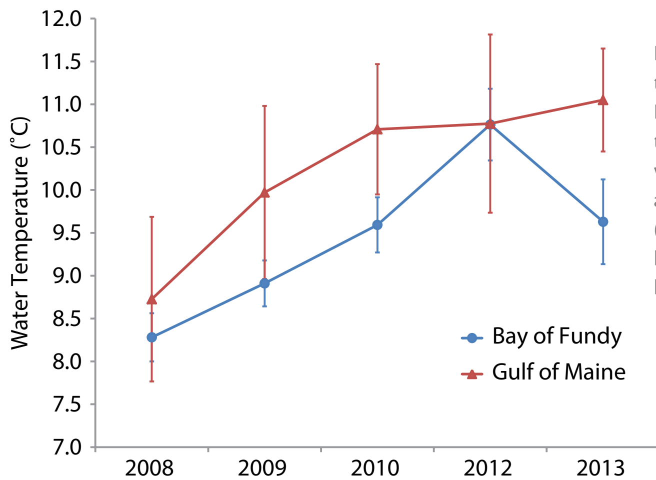

Figure 3. Mean water temperatures in the Bay of Fundy (below 100 m) and in the Gulf of Maine (at 150 m water depth) during August and September 2008–2013 (excluding 2011). R^2 = 0.62 between the regions. Error bars are standard deviation.

fecundity (it is likely a function of both), the fact that female lobsters require cold temperatures for ovarian development (Waddy et al., 1995), combined with increased catch rates, could be cause for future concern for this lobster population. Unfortunately, the true test of this hypothesis will not come for another six to seven years, when lobster larvae will reach market size.

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