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Contributions of recent barometric pressure trends to rates of sea level rise in southeastern Massachusetts (USA)

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HIGHLIGHTS

- Trends in barometric pressure and sea level at Nantucket and Boston (Massachusetts) were analyzed.
- Declining barometric pressure has influenced sea level rise during recent decades.
- Barometric pressure trends are linked with air temperature increases and NAO patterns.
- The analyses show how regional atmospheric conditions affect coastal hydrology.

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ABSTRACT

Rates of sea level rise can vary substantially along coastlines due to the many factors. These include inputs of freshwater from glaciers, vertical repositioning of land masses, wind conditions, ocean and atmospheric circulations, regional and local hydrology, salinity, and barometric pressure. This study focused on the effects that recent trends in the barometric pressure have had on sea level rise in southeastern Massachusetts (USA) between 1982 and 2015. Barometric pressure and sea level have a direct inverse relationship in that reductions in the former translate to increases in the latter, and vice versa. Analysis of uncorrected vs. barometrically-corrected sea level data from National Oceanographic and Atmospheric Administration (NOAA) tide gauges in Boston Harbor and 54 nautical miles southeast of Nantucket indicate that between 6% and 21% of sea level rise can be attributed to significant declines barometric pressure, and the magnitude of the effect is highly seasonal. These trends may be the result of rising air temperatures in the region, and may strengthen with continued climate warming. The results help further our understanding of how local atmospheric trends on the order of several decades can influence the interpretation of relative sea level rise and assessments of coastal vulnerability to climate change. This is particularly important from the standpoint of salt marsh ecosystems, which have undergone major changes over the last several decades due to their inability to accrete vertically at the same rate as sea level rise, and are very sensitive to even minor hydrologic change over relatively short time scales.

1. Introduction

Air temperature and sea level rise (SLR) are two of the most common variables discussed within the context of climate change. They are intricately related in that the thermal expansion of water accounts for a large proportion of global sea level rise (SLR) (Wigley and Raper, 1987; Carson et al., 2016). Contributions of glacial meltwater (Meier et al., 2007), land subsidence or uplift (Teferle et al., 2006), winds (Timmermann et al., 2010), ocean and atmospheric circulation patterns (Yan et al., 2004; Sallenger et al., 2012; Kousari et al., 2013), changing hydrology of large basins (Pelling and Mattias-Green, 2013), and salinity (Durack et al., 2014), are also important.

Another factor acting on sea level in a very direct way, and across many spatial scales, is barometric pressure (BAR), which either forces the water surface downwards or allows it to rise. In this inverse relationship, a reduction in barometric pressure of 1 hectoPascal (hPa) translates to a ∼1 cm rise in sea level elevation, and conversely, and rise in BAR of 1 hPa equates to a lowering of sea level by 1 cm (1 hPa = 0.01 millibar). BAR effects on sea level are most notable during storms as extreme low pressures during these events can produce storm surges well above predicted tide levels and cause major erosion and flooding of coastal areas. However, the influence of longer-term trends in

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BAR on the rate of SLR has received little attention. Moreover, while most satellite altimeter data are pressure-corrected, datasets from tide recorders usually are not. For example, tidal data generated by the National Oceanographic and Atmospheric Administration (NOAA), which has the most extensive network of tide gauges in the US, is not barometrically-corrected—the obvious reason being that the principal objective of collecting these tidal data is to record actual sea level elevations, irrespective of which factors contribute to them.

Determining the extent to which BAR may be contributing to sea level trends is important for understanding and interpreting spatial and temporal variability in SLR and its impact along coastlines, and within the broader framework of climate change. One coastal ecosystem on the frontlines of SLR is the salt marsh. Salt marshes are extremely productive and offer a wide variety of well-known ecological and socio-economic services (Adam, 1993; Costanza et al., 1997; Nixon and Oviatt, 1976; Nixon, 1982; Shepard et al., 2011; Teal, 1986; Valiela et al., 2002). Tidal dynamics greatly influence these systems, regulating plant species composition, productivity, carbon sequestration, biogeochemistry, and fauna (Bertness, 1991; Kathilankal et al., 2008; Mendelssohn and Morris, 2000; Naidoo et al., 1992; Nuttle and Hemand, 1988; Rozas, 1995; Silvestri et al., 2005; Watson et al., 2014). Accordingly, changes in tidal hydrology due to SLR can have major ecological impacts. Currently, it appears that many salt marshes of the northeastern US are vulnerable to SLR rise due to their inability to accrete vertically (i.e., undergo a positive elevation change through root growth and sedimentation) at a comparable rate (Bricker-Urso et al., 1989; Carey et al., 2015; Chmura et al., 2001; Donnelly and Bertness, 2001; Nicholls and Cazenave, 2010; Orson et al., 1985; Turner et al., 2000; Warren and Neiring, 1993).

In a previous paper, Smith (submitted for publication) showed that BAR exhibited a decreasing trend from 1983 to 2011 in Atlantic Ocean waters offshore of Nantucket (MA), with the strongest declines in summer and fall months. This coincides with significant air temperature increases in all seasons during this period (Smith, submitted for publication). Others have similarly observed multidecadal changes in BAR in various regions throughout the world. Chase et al. (2003) reported increases of sea level pressure over Africa and Asia since ∼1950, as did Piervitali et al. (1997) in the Mediterranean. Gillett et al. (2003) found increases in sea-level pressure between 1948 and 1998 over the subtropical North Atlantic Ocean, southern Europe and North Africa, contrasted by decreases in the polar regions and the North Pacific Ocean, in response to human influence. Wendler and Shulski (2009) tracked barometric pressure declines between 1906 and 2006 during the winter in Fairbanks, Alaska. Nabil et al. (2013) documented a steady rise in air pressure in Egypt since 1978 and sea level pressure in the central Artic decreased during 1979–1994 according to Walsh et al. (1996).

With respect to how changes in atmospheric pressure trends have influenced sea level, Church et al. (2004) reported that the rate of eustatic global mean sea level rise during 1993–2000 was 0.3 mm/year lower when barometric correction was applied. Church et al. (2006) also discovered that SLR was ∼2 mm/year less than rates determined from tide gauge data alone in the western Pacific and eastern Indian Ocean. In southern Africa, barometric pressure declined along the west coast at 1.63 hPa per decade (1957–2006), remained relatively unchanged along the southern coast (1959–2006), and increased at 0.30 hPa per decade along the east coast (1967–2006) (Mather et al., 2009). These BAR trends enhanced or reduced rates of sea level rise in these three regions. Singh and Aung (2004) showed that sea level in the southern Pacific responded to pressure changes during La Niña which and El Niño events between 1992 and 2005, which altered the calculated rate of SLR. Torres and Tsimplis (2013) reported that sea level rise during 1993–2010 in the Caribbean Sea being was significantly lower when BAR-corrected data was used.

Across much of the world, however, long term changes in BAR and its potential contribution to relative rates of SLR (RSLR) (i.e., rates of SLR specific to particular locations, which may be very different from eustatic SLR) have not been examined. This is somewhat surprising given that RSLR can vary over relatively small spatial scales and may have low correspondence with the global mean (Stammer et al., 2013; Ezer, 2013). For example, current rates of RSLR along the northeastern Atlantic coast range between 1.76 and 3.58 mm/year (https://tidesandcurrents.noaa.gov/sltrends). Additionally, seasonal differences are not well-understood, although it is precisely the seasonality of sea level changes that are potentially most important to coastal ecosystems. In this regard, spring through early fall trends in RSLR may be the most biologically meaningful, since this period is when both vegetation and wildlife is most biologically active, while winter trends may be more critical to physical processes such as erosion and flooding.

The objective of this analysis was to determine the extent to which recent multidecadal trends in BAR in the Boston–Cape Cod region of southeastern Massachusetts may be influencing sea level variation, with an emphasis on rates of annual and seasonally-based change and relationships with the North Atlantic Oscillation (NAO). The results are informative in terms of understanding the driving mechanisms behind spatial variances in RSLR along coastlines in response to climate change. With a major issue being salt marsh losses in response to RSLR over decadal time scales, this information is particularly relevant. Erosion and shoreline change are also at the forefront of environmental management concerns in this region. The findings may be useful to scientists and managers in terms of understanding interactions between the coastal ocean and its adjacent land masses and ecosystems.

2. Materials and methods

Hourly barometric pressure data collected from two NOAA weather stations (Rosemont, Setra barometers) near Nantucket (station 44008, 54 nautical miles southeast of Nantucket, MA) and Boston Harbor (station 44013,16 nautical miles East of Boston, MA) were downloaded from http://www.ndbc.noaa.gov (Fig. 1). The National Data Buoy Center (NDBC) calibrates each sensor prior to deployment. After two years they are replaced with newly calibrated instruments and the old ones are returned for post-deployment calibration, refurbishment, and recalibration. The longest period of record for verified BAR data from these sites was 1982–2015 for Nantucket and 1984–2015 for Boston. Hourly NOAA tidal data were acquired from tide gauges in Boston Harbor (8443970 Boston, MA) and Nantucket Harbor (8449130 Nantucket Island) for these same years (https://tidesandcurrents.noaa.gov). Boston Harbor tidal data were available in meters NADV88, whereas Nantucket data were in meters relative to the National Tidal Datum Epoch (NTDE). Sea surface air temperatures were also available in these datasets.

RSLR for both sites during the period of record was calculated using linear regression, with the slope indicating increase in mean sea level in mm/year. The tidal data then were corrected using an inverse barometric correction factor. To do this, the mean BAR for the entire time series was subtracted from each hourly BAR value to determine its variance from the long-term mean. The magnitude of these variances (in hPa) were then translated into sea level corrections based on the inverse relationship of δBAR (hPa) $= -\delta$ sea level (cm). In doing this, all sea level data were normalized to a standard BAR value (in this case the mean of time series) to remove its influence. Corrected hourly sea level elevations were calculated as: [sea level in meters] + [BAR in hPa − mean BAR for 1985–2015].