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Marked contrast in wind-driven upwelling on the southeastern Nova Scotia coast in July of two years differing in ENSO conditions

by

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Abstract

Upwelling occurs on several coasts of the world, but it has mostly been studied on eastern ocean boundaries. We investigated upwelling on a western ocean boundary for which limited information exists. Using daily in-situ data on sea surface temperature (SST), we found a marked contrast in coastal cooling between July 2014 (pronounced) and July 2015 (weak) at two locations 110 km apart on the Atlantic coast of Nova Scotia, Canada. These findings are consistent with a marked interannual difference in wind-driven upwelling. On the one hand, southwesterlies (which cause upwelling on this coast) were more frequent in July 2014 than in July 2015. On the other hand, Bakun's upwelling index (which is based on wind data and geographic information) indicated that coastal upwelling was more common and intense in July 2014 than in July 2015, while the reverse was true for downwelling. Interestingly, a strong El Niño event occurred in July 2015, while no El Niño (or La Niña) conditions happened in July 2014. In a recent book evaluating upwelling systems around the world, the system that is the focus of the present study was not included. Therefore, our findings should stimulate future research on upwelling on the Atlantic Canadian coast, in that way helping to further develop the knowledge base for western ocean boundaries.

Key words: Atlantic Canada, Bakun's index, Nova Scotia, sea surface temperature, upwelling

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Introduction

Coastal upwelling refers to the rise of deep, cool waters to the surface of coastal marine environments as warmer surface waters move offshore. As upwelled waters are rich in inorganic nutrients, they are typically associated with a high biological productivity and important fisheries (FAO 2018). A common cause of coastal upwelling involves the action of winds and the Coriolis force. In the northern hemisphere, persistent alongshore winds blowing with the coast on the left (on the right in the southern hemisphere) generate an offshore surface Ekman transport that triggers coastal upwelling (Stewart 2008). There are four major wind-driven upwelling systems in the world, all of them located on eastern ocean boundaries: the California Current system, the Humboldt Current system, the Canary/Iberia Current system, and the Benguela Current system. Due to their magnitude and environmental relevance, most research on coastal upwelling has been done, by far, on these systems (Kämpf & Chapman 2016).

Coastal upwelling also occurs on western ocean boundaries (Kämpf & Chapman 2016; Varela et al. 2018). As less information is available for these systems, more research is necessary to improve our global understanding of upwelling. This article focuses on the Nova Scotia coast, a western ocean boundary located in eastern Canada (Fig. 1). Off southwestern Nova Scotia (in the outer Gulf of Maine), upwelling is mainly caused by tidal mixing and submarine topography (Tee et al. 1993; Chegini et al. 2018). However, on the southeastern (open Atlantic) coast of Nova Scotia, upwelling is mainly caused by wind action (Petrie et al. 1987; Shan et al. 2016). On the southeastern Nova Scotia coast, upwelling has been noted particularly in July, favoured by southwesterly winds that then blow parallel to the shore (Petrie et al. 1987). However, it is unknown to what extent July upwelling may change between years. In addition, basic comparisons of upwelling with other coasts remain unavailable. To address these knowledge gaps, here we use daily in-situ data on sea surface temperature (SST) to show a marked contrast in coastal cooling between July 2014 and July 2015 and show that changes in the frequency of southwesterly winds were related to such a contrast. Then, we calculate an upwelling index based on wind and geographic data (Bakun 1973) to further support the notion that differences in wind-driven upwelling explain the SST contrast between both such periods. Lastly, we make basic comparisons of upwelling with other coasts of the world for which Bakun's index has previously been reported.

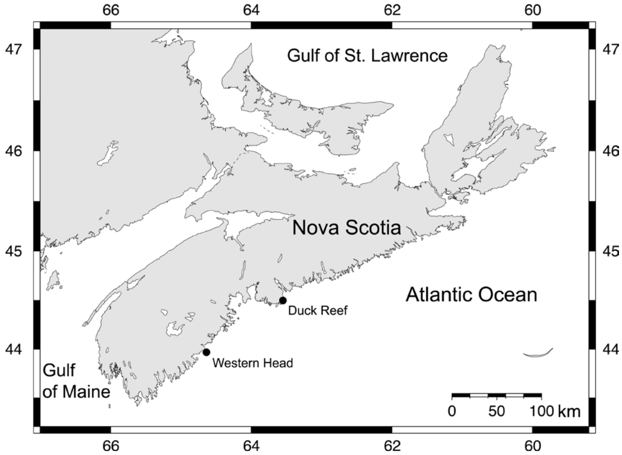

Figure 1

Map of Nova Scotia indicating the two intertidal locations surveyed for this study

Materials and methods

A study done in 1984 on the southeastern (open Atlantic) coast of Nova Scotia (Petrie et al. 1987) indicated that, in July, coastal SST at shallow depths (6–20 m deep) decreased relative to June because of wind-driven upwelling. August SST returned to the seasonal rise expected from heat flux from the atmosphere. Therefore, given our research goals, we focused our study on the month of July, monitoring also late June simply as a reference. Specifically, we measured SST daily between 20 June and 31 July of two consecutive years (2014 and 2015) at two intertidal locations approximately 110 km apart: Duck Reef (44.4913 N, 63.5270 W) and Western Head (43.9896 N, 64.6607 W; Fig. 1). These are wave-exposed locations that face the open Atlantic Ocean directly, without any obstructions. The intertidal substrate is stable bedrock and there are no human-made constructions nearby.

We measured temperature with submersible loggers (HOBO Pendant logger, Onset Computer, Bourne, MA, USA) that were attached to the intertidal zone with eye screws and cable ties, allowing almost no contact between the loggers and the intertidal rocky substrate. At each location, we installed four loggers in 2014 and two in 2015 just above the mid-intertidal zone (the tidal amplitude is 2.2 m on this coast). At each location, the replicate loggers were located tens of m apart from one another. Each logger recorded temperature every 30 min. From the resulting time series, we extracted the values of daily SST, which we considered to be the temperature recorded closest to the time of the highest tide of each day (when the loggers were fully submerged in

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seawater). We determined the time of such tides using information for the nearest tide reference stations: Sambro (44.4833 N, 63.6000 W) for Duck Reef and Liverpool (44.0500 N, 64.7167 W) for Western Head (Tide and Current Predictor 2019). For each location and year, daily SST was highly correlated between the replicate loggers (average r = 0.98), so we averaged the corresponding daily values to generate one time series of daily SST data for each location and year. We then compared SST between 2014 and 2015 for each location.

Since the SST data revealed a marked difference in cooling between July 2014 and July 2015 (see Results), we investigated if wind data could explain such a difference, under the premise that southwesterly winds cause upwelling (and thus cooling) on this coast (Petrie et al. 1987). The studied coast has an average orientation of approximately 60° measured clockwise from the north (0°). Thus, for each day of July 2014 and July 2015, we counted for each location the number of hours in which winds blew from the southwest (hereafter, "duration of SW winds") from any direction between 230°–250° measured clockwise from the north. We made these calculations using information from the nearest sources of wind data: Herring Cove Buoy (44.5586 N, 63.5453 W; SmartAtlantic 2019) for Duck Reef and Western Head Station (43.9900 N, 64.6642 W; Government of Canada 2019) for Western Head. We then compared the daily duration of SW winds between July 2014 and July 2015 for each location with two-sample *t*-tests (Sokal & Rohlf 2012).

Finally, for each day of July 2014 and July 2015 for each location, we calculated Bakun's upwelling index (UI), which depends on wind data and geographic information (Bakun 1973). For each location, we used the wind data produced by the closest data source: Herring Cove Buoy for Duck Reef and Western Head Station for Western Head. We calculated UI in three steps. In the first step, we used equation 4.2 in Stewart (2008) to calculate wind stress (τ) as:

$$\tau = \rho_{air} C_D U^2$$

where ρ_{air} is air density (1.28 kg m^{-3}), C_D is the wind drag coefficient (0.0015, based on Kämpf & Chapman 2016), and U is wind speed (in m s^{-1}). Since wind speed data were available hourly for the two wind data sources mentioned above, we calculated wind stress for each hour. In the second step, we used equation 2.2 in Kämpf & Chapman (2016) to calculate Ekman transport (M) as:

$$M = \frac{\tau}{\left(\rho_{seawater} |f|\right)}$$

where $\rho_{seawater}$ is seawater density (1026 kg m^{-3}) and f is the Coriolis parameter. The Coriolis parameter depends only on latitude (φ) and was calculated as:

$$f = \frac{4\pi}{T_{earth}\, sin(\varphi)}$$

where T_{earth} (86 400 s) is the period of the Earth's rotation (Kämpf & Chapman 2016). In the third and last step, we used equation 2.3 in Kämpf & Chapman (2016) to calculate UI as:

$$UI = M\ cos(\alpha)$$

where the angle α is the difference between the average orientation of our coast (60°, measured clockwise from the north) and the angle (also measured clockwise from the north) denoting wind direction with the wind vector's origin centered in the target location. For example, for our coast, a southwesterly wind blowing perfectly parallel to the shore yields α = 0° and, thus, cos(α) = 1. Since wind direction data were also available hourly for the two wind data sources mentioned above, we calculated UI for each hour. To calculate daily UI values for each location, we averaged the corresponding hourly UI values. In this study, we express UI as cubic meters of seawater transported per second per 100 m of coastline. Positive UI values indicate upwelling, whereas negative values indicate downwelling (Kämpf & Chapman 2016).

Results

Daily SST was highly correlated between Duck Reef and Western Head for the studied periods of 2014 (r = 0.86, $p < 0.001$) and 2015 (r = 0.84, $p < 0.001$). In late June 2014, SST ranged between 9–14°C at Duck Reef and 8–13°C at Western Head (Fig. 2). However, during the first half of July 2014, SST decreased markedly at both locations, reaching minima of 6°C at Duck Reef and 4°C at Western Head (Fig. 2). During the rest of July 2014, SST alternated drops and rises at both locations (Fig. 2). In late June 2015, SST showed a similar range than in late June 2014 (Fig. 2). However, in July 2015, SST did not exhibit the pronounced decrease seen in July of the previous year, in fact showing a mildly increasing trend (also with alternating drops and rises) towards the end of the month (Fig. 2).

Southwesterly winds were more common in July 2014 than in July 2015 at both locations. For Duck Reef, the mean daily duration of SW winds was 10.4 h (range = 0–22 h) in July 2014 and only 2.3 h (range = 0–9 h) in

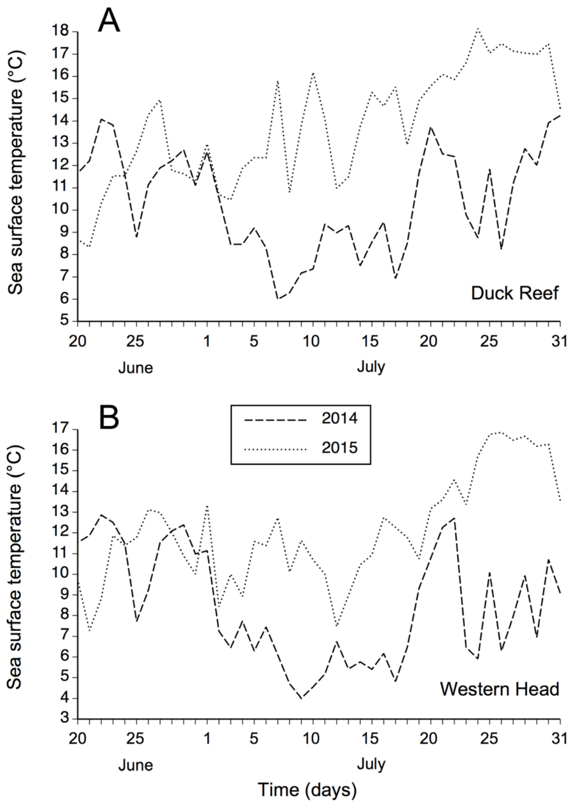

Figure 2

Daily change of sea surface temperature between 20 June and 31 July of 2014 and 2015 at (A) Duck Reef and (B) Western Head

July 2015, which was a significant difference (*t* = 5.86, *p* < 0.001). For Western Head, the mean daily duration of SW winds was 5.5 h (range = 0–12 h) in July 2014 and only 2.9 h (range = 0–9 h) in July 2015, which was also a significant difference (*t* = 3.18, *p* = 0.003).

The UI was highly correlated between Duck Reef and Western Head in July 2014 (*r* = 0.91, *p* < 0.001) and July 2015 (*r* = 0.85, *p* < 0.001). In July 2014, the UI was mostly positive, peaking at 190 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ at Duck Reef and 161 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ at Western Head. These peaks in UI occurred in the first week of July (Fig. 3) and were followed a few days later by the lowest SST values recorded for this study (Fig. 2). Similarly high values of UI were uncommon in July 2014, however, because 81% of the 27 positive values of daily UI for Duck Reef were lower than 100 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$, while 86 % of the 28 positive values of daily UI for Western Head were lower than 50 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$. The few negative values of UI recorded in July 2014 were not lower than –6 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ (Fig. 3). In July 2015, positive UI values were also common, but generally lower than in July 2014, reaching peaks of only 68 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ at Duck Reef and 52 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ at Western Head (Fig. 3). In July 2015, negative values were more frequent than in July of the previous year, reaching minima of –65 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ at Duck Reef and –16 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ at Western Head (Fig. 3). Overall, mean monthly UI (averaging all 31 daily values) was 57 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ for Duck Reef and 30 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ for Western Head in July 2014 and only 11 $m^3\ s^{-1}$ (100 m of coastline)$^{-1}$ for both Duck Reef and Western Head in July 2015.

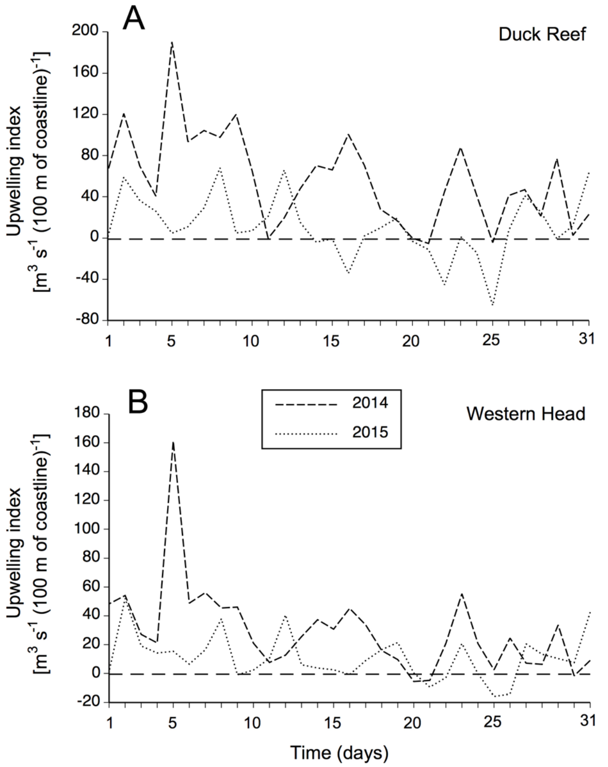

Figure 3

Daily change of Bakun's upwelling index between 1–31 July 2014 and 2015 at (A) Duck Reef and (B) Western Head

We note that, in July 2014, the two periods of most pronounced cooling (1–7 and 20–24 July at Duck Reef and 1–9 and 22–24 July at Western Head; Fig. 2) occurred around periods of neap tides (Fig. 4).

Discussion

A study in 1984 showed that wind-driven upwelling can occur in July on the Atlantic coast of Nova Scotia (Petrie et al. 1987). The present study reveals that

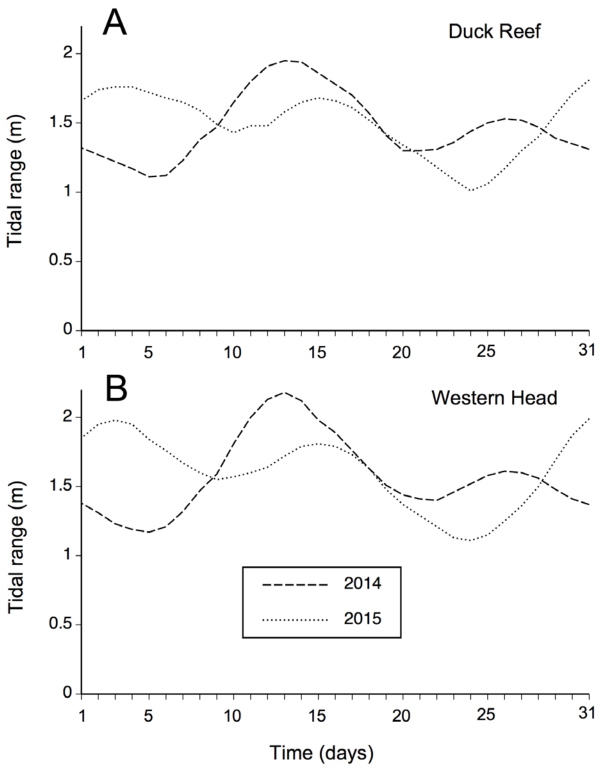

Figure 4

Daily change of tidal range (difference between the highest and lowest tide of each day) between 1–31 July 2014 and 2015 at (A) Duck Reef and (B) Western Head

marked differences can occur in July of consecutive years. This was evident in the dynamics of daily SST, as seawater cooling was prevalent in July 2014 but inconspicuous in July 2015. These are valuable results because they are based on in-situ SST data, as opposed to satellite SST data, which are often less accurate (Smale & Wernberg 2009) and sometimes even unavailable for some days. The wind direction data provided further support, as southwesterly winds (which favour coastal upwelling and thus cooling; Petrie et al. 1987) were more common in July 2014 than in July 2015, about twice as common at one location and four times at the other location. Ultimately, the values of UI, obtained independently from the SST data, confirmed the marked difference in wind-driven upwelling between both periods, revealing that upwelling was more frequent and intense in July 2014 than in July 2015 (when a few days with clear downwelling conditions were even registered). The occurrence of pronounced cooling around neap tides in July 2014 suggests that tidal mixing is unimportant as a driver of cooling on the studied coast (cooling would be expected under spring tides; Kang & Lee 2014; Shanks et al. 2014; Iwasaki et al. 2015), as discussed in previous studies for this coast (Petrie at al. 1987; Shan et al. 2006). This is possibly partially a result of the relatively limited tidal amplitude of this coast (2.2 m).

Our UI values are also useful to make basic comparisons with other coasts of the world. The highest values that we encountered for Nova Scotia, 190 m^3 s^{-1} (100 m of coastline)$^{-1}$ for Duck Reef and 161 m^3 s^{-1} (100 m of coastline)$^{-1}$ for Western Head in July 2014, are clearly lower than the highest values reported for the major upwelling systems from eastern ocean boundaries, where UI can reach or surpass 500 m^3 s^{-1} (100 m of coastline)$^{-1}$ (Schwing et al. 1996; Demarcq 1998; Menge & Menge 2013; Costa Goela et al. 2016; Kämpf & Chapman 2016). Some coastal sections of those eastern-boundary systems (e.g. Oregon) and other upwelling systems from western ocean boundaries (e.g. in Brazil, Caribbean Mexico, and Madagascar) exhibit UI values only up to nearly 200 m^3 s^{-1} (100 m of coastline)$^{-1}$ (Castelao & Barth 2006; Reyes-Mendoza et al. 2016; Ramanantsoa et al. 2018). Therefore, the Nova Scotia coast is similar to those coasts in terms of UI.

As southwesterly winds are needed for upwelling to occur on the southeastern Nova Scotia coast (Petrie et al. 1987), an interesting question is what may have caused the wind differences between July 2014 and 2015. As no studies have investigated this for our coast, no clear reasons are evident, but here we provide a few remarks to help orient future research. The El Niño Southern Oscillation (ENSO) is a climatic phenomenon that, by altering wind patterns, affects the air and sea along the equatorial Pacific (Philander 1990). This phenomenon is also the largest source of year-to-year fluctuations in global weather patterns (Stewart 2008; Timmermann et al. 2018). For example, teleconnections between ENSO and weather patterns in some areas of North America have been identified (George & Wolfe 2009; Wu & Lin 2012; Whan & Zwiers 2017). Whether such teleconnections reach coastal Nova Scotia in any meaningful way is not known, but it might be worth investigating. For instance, the persistent upwelling of July 2014 was associated not only with frequent southwesterly winds but also with an absence of El Niño or La Niña conditions, as the Oceanic Niño Index (ONI) centered on that month was 0.1 (NOAA 2019). The upwelling reported by Petrie et al. (1987) for July 1984 was also associated with a lack of El Niño or La Niña conditions, as ONI was then −0.3 (NOAA 2019). Conversely, the weak upwelling and infrequent southwesterly winds observed in July 2015 occurred during a strong El Niño event, as ONI was then 1.5 (NOAA 2019). Therefore, investigating possible atmospheric–oceanic links might help to identify the ultimate drivers of interannual changes in summer upwelling on the southeastern Nova Scotia coast.

In addition to enhancing coastal fisheries (FAO 2018), coastal upwelling is expected to buffer the effects of global warming in nearshore environments (Varela et al. 2018). In a recent book evaluating upwelling systems around the world (Kämpf & Chapman 2016), the system that is the focus of the present study was not included. Therefore, our findings should stimulate future research on coastal upwelling in Nova Scotia, helping to further develop the knowledge base for western ocean boundaries.

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