Coastal winds, sea surface temperature, and upwelling in Atlantic Canada in two years differing in ENSO and NAO conditions

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Abstract

The most studied upwelling systems occur on eastern ocean boundary coasts. We hereby focus on a western ocean boundary coast upwelling system located in Atlantic Canada. Using daily in-situ data on sea surface temperature (SST), we demonstrate a marked contrast in cooling between July 2014 (pronounced) and July 2015 (weak) for two locations ca. 110 km apart on the southeastern coast of Nova Scotia. Southwesterly winds blow parallel to this coast. In July 2014, such winds were common and their daily duration was negatively related to coastal SST. In July 2015, however, such winds were considerably less prevalent and unrelated to SST. These results are consistent with a marked interannual contrast in wind-driven upwelling. Independent measures of an upwelling index confirm this view, as the index was largely positive (indicative of upwelling) during July 2014 but, albeit generally positive, often lower, and sometimes even negative (indicative of downwelling), during July 2015. Both studied periods also experienced considerable differences in climatic phenomena such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). In July 2015, a strong El Niño event co-occurred with a negative NAO index, while both phenomena exhibited near-zero indices in July 2014. Influences of these phenomena on coastal winds and upwelling are known for other regions. Thus, given the relationships hereby reported for Atlantic Canada and the oceanographic and ecological importance of upwelling, it would be profitable to further investigate the nature and extent of atmospheric–oceanic links on this western ocean boundary coast.

Introduction

Coastal upwelling refers to the rise of deep, cool waters to the surface of nearshore pelagic environments as warmer surface waters move offshore. As upwelled waters are often rich in nutrients, they are typically associated to a high biological productivity and important fisheries (FAO 2016). Several mechanisms can trigger coastal upwelling, but a common one involves the combined 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 (Kämpf and Chapman 2016).

There are four major wind-driven upwelling systems in the world, all of them located on eastern ocean boundary coasts: the California Current system, the Humboldt Current system, the Canary/Iberia Current system, and the Benguela Current system (Kämpf and Chapman 2016). With generally a lower extent or prevalence, wind-driven upwelling also occurs on western ocean boundary coasts, such as the coasts of Somalia (Currie et al. 1973) and Brazil (Mazzini and Barth 2013).

Upwelling has also been reported for the Nova Scotia shore, another western ocean boundary coast that is located in eastern Canada. Off southwestern Nova Scotia, upwelling is mainly caused by tidal mixing and submarine topography (Tee et al. 1993; Chegini et al. 2018). However, along the southeastern (open Atlantic) coast of Nova Scotia, upwelling is mainly caused by wind action (Petrie et al. 1987; Shan et al. 2016). On this coast, upwelling is particularly noticeable in July, favoured by southwesterly winds that blow parallel to the shore (Petrie et al. 1987). However, recent information on interannual differences and comparisons with other coasts are unavailable. To address this knowledge gap, the present paper examines differences in July upwelling on this coast between 2014 and 2015, shows how coastal winds relate to such variation, and provides values of an upwelling index to enable comparisons with other coasts of the world. We also briefly discuss the relationship of the observed upwelling and wind interannual changes with large-scale climatic phenomena.

Materials and methods

In July, seawater temperature in shallow (6–20 m deep) nearshore environments on central and southern sections of the Atlantic coast of Nova Scotia decreases relative to June because of wind-driven upwelling. August temperatures tend to return to the expected seasonal rise according to heat flux from the atmosphere (Petrie et al. 1987). Thus, given our research goals, we focused our study on the month of July, monitoring also late June as a reference. Specifically, we measured sea surface temperature (SST) daily between 20 June and 31 July for two consecutive years (2014 and 2015) at two intertidal locations ca. 110 km apart: Duck Reef (44.4913, -63.5270) and Western Head (43.9896, -64.6607). Both locations consist of stable bedrock, face the open ocean directly, and lack any human-made constructions nearby. At the mid-to-high intertidal zone of each location, we used eyescrews and cable ties to permanently attach submersible loggers (HOBO Pendant logger, Onset Computer, Bourne, MA, USA) to the rocky substrate, allowing very little contact between the loggers and the substrate. At each location, we installed four loggers in 2014 and two in 2015, replicate loggers being tens of m apart. Each logger recorded temperature every 30 min. From the resulting time series, we extracted the values of daily SST, here considered as the temperature recorded nearest to the time of the highest tide of each day (when the loggers were submerged). We determined the time of such tides using information for the closest tide reference stations to our locations: Sambro (44.4833, -63.6000) for Duck Reef and Liverpool (44.0500, -64.7167) for Western Head (Tide and Current Predictor 2018). For each location and year, SST was highly correlated between 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 dynamics between 2014 and 2015 for both locations.

Since SST dynamics suggested a stronger upwelling in 2014 than in 2015 (see Results), we investigated if wind data could explain such a difference, under the knowledge that southwesterly winds trigger upwelling on this coast (Petrie et al. 1987). The studied coast has an orientation of ca. 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 data for the closest wind reference stations to our locations: Herring Cove Buoy (44.5586, -63.5453; SmartAtlantic 2018) for Duck Reef and Western Head Station (43.9900, -64.6642; Government of Canada 2018) for Western Head. We then calculated the Pearson correlation coefficient between the duration of SW winds and daily SST for each location and year.

Finally, for each day of July 2014 and July 2015 for each location, we calculated a commonly used upwelling index (UI) that is based on wind data and geographic information. First, we calculated wind stress (equation 4.2 in Stewart 2008) by multiplying air density (1.28 kg m^{-3}), the wind drag coefficient (0.0015; Kämpf and Chapman 2016), and the square of wind speed (in m s^{-1}). Wind speed data were available hourly for the two wind reference stations mentioned above, so we calculated wind stress for each hour. Then, we calculated Ekman transport (equation 2.2 in Kämpf and Chapman 2016) by dividing wind stress by seawater density (1026 kg m^{-3}) and by the Coriolis parameter, which depends on latitude. We calculated UI (equation 2.3 in Kämpf and Chapman 2016) by multiplying Ekman transport by the cosine of an angle (α) that represented the difference between the orientation of our coast (60°) and the angle (also measured clockwise relative to 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 would yield $\alpha = 0°$. Wind direction data were also available hourly for the two wind reference stations mentioned above. To calculate daily UI values, we averaged the corresponding hourly UI values. In this paper, we express UI values in terms of cubic meters of seawater transported per second per 100 m of coastline. Positive UI values indicate upwelling, whereas negative values indicate downwelling (Menge and Menge 2013). The dataset used for the analyses described in the Results section is available online (Scrosati and Ellrich 2018a).

Results

In late June 2014, coastal SST ranged between 9-14 °C at Duck Reef and 8-13 °C at Western Head. However, during the first half of July, SST exhibited a persistent decrease at both locations, reaching minima of 6 °C at Duck Reef and 4 °C at Western Head (Fig. 1). The rest of July showed frequent alternations of drops and rises of SST at both locations (Fig. 1). In late June 2015, the SST range was similar to that recorded in the same period of the previous year. However, in July 2015, SST did not exhibit the persistent decrease seen in July of the previous year, in fact showing a mildly increasing trend (also with some alternations between drops and rises) towards the end of the month (Fig. 1).

Southwesterly winds were more common in 2014 than in 2015. The mean daily duration of SW winds was 10 h (range = 0-22 h) in July 2014 and only 2 h (0-9 h) in July 2015 at Duck Reef and 6 h (0-12 h) in July 2014 and only 3 h (0-9 h) in July 2015 at Western Head. Daily SST was negatively related to the daily duration of SW winds in July 2014 (r = -0.43, p = 0.016 for Duck Reef and r = -0.38, p = 0.037 for Western Head), but both variables were uncorrelated in July 2015 (r = 0.06, p = 0.749 for Duck Reef and r = -0.27, p = 0.141 for Western Head; Fig. 2).

UI was overwhelmingly positive in July 2014, 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. Both peaks occurred in the first week of July (Fig. 3), just a few days before the lowest SST values were reached (Fig. 1). Similarly high UI values were uncommon, however, as 81 % of the 27 positive values of daily UI from 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 from Western Head were lower than 50 m^3 s^{-1} (100 m of coastline)$^{-1}$. The few negative UI values 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 predominant, 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). Negative values occurred more frequently than in July 2014, 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 (considering all 31 daily values) was 57 m^3 s^{-1} (100 m of coastline)$^{-1}$ at Duck Reef and 30 m^3 s^{-1} (100 m of coastline)$^{-1}$ at Western Head in July 2014 and 11 m^3 s^{-1} (100 m of coastline)$^{-1}$ at both Duck Reef and Western Head in July 2015.

Discussion

Past studies had determined that wind-driven upwelling occurs on the Atlantic coast of Nova Scotia, especially in July (Petrie et al. 1987; Shan et al. 2016). The present study has revealed that marked interannual variation can exist. This was evident in the dynamics of SST, as seawater cooling (relative to late June) was prevalent in July 2014 but inconspicuous in July 2015. These results are valuable because they are based on in-situ SST data (as opposed to satellite data, which may be less accurate and sometimes even unavailable for some days).

The independent data on wind direction explained the basic interannual difference in SST dynamics under a model of wind-driven coastal upwelling. This is so because southwesterly winds (which favour coastal upwelling and thus cooling; Petrie et al. 1987) were considerably more common in July 2014 than in July 2015. Lastly, UI values, also obtained independently from SST data, indicated that coastal upwelling was more frequent and intense in July 2014 than in July 2015 (when a few days with clear downwelling conditions were even registered).

A recent study (Menge and Menge 2013) measured UI for various coastal locations in California, Oregon, and New Zealand. Our highest values 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 (measured in July 2014), are similar to the highest values published by Menge and Menge (2013) for California, a region of intense summer upwelling. However, the published California values are averages for several months and years, so values for peak days would be higher than ours. In addition, as described in Results, high UI values were in fact uncommon in Nova Scotia. The July means of UI reported in Results actually place Nova Scotia in the range of values that typically describe locations in Oregon and western New Zealand, where upwelling is, on average, less intense and more intermittent than in California (Menge and Menge 2013).

As winds are central to the occurrence of upwelling on the southeastern coast of Nova Scotia (Petrie et al. 1987; Shan et al. 2016), an emerging question is what caused the interannual wind differences described above. The El Niño Southern Oscillation (ENSO) is a climatic phenomenon that, through alterations of wind patterns, greatly affects the air and sea along the equatorial Pacific (Philander 1990). However, this phenomenon is also the largest source of year-to-year fluctuations in global weather patterns (Stewart 2008; Timmermann et al. 2018). Teleconnections between ENSO and weather patterns (including winds) in North America have been identified (George and Wolfe 2009; Wu and Lin 2012; Whan and Zwiers 2017). Thus, influences on the interannual wind changes hereby reported for Nova Scotia seem possible. Interestingly, the persistent upwelling seen in July 2014 was associated not only to frequent southwesterly winds but also to an absence of El Niño or La Niña conditions, as the Oceanic Niño Index (ONI) centered on that month was 0.1 (NOAA 2018a). The upwelling reported by Petrie et al. (1987) for July 1984 was also associated to a lack of El Niño or La Niña conditions, as ONI was then -0.3 (NOAA 2018a). Conversely, the weak upwelling and infrequent southwesterly winds in July 2015 occurred during a strong El Niño event, as ONI was then 1.5 (NOAA 2018a).

The North Atlantic Oscillation (NAO) is another large climatic phenomenon. It mainly affects the North Atlantic basin, although it also influences atmospheric variability at middle and high latitudes elsewhere in the northern hemisphere (Hurrell 1995; Whan and Zwiers 2017). In relation to our findings, it is interesting to note that, like the ONI, the NAO Index differed greatly between July 2014 (0.2) and July 2015 (-3.2; NOAA 2018b). Thus, as found for other weather phenomena in the northern hemisphere (Wu and Lin 2012; Hafez 2017), both ENSO and NAO might contribute to alter wind patterns on the Nova Scotia coast, thereby affecting coastal upwelling (see Santos et al., 2005, for a NAO example elsewhere). The effects of ENSO and NAO could even be synergistic when a high ONI and low NAO Index co-occur (Wu and Lin 2012), as was the case in July 2015.

Overall, the relationships reported in this paper suggest that atmospheric-oceanic coupling is worth investigating further in Atlantic Canada. Such links are relevant not only environmentally (Varela et al. 2018) but also ecologically, as upwelling is thought to influence pelagic primary production (Menge and Menge 2013) with bottom-up effects on coastal benthic species, as recent data suggest for Nova Scotia (Scrosati and Ellrich 2018b).

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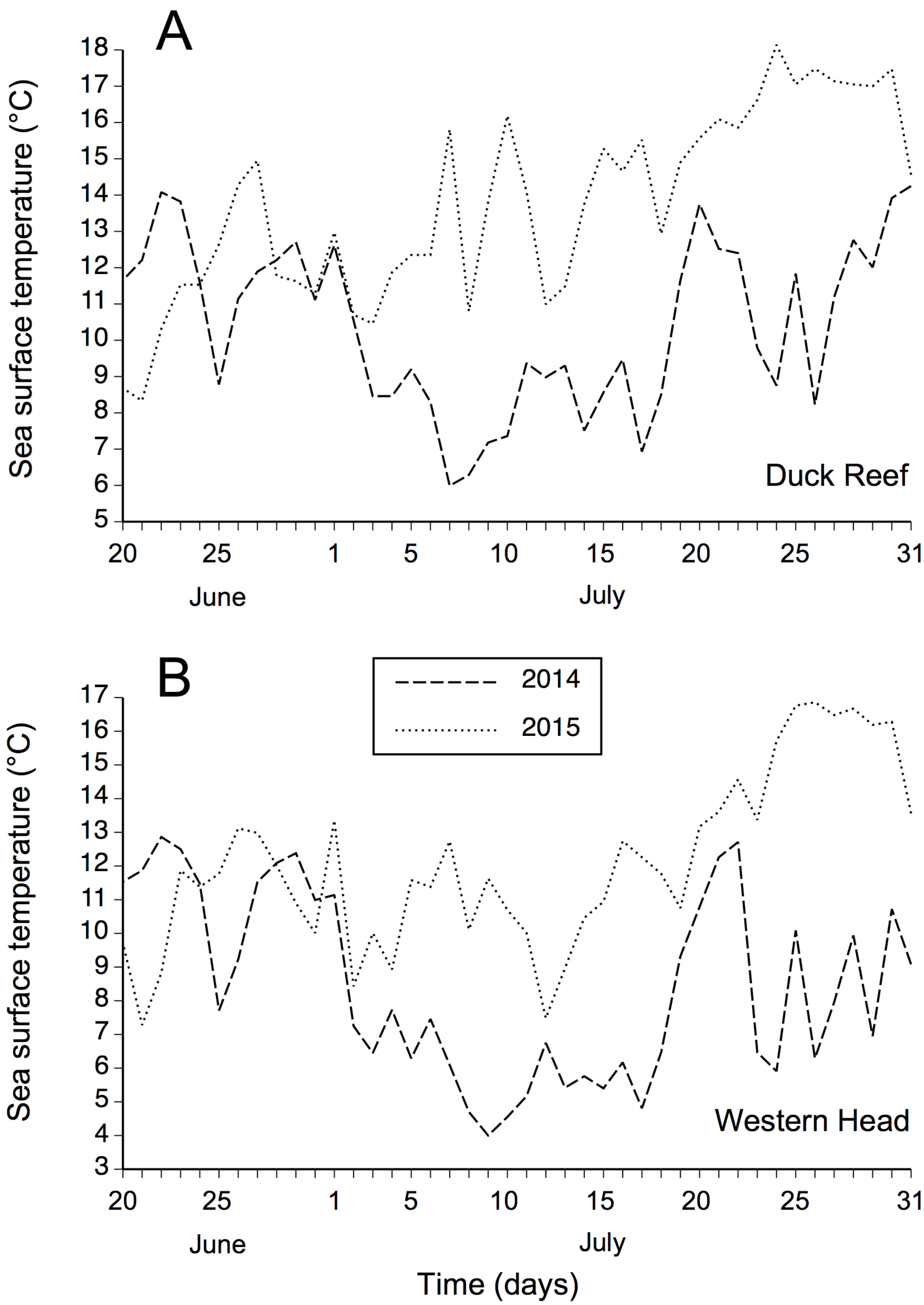

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259 **Fig. 1.** Daily change of sea surface temperature between 20 June and 31 July 2014 and 2015 at
260 (A) Duck Reef and (B) Western Head.
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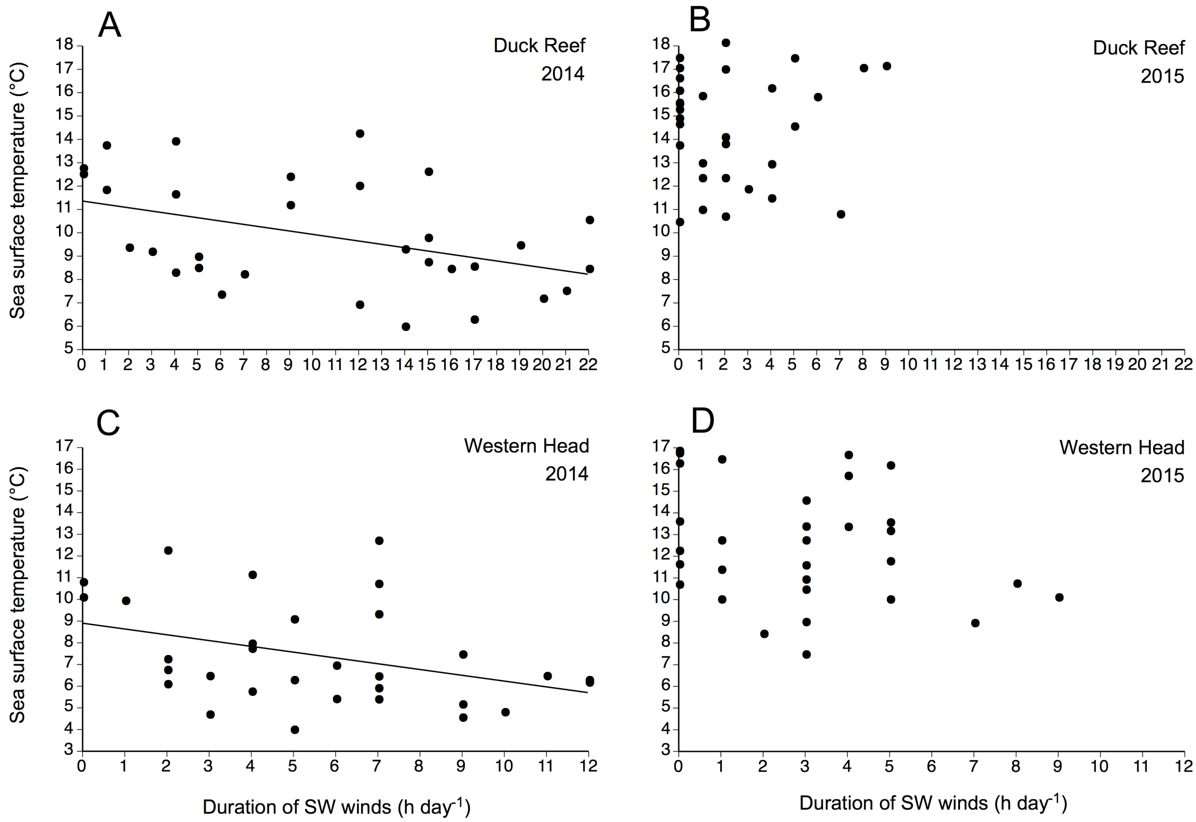

Fig. 2. Daily sea surface temperature versus daily duration of SW winds for Duck Reef in (A) 2014 and (B) 2015 and for Western Head in (C) 2014 and (D) 2015. Only (A) and (C) exhibited a significant relationship (see Results for details).

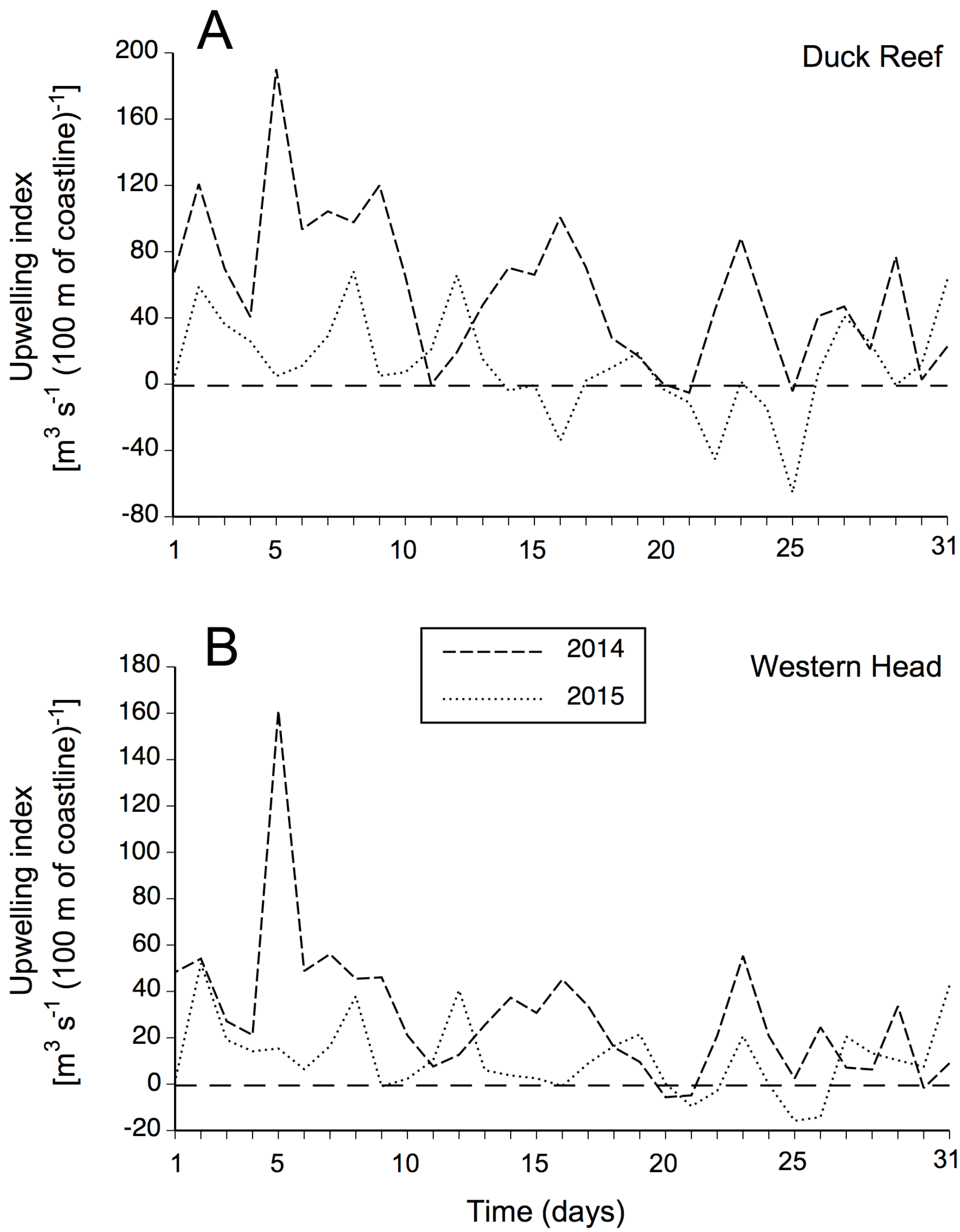

Fig. 3. Daily change of the upwelling index between 1–31 July 2014 and 2015 at (A) Duck Reef and (B) Western Head.