Half-hourly changes in intertidal temperature at nine wave-exposed locations along the Atlantic Canadian coast: a 5.5-year study

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Abstract. Intertidal habitats are unique because they spend alternating periods of submergence (at high tide) and emergence (at low tide) every day. Thus, intertidal temperature is mainly driven by sea surface temperature (SST) during high tides and by air temperature during low tides. Because of that, the switch from high to low tides and viceversa can determine rapid changes in intertidal thermal conditions. On cold-temperate shores, which are characterized by cold winters and warm summers, intertidal thermal conditions can also change considerably with seasons. Despite this uniqueness, knowledge on intertidal temperature dynamics is more limited than for open seas. This is especially true for wave-exposed intertidal habitats, which, in addition to the unique properties described above, are also characterized by wave splash being able to moderate intertidal thermal extremes during low tides. To address this knowledge gap, we measured temperature every half hour during a period of 5.5 years (2014-2019) at nine wave-exposed rocky intertidal locations spanning 415 km of the Atlantic coast of Nova Scotia, Canada. This data set is freely available from the figshare online repository (Scrosati and Ellrich, 2020a; https://doi.org/10.6084/m9.figshare.12462065.v1). We summarize the main properties of this data set by focusing on location-wise values of daily maximum and minimum temperature and daily SST, which we make freely available as a separate data set in figshare (Scrosati et al., 2020; https://doi.org/10.6084/m9.figshare.12453374.v1). Overall, this cold-temperate coast exhibited a wide annual SST range, from a lowest overall value of -1.8 °C in winter to a highest overall value of 22.8 °C in summer. In addition, the latitudinal SST trend along this coast experienced a reversal from winter (when SST increased southwards) to summer (when SST decreased southwards), seemingly driven by alongshore differences in summer coastal upwelling. Daily temperature maxima and minima were more extreme, as expected from their occurrence during low tides, ranging from a lowest overall value of -16.3 °C in winter to a highest overall value of 41.2 °C in summer. Daily maximum temperature in summer varied little along the coast, while daily minimum temperature in winter increased southwards. This data set is the first of its kind for the Atlantic Canadian coast and exemplifies in detail how intertidal temperature varies in wave-exposed environments on a cold-temperate coast.

1 Introduction

Rocky intertidal habitats are those occurring on marine rocky shores between the highest and lowest elevations reached by tides. These environments are unique because they spend alternating periods of submergence (during high tides) and emergence (during low tides) every day (Raffaelli and Hawkins, 1999; Menge and Branch, 2001). Thus, on the one hand, intertidal conditions are influenced by the seasonal changes in sea surface temperature (SST), which can be pronounced on temperate shores, which display warm waters in summer and cold waters in

41 winter. On the other hand, an even greater degree of thermal variation can occur at hourly scales
42 once intertidal habitats become exposed to the air at low tide, especially on hot days in spring
43 and summer (Watt and Scrosati, 2013; Lathlean et al., 2014; Umanzor et al., 2017) and cold
44 days in winter (Scrosati and Ellrich, 2018a).

45   Temperature is a major factor influencing the distribution and abundance of species
46 (Pörtner, 2002; Körner et al., 2016; Lancaster and Humphreys, 2020). Thus, SST plays an
47 important ecological role in intertidal habitats during high tides (Sanford, 2014), while high
48 (Somero, 2007) and low (Braby, 2007) air temperatures are ecologically relevant during low
49 tides. In addition, not only average temperature is ecologically important, but its temporal
50 variability as well (Bennedetti-Cecchi et al., 2006). Overall, then, having detailed temperature
51 data across periods of low and high tide is important for intertidal ecology and to make
52 biogeographic predictions based on climate change expectations (Wethey et al., 2011).

53   Temperature data are available for surface ocean waters worldwide (Fay and McKinley,
54 2014; Banzon et al., 2016; Freeman and Lovenduski, 2016; Aulicino et al., 2018; Yun et al.,
55 2019). However, data on intertidal temperature are considerably less common, both in terms of
56 spatial and temporal coverage (Lathlean et al., 2014; Umanzor et al., 2017; Scrosati and Ellrich,
57 2018a). This is especially true for wave-exposed intertidal habitats, as remote sensing methods
58 that are commonly used for open waters (e.g., satellites) cannot capture the quick, localized
59 temperature changes caused by tides and waves. Waves can also damage equipment deployed
60 in-situ to measure intertidal temperature. For wave-exposed intertidal habitats, temperature data
61 between consecutive low and high tides can also be used to infer physical aspects of the
62 environment such as wave action itself (Harley and Helmuth, 2003).

63   Wave-exposed rocky intertidal habitats are common along the Canadian coast in Nova
64 Scotia, as this coast faces the open Atlantic Ocean. Several studies have investigated the ecology
65 of these environments (Minchinton and Scheibling, 1991; Hunt and Scheibling, 1998, 2001;
66 Scrosati and Heaven, 2007; Arribas et al., 2014; Molis et al., 2015; Ellrich and Scrosati, 2016;
67 Scrosati and Ellrich, 2018b, 2019; Scrosati, 2020a,b). However, because of their research goals,
68 intertidal temperature was either not measured or analyzed for a few locations or for limited
69 time periods. Therefore, there is a knowledge gap on broad spatio-temporal patterns in intertidal
70 temperature for wave-exposed environments along this coast. To address this gap, this paper
71 discusses a data set consisting of intertidal temperature values measured every half hour at nine
72 wave-exposed locations along the Atlantic coast of Nova Scotia spanning a period of 5.5 years.

73 **2 Methods**

74   We monitored intertidal temperature at nine locations that span the full extent of the open
75 Atlantic coast of mainland Nova Scotia, nearly 415 km (Fig. 1). For simplicity, these locations
76 are hereafter referred to as L1 to L9, from north to south. Their names and coordinates are
77 provided in Table 1. The substrate of these intertidal locations is stable bedrock. All of them
78 face the open Atlantic Ocean without physical obstructions, so they are wave-exposed. Values
79 of daily maximum water velocity (an indication of wave exposure) measured with
80 dynamometers (see design in Bell and Denny, 1994) in wave-exposed intertidal habitats from
81 this coast range between 6-12 m s^{-1} (Hunt and Scheibling, 2001; Scrosati and Heaven, 2007;
82 Ellrich and Scrosati, 2017). This coast is washed by the Nova Scotia Current, which is a
83 nearshore cool current that flows southwestward from the Cabot Strait to the Gulf of Maine
84 (Fig. 1) and is more prevalent in winter than in summer (Han et al., 1997).

85   We started to monitor intertidal temperature in April-May 2014 at L2-L9 and in April 2015
86   at L1 (see the precise dates in Scrosati and Ellrich, 2020a). We measured temperature with
87   submersible loggers (HOBO Pendant logger, Onset Computer, Bourne, MA, USA) that were
88   kept attached to the intertidal substrate with plastic cable ties secured to eye screws drilled into
89   the substrate, allowing almost no contact between the loggers and the substrate. We kept the
90   substrate around the loggers always free of macroalgal canopies and sessile invertebrates. To
91   have a continuous temperature record during the 5.5 years of this study, we replaced the loggers
92   periodically. At each location, we installed replicate loggers several meters apart from one
93   another at the same elevation (just above the mid-intertidal zone). As tidal amplitude increases
94   by 33 % from 1.8 m at L1 to 2.4 m at L9 (Tide-Forecast, 2020) and as wave exposure could
95   change along the coast (and thus wave splash up the shore at low tides) even though all
96   locations face the open ocean, we had to carefully determine the elevation of installation of the
97   loggers at each location to have all loggers installed at the same relative elevation along the
98   coast in terms of exposure to aerial conditions during low tides. To achieve this, for each
99   location we considered the intertidal range to be the vertical distance between chart datum (0 m
100   in elevation, or lowest normal tide in Canada) and the highest elevation where sessile perennial
101   organisms (the barnacle *Semibalanus balanoides*) occurred on the substrate outside of crevices,
102   as such a high boundary summarizes differences in tidal amplitude and wave exposure along the
103   coast (Scrosati and Heaven, 2007). Then, we divided the resulting intertidal range for each
104   location by three and installed the loggers just above the bottom boundary of the upper third of
105   the intertidal range. Following this method, loggers were installed at an elevation (in m above
106   chart datum, with the high barnacle boundary stated in parenthesis) of 1.17 m at L1 (1.75 m),
107   1.13 m at L2 (1.69 m), 1.30 m at L3 (1.95 m), 1.57 m at L4 (2.36 m), 1.08 m at L5 (1.62 m),
108   1.49 m at L6 (2.24 m), 1.49 m at L7 (2.24 m), 1.41 m at L8 (2.11 m), and 1.63 m at L9 (2.44 m).
109   We set all loggers to record temperature every 30 min. We stopped recording temperature in
110   November 2018 at L1 and L3 and in August-October 2019 at L2 and L4-L9 (see the precise
111   dates in Scrosati and Ellrich, 2020a). For each location, temperature was highly correlated
112   between the replicate loggers during the study period (mean $r = 0.97$). Thus, we averaged the
113   corresponding half-hourly values to generate one time series of half-hourly temperature data for
114   each location for the studied period, which is the data set discussed in this paper, being publicly
115   available from the figshare online repository (Scrosati and Ellrich, 2020a).

116   Due to its high temporal resolution, this data set could be used in the future for a variety of
117   purposes. To summarize its main properties here, we extracted values that are commonly used in
118   intertidal ecology and coastal oceanography and that therefore could be of immediate interest:
119   daily maximum and minimum temperature (MaxT and MinT, respectively) and daily SST. As
120   the Nova Scotia coast is cold-temperate, we expected SST to be often considerably lower than
121   MaxT in spring and summer, as MaxT is then reached during low tides when intertidal
122   environments are usually exposed to high air temperatures. Conversely, we expected SST and
123   MaxT to be more similar or even the same in winter, as low tides then often expose intertidal
124   habitats to negative air temperatures below the freezing point of seawater. For these same
125   reasons, we also expected SST to be typically higher than MinT in winter, as MinT is then
126   generally reached during low tides, but more similar to MinT in spring and summer. For each
127   location, we extracted the values of daily MaxT, MinT, and SST from the corresponding set of
128   half-hourly data on intertidal temperature (Scrosati and Ellrich, 2020a). We considered daily
129   SST as the temperature recorded closest to the time of the highest tide of each day, as the
130   loggers were then fully submerged in seawater. We determined the time of such tides using

131   information (Tide and Current Predictor, 2020) for the tide reference stations that are closest to
132   our intertidal locations (Table 1).

133   **3 Main patterns in the data and relevance to future research**

134   We obtained half-hourly temperature data during the monitoring period specified above for
135   each location with just two exceptions: the period between 20 March and 12 April 2017 for L1
136   (because of logger removal by drift sea ice coming from the Gulf of St. Lawrence) and the
137   period between 30 September 2014 and 26 April 2015 for L9 (because of logger loss caused by
138   wave action). Continued monitoring after both such periods was possible after installing new
139   loggers. This data set is available online (Scrosati and Ellrich, 2020a).

140   The temporal changes in daily MaxT, MinT, and SST during the studied period at each
141   location are shown in Fig. 2. For convenience, all of these daily values are also available from
142   the figshare online repository (Scrosati et al., 2020). The highest and lowest values of SST for
143   each location (Table 2) reveal that this cold-temperate coast has a wide seasonal range of SST
144   (see worldwide SST ranges in figure 6.3 in Stewart, 2008). The highest location-wise values of
145   SST occurred in summer and ranged between 20 °C and 22.8 °C, while the lowest location-wise
146   SST values occurred in winter and were near the freezing point of seawater, between -0.9 °C
147   and -1.8 °C (Table 2, Fig. 2). We note that, unlike the nearby Gulf of St. Lawrence (Fig. 1;
148   Saucier et al., 2003) or wave-sheltered coves along the Atlantic coast of Nova Scotia, open
149   waters washing wave-exposed habitats along the Atlantic coast of Nova Scotia do not freeze in
150   winter (Canadian Ice Service, 2020). Overall, for the studied period, the location-wise difference
151   between the highest and lowest SST values ranged between 21.1 °C and 24.6 °C. Although there
152   was some patchiness in this seasonal SST range along the coast, it was lowest in two southern
153   locations (L7 and L9) driven by lower values of maximum summer SST there (Table 2).

154   The occurrence of the lowest location-wise values of maximum summer SST at two
155   southern locations (L7 and L9) is related to a broader alongshore pattern. Based on the data for
156   the summer months (for convenience, July, August, and September) for the years when SST was
157   measured at all locations in those months (2015, 2016, 2017, and 2018), mean location-wise
158   SST in summer decreased from north to south, from 17.5 °C at L1 to 13.2 °C at L9 (Table 2). In
159   contrast, an equivalent analysis done for winter months (for convenience, January, February,
160   and March) for the years when SST was measured at all locations in those months (2016, 2017,
161   and 2018) revealed that mean location-wise SST in winter actually increased from north to
162   south, from 0.8 °C at L1 to 3.0 °C at L9 (Table 2). In other words, a summer-to-winter reversal
163   in the latitudinal trend in intertidal SST takes place on this coast, as waters are warmer in
164   summer and colder in winter in northern locations than in southern locations.

165   The southward decrease of intertidal SST in summer is likely influenced by alongshore
166   differences in coastal upwelling. On the Atlantic coast of Nova Scotia, upwelling-favourable
167   winds are more common in summer than in winter (Garrett and Loucks, 1976; Dever et al.,
168   2018). Although possible alongshore differences in upwelling have not been studied in detail,
169   they seem to exist. For example, Petrie et al. (1987) reported that seawater temperature at 6-20
170   m of depth decreased from June to July 1984 near L6–L7 because of wind-driven upwelling,
171   while temperature at those depths increased north of that coastal range during that period. More
172   recently, Shan et al. (2016) have also referred to wind-driven upwelling on the southeastern
173   Nova Scotia coast. A detailed analysis of daily changes in intertidal SST is beyond the
174   objectives of this paper. However, Fig. 2 reveals basic differences in summer cooling between

175 northern and southern locations. Summer cooling events were generally marked in southern
176 locations, especially at L6 and L7, where SST could drop by 10 °C in 5-10 days, in some cases
177 reaching values below 5 °C (Fig. 2). An analysis of coastal winds at L6 and L7 indicated that
178 wind-driven upwelling explained the cooling observed at those locations in July 2014 (Scrosati
179 and Ellrich, 2020b). Although persistent, the summer cooling signal that was often pronounced
180 at L6 and L7 (Fig. 2) weakened progressively towards northern locations, especially at L1 and
181 L2. In fact, at L1, SST never dropped below 10 °C in summer months (Fig. 2). These
182 considerations could orient future research to unravel the drivers of the latitudinal changes in
183 summer SST revealed by this study.

184   The southward increase of intertidal SST observed in winter could be a result of latitudinal
185 changes in heat flux from the atmosphere (Stewart, 2008; Deser et al., 2010; Shan et al., 2016),
186 although other processes are also generally at play in coastal environments (Hebert et al., 2016;
187 Larouche and Galbraith, 2016). For example, for the studied coast, the abundant sea ice formed
188 across the Gulf of St. Lawrence (Fig. 1) every winter (Saucier et al., 2003) may contribute to
189 keep intertidal SST low at our northern locations, as the waters that leave this gulf flow
190 southwards following the coast of mainland Nova Scotia (Han et al., 1997; Hebert et al., 2016;
191 Dever et al., 2018), reaching our northern locations first before they warm up on their way
192 south.

193   As expected from the warm summers and cold winters that characterize eastern Canada
194 (Government of Canada, 2020), MaxT was often considerably higher than SST in spring and
195 summer and MinT was often lower than SST in fall and winter (Fig. 2), as MaxT and MinT
196 typically take place at low tide during those respective seasons. The highest location-wise values
197 of MaxT almost doubled those of SST, as they ranged between 36.1°C and 41.2 °C. The lowest
198 location-wise values of MinT ranged between -9.1 °C and -16.3 °C. Therefore, the location-wise
199 difference between the highest and lowest daily temperatures, which ranged between 46.1 °C
200 and 54.4 °C, generally more than doubled the location-wise difference between the highest and
201 lowest daily SST values (Table 2).

202   The highest value of MaxT differed little among locations (Table 2). Based on the data for
203 the summer months (for convenience, July, August, and September) for the years when MaxT
204 was measured at all locations in those months (2015, 2016, 2017, and 2018), mean location-wise
205 MaxT in summer exhibited patchiness along the coast without any clear latitudinal trend (Table
206 2). As MaxT in summer generally occurs during aerial exposure at low tides, both climatic and
207 oceanographic influences may interact to determine its alongshore pattern. For instance, summer
208 values of MaxT might simply be expected to increase southwards following warmer air
209 temperatures on land (Government of Canada, 2020). However, the SST drops in southern
210 locations in summer due to coastal upwelling might actually temper air temperatures right on the
211 coast, thus limiting MaxT. In the end, climate and oceanography might together be responsible
212 for the patchy alongshore MaxT pattern, which seems dependent on local conditions.
213 Researching these possibilities could thus be of interest. In contrast, the data for winter months
214 (for convenience, January, February, and March) for the years when MinT was measured at all
215 locations in those months (2016, 2017, and 2018) revealed that mean location-wise MinT in
216 winter generally increased from north to south, the lowest such average (-2.7 °C) registered at
217 L1 and the highest one (0.2 °C) at L9 (Table 2). Thus, the alongshore pattern of winter MinT
218 may more clearly respond to typical latitudinal changes in winter air temperatures and perhaps
219 also to influences of Gulf of St. Lawrence sea ice (see above) on northern locations.

220   Another salient property of our data is that the daily changes in MaxT in spring and
221   summer and MinT in fall and winter were much larger than the corresponding daily changes in
222   SST (Fig. 2). Such a high day-to-day variability in MaxT and MinT likely reflects daily changes
223   in weather conditions, which affect intertidal habitats at low tides, as well as wave exposure, as
224   wave-generated splash during low tides on wavy days keep intertidal habitats wet and, thus,
225   often cooler than the air in summer and warmer than the air in winter. Thus, the interaction
226   between weather and wave action as a determinant of intertidal thermal extremes is another
227   research area deserving attention in the future. Ultimately, given the prominent role of extreme
228   abiotic events in ecology (Denny et al., 2009; Smith, 2011; Nowicki et al., 2019), the marked
229   daily changes in MaxT and MinT during those seasons highlight the potentially critical role of
230   low tides for the survival of intertidal organisms in these environmentally variable habitats.

231   Another interesting characteristic of our data set is that the daily average between MaxT
232   and MinT was generally higher than SST in spring and summer but generally lower than SST in
233   fall and winter (Fig. 2). In other words, the average intertidal temperature measured during low
234   tides increased faster from winter to summer and decreased faster from summer to winter than
235   SST. This difference likely reflects the difference in heat capacity between air and water, which
236   makes SST follow air temperatures throughout seasons with a delay (Stewart, 2008).

237   Our data set could also be useful to investigate climatic drivers of interannual differences in
238   intertidal temperature. For example, a marked difference in upwelling-driven coastal cooling at
239   L6 and L7 between July 2014 (strong) and July 2015 (weak) was related to a normal (2014)
240   versus El Niño (2015) conditions (Scrosati and Ellrich, 2020b). Although El Niño (ENSO) is
241   predominantly a Pacific phenomenon (Timmermann et al., 2018), it is also related to interannual
242   weather changes in North America through climatic teleconnections (George and Wolfe 2009;
243   Wu and Lin 2012; Whan and Zwiers 2017; Dai and Tan, 2019). Another large-scale climate
244   phenomenon, the North Atlantic Oscillation (NAO), influences weather patterns mainly in the
245   North Atlantic basin (Hanna and Cropper, 2017). It would thus be interesting to study whether
246   NAO and ENSO might interact (Wu and Lin, 2012; Nalley et al., 2019) to affect winds,
247   upwelling, and ultimately intertidal temperature along the Nova Scotia coast.

248   **4 Conclusions**

249   This is a unique data set because it describes intertidal temperature with a high temporal
250   resolution during a period of 5.5 years at nine wave-exposed locations spanning the full extent
251   of the Atlantic coast of mainland Nova Scotia. The main patterns described above have revealed
252   previously unknown latitudinal and seasonal trends in intertidal temperature on this coast. The
253   above considerations on the possible mechanisms underlying these patterns should help orient
254   future research on the drivers of thermal variation in these intertidal environments. Because of
255   the temporal and spatial scales of this data set, future research using these data could lead to
256   theoretical advances in coastal oceanography and intertidal thermal ecology. Ultimately, this
257   data set represents a detailed baseline on which to study the influence of climatic and
258   oceanographic change on intertidal temperature variation on this cold-temperate coast.

259   **Data availability**

260   The full data set on half-hourly temperature measured at the nine intertidal locations
261   between 2014 and 2019 is available from the figshare online repository (Scrosati and Ellrich,
262   2020a; https://doi.org/10.6084/m9.figshare.12462065.v1). The daily values of MaxT, MinT, and

263 SST for these locations during this time period are also available from the figshare online
264 repository (Scrosati et al., 2020; https://doi.org/10.6084/m9.figshare.12453374.v1).

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436

437 **Table 1.** Basic information about the nine wave-exposed intertidal locations surveyed for this
438 study.
439

Location code	Name of studied intertidal location (geographic coordinates)	Closest tide reference station (geographic coordinates)
L1	Glasgow Head (45.3203° N, 60.9592° W)	Canso (45.3500° N, 61.0000° W)
L2	Deming Island (45.2121° N, 61.1738° W)	Whitehead (45.2333° N, 61.1833° W)
L3	Tor Bay Provincial Park (45.1823° N, 61.3553° W)	Larry's River (45.2167° N, 61.3833° W)
L4	Barachois Head (45.0890° N, 61.6933° W)	Port Bickerton (45.1000° N, 61.7333° W)
L5	Sober Island (44.8223° N, 62.4573° W)	Port Bickerton (45.1000° N, 61.7333° W)
L6	Duck Reef (44.4913° N, 63.5270° W)	Sambro (44.4833° N, 63.6000° W)
L7	Western Head (43.9896° N, 64.6607° W)	Liverpool (44.0500° N, 64.7167° W)
L8	West Point (43.6533° N, 65.1309° W)	Lockport (43.7000° N, 65.1167° W)
L9	Baccaro Point (43.4496° N, 65.4697° W)	Ingomar (43.5667° N, 65.3333° W)

440

441 **Table 2.** Summary values of daily MaxT, MinT, and SST (°C) for the nine wave-exposed
442 intertidal locations (L1 to L9, from north to south) surveyed between 2014 and 2019 along the
443 Atlantic Canadian coast (see Methods for details on how each row of values was determined).

444

	L1	L2	L3	L4	L5	L6	L7	L8	L9
Highest daily MaxT	38.1	38.3	37.9	36.1	41.2	36.5	37.1	37.2	38.5
Lowest daily MinT	-16.3	-10.8	-11.0	-10.0	-12.2	-15.5	-13.0	-9.1	-11.6
Highest temperature range	54.4	49.1	48.9	46.1	53.4	52.0	50.1	46.3	50.1
Summer mean MaxT	25.1	22.9	22.6	20.7	25.5	23.5	22.8	23.2	21.8
Winter mean MinT	-2.7	-1.4	-1.3	-0.4	-2.2	-1.2	-0.3	0.02	0.2
Highest daily SST	22.5	21.5	21.8	22.8	22.2	21.9	20.3	22.1	20.0
Lowest daily SST	-1.7	-1.7	-1.4	-1.8	-1.8	-1.8	-0.9	-1.7	-1.7
Highest SST range	24.2	23.2	23.2	24.6	24.0	23.7	21.1	23.7	21.7
Summer mean SST	17.5	16.4	16.1	16.1	15.8	15.2	13.3	14.2	13.2
Winter mean SST	0.8	1.0	1.3	1.3	1.6	2.2	2.7	2.8	3.0

445

446   Figure legends

447   **Figure 1.** Map indicating the position of the nine wave-exposed intertidal locations surveyed
448   along the Atlantic coast of mainland Nova Scotia, Canada.

449   **Figure 2.** Daily MaxT (red line), MinT (blue line), and SST (black line) at the nine intertidal
450   locations (L1 to L9, from north to south) surveyed between April 2014 and October 2019.