The influence of wind and temperature on the catch rate of the American lobster (*Homarus americanus*) during spring fisheries off eastern Canada

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ABSTRACT

The effects of wind and temperature on catch rate of American lobster (*Homarus americanus*) in the Baie des Chaleurs and off Cape Breton Island in Eastern Canada were investigated. Data on lobster catch and the number of trap hauls were available through a fishermen's volunteer logbook program, bottom temperatures were measured from thermistors either moored nearby or placed inside lobster traps and wind measurements were obtained from local airports. In the Baie des Chaleurs and off the east coast of Cape Breton, a positive and significant correlation was found between the mean temperature change during the 24 h prior to the traps being hauled and the change in the average catch of lobsters per trap haul. Catch rates rose with increasing bottom temperatures and fell with declining bottom temperatures. Higher correlations between changes in temperature and catch rates occurred at sites where the temperature variance was greater. The short-term fluctuations in lobster catch rates corresponding to temperature changes are hypothesized to result from behavioral changes affecting lobster activity. In both study areas, the large temperature variability was mainly forced by alongshore winds producing upwelling and downwelling, consistent with a classical Ekman response. The effect of the winds on lobster catch is shown to be principally due to their influence on ocean bottom temperatures. Along the south coast of Cape Breton, no relationship was found between catch rates and either temperature or wind, perhaps because lower lobster abundance resulted in a lower signal-to-noise ratio. The results of this study qualitatively support the observations by fishermen of a wind-induced effect on lobster catch rates.

Key words: American lobster, catch rate, Ekman response, temperature, winds

INTRODUCTION

Given the use of commercial catch rates as an index of abundance in American lobster (*Homarus americanus*) assessments, it is important to understand mechanisms that affect its variability over the fishing season. The catch rate is a function of lobster abundance and catchability (q) of the gear, where q can be defined as the probability of an animal being captured by a randomly applied unit of effort (Paloheimo, 1963). For lobster fisheries, the unit of effort is the baited trap, and the catchability is affected by a host of factors related to lobster biology (e.g. molting), the environment (e.g. temperature, habitat), mechanical design of traps, and fishing strategy (Caddy, 1979; Krouse, 1989; Miller, 1990; Tremblay and Smith, 2001).

From the perspective of fishermen, wind is often observed to be an important determinant of catch rate. Many note that winds from a particular direction result in good catches, while winds blowing from the opposite direction drive catches down, with the absolute directions being site dependent. Wind can affect lobster catch rates by modifying bottom temperature through wind-induced upwelling and downwelling, as hypothesized by Drinkwater (1994) to explain fishermen's observations of a wind effect on lobster catches in St Georges Bay in the southern Gulf of St Lawrence, Canada. McLeese and Wilder (1958) had found that catch rates increase with ocean temperature from experimental fishing they conducted. They also showed that lobster activity, as measured by walking rate, is temperature dependent and

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hypothesized that greater activity led to higher catch rates because the more active the lobsters were, the more likely they were to encounter a trap.

Several studies have examined the effects of temperature on lobster catches from commercial fisheries. A relationship between temperature and the seasonal catchability of western rock lobster was documented by Morgan (1974). He found that monthly catchability coefficients were positively correlated with water temperature and salinity, and negatively related to an index of molting. Seasonal fishing of a small, lightly fished population of American lobster also indicated a positive relationship between seasonal catch rate and temperature (McLeese and Wilder, 1958). The effect of temperature on lobster catches on longer time scales has been more difficult to demonstrate. Time-series analyses of annual means suggested the catch of American lobster was greater in years with higher temperatures (Dow, 1969; Flowers and Saila, 1972; Campbell *et al.*, 1991; Koeller, 1999), which could be related to thermal-dependent lobster activity but also could be due to molting frequency (more lobsters molt in warm years and thus are available to the fishery). However, most of these relationships between concurrent temperature and landings did not hold up for the period of the late 1980s and 1990s when American lobster landings increased dramatically throughout their geographic range (Drinkwater *et al.*, 1996).

Although temperature is one of the causal mechanisms for observations of changes in catch rate with wind, wind could also modify lobster behavior and thus catch rates by causing increased bottom surges, turbidity, or trap movement. Off the coast of mainland Nova Scotia, within-season changes in the lobster catch rates appear to be less related to temperature than to effort, perhaps because of wind limiting fishing activity (Koeller, 1999).

In this paper, we explore the relationships among wind, temperature and daily catch rate using 1–3 yr of data for several ports in both the Baie des Chaleurs region of northeastern New Brunswick and along the eastern and southern coasts of Cape Breton in Nova Scotia (Fig. 1). We begin by examining the variability of temperature and catch rate in both regions and explore the spatial structure of the variability. Two hypotheses are then tested. The first is that temperature affects the daily catch per unit effort of lobster (hereafter referred to as catch per trap haul, i.e. CPTH). The second hypothesis is that the temperature variability in these regions is principally wind driven. In addition we examine the direct effect of wind on the lobster CPTH.

METHODS

Data

Data on daily catch rates of commercially legal lobsters were obtained through a voluntary logbook program for fishermen. Legal lobsters constitute males and non-ovigerous females above the local minimum legal size. Bottom temperatures were obtained concurrently with the lobster data. In the Baie des Chaleurs, one to five volunteer fishermen per site hauled their traps daily throughout the fishing season in May and June. Lost days were only due to bad weather or mechanical

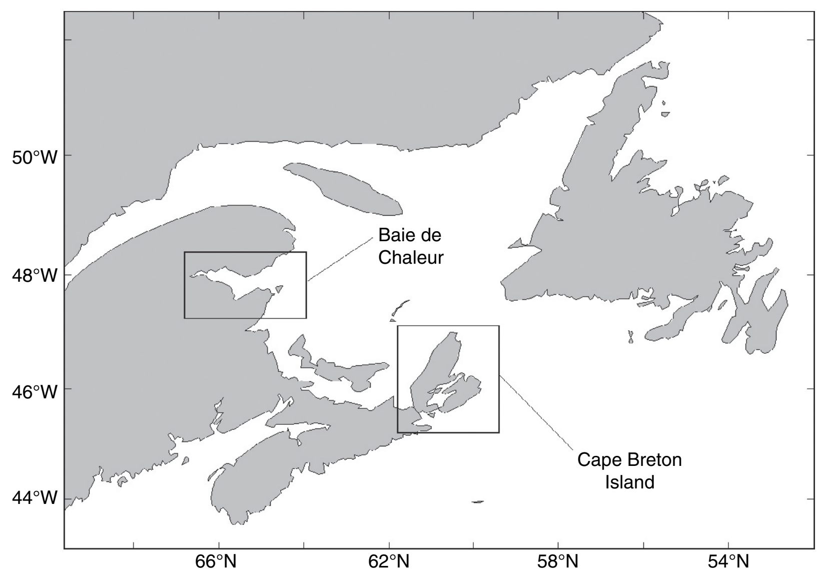


Figure 1. Eastern Canada showing the two study areas.

problems. The total number of traps allowed per fisherman during the study was 375 and they typically were placed at depths ranging from 2 to 25 m, and most were between 5 and 20 m. Off Cape Breton, each of the two to four volunteer fishermen per site had a fleet of 250–275 traps that was spread over an area of several square kilometers at depths ranging from 2 to 40 m. Most traps were set between 10 and 30 m. Traps are hauled every day throughout the 9-week season in the months of May–July except for Sundays (when many fishermen do not work) and windy days (a few every season). In both study areas the volunteer fishermen recorded their total number of trap hauls and their catch weights. From these data, the daily mean CPTH in kg was calculated. Data were collected during 1994–96 at five sites along the southern shore of the Baie des Chaleurs extending from New Mills at the head of the bay to Petit Shippagan near the mouth (Fig. 2). Two additional sites, off Miscou and Val Comeau, were situated outside the bay along the eastern shore of New Brunswick within the Gulf of St Lawrence (Fig. 2). Off Cape Breton Island, there were five sites along the east coast from Aspy Bay in the north to False Bay in the south and three off the southern coast from Louisbourg to Petit de Grat during 1996–98 (Fig. 3). Not all sites were occupied in all years (see Tables 1 and 2).

Temperature data were collected every 1–2 h using electronic recorders either on stationary moorings or in lobster traps during the fishing season. During 1994 in the Baie des Chaleurs, thermistors (Hobo-Temp; Hobo^{TM} Onset Computer Corp., Pocasset, MA, USA) were moored at a nominal depth of 10 m. In 1995 and 1996, Vemco Minilogs^{TM} were placed on fixed moorings at 20-m depth at all sites except Miscou, off of which a Hobo-Temp was attached to the fisherman's lobster trap (Fig. 1). Off Cape Breton, Vemco Minilogs were placed in lobster traps at two depths at each site, one shallow (10–15 m) and another deeper (18–22 m). The traps with temperature recorders were not moved more than a few hundred meters over the course of the fishing season. There were annual differences in the length of the temperature time series because fishermen did not always start their temperature recorders on the first day of the fishing season. Hourly wind data were obtained from the Atmospheric Environment Service of Canada at Miscou Island in northeastern New Brunswick (Fig. 2) and at both Sydney airport and Hart Island near Canso on Cape Breton Island (Fig. 3).

Analysis

The daily CPTH and the mean daily temperature (MDT) were used to investigate the relationship between catch rate and temperature. Because the efficiency of the traps varies non-linearly depending upon the number of days between hauls (Bennett and Brown, 1979; Krouse, 1989), we restricted our analyses to 1-day soak times rather than adjust longer soak times to a 1-day equivalent. The small differences in the soak times from an exact 24-h duration were assumed to have a negligible effect on catch rate and no correction for such differences was applied. To reflect the average temperature experienced during a fishing period (being the time between the setting and hauling of the traps), the MDT for comparison with the CPTH on day i was calculated by averaging temperatures over a 24-h period beginning at 8:00 am the previous day as most traps are hauled and redeployed during the early morning. Prior to this averaging, the temperature data were linearly interpolated to values on the hour (i.e. 1:00, 2:00, etc.). Off Cape Breton, we used the deeper (18–22 m) temperatures only. They were positively correlated with the shallower records but exhibited higher variance.

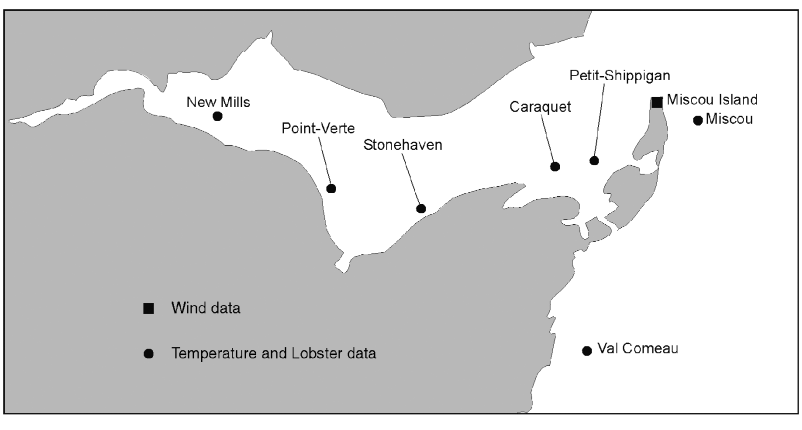


Figure 2. The sites of the lobster trap hauls and temperature recorders in the Baie des Chaleurs and vicinity. Also shown is the site of the wind measurements on Miscou Island.

Figure 3. The sites of the lobster trap hauls and temperature recorders off Cape Breton. Also shown are the sites of the wind measurements at Sydney and Hart Island.

Table 1. The mean weight (kg) of lobster per trap haul (CPTH) by site and by year for the Baie des Chaleurs.

Year	NM	PV	ST	CA	PS	MI	VC	Inside	Outside	All
1994		0.60	0.66	0.41			0.93	0.56	0.93	0.65
1995	0.31	0.46	0.54	0.29		0.63	0.48	0.40	0.55	0.45
1996		0.50	0.48	0.25	0.27		0.37	0.37	0.37	0.37
Average	0.31	0.52	0.56	0.32	0.27	0.63	0.59	0.44	0.62	0.49

The last three columns indicate, respectively, the average of the stations inside and outside the Baie des Chaleurs and all of the stations combined.
NM, New Mills; PV, Point Verte; ST, Stonehaven; CA, Caraquet; PS, Petit-Shippagan; MI, Miscou; VC, Val Comeau.

Table 2. The mean weight (kg) of lobster per trap haul CPTH by site and by year for Cape Breton sites.

Year	AB	LR	PA	GB	FB	LO	LA	PG	East	South	All
1996	0.39	0.35	0.36	0.25	0.37	0.32	0.15	0.09	0.34	0.19	0.28
1997	0.48	0.42	0.26	0.26		0.26	0.17		0.35	0.21	0.31
1998	0.38	0.38	0.30	0.26		0.27	0.12	0.12	0.33	0.17	0.26
Average	0.41	0.38	0.31	0.26	0.37	0.28	0.15	0.11	0.34	0.19	0.28

The last three columns indicate, respectively, the average of the stations along the east and south coasts and all of the stations combined.
AB, Aspy Bay; LR, Little River; PA, Point Aconi; GB, Glace Bay; FB, False Bay; LO, Louisbourg; LA, L'Ardoise; PG, Petit de Grat.

To examine the direct relationship between winds and CPTH, we first converted the winds to wind stress (the force applied to the sea surface by the wind) using the formulation of Large and Pond (1981), i.e.

$$\tau_{amp} = \rho_a C_d U_w^2$$

where ρ_a is the density of air in kg m^{-3}, C_d is the drag coefficient, and U_w is the wind speed in ms^{-1} and C_d is given by

$$C_d = 1.14 \times 10^{-3} \text{ for } 4 < U_w \leq 10 \text{ms}^{-1}$$

$$C_d = (0.49 + 0.065U_w) \times 10^{-3} \text{ for } 10 < U_w \leq 26 \text{ms}^{-1}.$$

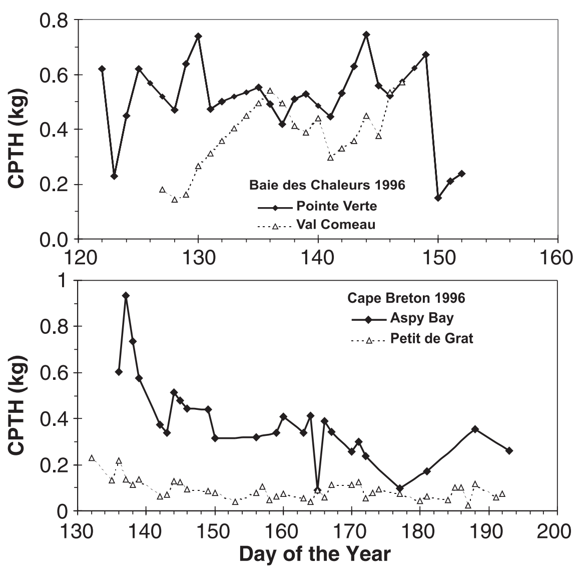
On no day did the wind speed exceed 26 m s^{-1}. The mean daily wind stress amplitude (τ_{amp}) and the directional components (τ_x, τ_y; being defined respectively as positive eastwards and northwards) were then calculated using the same method as for the MDT.

During the spring lobster fishery, the temperatures in the relatively shallow regions that the lobster inhabit increase steadily because of solar heating (Lanteigne *et al.*, 1996) while for some of our lobster sites, the CPTH declined from the beginning to the end of the fishing season. The CPTH decline was strongest off eastern Cape Breton and less pronounced or absent along southern Cape Breton and in the Baie des Chaleurs (Fig. 4). Where there is a CPTH decline, it corresponds to the gradual depletion of the resource by fishing (Tremblay and Eagles, 1996). To remove the confounding effects of the seasonal decline in catch rate and seasonal warming, we calculated the first differences of the CPTH (when available), the MDT, the MDτ_{amp} and the corresponding wind stress components (MDτ_x and MDτ_y), i.e.

$$\Delta\text{CPTH} = \text{CPTH}(t_{i+1}) - \text{CPTH}(t_i)$$
$$\Delta\text{MDT} = \text{MDT}(t_{i+1}) - \text{MDT}(t_i)$$
$$\Delta\text{MD}\tau = \text{MD}\tau(t_{i+1}) - \text{MD}\tau(t_i)$$

where Δ represents the difference between day i and day i + 1, i.e. the first difference. No serial correlation of the residuals of these transformed data was found (Durbin–Watson test, $P \leq 0.05$; Ott, 1993). We further restricted the analysis to the first 4 weeks of the fishing season for northern New Brunswick and the first 5 weeks for eastern Cape Breton. These periods account for approximately 66% of the landings. Dropping the last weeks of the fishing season also helped to eliminate the possible confounding problem of decreased catchability related to molting after mid-June (Tremblay and Eagles, 1997). The additional week in eastern Cape Breton compared with northern New Brunswick is justified because of a later molting season. As the season progresses, the variability in catch declines and hence the signal-to-noise ratio decreases.

Figure 4. Representative patterns of the catch of lobster (kg) per trap haul (CPTH) in the Baie des Chaleurs region (top panel) and off Cape Breton Island (bottom panel) during 1996. The locations of the sites are given in Fig. 2 (Baie des Chaleurs) and Fig. 3 (Cape Breton).



Standard correlations were run using the transformed (first-differenced) CPTH, temperature and wind data. These variables were also compared using the binomial test (Conover, 1980) based on the ΔCPTH versus ΔMDT and ΔMDτ scattergrams where coordinates of the paired variables located in the upper right (+/+) or the lower left (−/−) quadrant contribute to a significant relationship. Significance ($P \leq 0.05$) was determined using the one-tailed test. The data from all available years were combined at each site in our analyses to increase the statistical power.

Spectral analysis techniques (Jenkins and Watts, 1968) were used to investigate the relationship between temperature and wind stress components. Spectra of the temperatures and winds were calculated by dividing the records into 12 blocks of 256 points with 50% overlap. The mean and trend were removed from each block and the data were tapered using a Hanning window (Bloomfield, 1976). The spectrum, plotted as log frequency versus spectral density, represents the variance as a function of frequency, and the area under the spectral curve is the total variance. A multivariate frequency–response analysis (Jenkins and Watts, 1968), which is the frequency–domain analogue to time–domain regression for a multiple input–single output model, was also undertaken. In this study, temperature was modeled as a function of the wind stress components, τ_x and τ_y. For further details see Drinkwater (1994).

RESULTS

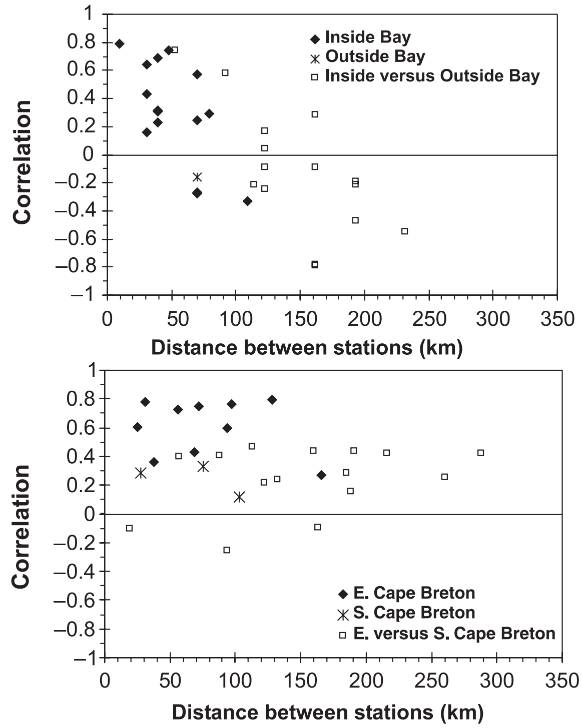
Temporal and spatial variability in lobster CPTH

In the Baie des Chaleurs area, catch rates at each location showed relatively high haul-to-haul variability as well as week-to-week variability but little or no seasonal trend (Fig. 4). The seasonal mean CPTH for the stations typically ranged from 0.3 to 0.6 kg (Table 1), with the highest value (0.93 kg) at Val Comeau in 1994 and the lowest (0.27 kg) at Petit Shippagan in 1996. The CPTH at the two outside sites generally was higher than those inside the Bay. There was also a noticeable decline in the catch rates from 1994 to 1996 throughout the region (Table 1).

To investigate the spatial scale of the lobster catch rates, correlations of both the CPTH and the ΔCPTH between sites were calculated. The correlations with CPTH show a general decline with increasing separation distance between the sites (Fig. 5). Similar results were found using ΔCPTH. The correlations were highest and positive within the Bay, and these catches were generally negatively correlated with those outside the Bay. The correlation between the two sites outside the Bay, Val Comeau and Miscou, was negative and not significant (i.e. $P > 0.05$).

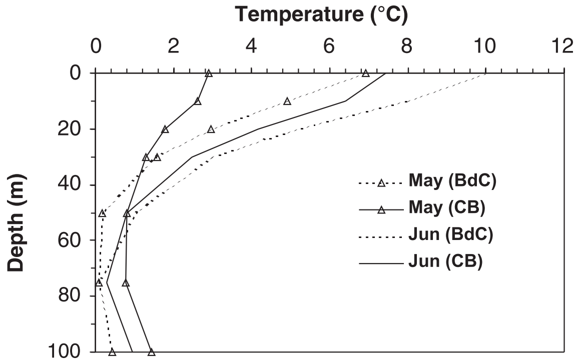
In Cape Breton, the CPTH was highest in the north and tended to decline southwards (Table 2). The lowest values were along the south coast of the Island and were approximately a quarter to half those off the east coast. The east coast values were slightly lower than those in the Baie des Chaleurs (Table 1). The time series of the CPTH from the east and south coasts of the Island were also different. The former (as represented by Aspy Bay in Fig. 4) declined gradually from a maximum at the beginning of the lobster season and displayed relatively high haul-to-haul variability. The amplitude of the seasonal decline decreased almost linearly from Aspy Bay to False Bay. In contrast, on the south coast (Petit de Grat, Fig. 4), catch rates were comparatively low, showed no mean trend and exhibited lower amplitude haul-to-haul variability. The coefficients of variation (standard deviation divided by the mean) of the catch rates were similar along both coasts, however. Along the south coast, the catch rate pattern at L'Ardoise was similar to Petit de Grat while at Louisbourg it lay intermediate between those observed on the south and east coasts of Cape Breton.

Figure 5. The correlation of the catch of lobster (kg) per trap haul (CPTH) between stations for the Baie des Chaleurs (top panel) and Cape Breton (bottom panel). For the Baie des Chaleurs the correlations were divided into those derived between stations inside the Bay (New Mills, Pointe Verte, Stonehaven, Caraquet, and Petit-Shippagan), stations outside (Miscou and Val Comeau) and correlations between stations inside and outside. For Cape Breton, they were divided into correlations between stations along eastern Cape Breton (Aspy Bay, Little River, Point Aconi, Glace Bay, and False Bay), between those on the south coast (Louisbourg, L'Ardoise, and Petit de Grat), and correlations between stations on the east and south coasts.



Correlations of CPTH in Cape Breton were relatively high between sites along the east coast from Aspy Bay to Glace Bay, slightly lower for these sites and False Bay, and then rapidly decreased from Louisbourg to Petit de Grat (Fig. 5). The CPTHs at Louisbourg, L'Ardoise and Petit de Grat were positively correlated with one another but the correlations were weak and not significant (Fig. 5). Similar results were obtained using ΔCPTH, although the correlations were generally lower amongst the sites along the east coast. This arises because of the strong seasonal decline in the CPTH data, which is eliminated using the ΔCPTH. The lack of any seasonal trend in the catch rates along the south coast meant there was less of a difference in the results using CPTH or ΔCPTH.

Figure 6. Typical vertical temperature profiles for May and June in the Baie des Chaleurs (BdC) and off eastern Cape Breton Island (CB). The profiles were taken from published atlases of long-term monthly means of temperature and salinity (for Baie des Chaleurs, area 18 of Petrie *et al.* (1996a); for Cape Breton, area 1 of Petrie *et al.* (1996b).



Temperature variability

During the spring a strong vertical temperature gradient develops in most eastern Canadian waters because of the solar heating of the surface layers that overlay the colder winter-cooled waters. The thermocline (depth of the maximum temperature gradient) deepens during the lobster season but is typically between 15 and 25 m and the gradient increases through the spring to summer from approximately 0.2–0.4°C m^{-1} (Fig. 6). The temperature gradient in the thermocline zone tends to be steeper in the Baie des Chaleurs than off Cape Breton (Fig. 6). Given that most of the lobster traps within this study were placed at 10–30 m they were thus located within or near to the thermocline.

The temperature time series at the trap sites from both the Baie des Chaleurs and Cape Breton showed seasonal warming (Fig. 7). In the former, temperatures typically increased from below 0°C to upwards of 20°C while in Cape Breton they rose from near 0°C to between 10 and 15°C. In addition, temperatures exhibited large fluctuations with events typically lasting from one to several days (Fig. 7). This can also be seen in the temperature spectra, which show a broad peak at the lowest frequencies resolved, i.e. periods of 3–10 days (Fig. 8). The spectra also reveal peaks at tidal frequencies, i.e. semi-diurnal (2 cpd or cycles per day) and diurnal (1 cpd), at some stations. There was high coherence in temperature variability between sites at the longer periods. Also, there is an observed lag between the timing of several of the large temperature events at different sites, indicating they propagate eastward in the Baie des Chaleurs and southward along the east coast of Cape Breton (Fig. 9).

Effects of temperature variability on lobster CPTH

Comparison of the first-differenced MDT and CPTH show high similarity at many sites within each of the study areas (Caraquet provided as example in Fig. 10). This was confirmed from both standard correlation

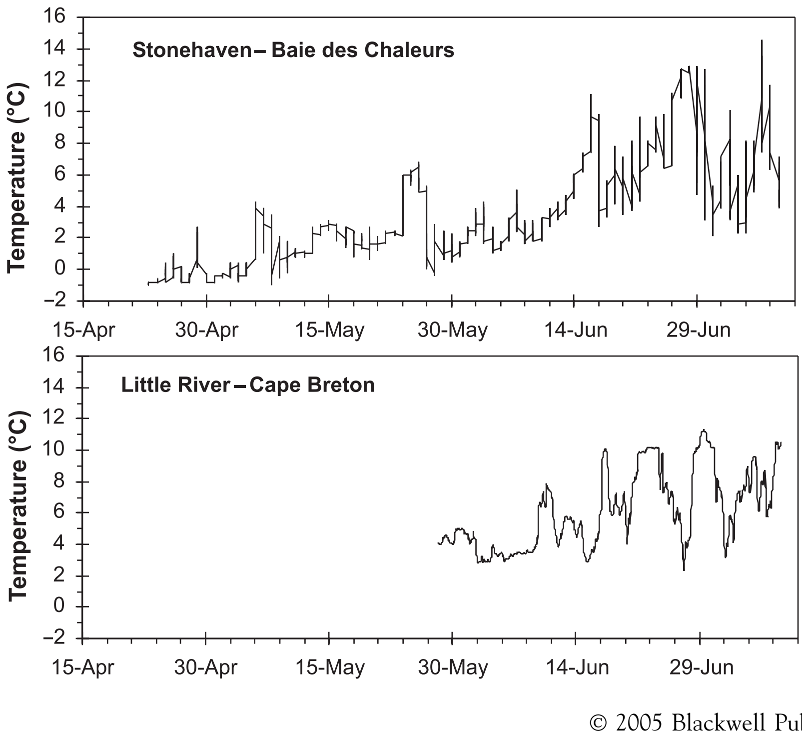


Figure 7. Temperatures during 1996 from Stonehaven in the Baie des Chaleurs and off Little River in Cape Breton. The multiple spikes and coarse nature of the Stonehaven record compared with that of Little River are because of the less frequent sampling in the former.

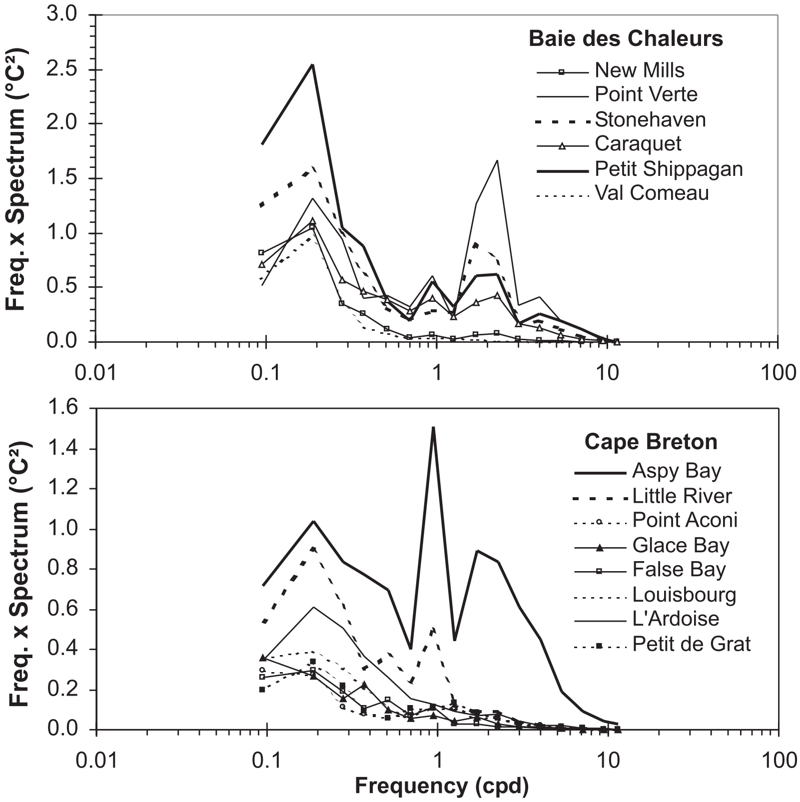


Figure 8. Average temperature spectra from the sites in the Baie des Chaleurs (top panel) and off Cape Breton (bottom panel) plotted as a function of frequency in cycles per day (cpd). The locations of the sites are found in Fig. 2 (Baie des Chaleurs) and Fig. 3 (Cape Breton).

Figure 9. Temperatures along the east coast of Cape Breton during a 15-day period in 1996. Note that the temperature fluctuations appear to occur first in the north (Aspy Bay) and progress later farther to the south. This suggests that the temperature events were propagating southward.

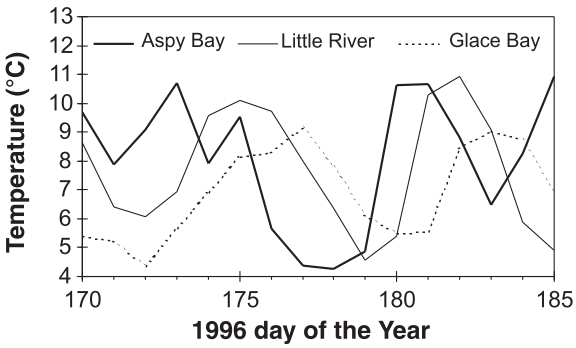
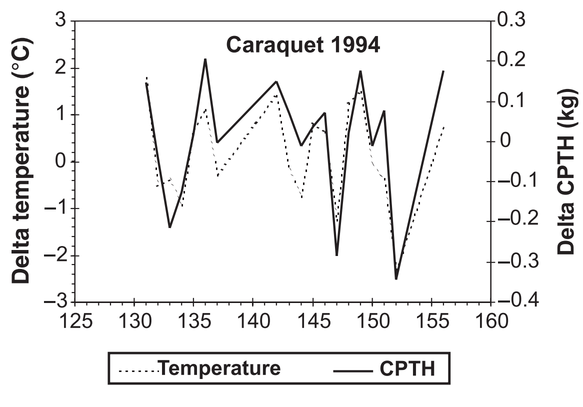


Figure 10. The comparison between the differences in mean daily temperature (ΔMDT) and the differences in the catch of lobster (kg) per trap haul (ΔCPTH) at Caraquet in the Baie des Chaleurs during 1994. The lobster catch rate data were confined to those having only 1-day soak times.



analysis as well as the binomial test using scattergrams (Table 3; Figs 11 and 12). An increase in temperature leads to higher CPTH. In the Baie des Chaleurs area, six of the seven sites were significantly correlated ($P \le 0.05$), with the temperature variability accounting for from 15 to 60% of the variance in ΔCPTH, depending upon the site. Of those six sites, all but Val Comeau were significant using the binomial analysis (Table 3). On the eastern coast of Cape Breton, changes in CPTH were significantly correlated with temperature variability in four of the five sites using the binomial analysis and for three of the five sites using the standard correlation analysis (Table 3). Temperature changes accounted for from 5% to over 80% of the ΔCPTH variance. None of the sites along

Table 3. The correlations (R) between the daily changes in mean weight (kg) of lobster per trap haul (ΔCPTH) and in the mean temperature of the 24 h prior to 8 am on the day of the trap hauls (ΔMDT), the variance (R^2) of ΔCPTH accounted for by ΔMDT, the number of days with 1-day soak times, the number of days in which the ΔCPTH and ΔMDT were located in either the first or third (positive) quadrants in the scatter diagram, and the variances in temperature (°C^2) and CPTH (kg^2) based on data from the Baie des Chaleurs and Cape Breton.

	Correlations			Binomial test			Variance	
	R	R^2	P-value	No. of points	No. in + Quadrant	P-value	Temperature	CPTH
Baie des Chaleurs								
New Mills	0.71	0.50	0.002	16	12	0.01	0.16	0.014
Pointe Verte	0.37	0.14	0.03	33	23	0.01	0.41	0.046
Stonehaven	0.60	0.35	0.00005	40	29	0.001	1.84	0.034
Caraquet	0.72	0.52	0.00	51	44	0.00	0.81	0.012
Pe. Shippagan	0.77	0.59	0.01	11	10	0.0005	0.94	0.004
Miscou	0.11	0.01	0.59	25	11	0.65	0.05	0.011
Val Comeau	0.38	0.14	0.02	39	23	0.10	0.42	0.017
Cape Breton								
Aspy Bay	0.49	0.24	0.004	32	21	0.03	1.73	0.023
Little River	0.35	0.12	0.03	39	25	0.03	0.98	0.011
Point Aconi	0.20	0.04	0.23	37	23	0.05	0.28	0.012
Glace Bay	−0.06	0.00	0.69	44	23	0.33	0.41	0.008
False Bay	0.89	0.80	0.02	6	5	0.02	0.34	0.009
Louisbourg	0.00	0.00	0.99	54	30	0.17	0.40	0.009
L'Ardoise	0.00	0.00	0.99	54	24	0.75	1.04	0.019
Petit de Grat	0.16	0.03	0.51	19	12	0.08	0.69	0.004

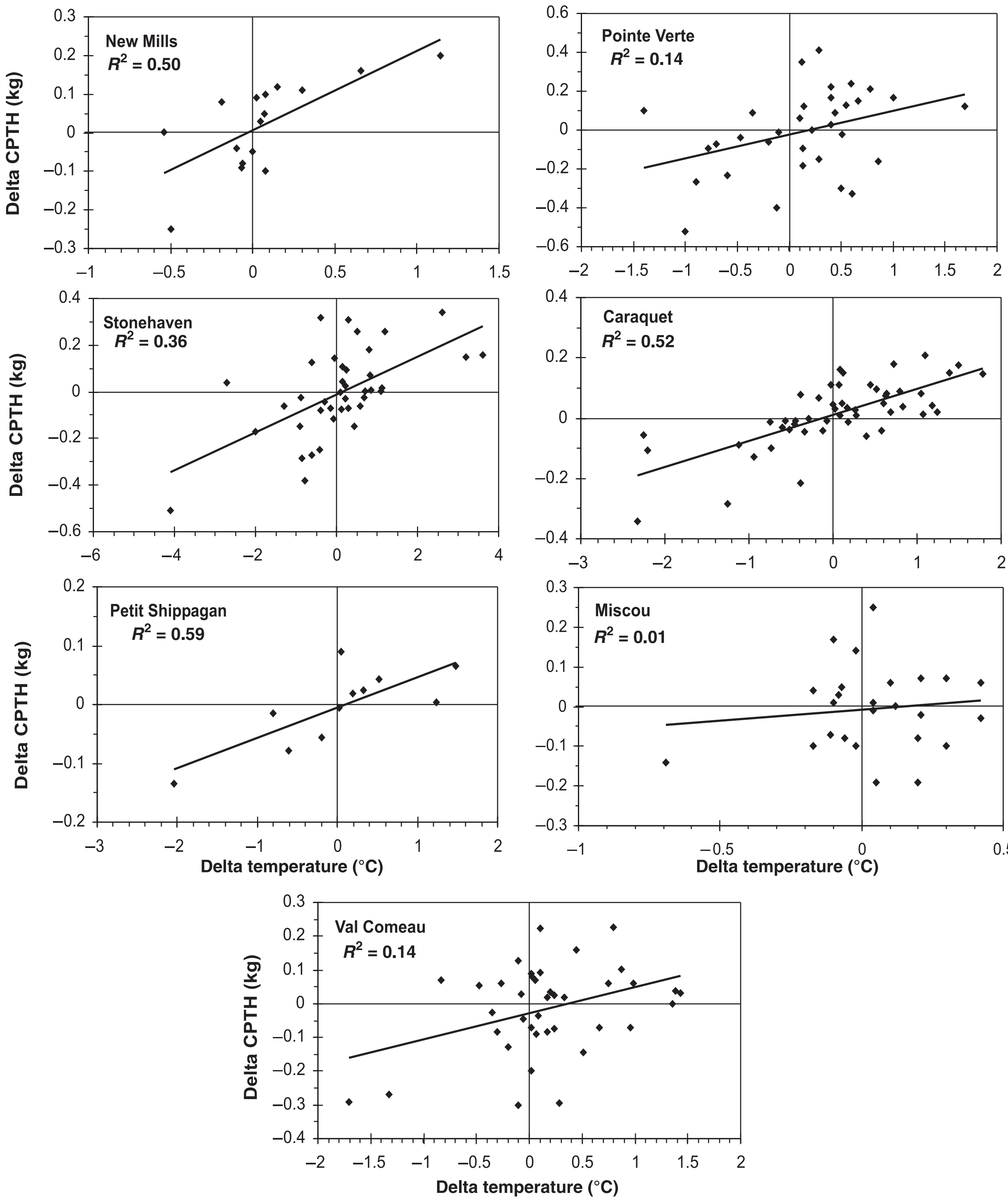
the south coast produced significant correlations (Table 3).

Why did some sites show a very strong relationship of CPTH with temperature whereas at other sites the relationship was weak or non-existent? To answer this question we explored the relationship between the strength of the correlations and the amplitude of the temperature fluctuations. We found a weak positive relationship (Fig. 13). Higher correlations were achieved when we removed some sites that were based on low numbers of data points, i.e. New Mills in Baie des Chaleurs and False Bay off Cape Breton (Fig. 13).

Wind effects on temperature

Having found temperature-dependent catch rates within the Baie des Chaleurs and along the east coast of Cape Breton, we investigated the relationship between the temperature and local winds to determine if the fisherman's observations of wind-related effects on catches could be through the wind's effect on temperature. Coherence between temperature and the two wind stress components at sites within the Baie des Chaleurs show peak values at periods of 5–10 days for τ_x, the east–west component (Fig. 14). Phase spectra (not shown) indicate an eastward wind produces warmer water and westward winds colder water. This is consistent with the classical Ekman response. The eastward wind, which is approximately aligned alongshore in the Baie des Chaleurs, forces the warmer upper layers shoreward on the south side of the Bay causing downwelling, which in turn causes the nearshore bottom water temperatures to increase. The opposite response occurs under westward winds, i.e. upwelling of colder deeper water causing temperatures to decrease. For τ_y (north–south component), which is directed across shore, the coherence was lower than for τ_x but the highest coherence also occurred at periods below 2 days. Off Val Comeau, the strongest temperature response is to τ_y, but as the orientation of the coastline is north–south, the temperatures again are primarily responding to the alongshore wind component (Fig. 14). A similar analysis was carried out for Cape Breton. The highest coherences between temperature and the winds were generally aligned alongshore, which for eastern Cape Breton was principally τ_y (Fig. 14). On the south shore of Cape Breton (L'Ardoise and Petit de Grat with Hart Island winds), the temperatures appeared to respond equally to both wind stress components. This suggests the maximum response is to northeast–southwest winds, which are again roughly aligned alongshore (Fig. 2). At all sites, the alongshore

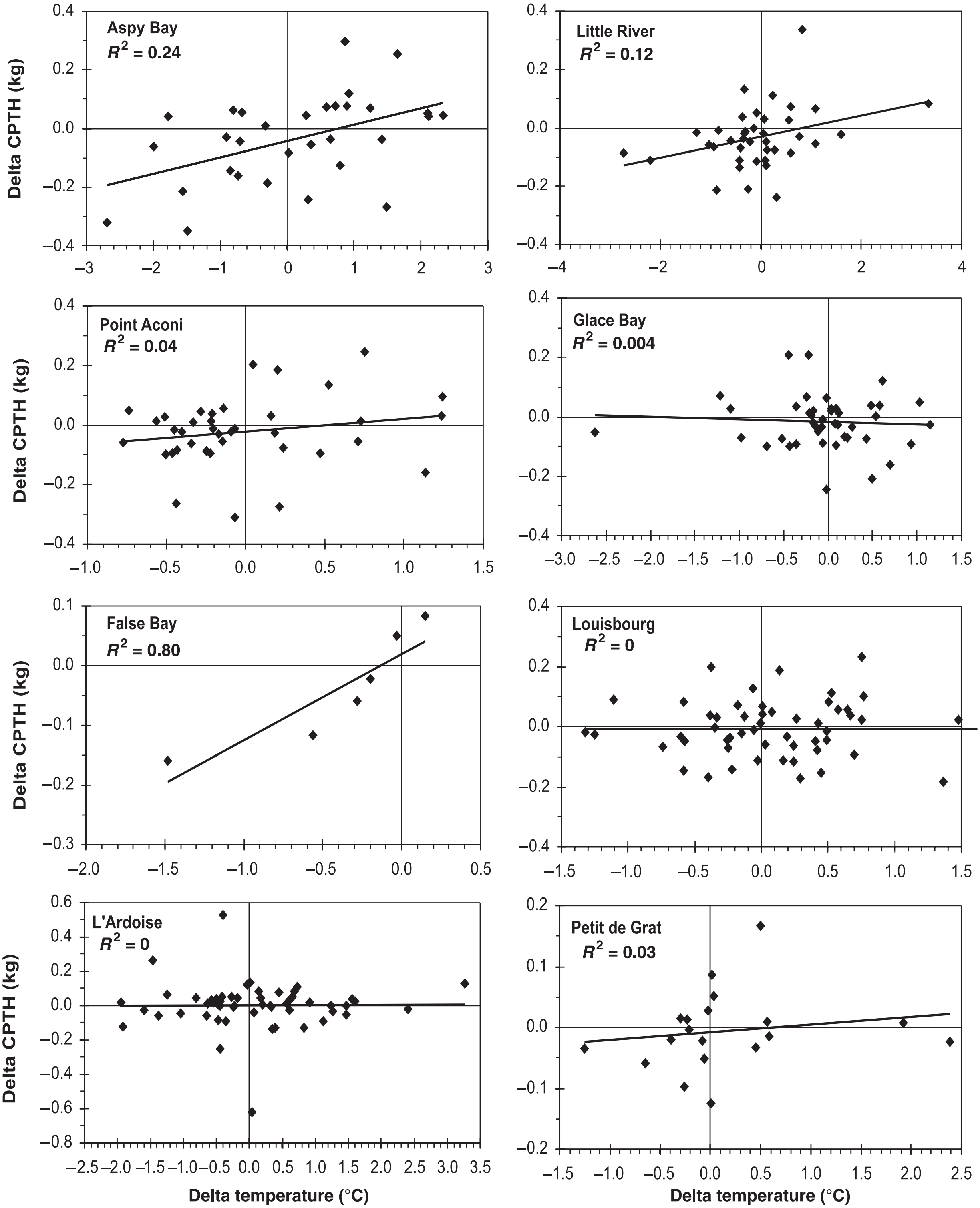
Figure 11. The scatter plots of the differences in mean daily temperature (ΔMDT) and the differences in the catch of lobster (kg) per trap haul (ΔCPTH) for the sites in the Baie des Chaleurs and vicinity combining all years of data.



winds blowing such that the coast is on the right looking downwind resulted in increasing temperatures, and the opposite winds produced decreasing temperatures, i.e. consistent with Ekman dynamics.

Multiple-frequency response analysis was performed to calculate the combined coherence using both stress components together, after accounting for the coherence between wind stress components. It confirmed

Figure 12. The scatter plots of the differences in mean daily temperature (ΔMDT) and the differences in the catch of lobster (kg) per trap haul (ΔCPTH) for the sites off Cape Breton combining all years of data.



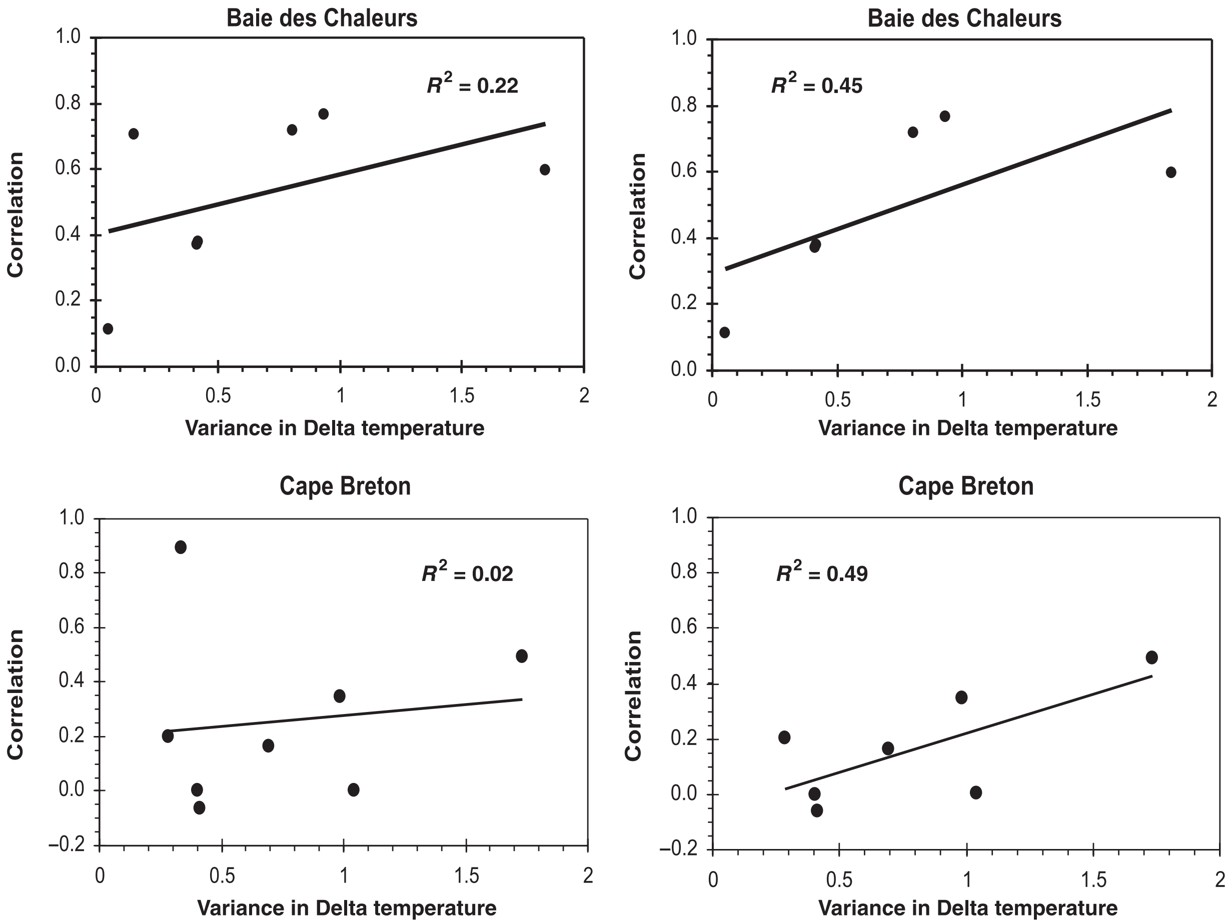


Figure 13. The correlations between the differences in mean daily temperature (ΔMDT) and the differences in the catch of lobster (kg) per trap haul (ΔCPTH) as a function of the variance in the temperature change (Delta Temperature). The left-hand figures contain data from all sites. The right hand figures are based upon all sites but one (eliminated New Mills in the Baie des Chaleurs; False Bay in Cape Breton; see *Discussion* in text).

temperature coherence was highest at periods of 2–10 days and the temperature responded primarily to changes in alongshore winds.

Wind effects on lobster CPTH

The above results have shown that the winds do have an effect on temperature variability in both the Baie des Chaleurs and off Cape Breton and that temperatures in turn affect lobster catch rates. We conducted further analysis to determine if there was a direct effect of wind on lobster catches, over and above the influence on temperature. If the latter was true, then correlations between the changes in wind and the CPTH should be significantly higher than with temperature alone, or at least adding wind together with temperature in a regression analysis should significantly increase the total variance accounted for. Correlations between either one of the wind components or the amplitude of the wind stress with the CPTH where the significance level was estimated to be $P < 0.1$ were found in 12 of 45 possible opportunities. There were four of 21 in the Baie des Chaleurs (seven sites with τ_x, τ_y and τ_{amp}) and eight of 24 in Cape Breton (eight sites with τ_x, τ_y and τ_{amp}). The choice of P larger than that used for temperature was to ensure that we included all cases where there might be the slightest possibility of an effect of wind on CPTH. The correlation coefficients in the 12 selected cases were all less than those obtained with temperature. To explore further, we ran a multiple regression analysis in these 12 cases using both wind and temperature. In no case did the wind add significance to the CPTH variance explained over that of temperature alone. Indeed, neither the wind stress components nor the wind stress amplitude were significantly correlated with CPTH at any site after temperature was accounted for (i.e.

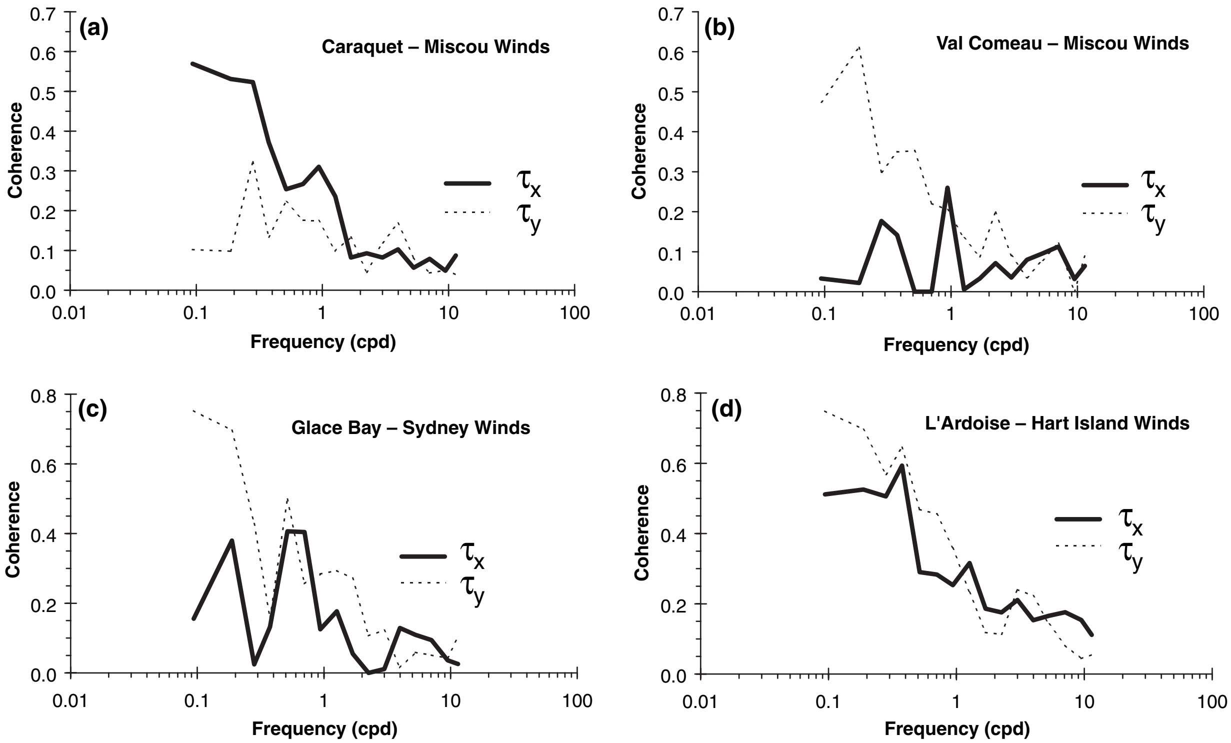


Figure 14. The coherence between the directional wind stress components (τ_x, positive eastward; τ_y, positive northward) and temperature at (a) Caraquet and (b) Val Comeau on the Baie des Chaleurs and at (c) Glace Bay and (d) L'Ardoise off Cape Breton plotted as a function of frequency in cycles per day (cpd). These are the mean coherences based upon all available data.

$P > 0.1$). This indicates that any correlation of wind stress with the CPTH was through the wind's influence on temperature.

DISCUSSION

In the mid- to late-1990s, volunteer lobster fisherman along the south shore of the Baie des Chaleurs in northern New Brunswick and along the east and south coasts of Cape Breton Island kept logbooks of their catches and trap hauls. The data suggest two separate patterns of lobster catch rates in each of the two study areas. In the Baie des Chaleurs, the catch rate variability is similar throughout the bay, although the strength of the correlation decreases with separation distance. The CPTH in the bay is lower than, and uncorrelated with, those along the east coast of New Brunswick (Miscou and Val Comeau). Off Cape Breton, catches along the eastern shore tend to be higher and more variable, with a stronger and more distinct seasonal decline in CPTH than those along the south coast of the Island. The lower CPTH on the south coast of Cape Breton compared with the east coast is consistent with lower abundance as reflected by lower mean annual landings (Harding *et al.*, 1983; Drinkwater *et al.*, 1996).

During our study, temperature data were collected at or near the location of the lobster catches. Restricting the analysis to 1-day soak times of the lobster traps to avoid uncertainties in the effects on catch of differences in soak times, we found that CPTH was affected by temperature changes measured over the previous day in both the Baie des Chaleurs and along the east coast of Cape Breton. Catch rates rose as temperatures increased and fell when temperatures decreased. A similar temperature effect was observed during two experimental trap surveys conducted just 3 days apart off Little River by Smith and Tremblay (2003). They found significantly lower catch rates in their second survey that were associated with bottom temperature reductions of 2–3°C. Along the south shore of Cape Breton Island, however, no significant correlations between the CPTH and temperature were found. This is consistent with the weak correlations of CPTH with temperature for sites on the coast of mainland Nova Scotia, immediately to the southwest of Cape Breton, found by Koeller (1999).

The short-term fluctuations in lobster CPTH corresponding to temperature changes are hypothesized to result from short-term behavioral changes affecting lobster activity and thus catchability. Under this hypothesis lobsters reduce foraging activities when temperature declines suddenly and then increase again as the temperature warms. Catch rate is affected because trap encounter rates must increase with activity levels. There is evidence from laboratory studies that lobsters respond to quite small temperature changes. Jury and Watson (2000) found that lobsters respond to temperature changes of 1°C min^{-1} and possibly as low as 0.15°C min^{-1}. These authors suggest that in nature lobsters could experience temperature changes of this magnitude as a result of tidal changes or thermocline movements.

The alternative hypothesis of lobster movement out of the trapping area as temperatures decline with return movement after 1–2 days is unlikely. Although not designed to address movements on short time scales, within-season tagging studies of lobster movement in these areas indicate movements are restricted (Tremblay *et al.*, 1998; Comeau *et al.*, 1999; Comeau and Savoie, 2002).

In general, the strength of the correlation between ΔCPTH and the ΔMDT in each study area appears related to the extent of the temperature variability, with higher correlations at sites with greater temperature fluctuations (Fig. 13). This result was not statistically significant ($P > 0.05$) because of the low number of sites per area and the high scatter in the data; however, we believe that future studies should examine this further. The correlations between ΔCPTH and the ΔMDT were generally higher in the Baie des Chaleurs than off Cape Breton for the same amplitude of temperature variability (Fig. 13). Cause of this difference is uncertain but may be related to the higher absolute temperatures typically found in the Baie des Chaleurs (Fig. 6). Also, on average, the traps there tended to be set in shallower, warmer waters than those off Cape Breton. Higher temperatures might lead to greater lobster activity levels and hence higher catch rates for the same temperature change. A second possibility is that the response reflects differences in lobster density in the two regions. Assuming a similar activity response of lobsters to a given change in temperature, the catch rate would tend to be higher where the lobster density was greater as there would be an increased probability of a lobster encountering a trap. Unfortunately we do not have concurrent data on the lobster densities in the vicinity of the traps for either area; however, the mean catch rate is higher in the Baie des Chaleur than in Cape Breton (Tables 1 and 2).

Why is there a lack of correlation along the south coast of Cape Breton? The mean temperatures measured at the sites along the south shore were similar to those observed off eastern Cape Breton, while the temperature variability on the south coast was two to three times lower than along the east coast during 1996 and 1997 but higher by a factor of 2 in 1998. The lower catch rates off southern Cape Breton and the lower temperature variability in the 2 yr might have contributed to the lack of an observable temperature effect, i.e. a lower signal-to-noise ratio. The lower catch rates and landings from the south coast suggest the likelihood of lower lobster densities than off eastern Cape Breton or the Baie des Chaleurs.

Interannual variability in CPTH of lobster was evident in many of the sites in both study areas, but only in the Baie des Chaleurs was there consistency between sites in the interannual trend where the CPTH declined from 1994 to 1996. The number of years (3) is insufficient to determine if the mean CPTH is greater in years of higher temperatures. There was no clear interannual trend in the measured temperatures or their variance but this might be confounded because of the differences in the depth of the measurements between 1994 and the other 2 yr. The decline in the CPTH during the years of our study in the Baie des Chaleurs may reflect decreases in abundance caused by declining recruitment, although we do not have the data to test this.

In regards to the physical oceanography, we found that the temperature variability at periods of 2–10 days in both study areas were principally due to wind-induced upwelling and downwelling through Ekman drift, which is a common phenomenon in coastal regions (Csanady, 1984). The observed time delay between many of the large-scale temperature events between sites is consistent with alongshore propagation, with the coast on the right looking in the direction of propagation. The direction is eastward on the south coast of the Baie des Chaleurs and southward along the east coast of Cape Breton. Propagation of temperature events had been observed in the Baie des Chaleurs (Bonardelli *et al.*, 1993) but to our knowledge, we are the first to document such phenomena along the Cape Breton coast.

Bonardelli *et al.* (1993) suggested that the propagating temperature events along the north shore of the Baie des Chaleurs were internal Kelvin waves. The cause of the propagation was because of spatial variations in the wind orientation relative to the alongshore coastline (Crepon and Richez, 1982; Csanady, 1984). Such variations can arise from an irregular coastline under uniform wind conditions or spatial variations in the wind direction along a straight coastline or a combination of the two. Either results in spatial differences in the extent of wind-induced upwelling or downwelling, which under stratified conditions, lead to alongshore, internal pressure gradients that drive alongshore currents. Because of the influence of the earth's rotation, these currents, and the associated upwelling or downwelling, tend to propagate with the coast on the right in the northern hemisphere. If the wind drops, the wind-induced currents and the associated upwelling/downwelling continue to move along the coast until destroyed by an opposing wind or dissipated by friction. Thus, the observed temperature response at a given site is not only due to the local forcing but also to earlier upstream events that propagate into the area.

As stated earlier, one of the main motivations for this work came from the observations by fishermen that lobster catches often depend upon the winds. Typically, they observe that a certain wind direction will promote good catches and the opposite wind poor catches but the actual directions are site dependent. While we found few statistically significant relationships between the wind stress components and the lobster catch rates, the fishermen's observations were qualitatively consistent with our results. We demonstrated a significant relationship between temperature and CPTH as well as between temperature and winds. In our experience, the wind directions that the fishermen identified as promoting good catch rates were consistent with alongshore winds that produce downwelling and hence higher temperatures through Ekman dynamics, regardless of the location site. When we used both temperature and winds in a multiple regression analysis for those locations where there was a significant relationship between winds alone and CPTH, we found that only the temperature was significant. This implies that the link between the wind and the CPTH is through the wind-induced temperature changes. If wind is so important, why did the winds not show higher correlations with the CPTH and at more sites? The following are two possible reasons. First, as noted above the temperature response at a given site is not simply due to local wind forcing. It also depends upon the wind response upstream (and earlier) that propagated into the region. This would tend to reduce the strength of the correlations between the prior daily winds and the catch rate if, as our study suggests, the main effect of the wind is through its effect on temperature. Secondly, land features can have a significant impact on local winds, both in terms of strength and direction. The only available wind data were collected at airports and hence not close to most of the lobster trap sites. While they do reflect the large-scale wind patterns, some differences with the winds at each of the sites are to be expected. These too might degrade the correlations based upon airport winds.

In summary, our analysis has shown that in both Baie des Chaleurs and off eastern Cape Breton Island, ocean temperature has a significant effect upon catch rates of lobsters. The short-term fluctuations in lobster CPTH corresponding to temperature changes are hypothesized to result from behavioral changes affecting lobster activity. The temperature changes are principally due to alongshore winds forcing upwelling or downwelling in the classical Ekman sense. The results provide qualitative confirmation of fishermen's observations of the wind's effect on catch rates. Finally, this study has shown the great value of the logbooks kept by volunteer fishermen and efforts should be taken to continue and expand such programs.

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