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Temperature Variability in the Coastal Waters of Eastern Newfoundland

Variabilité de la température des eaux côtière de l'est de Terre-Neuve

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Abstract

We investigated the spatial distribution around coastal Newfoundland of the temperature signal as well as the semiannual, annual and high frequency temperature variability. Thermograph, meteorological and sea surface temperature time series were used to explore variability. Annual cycles were calculated and compared for several inshore areas. The timing of the annual temperature maxima varied with location. This was associated with phase changes in the second harmonic of the annual cycle. High frequency variability comprised negative temperature excursions. The timing and frequency of these were related to events in wind speed data and were consistent with coastal upwelling. We found that wind forcing appears to account for most of the variability in the thermograph time series. On the northeast coast of Newfoundland, the variability during three months preceding the seasonal temperature maximum was significantly greater than for those following the peak. This variability difference was smaller in Placentia Bay on the southern part of Newfoundland.

Résumé

Nous étudions la distribution spatiale du signal de température obtenu pour les eaux côtières de Terre-Neuve ainsi que la variabilité semi-annuelle, annuelle et de haute fréquence de la température. Des successions chronologiques de données de thermographes, de données météorologiques et de données de température de la surface de la mer ont été utilisées pour explorer cette variabilité. Des cycles annuels ont été calculés et comparés pour plusieurs régions près des côtes. Le moment auquel est observée la température maximum annuelle varie selon l'endroit, ce qui a été associé à des changements de la phase de la deuxième harmonique du cycle annuel. La variabilité de haute fréquence englobe des excursions dans les températures négatives et le moment auquel elles surviennent ainsi que leur fréquence sont reliés à des épisodes identifiables dans les données sur la vitesse des vents et conformes aux remontées d'eau froide côtières. Nous constatons que le forçage éolien semble expliquer la plus grande partie de la variabilité observée dans les successions chronologiques de données des thermographes. Sur la côte nord-est de Terre-Neuve, la variabilité pendant les trois mois précédant le maximum saisonnier de la température a été beaucoup plus grande que pendant les mois suivant ce maximum. Cette différence de variabilité était moindre dans la baie Placentia sur la côte méridionale de Terre-Neuve.

Introduction

The Long Term Temperature Monitoring Programme (LTTMP) of the Department of Fisheries and Oceans started in 1967 with monitoring stations at several coastal and fresh-water sites in Newfoundland and Labrador. Hourly temperature measurements accurate to within 0.1 °C were recorded for over 150 sites at depths to 100 metres. Data for most of the thermograph stations were seasonal, generally covering the summer and fall. Some sites have data spanning a decade or more with near continuous coverage. This LTTMP data has been reported previously by Narayanan et al. (1996), Colbourne et al. (1998) and Senciall et al. (2002), and many others.

Colbourne (2001) observed that the anomaly time series, calculated from monthly means averaged over several decades of available data, for three inshore sites and that the long-term temperature trends were consistent with regimes seen on the Newfoundland shelf. Narayanan et al (1996) noted that the predominant annual cycle amplitude decreased with depth and latitude while increasing from east to west. These results were generally consistent with the findings of Petrie et al. (1991) who made similar observations of the amplitudes and phases of the annual harmonics derived from hydrographic temperatures on the shelf waters of Newfoundland.

The inshore LTTMP thermograph data set has clear utility for industry and research. In aquaculture, an understanding of the temperature variability may be important in site selection. In physical oceanography, temperature plays a key role in water motion and stability and is frequently used to identify a water type and origin. Several questions about physical processes can be posed and answered by examining thermograph data. For instance, can we determine if advection of Labrador Sea Water plays a role in the inshore thermal patterns? How do these regimes vary from bay to bay? We present a review of the coastal thermograph data and attempt to understand its features in the context of other environmental variables such as wind and circulation dynamics.

Data

Thermographs from two manufacturers were used to acquire the LTTMP data. Hugrun Seamon thermographs provided an accuracy of ± 0.1 °C with a resolution of 0.05 °C. These have been used since 1980. The two types of instruments from Vemco were accurate to 0.2 and 0.3 degrees and provided a resolution of 0.1 and 0.2 degrees respectively. Early data was obtained from Ryan analogue and digital thermographs. A detailed report of the instrumentation was provided by Senciall et al. (2002). The instruments were subject to an in-house calibration procedure prior to deployment (Narayanan et al. 1996.) On recovery of the instrument, the data was despiked and truncated to the duration of its deployment. All data were archived at both the Marine Environmental Data Services (MEDS) in Ottawa at the Northwest Atlantic Fisheries Centre (NAFC) in St John's, Newfoundland and Labrador.

The Remote Sensing Unit of the Bedford Institute of Oceanography furnished sea surface temperature (SST) and Environment Canada provided the meteorological data which included wind speed and direction.

Analysis

Few sites had continuous observation periods throughout all seasons; most were only observed during summer and fall. Four sites had continuous long-term observation periods extending over several decades. These were located on the northeast shore of Newfoundland at Stock Cove and Comfort Cove with the remaining sites in the south in Placentia Bay, Fig. 1. For these sites, the thermographs were mounted on the bottom at a depth of nine metres.

Annual Cycles

We compared the annual cycles between Placentia, Bonavista and Notre Dame Bays. The amplitude of the annual harmonic remained relatively uniform between these sites. However, phase varied with the summer maximum temperatures. The uniformity of the annual cycle throughout the Newfoundland and Labrador region and its depth dependence has been reported by Narayanan et al (1996). These findings were consistent with those of Petrie et al. (1991) for the surface waters on Eastern Newfoundland shelf. We examined the thermograph data at higher temporal resolution, i.e. for periods of one week or less, to better characterise the timing of the maximum. Using data from each of the four sites with essentially continuous data over the past decade, we calculated daily means from the hourly temperature measurements. Using a least squares harmonic regression procedure with four harmonics (N=4) as described by Craig et al. (2000), the annual temperature signal was obtained for each site based on the daily means. This was expressed as:

$$T(t) = \langle T \rangle + \sum_{i=1}^{N} A_i \sin(i\omega t) + B_i \cos(i\omega t)$$

where <T> is the aperiodic (mean) component and t is the time in days. This expression gives the amplitudes and phases for the annual, semiannual, four and three-month periods.

Annual phase and amplitude differences between sites on the northern part of Newfoundland (Bonavista and Notre Dame Bays) and those to the south (Placentia Bay) were 15 days in phase and 2 °C in amplitude respectively, Fig. 2. The average difference in temperature between these sites was 2 °C and is greatest in July. Data from the upper 10 metres at station 27, interpolated at one metre intervals was treated similarly. The corresponding annual cycle was intermediate in amplitude between the two regimes above, but closer in phase to that of Placentia Bay. It was noted that the phase of the annual harmonic $\varphi = \arctan(A_i/B_i)$ for i = 1, remained approximately constant, increasing by only 6 days from Placentia to Notre Dame bays, but that for the semiannual harmonic (i =2) increased from 90 to 136 days. In Stock Cove (Bonavista Bay) this phase was 122 days. The amplitudes for this semi-annual component were comparable for all sites, ranging from 1 to 1.5 degrees.

To examine spatial variability of the annual cycle within large bays, we used the archived hydrographic (CTD and XBT) data for several major bays around the island to calculate annual cycles based on the monthly mean of observed temperatures. This was done for Bonavista, Conception, Notre Dame, Placentia and Trinity Bays. Monthly mean temperatures were calculated from the hydrographic temperatures in the upper 10 metres of the water column using data extending back to 1991. For each profile, temperatures were interpolated at 2 metre intervals before averaging to avoid biasing that might arise from sampling. The resulting annual time series generally fell between the limits of the harmonic regressions of the annual cycles in Fig. 2 in terms of amplitude, phase and width of the summer peaks. The minima were as not as well represented by the data, a result of limited sampling during the winter months. In general, data was available for six months in a given year. Spatial coverage was fairly uniform and representative. The consistency between these data sets indicates that the thermograph data set is reasonably representative of the coastal water of comparable depth for each of the major bays at least for the annual and lower frequency components.

In bays where two or more thermographs were simultaneously deployed, there was some evidence of small spatial structure in the temperature field. For example, in Conception bay, there were differences in the temperature time series between Upper Gullies and Bristol's Hope, Fig. 3. The latter, located on the northwest bank of the bay, (Fig. 1) was almost consistently lower in temperature by about a degree or two. Despite this, there were strong similarities between the two time series at scales of several days and greater periods. Wind generated coastal trapped Kelvin waves have a greater influence on the western side of the bay where the wave generating coastal headlands are closer in the upstream wave propagation sense (Davidson et al 2001). Kelvin waves travel with the coast to the right of their direction of motion.

Anomalies at the long term sites

For each site, an anomaly time series was obtained by removing the mean cycle, based on the entire time series. There were three decades of data for Stock Cove and two for Arnold's Cove and Comfort Cove. Daily averages were calculated from the hourly data and the annual cycle was computed at daily intervals. Yearly and 5-year running means were calculated to remove high frequency fluctuations. There was considerable interannual variability for the temperature anomaly for all three sites, however the 5-year running means showed spatial consistency of the long-term trends for Figs. 4-6. The temperature at each site decreased in the late 1980's reaching a minimum in 1992. After this the 5-year running means of the anomalies increased consistently and reached values almost 1.5 degrees higher than the 1992 minimum. A very similar trend was seen for Station 27.

These similarities suggest that the long term trend is due to large scale shelf and basin processes and not due to a smaller scale local process. The latter would be less likely to produce such similar trends given the great difference in geography of the land and ocean in these areas and the dissimilar ocean current regimes.
The shallowness of the water suggested surface warming might have played a role in this, however upwelling regions could induce differences.

The similarities persist at the annual time scale, but are less pronounced. For instance, at all three sites in 1996 there is a positive anomaly that becomes negative in the following year. In contrast, this feature is absent in the Station 27 anomaly time series, Figs. 7 and 8. The temperature regime at Station 27 is strongly influenced by the inshore branch of the Labrador Current. At the other sites, this influence is weaker or delayed. The time series was very coherent to at least the 10-metre level. This was depth at which the thermographs were deployed at the three sites.

High Frequency Variability

The annual cycles of data taken from the southern and north east coasts, Figs. 9 and 10, for Arnold's Cove and Stock Cove respectively, showed comparable amplitudes and phases, but clear differences in the variability between the warming and cooling phases of the annual cycles at the two sites. These differences occur at times when the water is stratified and wind forcing modifies local stratification

To further investigate this effect, the annual cycle was removed from daily temperature data at the four sites based on all available data over at least the past decade at the four sites. Two of these, Stock Cove and Comfort Cove, were on the northern coast while the others, Shag Rocks and Arnold's Cove were on the southern portion of the island. The annual cycles were partitioned into warming (day 140-240) and cooling phases (day 240-340). The variance of each phase was calculated for each site for a decade and tabulated, Table 1.

Year	Shag Rocks	Arnold's Cove	Comfort Cove	Stock Cove
1990	3.17 1.45	3.27 2.32	8.94 1.96	2.24 1.13
1991	6.20 0.45	3.14 4.46	6.20 0.45	5.73 2.09
1992	- -	- 5.94	- 1.47	2.14 0.33
1993	4.97 -	4.36 -	9.71 0.86	5.03 3.26
1994	1.71 1.36	- -	- -	1.80 0.39
1995	1.69 1.21	2.78 1.76	2.61 1.12	2.54 0.84
1996	1.58 1.22	2.25 2.09	2.15 1.12	2.18 0.54
1997	1.82 2.05	2.59 4.63	4.96 -	2.93 1.52
1998	2.38 4.05	2.33 2.99	5.26 0.42	3.29 1.89
1999	2.13 2.87	0.71 1.93	5.53 -	4.82 -
2000	- 2.42	6.42 -	- 0.59	- 0.48

Table 1. Variance of warming (left) and cooling phases (right) from thermograph data at four sites.

These results showed that there was a substantial difference between the variance of the warming and cooling phases for Comfort Cove and Stock Cove whereas they were more uniform for Shag Rocks and Arnold's Cove in Placentia Bay.

Variability associated with Wind stress

Studies of upwelling have recently been completed in Trinity Bay, Davidson (1999). This site was selected because of the favourable geometry for potential upwelling events; the site was on a north-west coast in an region which has prevailing south west-winds, as shown by the arrow in Fig. 1. One thermograph site in Trinity Bay was at Old Bonaventure. The water depth was 22 metres and the instrument was deployed at the 10 metre level. Although the data from this site was fragmented and available for only portions of a given year, it showed some interesting features. The time series, shown in the upper traces of Fig. 11 exhibited considerable variability, comprising primarily negative excursions and usually lasting on the order of a day or days. Wind speed and direction data were obtained from the closest meteorological station, located at Bonavista to compare with thermograph data from Old Bonaventure.

To determine if the these excursions in temperature were associated with wind events in the Trinity Bay area, we calculated the component of the wind speed in metres/second that was parallel to the axis of the bay, taken as 45 degrees from true north. This value was squared, divided by a scaling factor of 50 and plotted along with the thermograph temperature to allow a temporal comparison of relative wind stress and temperature. To simplify the graphs, wind stress arising from wind moving in the opposite direction was not plotted. Wind and temperature data at hourly intervals was converted from NDT to UTC, but no time averaging was applied.

The timing and duration of dips in the thermograph data coincided well with along-bay-axis wind events, Fig. 11. It was also noted that the duration of the negative excursion appeared to be directly related to that of the wind event. This would be expected from Ekman transport of water away from the coast with the resulting upwelling of cold water as required by continuity. The magnitudes of the wind stress and the temperature dips appeared to be less clearly correlated although a phase delay was seen with the wind preceding the temperature by several hours to half a day. A similar set of observations was made in Conception bay at the Bristol's Hope thermograph site, (Fig. 3.) It was noteworthy that the temperature dropped, although not as dramatically, in Upper Gullies on the east bank of Conception bay when the wind was from the opposite direction. This was plotted in the upper trace in Fig.3.

The sea surface temperature (SST) as determined from satellite radiometry, was observed to be a few degrees lower along the northwest coast on clear days during which apparent upwelling events were seen from the thermograph data, Fig. 3a. This provides evidence that the event covered a large area and was not simply a result of a localised temperature drop in the area of the thermograph. The scale of these events is given by the Rossby radius, which is of the order of 5 km on the shelf.

Frequency Domain Analysis

Spectral analysis of several sets of thermograph data showed most of the expected features with tidal, diurnal and inertial oscillation signals being evident in many records. It was hoped that consistent signals with periods of the order of several days could be resolved to further explore the variability and to better tie the wind events with the negative temperature excursions. An analysis following that of Drinkwater (1994) was attempted. Using a multivariate frequency response method, Drinkwater determined that wind stress accounted for up to 65% of the variance in temperature. The model used was

$$Y_i = H_{ix}\tau_x + H_{iy}\tau_y + Z_i$$

Where τ_x and τ_y are the components of wind stress. Y_i was the temperature at the i^{th} frequency and the response functions H were periodic exponential functions at the frequencies of the wind stress, containing amplitude and phase components of temperature and Z_i was the residual noise. From this model was derived an expression for optimum temperature response and coherence as a function of wind direction. The ratio of variance of temperature accounted for by the wind stress was calculated as the coherence squared. Preliminary results have not identified persistent spectral features at periods of a few days or longer in either Conception or Trinity bays as was found by Drinkwater in St George's Bay. This was surprising considering the apparent geographical similarities between these bays.

Discussion and Conclusions

Significant differences in the amplitude and the timing of the seasonal maxima were seen between thermograph stations at different locations along the coast of Newfoundland. There was a delay in the seasonal maximum for sites on the northeast coast of just over 2 weeks compared with that in Placentia Bay. A difference in the annual cycle amplitude of about 2 degrees over year was much greater than would be expected from reduced solar radiation flux as a result of the greater latitude and was indicative of other processes such as advection of cold water or the effects of ice. The difference could also be explained on the basis that water farther south has more time to be heated since the flow is southward. The phase of the annual harmonic was very similar at both sites, however the semiannual component exhibited a phase delay of about 45 days for the northeast coast. This could be associated with processes such as stratification or ice cover.

In general, the thermographic temperature regimes were consistent with hydrographic data for the upper 10 metres of the water column and essentially representative of the larger bays in which the instruments were deployed.

Temperature anomalies showed patterns consistent with trends on a decadal scale and these were more uniform across the regions. This suggested a large-scale process dominates long-term trends. Consistency between the inshore and offshore temperature regimes was seen at decadal time scales although at shorter scales, for example interannual periods, significant differences were observed.

High frequency variability was evident in all the data, but there were notable differences in variability between the regions. The warming and cooling phases of the temperatures in Placentia Bay were relatively uniform, but this was not the case for the northeast coast where the variability was substantially greater during the period preceding the annual temperature maximum. The reason for this was unclear. It may have been due to differences in density stratification between the two sites, possibly associated with differences in fresh water run off from the land, ice melting or the advection of cold Labrador Sea water onto the northeast coast during the early summer. Propagation of Kelvin waves along the northeast coast could also contribute to differences in variability (Davidson et al. 2003).

It was determined that much of the variability with short periods of a day or less could be explained by wind driven upwelling. When the wind was aligned with the axis of the bay, negative temperature excursions were seen in the time series of thermographs on the west bank of the bay, consistent with Ekman upwelling.

Spectral analysis was used to attempt to determine the cause of the variability. The apparent absence of consistent periodicities in the temperature time series greater than a few days made it difficult to accurately assign a value to the amount of variability caused by upwelling.

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References

Colbourne, E. B., P. Stead, and S. Narayanan. 1998. Long-term temperature monitoring program 1996-1997, Newfoundland Region. Can. Tech. Rep. Hydrogr. Ocean Sci. 198: xi: + 397p.

Colbourne, E. B., P. Stead. 1993. Long-term temperature monitoring program 1988, Newfoundland Region. Can. Data Rep. Hydrogr. Ocean Sci. 90: vi + 324 p.

Colbourne, E. B. 2001. Environmental Conditions in the Newfoundland Region during 2000. DFO Science Stock Status Report. G2-01

Craig, J. D. C., E. B. Colbourne and G. L. Maillet, 2001. Preliminary Studies of Density Stratification and Fluorescence on the Newfoundland Shelf. DFO Canadian Science Advisory Secretariat Research Document 2001/085

Davidson, F. 1999. Wind driven circulation in Trinity and Conception Bays. Doctoral thesis. Memorial University of Newfoundland.

Davidson, F., R. J Greatbatch and B. de Young, 2001. Asymmetry in the response of a stratified costal embayment to wind forcing. J. Geophys. Rev. 106, C4, 7001-7015

Drinkwater, K. 1994. The Response of an Open Stratified Bay to Wind Forcing, Atmosphere-Ocean 32 (4) 757-781

Drinkwater,K, 2003. Personal Communication.

Narayanan,S, E.B. Colbourne, E. B., and P. Stead, 1996. Temperature Climate Atlas for the Inshore Regions of Newfoundland and Labrador. Can. Tech. Rep. Hydrogr. Ocean Sci. 174: v + 181 p.

Petrie, B., J. Loader, S. Akenhead and J. Lazier. 1991. Temperature and salinity variability on the Eastern Newfoundland shelf: the annual harmonic. Atmosphere-Ocean, 29:14-36.

Senciall, D.R., P.Stead and E. B. Colbourne. 2002. Long-Term Temperature Monitoring Program 2000-2001, Newfoundland Region. Can. Tech. Rep. Hydrogr. Ocean Sci. 219: ix: +277p.

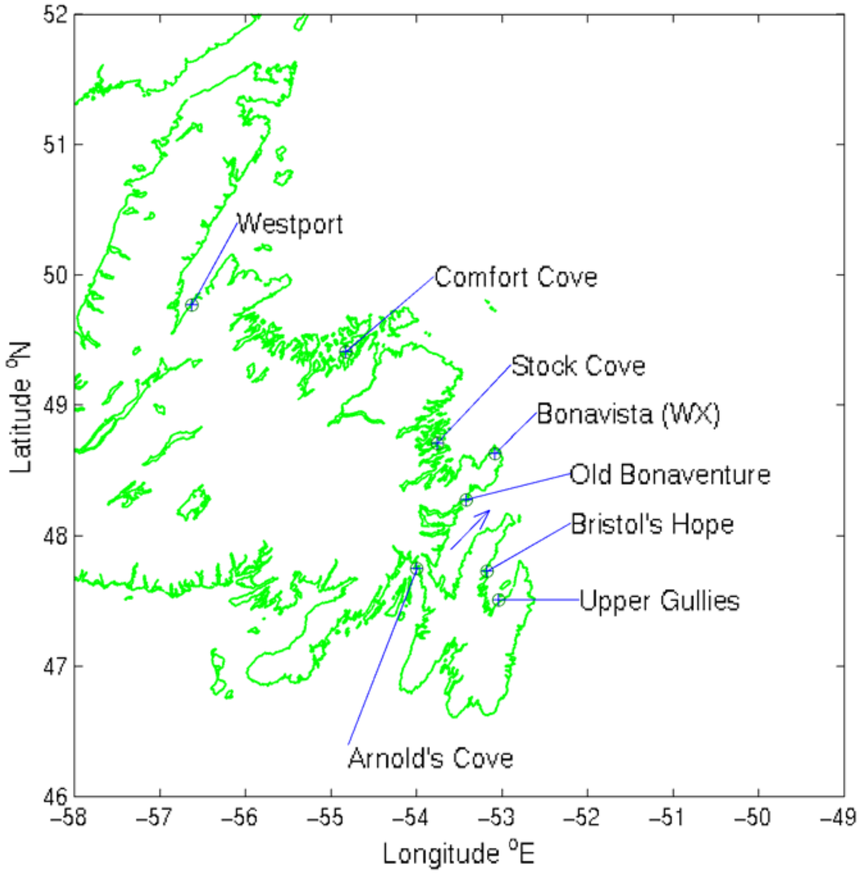

Fig. 1. Location of thermograph sites and the Bonavista meteorological station

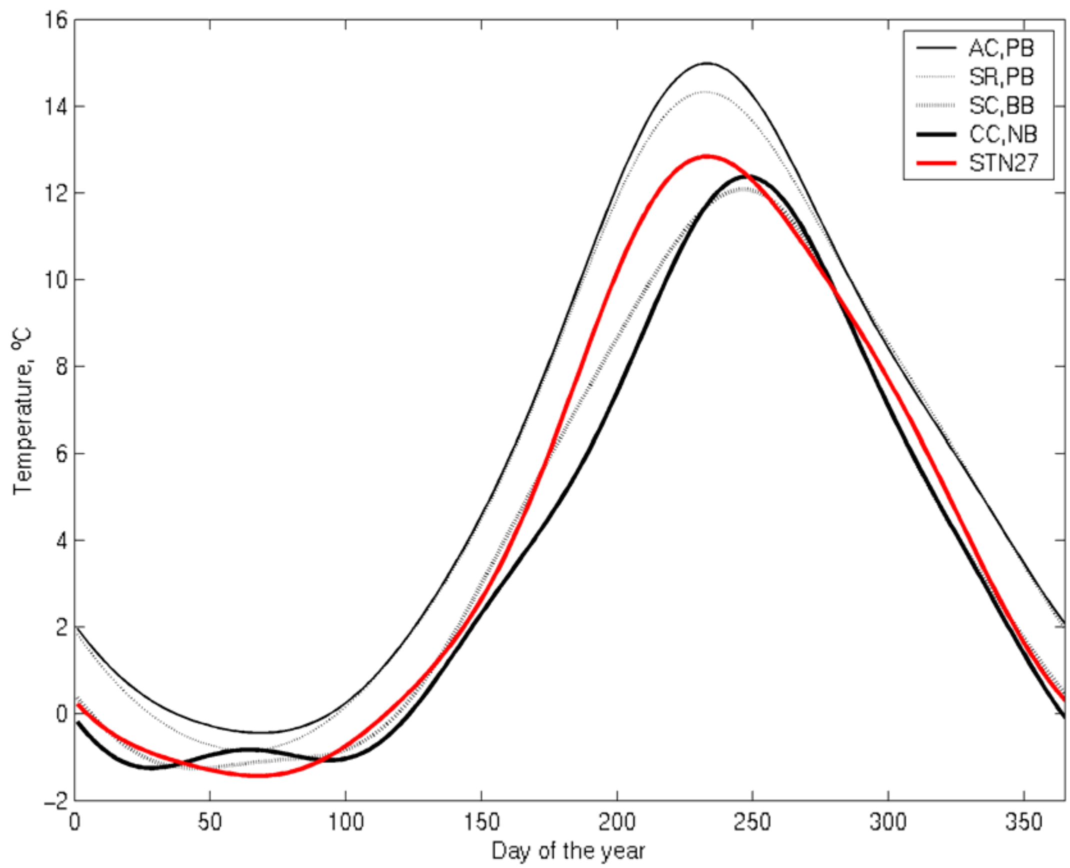

Fig. 2. Harmonic regressions (n=4) of the annual cycles for Arnold's Cove, Shag Rocks, Stock Cove, Comfort Cove and station 27.

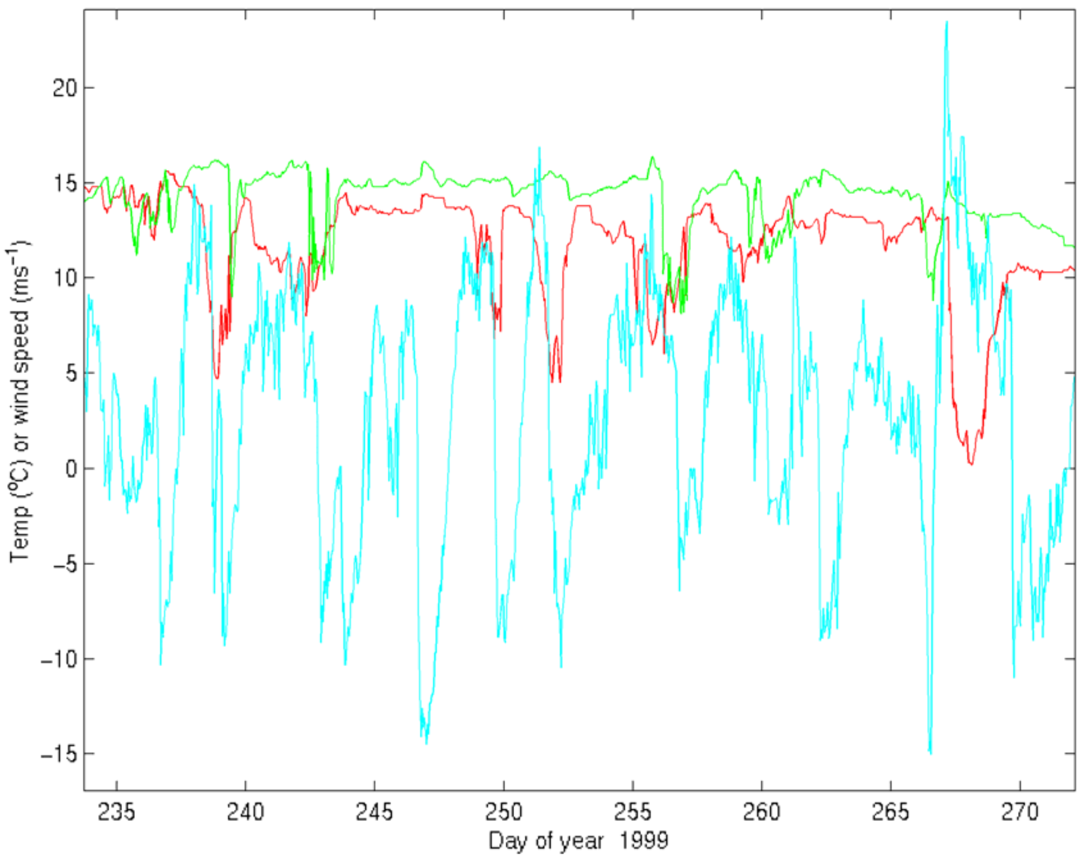

Fig. 3. Time series of thermograph data for Upper Gullies, (top) Bristol's Hope and the wind speed along the axis of the bay (bottom).

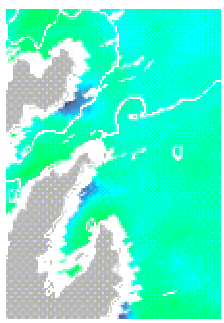

Fig. 3a. Sea Surface temperature for 24 September 1999, corresponding to day 267 in Fig. 3. The temperatures depicted in the image ranged from about 6 to 12 degrees.

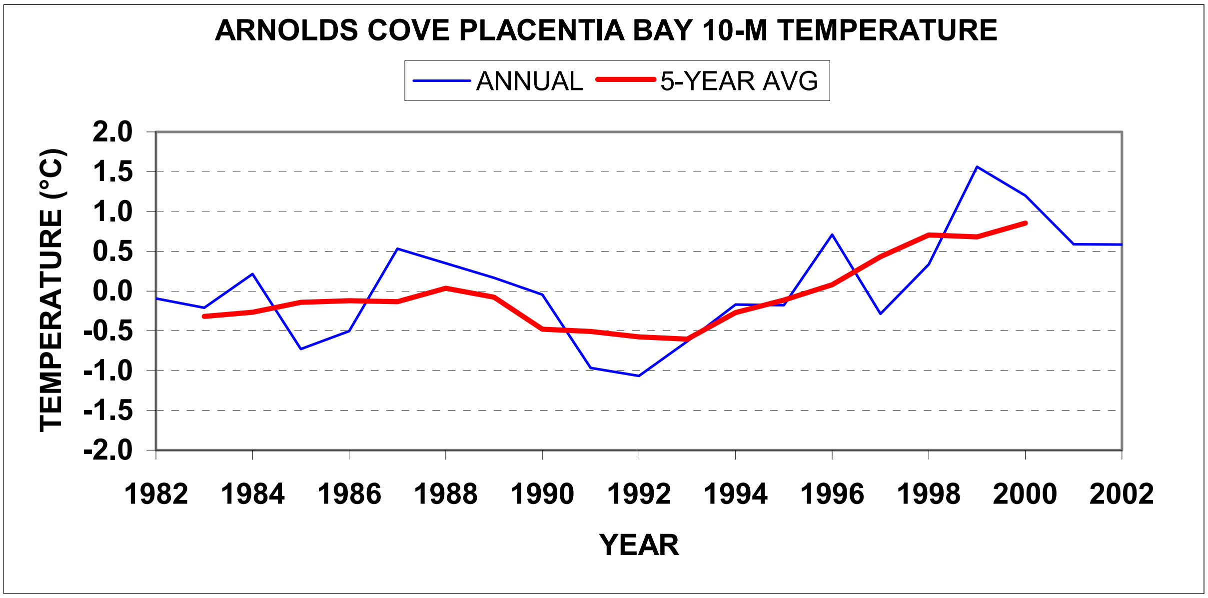

Fig. 4. Anomaly time series for Arnold's Cove.

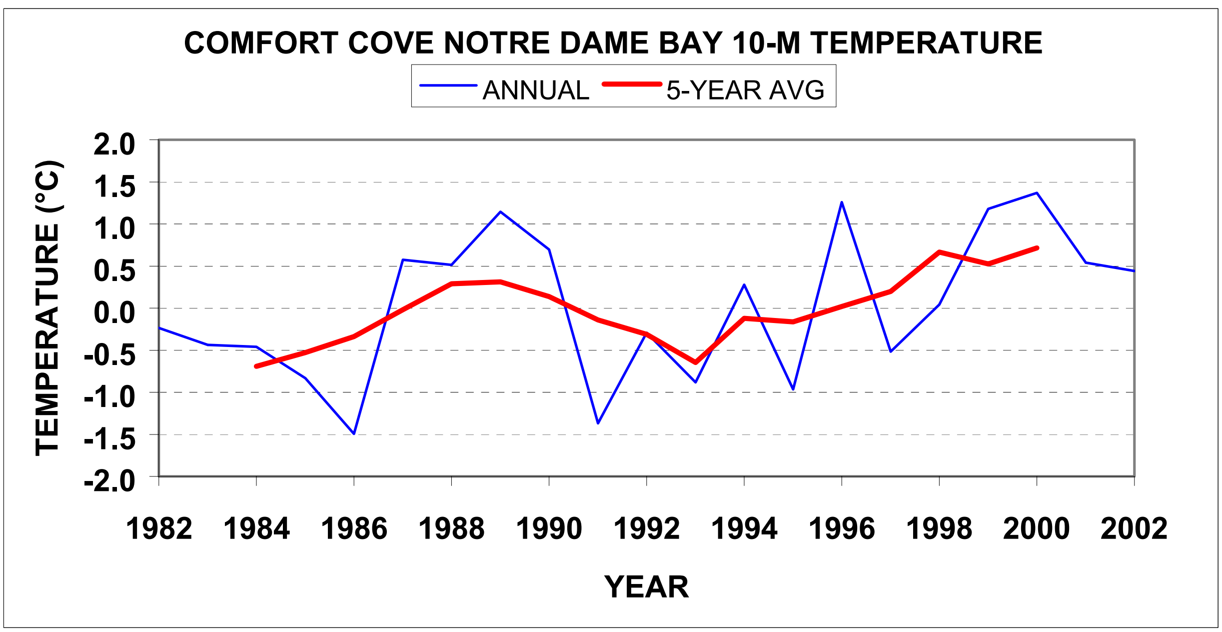

Fig. 5. Anomaly time series for Comfort Cove.

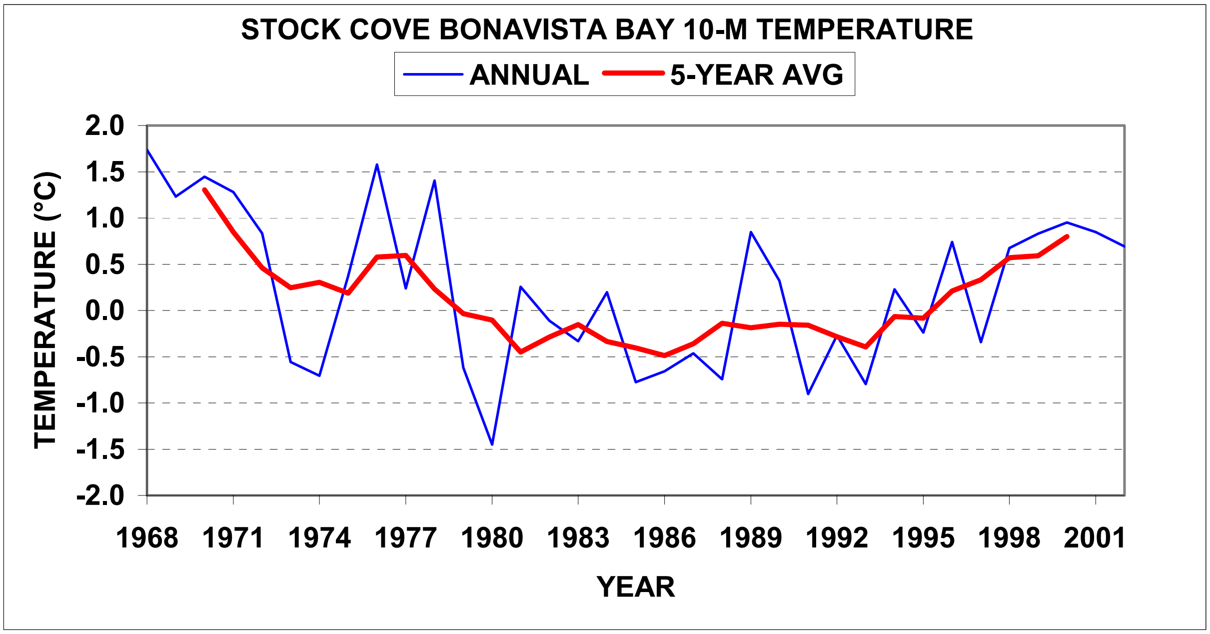

Fig. 6. Anomaly time series for Stock Cove.

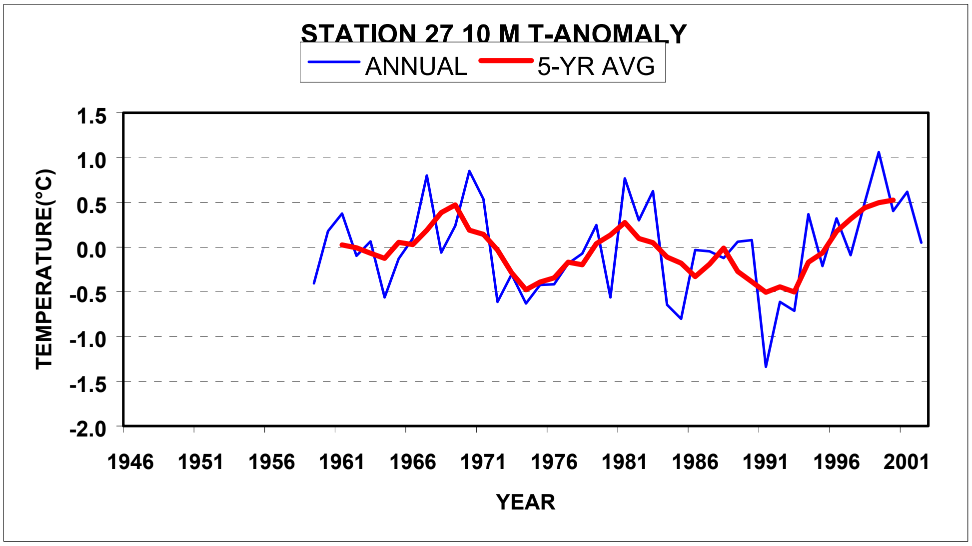

Fig. 7. Temperature anomaly at 10 metres for Station 27.

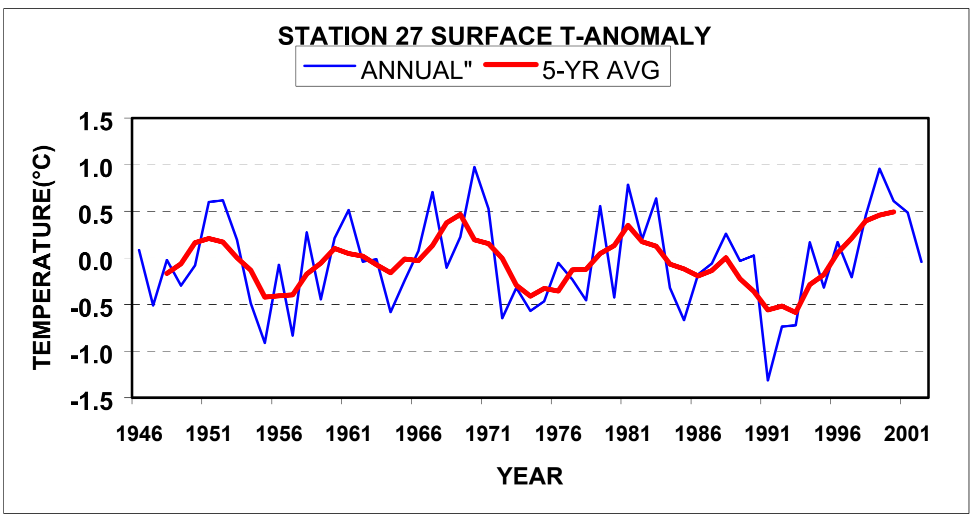

Fig. 8 Temperature anomaly for Station 27, surface water.

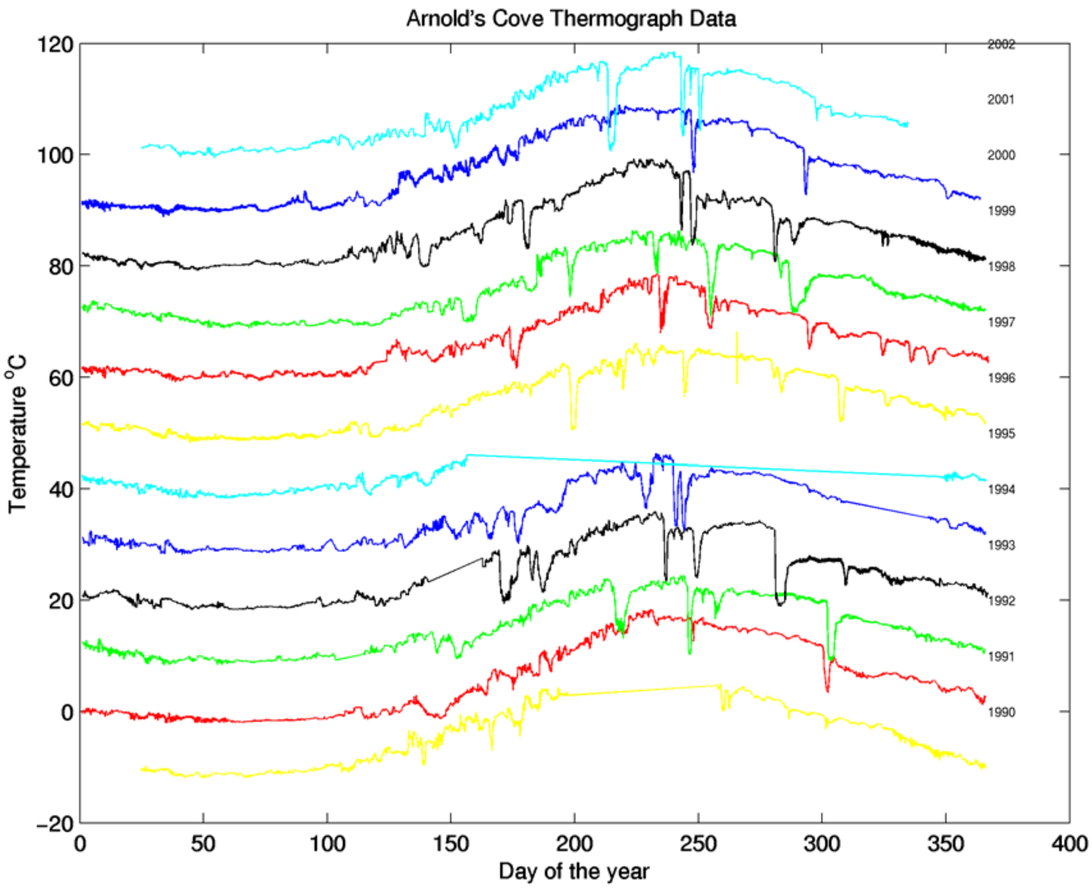

Fig.9. Arnold's Cove thermograph annual cycles.

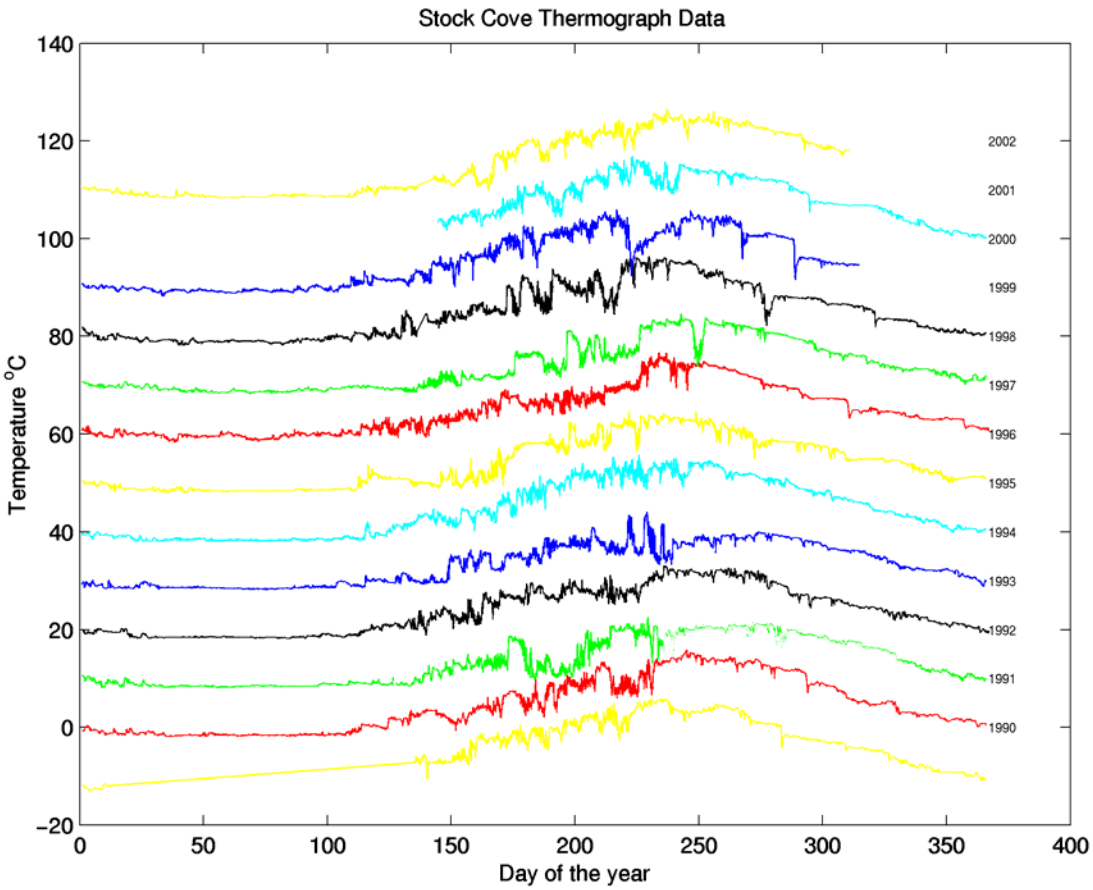

Fig. 10. Stock Cove thermograph data annual cycles.

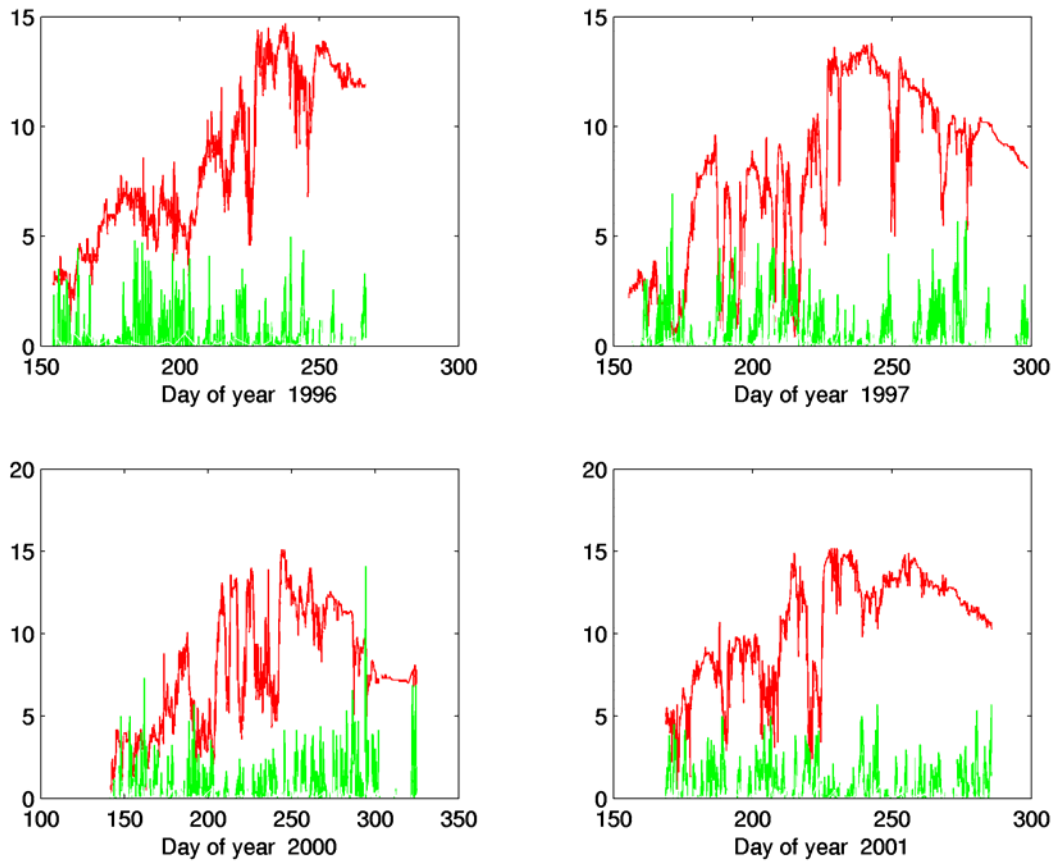

Fig 11. Thermograph data for old Bonaventure and relative wind stress at Bonavista.