CLIMATOLOGICAL DATA FROM THE WESTERN CANADIAN ODAS MARINE BUOY NETWORK

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1. Introduction

An array of 17 buoys along and off the west coast of Canada provides weather and ocean data for the Environment and the Fisheries departments of the Canadian federal government. The first buoys were installed in 1987 and the operational network was brought up to 16 buoys in 1993. An additional experimental buoy was added in 1998 for testing sensors for biological and optical variables. The buoys measure wind speed and direction, wave height and spectrum, surface water and air temperature and atmospheric pressure. All data are transmitted in real time at hourly intervals.

Time series from the buoys are now long enough to show a clear signature from short-term “climatic” effects such as El-Nino in sea surface temperature. Apparent long-term trends in temperature, wind speed and wave height need to be evaluated to check the quality of the buoy data as well as the possibility that the trends are the effects of long-term climatic change. Wind and wave data from the buoys have been used in validation of satellite sensors such as the TOPEX altimeter (Gower 1996) and of the COADS data set (Cherniawsky and Crawford, 1996).

This paper shows examples of time series of monthly average sea surface temperature, wind speed and wave height provided by the buoys in the time period May 1990 to May 1999, derived from a new data compilation provided by Environment Canada for this study.

2. Buoy data

The positions of the 17 buoys in the west coast Canadian network operated by Environment Canada and the Department of Fisheries and Oceans of the Canadian Federal Government are shown in Figure 1. Three outer buoys have “NOMAD” ship-like hulls measuring 6 m by 4m and are located well offshore, about 400 km west of the British Columbia coast. Other buoys have 3-meter discus hulls. Six of these are located in a line of exposed positions within 100 km of the coast, and a further 8 are located in more sheltered coastal waters, behind the Queen Charlotte Islands and Vancouver Island. Two buoys (46131 and 46146) are located the sheltered waters of Georgia Strait . A further two (46181 and 46134) are located in narrow coastal inlets. Buoy 46134 was installed only recently.

For this study, monthly mean sea surface temperatures (SST), wind speeds and significant wave heights (SWH) were computed from the hourly buoy measurements. Means were computed for all months for which at least 300 hourly values were collected. Nominal calibration accuracy is 0.2 C for sea surface temperature, 10% for wind speed, and 5% for Significant Wave Height. Temperatures are measured by thermistor at a depth of 80 cm. Wind speeds are measured by two propeller anemometers mounted at 3.7 and 4.7 m above the water. The higher anemometer is used unless its data are suspect. Both winds and temperatures are averages over 10 minute

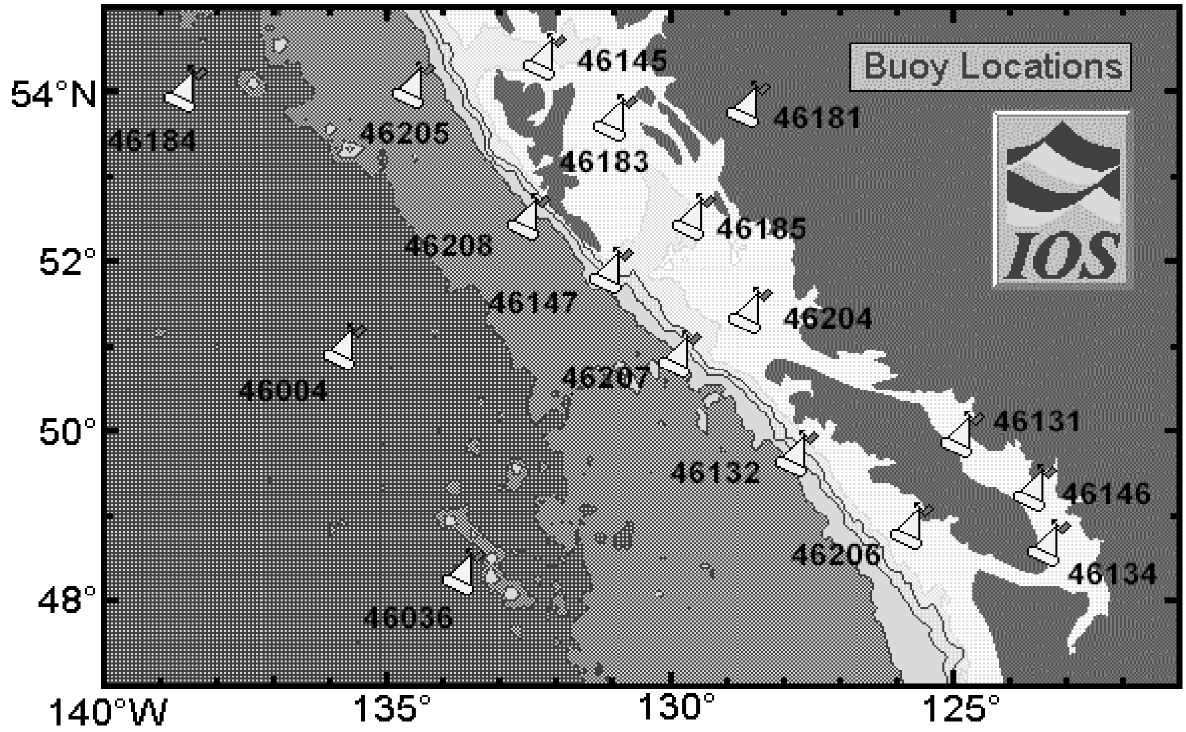


Figure 1. Map showing the locations of meteorological buoys on the west coast of Canada whose data are considered in this study.

periods. Winds are vector averages. The wave-heights are deduced from vertical "heave" accelerometers mounted inside the buoys. In the NOMAD hulls the sensors are gimballed to remain vertical when the buoy tilts. In the 3-meter hulls, the accelerometers are strapped down, and buoy tilt is a possible source of error. Buoy wave measurements are averages of 37 minutes of data collection.

In the data provided, "no data" was indicated by a zero-length string, or blank entry. The value "zero" was therefore available to indicate freezing water (not expected in these waters), zero wind (<0.05 m/s), or no waves (SWH < 0.05 m). Examination of the data however, showed some months with large numbers of zeros for all three types of measurement, apparently indicating output from broken sensors. Wave height appeared to be the cleanest data in this respect, in that zero values were relatively uncommon (1 hourly value per year per buoy) at exposed locations. Zeros were common for the most sheltered buoys (46131, 46181, and 46134). Zeros in the wind speed and SST tended to appear in bursts. For these reasons, hourly values indicating zero SST or zero wind speed were omitted from the averaging.

In the data analysis, we computed an annual cycle and a second harmonic (2 cycles per year) whose amplitudes and phases minimised the standard deviation of the residual monthly values obtained by subtracting these cycles from the data. Monthly mean data were tagged with the time of the middle of the month, assuming all months are 1/12 of a year long. In Tables 1, 2 and 3 we show the mean value for each buoy (average over the entire time interval), the trend of the data (slope of the standard regression applied to the residual values), the two amplitudes and the two phases, the length of the data record in months, and the number of months for which data were included in the analysis. The order of the buoys (north west to south east in four series) reflects their locations as shown in Figure 1, with the fourth series reserved for the two buoys in narrow coastal inlets (46181 and 46134). The phases show the phase lag in months after mid-summer for the maximum values. Maximum temperatures occur

Table 1 Buoy SST summary (C), phases and record lengths in months.

Buoy ID	Mean SST (C)	Trend (C/year)	Ampl. 1 (C)	Ampl. 2 (C)	Phase 1 (mos)	Phase 2 (mos)	Length (mos)	Number (mos)
46184	9.1	.001	4.2	0.9	1.8	4.6	108	98
46004	10.4	-.010	4.2	1	1.9	4.7	107	96
46036	11.2	-.024	3.9	1	2	4.8	108	96
46205	10.2	.027	3.7	0.8	1.7	4.7	107	101
46208	10.8	-.013	3.7	0.8	1.6	4.6	108	98
46147	10.6	.027	2.8	0.8	1.6	4.5	73	72
46207	11.1	.037	3.4	0.7	1.5	4.5	108	102
46132	11.7	.011	3.3	0.7	1.6	4.8	66	64
46206	11.4	.100	2.8	0.3	1.1	4	108	102
46145	9.4	.023	2.9	0.4	1.5	4.1	98	97
46183	10	.059	3.1	0.6	1.4	4.1	98	94
46185	10.7	.062	3.4	0.8	1.5	4.4	105	103
46204	10.8	.032	3.3	0.7	1.4	4	108	100
46131	11.5	.006	5	0.8	0.9	3.8	80	79
46146	11.6	-.096	5.7	0.7	0.8	4.1	87	85
46181	9.6	-.075	5.8	1.2	0.7	4	108	96
46134	11.5		5.9	1.3	1	4.8	4	4

about 2 months after the end of June (end of August). Maximum winds and waves occur with a lag of about 6 months. The phases of both fundamental and harmonic show systematic trends among buoys.

3. Sea surface temperature (SST)

Results of the analysis are summarised in Table 1. The mean temperature shows a clear trend with latitude (about 1 C colder for 3 degrees north-wards). The trend with time over the 9 year period is warmer for most buoys, but a trend of 0.02 C per year amounts to only 0.18 C total change over the 9 years, comparable to the planned accuracy for individual sensors. Calibration errors are therefore a potential source of error. Also, an apparent warm trend will be increased by the effect of the recent 1997/8 El Nino, which caused a significant rise in sea surface temperatures near the end of the time period. Two of the three NOMAD buoys show a slight decreasing trend in SST, the other shows no change. The largest (positive) trends are shown by buoys on the continental shelf (46206, 46145, 46183, 46185, 46204). The two buoys in Georgia Strait show no change (46131) and a cooling trend (46146). Buoy 46181, located in Douglas Channel south of Kitimat, also shows a cooling trend. This suggests coastal fresh water run-off as a possible influence. Buoy 46146 would be influenced by the Fraser River, buoy 46181 by run-off from the Kitimat and other smaller rivers flowing into Douglas Channel.

The annual cycle has an amplitude of about 4 C offshore, but is less (about 3 C) near the coast where coastal upwelling tends to cool summer temperatures. The amplitude is highest (5 C) in the more stratified waters of Georgia Strait and coastal inlets where the shallow surface layer is strongly warmed in summer. The phase lag of this cycle is lowest in these waters, since the shallow layer responds more quickly to the seasonal change in solar input.

Figure 2 shows a time series of the monthly average SST data from one of the offshore NOMAD buoys (46036), as well as the residual temperatures and the fitted trend line. This was one of two buoys whose SST data in the present compilation showed a significant, but short-term calibration error. Here all values in 1992 appear 2 C low. Similarly, buoy 46184 showed 5

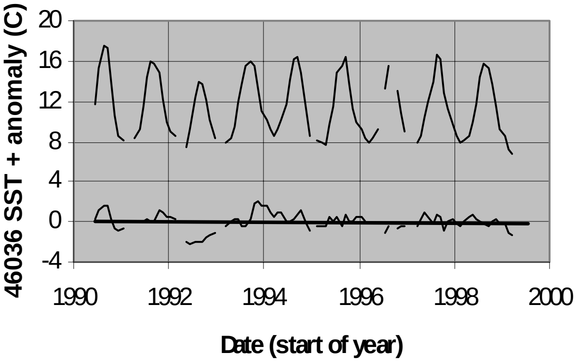


Figure 2. SST monthly average time series for buoy 46036, showing residuals after removal of annual cycle and harmonic, and trend.

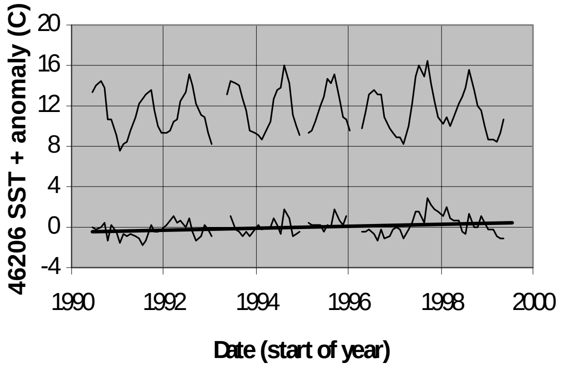


Figure 3. SST monthly average time series for buoy 46036, showing residuals after removal of annual cycle and harmonic, and trend.

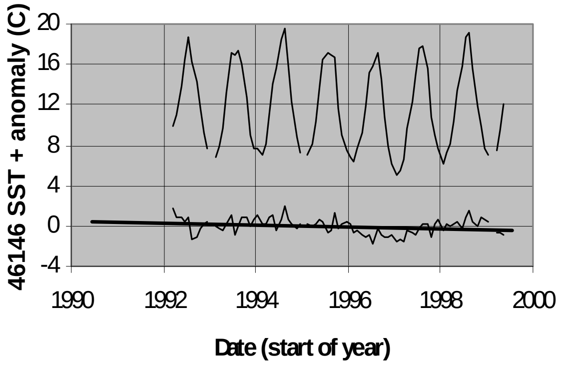


Figure 4. SST monthly average time series for buoy 46036, showing residuals after removal of annual cycle and harmonic, and trend.

months of low SST data in 1991. The nearly 2 C warm anomaly centred at the start of 1994, is shown by all 3 offshore buoys, and so must have covered a large area (the outermost buoys are separated by about 600 km).

An example of a time series from a 3-meter buoy (46206, on La Perouse Bank near the south west coast of Vancouver Island), is shown in Figure 3. The trend for this buoy shows the largest slope of +0.1 C per year (Table 1), almost 1 C over the time period shown. A 2 C warming, coinciding with the time of the 1997/8 El Nino is evident over the summer of 1997 and the subsequent winter. A similar 2 C temperature rise coinciding with the El-Nino is evident in SST data from all the 3-meter coastal buoys, with the exceptions of 46131, 46146 in Georgia Strait, and 46181 and 46134 from which no data were available. The annual cycle for 46206 has smaller amplitude than for 46036 (Fig 2), since summer temperatures are cooled by coastal upwelling. The sporadic nature of upwelling would also account for the spikier residuals in Figure 3 compared to Figure 2.

Figure 4 shows the time series from buoy 46146. The annual cycle is larger in the stratified waters of Georgia Strait. The residual plot shows a cooling trend, and a cool period in 1996 which is less evident in Figures 2 or 3. The other buoy (46131) in northern Georgia Strait shows similar residuals with lower trend and slight cooling in 1996.

4. Wind Speed

Results of the wind speed analysis are summarised in Table 2. The mean wind speed is highest at 7.5 m/s for the 3 offshore buoys, dropping slightly to 7.0 m/s near the coast. Buoy 46206 on the continental shelf shows a lower mean speed (5.8 m/s), whereas speeds for buoys round Queen Charlotte Islands remain near 7 m/s. Mean values for buoys in Georgia Strait and coastal inlets are significantly lower, clustering in the range 4.2 to 4.9 m/s. There is an apparent trend of increasing wind speed over the 9 year period for most buoys, up to as high as 0.25 m/s per year for buoy 46132. However, this buoy has a relatively short record, covering 66 months (5.5 years). The total change is therefore about 1 m/s. Trends in data from buoys with longer records are lower, and give total expected changes of less than 1 m/s. As

Table 2. Buoy wind summary (Wind speed in m/s, phases and record lengths in months)

Buoy ID	Mean (m/s)	Trend (m/s/yr)	Ampl. 1 (m/s)	Ampl. 2 (m/s)	Phase 1 (mos)	Phase 2 (mos)	Length (mos)	Number (mos)
46184	7.5	-.021	1.59	0.7	6	0.75	108	102
46004	7.55	.068	1.54	0.7	5.9	1.3	107	95
46036	7.44	.133	1.48	0.7	6.3	1.2	108	88
46205	7.18	.002	1.54	0.3	6	1.2	107	88
46208	6.96	.058	1.12	0.38	6.5	2	108	85
46147	6.8	.142	1.68	0.37	6.8	2.3	73	69
46207	6.96	.059	1.47	0.43	6.4	2.3	108	90
46132	7.01	.254	1.1	0.4	6.5	2.1	66	62
46206	5.8	.086	1.56	0.59	6.6	2.4	106	102
46145	6.57	.020	1.38	0.46	6.3	2.1	98	97
46183	7.06	.022	1.62	0.21	6.3	1.7	98	89
46185	6.98	.075	1.56	0.26	6	2.1	105	98
46204	7.07	.092	2.4	0.4	6.3	2.3	108	93
46131	4.71	.093	0.79	0.33	6.4	2.1	80	79
46146	4.91	.018	0.57	0.28	5.6	2.1	87	84
46181	4.59	-.027	0.89	0.81	5.9	3.1	108	105
46134	4.17		1.1	0.27	5.1	2.8	4	4

for SST, this change is comparable to the expected accuracy of the measurements (10% for wind speed). However, a systematic trend shown by so many buoys increases its significance. The north NOMAD buoy shows a slight negative trend with time, but the trend increases towards the south, with the south NOMAD showing the largest trend for any buoy covering the full 9 years. The same tendency for the trend to increase from north to south is evident in the other buoys. Only buoy 46146 appears to deviate from this pattern.

The amplitude of the annual cycle for the offshore buoys is about 1.5 m/s. Near the coast its value is quite variable with location. Of the exposed buoys (mean wind near 7.0 m/s), 46208 and 46132 show significantly lower amplitude (1.1 m/s), while 46204 shows higher (2.4). Buoys in Georgia Strait show a much lower amplitude (0.6 to 0.8 m/s). The phase lag of this cycle is close to 6 months, indicating a rapid response to the seasonal cycle.

Figure 5 shows the wind speed time series from the south offshore NOMAD buoy (46036). This shows the largest increasing trend in wind speed, of over 1 m/s over the 9 year period.

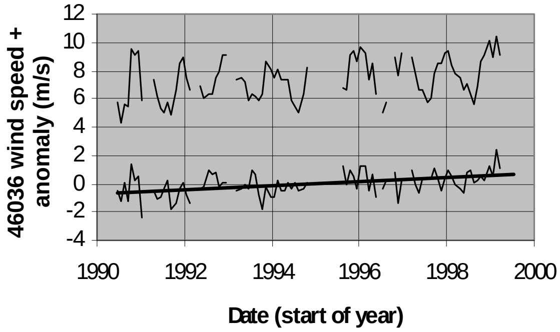


Figure 5. Wind speed monthly average series for buoy 46036, showing residuals after removal of annual cycle and harmonic, and trend.

Figure 6 shows the series from buoy 46204. This also shows a trend of increasing wind speed over the time period. This is also the buoy with the highest amplitude of annual cycle. The apparent sensor error in 1992, when measured winds decreased to near zero, is the only case where this was observed. Data in this period were not included in computing the trend, or other data in Table 2. Similar, but less evident errors may exist elsewhere in this data

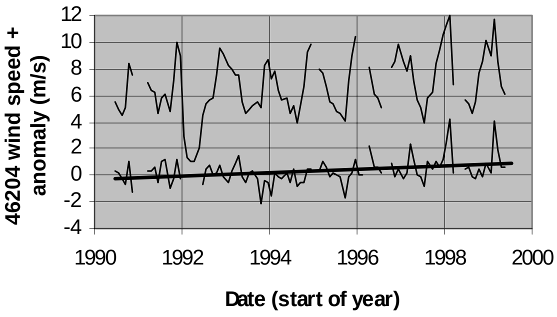


Figure 6. Wind speed monthly average time series for buoy 46204, showing residuals after removal of annual cycle and harmonic, and trend. Low readings in 1992 are omitted from the analysis.

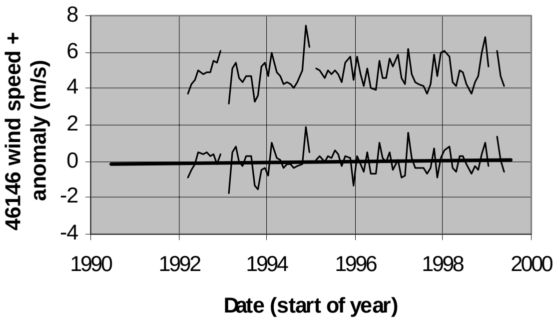


Figure 7. Wind speed monthly average time series for buoy 46146, showing residuals after removal of annual cycle and harmonic, and trend.

set, since anemometers have to be mounted in exposed positions and are subject to damage.

Figure 7 shows the wind speed time series from buoy 46146. The annual cycle has a very small amplitude. Trend with time is near zero. Buoy 46131 shows most of the same short-term variations, but with a larger increasing trend in wind speed.

5. Significant Wave Height (SWH)

Results of the SWH analysis are summarised in Table 3. The mean wave height is highest (3 m) for the 3 offshore buoys, dropping slightly to 2.6 to 2.8 m near the coast. Buoy 46206 on the continental shelf shows lower SWH (2.3 m). Buoys round Queen Charlotte Islands are more sheltered (1.3 to 1.9 m), with buoy 46204, north of Vancouver Island, at 2.2 m. Mean values for buoys in Georgia Strait are much lower (.42 and .45 m), and mean SWH in narrow inlets are lower still. Trends with time over the 9 year period appear more variable than for wind speed, but again there is a tendency for an increase, and by roughly the same percentage. The change is again highest for buoy 46132, which shows an increase by 15% in the 5 year period. A similar percentage change is shown by buoy 46131, for which mean SWH is much lower. Other buoys with longer records give total apparent changes of up to 10%, including the other buoy (46146) in Georgia Strait. These changes are somewhat larger than the 5% expected accuracy of the measurements. A systematic trend shown by several buoys again increases the significance of the increase.

One might also expect that real long-term changes in SWH should correlate with the trends in wind speed, though a major contribution to SWH will also be from swell due to remote winds. Comparing trends in Tables 2 and 3, the offshore NOMAD buoys show trends in SWH which increase towards the north, opposite to the pattern with wind speed. The buoys along the exposed continental shelf show similar trends in SWH as in wind speed, but the more sheltered buoys north of Vancouver Island show almost no trend. Buoys in Georgia Strait show an increase in SWH with time.

The amplitude of the annual cycle offshore and near the coast is about 1.2 m. For all buoys except 46146, 46181 and 46134, the amplitude is 40% to 45% of the long-term mean SWH.

Figure 8 shows the SWH time series from the south offshore NOMAD buoy (46036). This shows a very small long-term decrease. Relatively calm or stormy months show as residuals of up to ±1 m.

Figure 9 shows the series from buoy 46206. This shows a trend of slightly increasing SWH over the time period. The residuals show the same pattern of calm and stormy months as Figure 8.

Figure 10 shows the SWH time series from buoy 46146. The annual cycle has a very small amplitude, as in the case of wind speed. Trend with time is positive. Buoy 46131, also in Georgia Strait, shows most of the same short-

Table 3. Buoy Significant Wave Height summary (m, phases and record lengths in months)

Buoy ID	Mean (m)	Trend (m/year)	Ampl. 1 (m)	Ampl. 2 (m)	Phase 1 (mos)	Phase 2 (mos)	Length (mos)	Number (mos)
46184	2.9	.020	1.16	0.29	6.1	1	108	102
46004	3.06	.008	1.3	0.26	6.1	1.2	107	94
46036	2.98	-.005	1.2	0.22	6.3	1.2	108	96
46205	2.67	-.024	1.1	0.26	6.1	1.2	107	100
46208	2.77	.004	1.14	0.28	6.2	1.6	108	98
46147	2.8	.028	1.25	0.18	6.3	1.4	73	72
46207	2.76	.028	1.22	0.27	6.3	1.4	108	102
46132	2.61	.080	1.13	0.14	6.3	1.3	68	64
46206	2.28	.028	0.91	0.19	6.4	1.7	108	104
46145	1.64	-.004	0.68	0.17	5.9	1.4	98	97
46183	1.34	.001	0.58	0.07	6.2	2.5	98	95
46185	1.88	-.000	0.84	0.13	6.3	1.9	105	103
46204	2.23	-.001	0.95	0.21	6.2	1.6	108	99
46131	0.45	.013	0.18	0.03	6.7	1.8	80	79
46146	0.42	.006	0.08	0.04	6.3	2.5	87	84
46181	0.23	-.007	0.14	0.09	6.2	3.1	108	106
46134	0.07		0.08	0.021	8	3	4	4

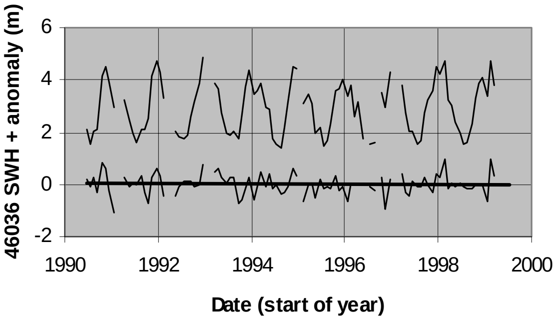


Figure 8. SWH monthly average time series for buoy 46036, showing residuals after removal of annual cycle and harmonic, and trend.

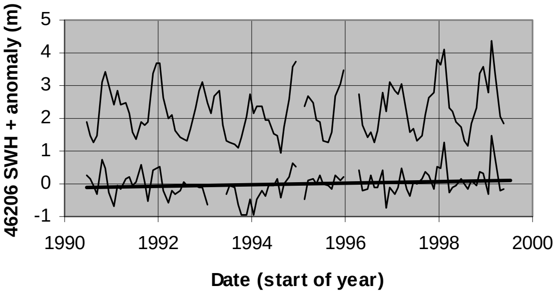


Figure 9. SWH monthly average time series for buoy 46206, showing residuals after removal of annual cycle and harmonic, and trend.

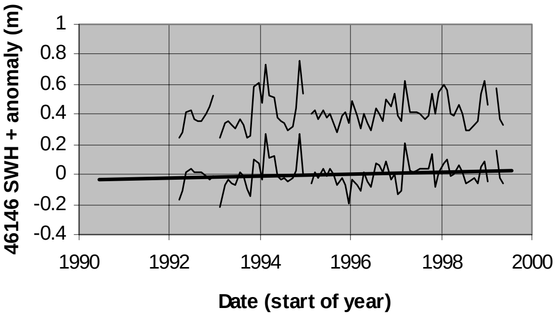
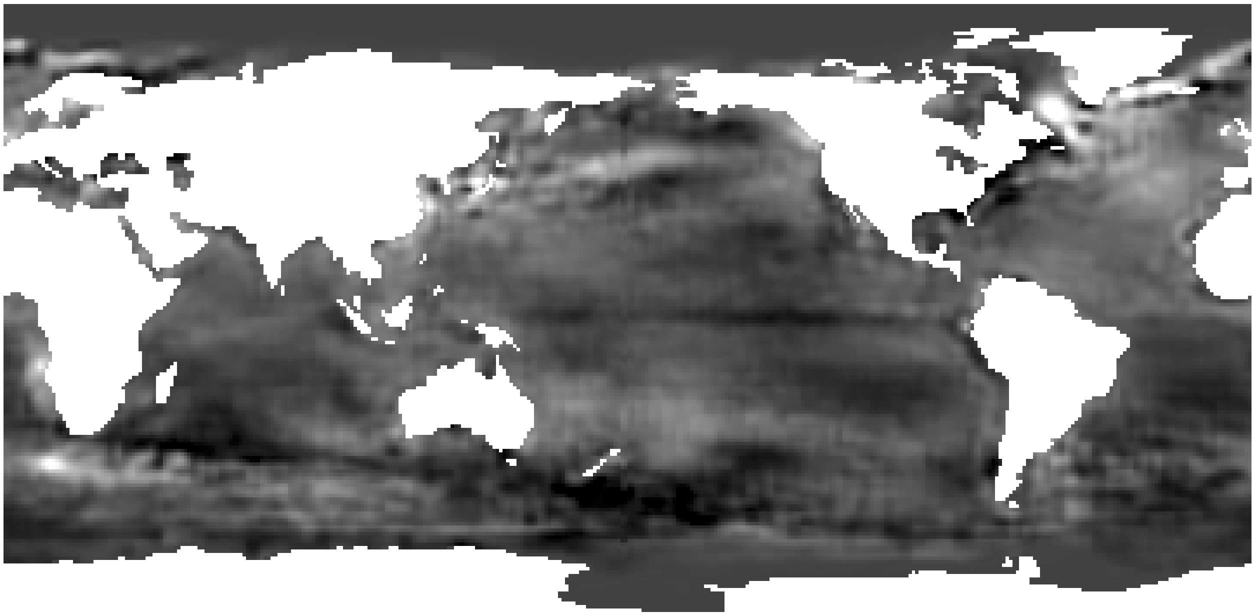


Figure 10. SWH monthly average time series for buoy 46146, showing residuals after removal of annual cycle and harmonic, and trend.

term variations. These variations are much less correlated with those shown in Figures 8 and 9. Buoy 46146 shows an increasing trend in SWH, amounting to about 10% over the 7 year period.

6. Optical data

Buoy 46134 was deployed in November 1998 as part of a program to provide time series of other ocean properties, especially the biological variables important for understanding marine ecosystems. The location of this buoy (Figure 1)



Global trends in SST over the period 1982 to 1999 derived from the Reynolds ship and satellite blend 1-degree data set (Reynolds and Marisca 1993). Lighter areas indicate more rapid warming, up to 0.1 C per year. Average global warming shown by these data for this period is about 0.01 C per year.

is in sheltered water close to the Institute of Ocean Sciences where it is easily accessible for installation, servicing and change-over of instruments. In addition to the meteorological sensors, this buoy is equipped with an insolation sensor measuring the Photosynthetically Active Radiation (PAR) that drives marine primary productivity, and with in-water sensors measuring chlorophyll fluorescence, water colour and salinity. An acoustic profiler for zooplankton mapping is in development. A system for real-time display of the data on the web is under development at http://www-sci.pac.dfo-mpo.gc.ca/ecobuoys. Optical sensors have also been tested on buoy 46146. The length of the data record from these new instruments is so far only a few months, but if problems of calibration and optical fouling can be overcome, the installation of optical instruments will be made more permanent and will be extended to other buoys in the west-coast network.

7. Conclusions

Time series from the buoys are now long enough to start to show signatures from short-term climatic effects such as El-Nino in sea surface temperature, and apparent long-term trends in temperature, wind speed and wave height. These trends need to be evaluated to check the calibration of the buoy data and to investigate whether they represent effects of long-term climatic change. Several examples are shown above of problems with the present data set. These are being addressed in an on-going program of data quality control and improvement.

It is interesting and possibly significant that the buoy data shows increasing trends in all 3 variables investigated. Global warming is a well discussed phenomenon, confirmed in many data sets. Reynolds (1993) presented a compilation of global monthly mean SST values derived from ships and satellite measurements on a 1-degree grid. This started at the beginning of 1982 and continues to be updated monthly. Figure 11 shows the global distribution of temperature trends for January 1982 to June 1999, computed from this data (annual cycle removed). The trends are shown as an image in which more rapidly warming areas are shown in lighter tones. The mean value for the global ocean is about 0.01 C per year. The image shows many hot spots of more rapid warming, among them the area of the buoy array plotted in Figure 1.

Here, the Reynolds data set shows average warming close to the coast of about 0.07 C per year, with less warming (0.02 to 0.03 C per year) at the locations of the offshore buoys. Table 1 shows average warming of 0.036 C close to the coast, and cooling at the offshore buoys by an average of 0.01 C per year. The Reynolds data therefore shows larger trends than those found in the buoy data by about 0.03 C per year. The Reynolds data covers a longer time period (1982-1999), but the time series for the near-shore area of rapid warming shows that most warming occurred since 1990.

Apparent trends in both wind speed and SWH have also been discussed (Gulev and Hasse, 1998, Cardone et al., 1990, Carter and Draper, 1988, Neu, 1984). Highest reported trends, of the order of 0.1 to 0.5 m/s per decade in wind speed, and 0.1 to 0.4 m per decade in SWH, are found in the North Atlantic. Many are at levels comparable to the accuracy of the data, and require longer data records for confirmation, as is the case for the buoy data we present here.

8. References

Cardone, V.J., J.G. Greenwood and M.A. Cane, 1990 , “On trends in historical marine wind data,” J. Climate, 3, 113-127.

Carter, D.J.T., and L. Draper, 1988, “Has the north-east Atlantic become rougher?” Nature, 332, 494.

Cherniawsky, J.Y., and W.R. Crawford, 1996, “Comparison between weather buoy and Comprehensive Ocean-Atmosphere Data Set wind data for the west coast of Canada,” J. Geophys. Res., 101, 18377-18389.

Gower, J.F.R., 1996, “Intercalibration of wave and wind data from TOPEX/Poseidon and moored buoys off the west coast of Canada,” J. Geophys. Res., 101, 3817-3829.

Gulev, S.K., and L. Hasse, 1998, “North Atlantic wind waves and wind stress fields from voluntary observing ship data,” J. Phys. Oceanography, 28, 1107-1130.

Neu, N.H.A, 1984, “Interannual variations and longer term changes in the sea state of the North Atlantic from 1970 to 1982,” J. Geophys. Res., 89, 6397-6402.

Reynolds, R.W., and D.C. Marisca, 1993, “An improved real-time global sea surface temperature analysis”, J. Climate, 6, 114-119.