The following supplement accompanies the article

Celestial mechanics affects emersion time and cover patterns of an ecosystem engineer, the intertidal kelp *Saccharina sessilis*

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Supplement. Additional methods and results regarding the relationship between kelp cover and environmental variables

MATERIALS AND METHODS

Wave height and wave force

Significant wave height measurements were obtained from NDBC Buoy 46088 (48.335556° N, 123.158611° W; www.ndbc.noaa.gov/station_page.php?station=46088) which came online in 2004. Because missing data may obscure patterns across years, we first eliminated days with <10 measurements, and then eliminated years with <350 d of data. This left us with data for the 12 mo periods preceding surveys in 2007, 2008, 2011, and 2012 (all with ≥365 d of data). One (in 2007 and 2008) or 2 (2011 and 2012) measurements are reported per hour from the buoy: all available measurements were used in calculating summary statistics. We measured 'elevated' wave exposure in two ways: by counting the number of days with wave heights >1 m and (in a separate analysis) >2 m. We calculated the maximum significant wave height for each day and used this to calculate the mean daily maximum significant wave height for each target period as an estimate of 'chronic' wave exposure. Each of these metrics was calculated for the 12 mo period preceding kelp surveys and the relationship between kelp cover and wave exposure was assessed using linear regression.

We also recorded maximum wave force at Pile Point on 68 days over multiple years (primarily during summer months, but with intensive sampling from February to April in 2000) by deploying 5 wave force dynamometers (Carrington Bell & Denny 1994) around the site at approx. 0 m tidal height. Dynamometers were read and reset every 24 h during low tide series.

We measured the force required to remove *Saccharina sessilis* adults from the substratum with a loop of string wound around the alga (at the blade/holdfast juncture) on one end and attached at the other end to a spring scale modified to record maximum force. Thalli (N = 20) were pulled parallel to the substratum until the holdfast was removed and force was recorded.

Water temperature

For long-term analysis of water temperature trends, we combined measurements from 2 sources. We obtained monthly mean water temperature values for 1998 to 2011 from Race Rocks Lighthouse (48.297778° N, 123.531667° W; www.racerocks.com/racerock/data/seatemp/airseatemp.htm). Because data from Race Rocks were not available past January 2011, we obtained seawater temperatures from NDBC Buoy 46088 (see above) for the 12 mo periods preceding kelp surveys in 2011 and 2012. This buoy records seawater temperatures at 30 min intervals. We used buoy data to calculate mean water temperature for each day, then used these values to calculate the mean temperature for each month. Buoy data only date back to 2004, and there were several periods with multiple days of missing data. To evaluate the relationship between temperatures collected from the buoy and from Race Rocks, we used a correlation analysis with data from 43 mo during the period of overlap. We only used months for which we had more than 26 d of data from the buoy. Temperatures from the 2 locations were significantly correlated ($r = 0.992$, $p < 0.0001$) with a mean difference of <0.21°C.

For selected periods from 1997 to 2012, temperature dataloggers ($N = 1$ to 5) were deployed in the intertidal zone at Pile Point at approx. 0 m tidal height. Logger model differed among years (1998–2000 = Optic Stowaway, 2004–2009 = Hobo TidBit, 2010–2012 = Hobo TidBit v. 2; Onset Computer Corporation). Daily water temperature values were extracted from loggers at high tide (defined as water level >1.86 m) by matching logger data with verified tidal height data from NOAA NOS station 9449880 (http://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=9449880). For each day, we calculated mean daily water temperature for each individual data logger and then averaged that value across all active data loggers. Daily mean on-shore water temperatures were significantly correlated with daily mean buoy temperatures ($N = 684$ d, $r = 0.98$, $p < 0.0001$) with a mean difference of <0.43°C. We did separate analyses using the highest and lowest monthly mean temperature for each year preceding the kelp surveys to estimate the effects of ‘acute’ temperature exposure. We averaged the monthly mean temperatures to get an overall mean water temperature for the year preceding kelp surveys as an estimate of ‘chronic’ temperature exposure. The relationship between kelp cover and water temperature was assessed using linear and quadratic regression.

Air temperature

For long-term analysis of air temperature, we obtained maximum and minimum daily values from the National Climatic Data Center station in Anacortes, Washington, USA (48.5119° N, 122.6136° W; GHCND: USC00450176) through Climate Data Online (www.ncdc.noaa.gov/cdo-web/). Using these daily air temperature values, we determined the absolute maximum and absolute minimum air temperature for the 12 mo period preceding each of the kelp surveys, with one exception: we did not calculate the absolute minimum air temperature for the 12 mo period preceding the 2009 surveys because the absence of data for November and December 2008 had the potential to severely skew this metric. We also calculated mean daily maximum temperature and mean daily minimum temperature for each month, and then averaged these monthly values to get an estimate of mean daily maximum or minimum temperature for the 12 mo period preceding each survey (except 2009, for which we did not estimate mean daily minimum temperature). We calculated mean temperatures in this manner (first averaging by month, then averaging months) to account for the difference in the number of days for which data were available among years (for example, in November 2010, only 15 d of data were available). The relationship between kelp cover and each of these air temperature metrics was assessed using linear and quadratic regression.

RESULTS

Wave height and wave force

There was no evidence that wave forces were driving patterns of kelp cover at Pile Point. Wave height, used as a proxy for wave force measurements, did not explain the observed patterns of kelp cover over time. There was no significant relationship between mean daily maximum significant wave height in the 12 mo periods preceding the kelp surveys and mean kelp cover in 1 m^2 plots for years 2007, 2008, 2011 and 2012 (Table S2; linear regression, $R^2 = 0.47$, $p = 0.32$). There was no significant relationship between kelp cover and the number of days with significant wave heights ≥1 m in the 12 mo periods preceding the surveys (linear regression, $R^2 = 0.72$, $p = 0.15$). Choice of wave height threshold did not influence the conclusion (e.g. linear regression on kelp cover vs. number of days with significant wave heights >2 m in the 12 mo periods preceding the surveys, $R^2 = 0.0008$, $p = 0.97$; range from 14 to 24 d over these 4 yr). In contrast, using data from only these 4 yr, the cumulative number of hours of emersion time was strongly and significantly related to kelp cover (linear regression, $R^2 = 0.97$, $p = 0.01$). Onshore, the absolute maximum wave force recorded at Pile Point was 22 N, approximately one-fifth of the minimum amount of force required to dislodge an adult *Saccharina* from the substratum.

Water temperature

Although seasonal patterns in water temperature were evident, temperature varied only slightly among years during the study (Fig. S2). The highest mean monthly temperature was similar among years, with a high of 12.3°C (in the 12 mo period preceding 1999 surveys) and a low of 10.92°C (in the 12 mo period preceding 2012 surveys). The lowest monthly average ranged from 7.0°C (in the 12 mo period preceding 2010 surveys) to 8.7°C (in the 12 mo period preceding 1998 surveys). Overall mean water temperature (the mean of monthly mean values) differed slightly among years, with a high of 10.44°C (in the 12 mo period preceding 1998 surveys) and a low of 9.02°C (in the 12 mo period preceding 2012 surveys).

There was no evidence that the pattern of change in kelp cover was related to water temperature. Neither maximum nor minimum monthly temperature was significantly related to kelp cover (maximum temperature: linear regression $R^2 = 0.007$, $p = 0.83$, quadratic regression $R^2 = 0.033$, $p = 0.30$; minimum temperature: linear regression $R^2 = 0.04$, $p = 0.60$, quadratic regression $R^2 = 0.05$, $p = 0.85$). Similarly, there was no relationship between overall mean temperature and kelp cover (linear regression $R^2 = 0.02$, $p = 0.70$, quadratic regression $R^2 = 0.14$, $p = 0.63$).

Air temperature

As with water temperature, no long-term cyclical trends in air temperature were evident over the course of the study (Fig. S3). Absolute maximum daily temperature varied greatly among years with a high of 38.36°C (in the 12 mo period preceding 2010 surveys) and a low of 27.24°C (in the 12 mo period preceding 2012 surveys). Variation in mean daily maximum temperature (calculated as the average daily maximum for each month, averaged over the 12 mo preceding the survey) was less dramatic, with a high of 16.10°C (in the 12 mo period preceding 2010 surveys) and a low of 14.29°C (in the 12 mo period preceding 2008 surveys). Similarly, absolute minimum daily temperature showed big differences among years with a high of –2.78°C (in the 12 mo period preceding 2000 surveys) and a low of –9.45°C (in the 12 mo periods preceding 1999 and 2007 surveys), while mean daily minimum temperature (calculated as the average daily minimum for each month, averaged over the 12 mo preceding the survey) did not vary greatly among years, with a high of 7.9°C (in the 12 mo period preceding 1998 surveys) and a low of 6.54°C (in the 12 mo period preceding 2008 surveys).

There was no evidence that the pattern of change in kelp cover was related to air temperature. Neither absolute maximum nor absolute minimum daily temperature was significantly related to kelp cover (maximum: linear regression $R^2 = 0.15$, $p = 0.30$, quadratic regression $R^2 = 0.43$, $p = 0.18$; minimum: linear regression $R^2 = 0.01$, $p = 0.84$, quadratic regression $R^2 = 0.07$, $p = 0.83$). Similarly, there was no detectable relationship between mean daily maximum temperature and average kelp cover (linear regression $R^2 = 0.04$, $p = 0.65$, quadratic regression $R^2 = 0.20$, $p = 0.57$) or between mean daily minimum temperature and average kelp cover (linear regression $R^2 = 0.10$, $p = 0.45$, quadratic regression $R^2 = 0.11$, $p = 0.74$).

Table S1. Timing of measurements in laboratory experiments for the kelp *Saccharina sessilis*. Net photosynthetic rates (NPR) were measured in air for all thalli. Maximum quantum yield (MQY) readings were taken each morning when blades were removed from dark tank (see Methods); blades were weighed immediately following MQY measurement. Hydrated (control) blades were not exposed to low tides

Experimental day	**Treatment**	**Measurements**	
		Before first light	Post-dawn or post low tide
Day 1	Hydrated (control)	MQY, Wet mass	Post-dawn: NPR
	Low-stress low tide	MQY, Wet mass	----
	High-Stress low tide	MQY, Wet mass	Post low tide: Wet mass, NPR
Day 2	Hydrated (control)	MQY, Wet mass	----
	Low-stress low tide	MQY, Wet mass	----
	High-stress low tide	MQY, Wet mass	Post low tide: Wet mass
Day 3	Hydrated (control)	MQY, Wet mass	----
	Low-stress low tide	MQY, Wet mass	----
	High-stress low tide	MQY, Wet mass	----

Table S2. *Saccharina sessilis* cover in 1 m^2 plots and significant wave height data from NDBC Buoy 46088

	2007	**2008**	**2011**	**2012**
Mean % cover in 1 m^2 plots (summer surveys)	21.50	34.74	71.92	84.36
Mean daily max. significant wave height (m) (12 mo period preceding survey)	0.86	0.87	0.84	0.85
Number of days with significant wave heights >1 m (12 mo period preceding survey)	120	115	115	112

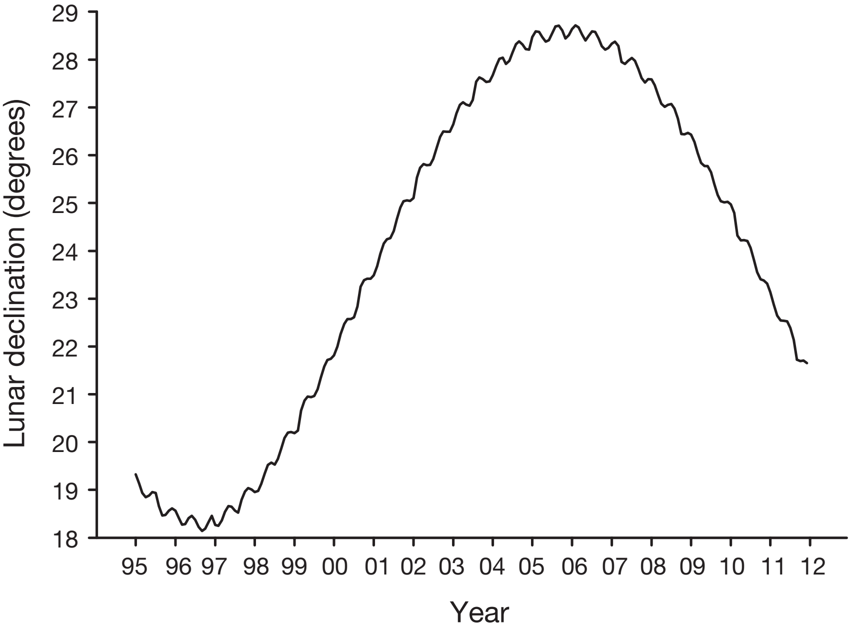

Fig. S1. Monthly maximum angle of lunar declination. Data from NASA JPL HORIZONS web interface (http://ssd.jpl.nasa.gov/horizons.cgi#top). X-axis tick marks are placed on July 1 of each year to indicate timing of annual summer kelp surveys

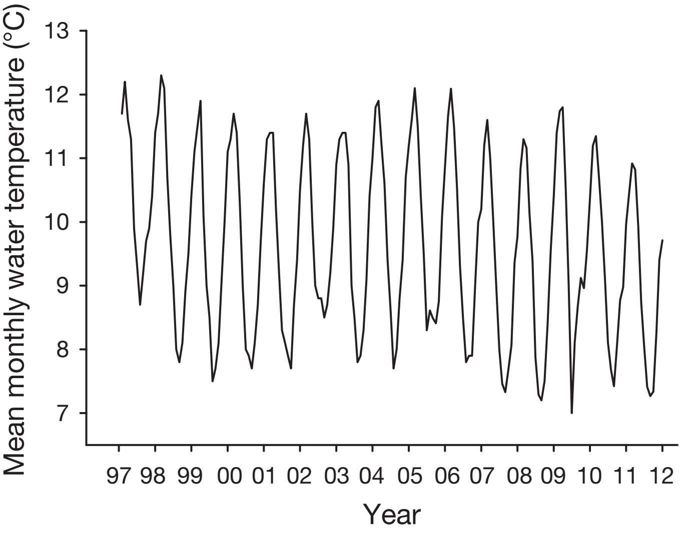

Fig. S2. Mean monthly water temperature. Data from July 1997 through June 2010 from Race Rocks Lighthouse (www.racerocks.com). Data from July 2010 through June 2012 from NBDC Buoy 46088 (www.ndbc.noaa.gov/station_page.php?station=46088). X-axis as in Fig. S1

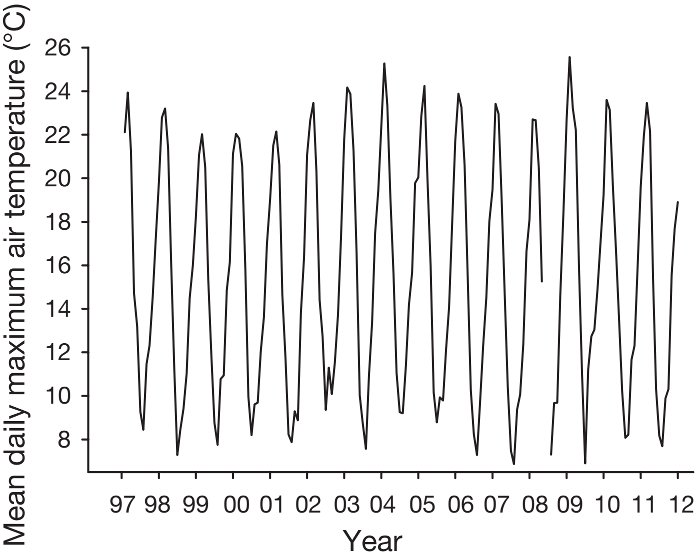

Fig. S3. Monthly means of daily maximum air temperature readings from Anacortes, Washington, USA. Data from Climate Data Online: www.ncdc.noaa.gov/cdo-web. X-axis as in Fig. S1

LITERATURE CITED

Carrington Bell E, Denny MW (1994) Quantifying 'wave exposure': a simple device for recording maximum velocity and results of its use at several field sites. J Exp Mar Biol Ecol 181:9–29