SUPPORTING MATERIALS:



Figure S1. Maximum air temperature (filled symbols) and minimum air temperature (open symbols) in each season for each region, Katmai National Park (KATM), Kachemak Bay (KBAY), Kenai Fjords National Park and Preserve (KEFJ) and western Prince William Sound (WPWS). Horizontal blue line indicates the -4 °C threshold and the horizontal red line indicates the 25 °C threshold.



Figure S2. Left panel: Seasonal mean water temperature at each sampling region, Katmai National Park (KATM), Kachemak Bay (KBAY), Kenai Fjords National Park and Preserve (KEFJ) and western Prince William Sound (WPWS). The vertical dashed line indicates the start of the PMH. Right panel: Seasonal baseline values from each region used for calculating water temperature anomalies.



Figure S3. Mean daily exposure to warm air (≥ 25 °C), cold air (≤ -4 °C), minimum, and maximum air temperatures at two sites where loggers were installed at start and end of the rocky site transect and one site where loggers were installed at the start of the rocky site transect and the start of the mussel site transect.

Table S1. Rocky site and mussel bed location details. Regions: Katmai National Park (KATM), Kachemak Bay (KBAY), Kenai Fjords National Park and Preserve (KEFJ) and western Prince William Sound (WPWS)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Region | Site Name | Rocky SiteLatitude, Longitude | Mussel BedLatitude, Longitude | Straight line distance between rocky site and mussel bed (km) |
| KATM | Amalik Bay | 58.079222, -154.466000 | 58.079222, -154.466000 | 0 |
|  | Kaflia Bay | 58.256944, -154.197694 | 58.256660, -154.201830 | 0.24 |
|  | Kinak Bay | 58.186556, -154.465750 | 58.191090, -154.485090 | 1.24 |
|  | Kukak Bay | 58.316583, -154.206583 | 58.310230, -154.194580 | 1.02 |
|  | Takli Island | 58.063500, -154.484056 | 58.060260, -154.459090 | 1.53 |
| KBAY | Bluff Point | 59.656700, -151.671167 | 59.656700, -151.671167 | 0 |
|  | Cohen Island | 59.539133, -151.476950 | 59.539133, -151.476950 | 0 |
|  | Elephant Island | 59.513961, -151.505881 | 59.513961, -151.505881 | 0 |
|  | Outside Beach | 59.464233, -151.708500 | 59.464233, -151.708500 | 0 |
|  | Port Graham | 59.373333, -151.894167 | 59.373333, -151.894167 | 0 |
| KEFJ | Aialik Bay | 59.876640, -149.632890 | 59.894830, -149.645170 | 2.19 |
|  | Harris Bay | 59.737660, -149.958370 | 59.731900, -149.917590 | 2.39 |
|  | McCarty Fjord | 59.508530, -150.341780 | 59.531380, -150.331510 | 2.68 |
|  | Nuka Bay | 59.537230, -150.607130 | 59.509030, -150.561550 | 4.10 |
|  | Nuka Passage | 59.420710, -150.646960 | 59.418450, -150.638260 | 0.56 |
| WPWS | Herring Bay | 60.459890, -147.717530 | 60.466850, -147.710400 | 0.87 |
|  | Hogan Bay | 60.201970, -147.759840 | 60.207070, -147.762500 | 0.59 |
|  | Iktua Bay | 60.130040, -147.998280 | 60.120090, -147.993060 | 1.15 |
|  | Johnson Bay | 60.339950, -147.834820 | 60.339310, -147.833020 | 0.12 |
|  | Whale Bay | 60.226610, -148.251050 | 60.226500, -148.250500 | 0.03 |
|  |  |  |  |  |

Table S2. Years when data were collected, the sample size for pre- and post-sea star wasting (SSW) comparisons, and the pre- and post-SSW periods for each region (Katmai National Park (KATM), Kachemak Bay (KBAY), Kenai Fjords National Park and Preserve (KEFJ) and western Prince William Sound (WPWS)).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | KATM | KBAY | KEFJ | WPWS |
| Mussel percent cover | 2006-2010; 2012-2019 Pre-SSW N = 50Post-SSW N = 15 | 2012-2020Pre-SSW N = 23Post-SSW N = 20 | 2008-2019Pre-SSW N = 35Post-SSW N = 25 | 2007; 2010-2019Pre-SSW N = 35Post-SSW N = 20  |
| Density of mussels ≥ 20 mm | 2008-2010; 2012-2019 Pre-SSW N = 39Post-SSW N = 15 | 2012-2020Pre-SSW N = 19Post-SSW N =20 | 2008-2019Pre-SSW N = 35Post-SSW N = 25 | 2010-2019Pre-SSW N = 30Post-SSW N = 20 |
| Density of mussels ≥ 2 mm | 2008-2010; 2012-2019Pre-SSW N = 39Post-SSW N = 15 | 2012-2020Pre-SSW N = 19 Post-SSW N =20 | 2008-2019Pre-SSW N = 35 Post-SSW N = 25 | 2010-2019Pre-SSW N = 30 Post-SSW N = 20 |
| Mussel bed width | 2008-2010; 2012-2019Pre-SSW N = 39Post-SSW N = 15 | 2012-2020Pre-SSW N = 17 Post-SSW N = 16 | 2008-2019Pre-SSW N = 35 Post-SSW N = 25 | 2010-2019Pre-SSW N = 30 Post-SSW N = 20 |
| Sea star density | 2006; 2008-2010; 2012-2019Pre-SSW N = 45Post-SSW N = 15 | 2005; 2009; 2011-2020Pre-SSW N = 31 Post-SSW N = 20 | 2008-2020Pre-SSW N =35 Post-SSW N =27 | 2007; 2010-2020Pre-SSW N =35 Post-SSW N = 25 |
| Intertidal temperature | 2007-2019 | 2013-2020 | 2007-2020 | 2010-2020 |
| Pre-SSW years | 2006-2016 | 2005-2016 | 2008-2014 | 2007-2015 |
| Post-SSW years | 2017-2020 | 2017-2020 | 2015-2020 | 2016-2020 |

Table S3. Literature information on diets of sea stars monitored in the Gulf Watch Alaska program.

|  |  |  |
| --- | --- | --- |
| Species | Mussel predator in the field? | Diet details |
| *Dermasterias imbricata*  | N | * Anemones (Annett & Pierotti 1984; Houtman et al 1997; Mauzey et al 1968)
* Fed *Mytilus trossulus* in lab experiments (Houtman et al 1997)
* Mostly anemones on exposed outer coast, mostly holothurians in more protected area (Mauzey et al 1968)
* Benthic diatoms, encrusting sponges, bryozoans, anemones, sea cucumbers, tunicates, chitons (O’Clair & O’Clair 1998)
 |
| *Evasterias troschelii* | Y | * Preference for *Balanus glandula* and *Protothaca staminea* (Mauzey et al 1968)
* *M. edulis* made up 81-84% of diet at two locations in AK (O’Clair & Rice 1985)
* Observed feeding on barnacles and mussels, mussels in 57.9% of meals (n=11) (Kay et al 2019)
* Eats *M. trossulus*, *Saxidomus gigantea, Protothaca staminea, Hiatella arctica, Mya* spp., *Posdodesmus cepio, Semibalanus balanoides, Balanus crenatus, Balanus glandula, Semibalanus cariosus,* chitons, small gastropods, lampshell, sea squirts (O’Clair & O’Clair 1998)
 |
| *Henricia leviuscula* | N | * Encrusting sponges and bryozoans, also sometimes suspension feeding (Mauzey et al 1968)
* Feeds on particulates (Ferguson et al 1969)
* Grazer (Palmer et al 1982)
* Encrusting bryozoans, *Halichondria panicea*, bacteria and detritus (O’Clair & O’Clair 1998)
 |
| *Mediaster aequalis* | N | * In rocky areas eats encrusting sponges and bryozoans (Mauzey et al 1968)
* May graze recently settled bivalve larvae (Sloan & Robinson 1983)
* Sponges and microscopic detritus on *Phyllochaetopterus* tubes (Birkeland et al 1970)
 |
| *Orthasterias koehleri* | N | * *Humilaria* and *Protothaca*, small individuals in shallow water eat *Tonicella* and small gastropods (Mauzey et al 1968)
* Chitons, gastropods, clams, squid, crabs, ascidians (O’Clair & O’Clair 1998)
 |
| *Pisaster ochraceus* | Y | * Preference for mussels, large portion of diet from barnacles and mussels, also eat miscellaneous other prey (Mauzey et al 1968)
* *P. ochraceus* recruits eat recently settled mussels (Sewell & Watson 1993)
* Observed feeding on barnacles and mussels, mussels in 73.7% of meals (n=28) (Kay et al 2019)
 |
| *Pycnopodia helianthoides* | Y | * Outer coast intertidal individuals mostly each urchins, preference for *Saxidomus* and urchins (Mauzey et al 1968)
* In subtidal kelp forest 79% of diet gastropods (Herrlinger 1983)
* Mussels often found in stomachs (Paul & Feder 1975)
 |
| *Solaster* spp. | N | * *Solaster stimpsoni* eats holothurians (96% of observations) (Mauzey et al 1968)
* *Solaster stimpsoni* eats sea cucumbers, ascidians, *Pyura haustor*, lampshells, sea pens (O’Clair & O’Clair 1998)
* *Solaster dawsoni* eats other sea stars, strong preference for *S. stimpsoni* (Mauzey et al 1968)
* *Solaster dawsoni* eats *Mediaster aequalis*, *Crossaster papposus, S. Stimpson*, *Evasterias troschelii*, *Pycnopodia helianthoides, Dermasterias imbricata, Henricia levisuscula*, cannibal, sea cucumbers, *Strongylocentrotus droebachiensis* (O’Clair & O’Clair 1998)
* *Solaster endeca* eats sea cucumbers, *Leptasterias*, bryozoans, ascidians (O’Clair & O’Clair 1998)
 |

Table S4. Results of linear mixed-effects models comparing abundance before and after the onset of sea star wasting (SSW) for each sea star species (N = 233 for all species). Significant differences indicated by bold p-values.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ***E. troschelii*** | Sum Sq | Mean Sq | DF | F-value | P-value | Random Effects | Variance | Std. Dev. |
| SSW | 5.496 | 5.496 | 1 | 41.883 | **<0.001** | Site | 0.019 | 0.138 |
| Region | 1.182 | 0.394 | 3 | 3.002 | 0.059 | Residual | 0.131 | 0.362 |
| SSW\*Region | 3.812 | 1.271 | 3 | 9.682 | **<0.001** |  |  |  |
| ***P. ochraceus*** | Sum Sq | Mean Sq | DF | F-value | P-value | Random Effects | Variance | Std. Dev. |
| SSW | 1.675 | 1.675 | 1 | 5.457 | **0.020** | Site | 0.305 | 0.553 |
| Region | 8.229 | 2.743 | 3 | 8.934 | **< 0.001** | Residual | 0.307 | 0.554 |
| SSW\*Region | 4.185 | 1.395 | 3 | 4.543 | **0.004** |  |  |  |
| ***P. helianthoides*** | Sum Sq | Mean Sq | DF | F-value | P-value | Random Effects | Variance | Std. Dev. |
| SSW | 2.070 | 2.070 | 1 | 104.144 | **< 0.001** | Site | 0.012 | 0.108 |
| Region | 0.344 | 0.115 | 3 | 5.775 | **0.007** | Residual | 0.020 | 0.141 |
| SSW\*Region | 0.350 | 0.117 | 3 | 5.892 | **0.001** |  |  |  |

Table S5. P-values of selected comparisons of Region\*SSW from linear mixed-effects models comparing abundance before and after the onset of SSW for each sea star species (N = 233 for all species). Significant p-values are bolded. Regions: Katmai National Park (KATM), Kachemak Bay (KBAY), Kenai Fjords National Park and Preserve (KEFJ) and western Prince William Sound (WPWS)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | ***E. troschelii*** | ***P. ochraceus*** | ***P. helianthoides*** |
| Pre KATM - Pre KBAY |  | 0.764 | 0.659 | 0.074 |
| Pre KATM - Pre KEFJ |  | **0.001** | 0.062 | 0.996 |
| Pre KATM - Pre WPWS |  | 0.057 | 0.978 | 0.766 |
| Pre KBAY - Pre KEFJ |  | 0.060 | **0.002** | **0.019** |
| Pre KBAY - Pre WPWS |  | 0.743 | 0.990 | **0.003** |
| Pre KEFJ - Pre WPWS |  | 0.730 | **0.010** | 0.986 |

Table S6. Results of linear mixed effects models tests for mussel percent cover at 0.5 and 1.5 m above mean lower low water (N = 223), large mussel (≥ 20 mm) density (N = 203), total mussel (≥ 2 mm) density (N = 203), and bed width (N = 197).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **0.5 m % Cover** | Sum Sq | Mean Sq | DF | F-value | P-value | Random Effects | Variance | Std. Dev. |
| SSW | 0.714 | 0.714 | 1 | 51.390 | **< 0.001** | Site | 0.009 | 0.093 |
| Region | 0.145 | 0.048 | 3 | 3.489 | **0.039** | Residual | 0.014 | 0.118 |
| SSW: Region | 0.125 | 0.042 | 3 | 2.992 | **0.032** |  |  |  |
| **1.5 m % Cover** | Sum Sq | Mean Sq | DF | F-value | P-value | Random Effects | Variance | Std. Dev. |
| SSW | 50.290 | 50.290 | 1 | 70.967 | **< 0.001** | Site | 0.693 | 0.833 |
| Region | 8.642 | 2.881 | 3 | 4.065 | **0.025** | Residual | 0.709 | 0.842 |
| SSW: Region | 2.205 | 0.735 | 3 | 1.037 | 0.377 |  |  |  |
| **≥ 20 mm Density** | Sum Sq | Mean Sq | DF | F-value | P-value | Random Effects | Variance | Std. Dev. |
| SSW | 7.568 | 7.568 | 1 | 10.851 | **< 0.001** | Site | 0.934 |  |
| Region | 3.533 | 1.178 | 3 | 1.688 | 0.209 | Residual | 0.698 |  |
| SSW: Region | 5.374 | 1.791 | 3 | 2.568 | 0.056 |  |  |  |
| **≥ 2 mm Density** | Sum Sq | Mean Sq | DF | F-value | P-value | Random Effects | Variance | Std. Dev. |
| SSW | 2.896 | 2.896 | 1 | 3.389 | 0.067 | Site | 1.585 | 1.259 |
| Region | 7.822 | 2.607 | 3 | 3.052 | 0.058 | Residual | 0.854 | 0.924 |
| SSW: Region | 4.131 | 1.377 | 3 | 1.612 | 0.188 |  |  |  |
| **Bed Width** | Sum Sq | Mean Sq | DF | F-value | P-value | Random Effects | Variance | Std. Dev. |
| SSW | 2.395 | 2.395 | 1 | 10.176 | **0.002** | Site | 0.201 | 0.448 |
| Region | 1.867 | 0.622 | 3 | 2.644 | 0.086 | Residual | 0.235 | 0.485 |
| SSW: Region | 2.779 | 0.926 | 3 | 3.936 | **0.009** |  |  |  |

Table S7. Alternative PERMANOVA models of the effects of temperature on mussel metrics. Significant values (p > 0.05) are bolded. df: degrees of freedom, SS: sum of square

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sources of variation | df | SS | Pseudo-F | P-value |
| Region | 3 | 217.830 | 2.023 | 0.062 |
| Site(Region) | 15 | 514.080 | 8.949 | **< 0.001** |
| SSW | 1 | 51.761 | 7.264 | **< 0.001** |
| Year | 10 | 71.319 | 1.888 | **0.023** |
| AirTempExpMDS1 | 1 | 8.600 | 2.276 | 0.084 |
| AirTempExpMDS2 | 1 | 6.196 | 1.640 | 0.160 |
| WaterTempPCA1 | 1 | 3.529 | 0.404 | 0.404 |
| WaterTempPCA2 | 1 | 7.210 | 0.119 | 0.119 |
| Residual | 93 | 336.260 |  |  |
| Total | 122 | 1216.800 |  |  |
| AIC = 731.600 |  |  |  |  |
| Sources of variation | df | SS | Pseudo-F | P-value |
| Region | 3 | 217.830 | 2.014 | 0.062 |
| Site(Region) | 15 | 514.081 | 8.668 | **< 0.001** |
| Year | 10 | 115.420 | 3.001 | **< 0.001** |
| WaterTempPCA1 | 1 | 2.972 | 0.773 | 0.510 |
| WaterTempPCA2 | 1 | 1.936 | 0.503 | 0.701 |
| AirTempExpMDS1 | 1 | 9.151 | 2.379 | **0.068** |
| AirTempExpMDS2 | 1 | 9.224 | 2.398 | 0.072 |
| Residual | 89 | 346.170 |  |  |
| Total | 122 | 1216.800 |  |  |
| AIC = 733.172 |  |  |  |  |

Table S8. Alternative models of the effects of sea stars on mussel metrics. Significant values (p > 0.05) are bolded. df: degrees of freedom, SS: sum of square.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sources of variation | df | SS | Pseudo-F | P-value |
| Region | 3 | 217.830 | 2.010 | 0.055 |
| Site(Region) | 15 | 514.080 | 8.678 | **< 0.001** |
| Year | 10 | 115.420 | 3.004 | **< 0.001** |
| Total Stars | 1 | 12.160 | 3.165 | **0.030** |
| Residual | 93 | 357.29 |  |  |
| Total | 122 | 1216.800 |  |  |
| AIC = 731.064 |  |  |  |  |
| Sources of variation | df | SS | Pseudo-F | P-value |
| Region | 3 | 217.830 | 2.023 | 0.058 |
| Site(Region) | 15 | 514.080 | 8.864 | **< 0.001** |
| SSW | 1 | 51.761 | 7.264 | **< 0.001** |
| Year | 10 | 71.319 | 1.869 | **0.023** |
| Total Stars | 1 | 10.747 | 2.817 | **0.044** |
| Residual | 92 | 351.040 |  |  |
| Total | 122 | 1216.800 |  |  |
| AIC = 730.891 |  |  |  |  |