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Long-term, high frequency in situ measurements of intertidal mussel bed temperatures using biomimetic sensors

Brian Helmuth  
Northeastern University

Francis Choi  
Northeastern University

Allison Matzelle  
Northeastern University

Jessica Torossian  
Northeastern University

See next page for additional authors

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Brian Helmuth, Francis Choi, Allison Matzelle, Jessica Torossian, Scott Morello, K.A.S. Mislan, Lauren Yamane, Denise Strickland, P. Szathmary, Sarah Gilman, Alyson Tockstein, Thomas Hilbish, Michael Burrows, Anne Marie Power, Elizabeth Gosling, Nova Mieszkowska, Christopher Harley, Michael Nishizaki, Emily Carrington, Bruce Menge, Laura Petes, Melissa Foley, Angela Johnson, Megan Poole, Mae Noble, Erin Richmond, Matt Robart, Jonathan Robinson, Jerod Sapp, Jackie Sones, Bernardo Broitman, Mark Denny, Katharine Mach, Luke P. Miller, Michael O'Donnell, Philip Ross, Gretchen Hofmann, Mackenzie Zippay, Carol Blanchette, J. Macfarlan, Eugenio Carpizo-Ituarte, Benjamín Ruttenberg, Carlos Peña Mejía, Christopher McQuaid, Justin Lathlean, Cristián Monaco, Katy Nicastro, and Gerardo Zardi. "Long-term, high frequency in situ measurements of intertidal mussel bed temperatures using biomimetic sensors"  
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Authors
Brian Helmuth, Francis Choi, Allison Matzelle, Jessica Torossian, Scott Morello, K.A.S. Mislan, Lauren Yamane, Denise Strickland, P. Szathmary, Sarah Gilman, Alyson Tockstein, Thomas Hilbish, Michael Burrows, Anne Marie Power, Elizabeth Gosling, Nova Mieszkowska, Christopher Harley, Michael Nishizaki, Emily Carrington, Bruce Menge, Laura Petes, Melissa Foley, Angela Johnson, Megan Poole, Mae Noble, Erin Richmond, Matt Robart, Jonathan Robinson, Jerod Sapp, Jackie Sones, Bernardo Broitman, Mark Denny, Katharine Mach, Luke P. Miller, Michael O'Donnell, Philip Ross, Gretchen Hofmann, Mackenzie Zippay, Carol Blanchette, J. Macfarlan, Eugenio Carpizo-Ituarte, Benjamin Ruttenberg, Carlos Peña Mejía, Christopher McQuaid, Justin Lathlean, Cristián Monaco, Katy Nicastro, and Gerardo Zardi

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Data Descriptor: Long-term, high frequency *in situ* measurements of intertidal mussel bed temperatures using biomimetic sensors

Brian Helmuth *et al.*

At a proximal level, the physiological impacts of global climate change on ectothermic organisms are manifest as changes in body temperatures. Especially for plants and animals exposed to direct solar radiation, body temperatures can be substantially different from air temperatures. We deployed biomimetic sensors that approximate the thermal characteristics of intertidal mussels at 71 sites worldwide, from 1998-present. Loggers recorded temperatures at 10–30 min intervals nearly continuously at multiple intertidal elevations. Comparisons against direct measurements of mussel tissue temperature indicated errors of ~2.0–2.5 °C, during daily fluctuations that often exceeded 15°–20 °C. Geographic patterns in thermal stress based on biomimetic logger measurements were generally far more complex than anticipated based only on ‘habitat-level’ measurements of air or sea surface temperature. This unique data set provides an opportunity to link physiological measurements with spatially- and temporally-explicit field observations of body temperature.

| Design Type(s) | observation design • time series design |
|----------------|----------------------------------------|
| Measurement Type(s) | temperature of environmental material |
| Technology Type(s) | biomimetic sensor |
| Factor Type(s) | geographic location |
| Sample Characteristic(s) | intertidal zone • New South Wales • Queensland • State of Victoria • Province of British Columbia • Coquimbo • England • Scotland • County Clare • Galway • County Mayo • Baja California Peninsula • Auckland Region • Canterbury Region • Coromandel Peninsula • Northland Region • West Coast Region • State of California • Commonwealth of Massachusetts • State of Oregon • State of South Carolina • State of Washington • Eastern Cape Province • KwaZulu-Natal Province • Northern Cape Province • Western Cape Province |

Correspondence and requests for materials should be addressed to B.H. (email: b.helmuth@northeastern.edu).

#A full list of authors and their affiliations appears at the end of the paper.
Background & Summary

Increasingly, researchers are emphasizing the need to consider physiological mechanisms when forecasting the effects of global climate change on organisms and ecosystems. Specifically, studies have highlighted a need to understand how environmental conditions vary in space and time in addition to the details of how organisms respond to those variables as a means of evaluating inter- and intraspecific vulnerability ('winners and losers'), the probability of invasion by non-native species, changes in patterns of abundance and distribution, and declines in biodiversity and ecosystem services.

Notably, there is concern that simple correlations between environmental measurements (such as air, land surface and sea surface temperature) and species distributions may fail under the novel conditions presented by climate change, highlighting the need to extrapolate from experiments conducted under controlled conditions to projections of future climate impacts. There has also been an emphasis on considering the cumulative impacts of physiological stress on patterns of growth and reproduction rather than focusing solely on lethal extremes.

However, making connections between the lab and field can be far more complex than is often assumed. For example, a number of theoretical and empirical studies have explored the often over-riding importance of spatial and temporal variability in environmental parameters, which is not captured when experiments are based only on monthly, yearly or decadal averages. Moreover, while large-scale measurements of environmental conditions made by satellites, buoys, and weather stations provide critical insights into rates of environmental change on large scales, at a proximal level these habitat-level measurements may not always serve as good indicators of physiological stress.

In fact, the only ‘environmental signals’ that matter to an organism are those that the organism actually experiences. Making connections across scales that span from organismal to biogeographic is no easy matter, but is crucial if we are to effectively forecast ongoing responses to environmental change.

One of the most obvious examples of the complex ways climate defines weather patterns, and weather then drives niche-level organismal responses, is how climate change is ultimately reflected as changes in plant and animal body temperatures. The vast majority of organisms on Earth are ectothermic poikilotherms, so that their body temperatures and thus levels of physiological performance change with ambient environmental conditions. For terrestrial and intertidal ectotherms (and even some shallow-water corals), body temperatures are driven by multiple environmental parameters, most notably solar radiation, air and water temperatures and wind speed. The structure of an organism’s microhabitat, and especially its exposure to direct solar radiation, can have enormous implications for its body temperature, such that animal temperatures are only close to air temperature in fully shaded microhabitats. While many animals can behaviourally select among these microhabitats as a means of thermoregulation, others are functionally sessile and thus have body temperatures determined by very local topography. To further complicate matters, the size, morphology and colour of organisms, as well as their ability to form aggregations, can affect heat exchange so that two organisms exposed to identical microclimatic conditions can have very different body temperatures. To contend with these issues, multiple authors have developed heat budget models that factor-in the characteristics of the organism to predict body temperatures using weather data as inputs.

An alternative approach—and one that is required to validate biophysical (heat budget) models—is to use in situ sensors specifically tailored to record temperatures relevant to the organism being studied, either directly or through the use of biomimics. Biomimetic sensors (biomimics) match the thermal characteristics (size, morphology, colour, material properties) of living organisms, serving as an effective tool for recording organismal body temperature in their natural environment. Here we report on a long-term data set of temperatures recorded by biomimetic loggers thermally matched to bivalves (mussels) in the intertidal zone, one of the most physiologically harsh habitats on Earth. Over the course of a 24-hr period, intertidal animals and algae are alternately exposed to water at high tide and to air, wind and solar radiation at low tide. Thus, their temperature not only depends on local weather conditions but also on the timing and duration of low tide. We have previously shown, for example, that consistent differences in the timing of low tide relative to high levels of solar radiation create geographic mosaics in low tide temperature, where mussel body temperatures at higher latitude sites can be much higher than those at low latitude sites. As ecosystem engineers, mussels in particular have a large influence on the stability and biodiversity of the intertidal community and so quantifying their survival and physiological performance has significant ecosystem-level consequences.

Methods

We used biomimetic loggers to estimate temperatures of the mussels Mytilus californianus (West coast of North America), M. edulis and Geukensia demissa (East coast of North America), M. chilensis (Chile), Perna perna (South Africa) and P. canaliculus (New Zealand). We also deployed unmodified commercial loggers directly on rock surfaces at multiple sites (Australia, Ireland, Mexico, Scotland, U.K., U.S.) that recorded temperatures relevant to barnacles, newly settled mussels and other organisms that are sufficiently small that their temperatures mirror those of the underlying rock.

Each biomimetic sensor (‘Robomussel’; Fig. 1) consisted of either a commercially-available TidbiT logger (TB132-20+50 and UTB1-001; Onset Computer Corporation, Pocasset, MA) encased in black-coloured polyester resin (Evercoat Premium Marine Resin, Illinois Tool Works, Inc.), or a real mussel...
shell filled with silicone and encasing a Tidbit or a Thermochron iButton logger (DS1922L-F5; Maxim Integrated, San Jose, California). Both instruments are factory calibrated: Tidbit loggers have a reported accuracy of 0.21 °C and a stability (drift) of 0.1 °C per year (http://www.onsetcomp.com/products/data-loggers/utbi-001) and ibuttons have an accuracy of 0.5 °C (https://datasheets.maximintegrated.com/en/ds/DS1922L-DS1922T.pdf); the drift is reported by the manufacturer to be negligible, especially when compared to the ~2 °C accuracy of the biomimic loggers (see Technical Validation below). Because of loss due to waves, each logger was typically used for only 2–3 years. Details on logger designs and field tests are described in detail in previous publications44,45,53. In brief, logger thermal characteristics were calculated using empirical measurements of shell and tissue mass against length from adult *Mytilus californianus* collected on the west coast of North America. In addition to morphology (which determines convective heat flux) and colour (which affects solar heat load), the primary consideration is the maintenance of thermal inertia (the tendency of an object to resist temperature change as a function of external forcing). Mass/length relationships were combined with measurements of the specific heat capacity of shell and tissue to estimate total thermal inertia as a function of size45. This was then compared to the thermal mass of polyester resin mussels of different lengths. The point where the two curves intersect is ~ 8 cm shell length; this was the size of the epoxy loggers. Silicone molds were cast from a representative 8 cm mussel, and were in turn used to pour two-part polyester resin (Evercoat) around the commercial TidbiT logger.

In some cases, iButton loggers were encased in ~8 cm mussel shells filled with silicone, which has a mass-specific heat similar to that of water. Comparisons of these instruments against adjacent mussels showed that silicone-filled shells recorded temperatures within ~1 °C of living animals54. However, these loggers were considerably less durable and required more frequent maintenance (~ bimonthly) than epoxy mussels (every 6–10 months), and so were used only infrequently at most sites. At some sites where the targeted mussel species is smaller (e.g., *M. edulis* in the Gulf of Maine), we used 4 cm mussel shells. Loggers of differing size were never used at the same site, and are distinguished from one another in the database. Nevertheless, any direct comparison between data collected by loggers of different sizes should be made with caution, as size can affect mussel temperature by several degrees55.

Robomussels were deployed primarily on hard rock substrate, in growth position (posterior upward) in intact beds using Z-spar splash zone epoxy putty (Fig. 1). Care was taken to ensure that the logger was completely surrounded by other mussels, as tests showed that loggers deployed as solitary individuals tended to yield anomalously high readings. On the east coast of North America, loggers were also deployed at soft sediment (marsh) sites in mud substrate by attaching the loggers to dowel rod.

Deployment began in 1998 at the Hopkins Marine Station in Pacific Grove, California54, and was expanded to other sites beginning in 2000 (Table 1 (available online only), Fig. 2). Total deployment time varied by location, ranging from less than a year to almost 18 years (average deployment time of 4 years). The number of loggers deployed and lost due to wave dislodgement also varied at each site, but a standard protocol was to deploy at least 3 loggers in the middle of mussel beds on horizontal, unshaded surfaces. At most sites, loggers were deployed at the upper edge of the mussel bed (‘upper’), half way between the upper and mid levels (‘upper mid’), mid level (‘mid’), half way between the mid and lower edge of the bed (‘lower mid’) and at the bottom of the mussel bed (‘lower’).
Loggers were programmed to record at intervals of 10–30 min and left in the field for periods up to 9 months before they were removed for downloading, and replaced with another logger. Every effort was made to place this new logger in precisely the same position in the bed as the logger being retrieved. All logger clock times were set to GMT. In the U.S., the absolute tidal elevation (height above chart datum) was measured with a Trimble R8 GNSS GPS system capable of sub-cm resolution. Temperature records were also used to record wave swash by comparing sudden drops in temperature (an indication of first wave splash following exposure at low tide) against predicted tidal elevations. The measurements of ‘Effective Shore Level’ can subsequently be compared against buoy records of significant wave height in order to estimate wave splash as a function of nearshore wave height56,57.

**Code availability**

Code written in R58 was used to trim data recorded by each logger before and after deployment. A separate software program (SiteParser) is also available on the Northeastern website to determine the incidence of wave splash56,57. This is accomplished by comparing rapid (user-defined) drops in temperature, indicative of the return of the tide, against predicted (Xtide software, www.flaterco.com/xtide) or measured (tidesandcurrents.noaa.gov) tide height for each site. By comparing these measurements against measured logger tidal elevations, it is possible to calculate the ‘effective shore level’ of a logger as a function of nearshore wave height56. This also provides a method of dividing logger temperatures into aerial and submerged records. Notably, the choice of temperature drop determines both the accuracy of the division between aerial and submerged records, as well as the total amount of data available. Specifically, the choice of a larger temperature drop tends to increase certainty as to temperature divisions, but can restrict the amount of data to days when such drops are observed. For this

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**Figure 2.** Map of logger deployment sites. Colors indicate approximate length of deployment, which ranged from one or two seasons to almost 18 years. Insets show (a) West and (b) East coasts of the United States and (c) New Zealand.
reason, the database provides data that have not been analyzed in this manner, but instead provides tools

Data Records

Data from all loggers are archived in two databases. The first is a searchable database maintained by Northeastern University (www.northeastern.edu/helmuthlab/Research/Database.html) and provides unrestricted access to data as well as to associated links such as the SiteParser software described above. Metadata for each microsite are included as a downloadable spreadsheet, which includes, for each site: Country, Region, Site name, and GPS coordinates (Table 1 (available online only)). The metadata file also includes information specific to each microsite, including: Biomimic logger type (unmodified ibutton, unmodified TidBit, epoxy [8 cm] mussel logger, shell (silicone-filled) mussel logger [4 or 8 cm length]), Substrate (rocky, muddy, tidepool), Tidal elevation zone (low, lower mid, mid, upper-mid, upper), Wave exposure (protected or exposed), and Start and end dates (Table 2). At the Northeastern website, data can be viewed and downloaded using a series of drop-down menus (Fig. 3). Given the range of selections, the database provides the range of dates over which data meeting those criteria are available (this information is also included in the metadata file). Data from each logger can be downloaded as raw data, as well as daily, monthly or annual maxima, minima and averages. Note that data include both aerial and submerged temperatures, but raw data can be parsed using the software provided. In instances

| Parameter       | Description                                                                 | Unit  |
|-----------------|-----------------------------------------------------------------------------|-------|
| Logger type     | Type of biomimic or logger                                                  | Text  |
| Site Code       | 6-character site identification code (1st 2-characters: country; 2nd 2-characters: state; 3rd 2-characters: site) | Text  |
| Site Name       | Name of the site                                                            | Text  |
| Region          | Name of the region or jurisdiction                                          | Text  |
| Country         | Name of the country                                                         | Text  |
| Latitude        | Latitude of the site                                                        | Decimal degree |
| Longitude       | Longitude of the site                                                       | Decimal degree |
| Zone            | Intertidal zone (low, lower mid, mid, upper-mid, upper)                     | Text  |
| Substrate       | Additional characteristics: muddy intertidal, rocky intertidal               | Text  |
| Wave Exposure   | Wave exposure of logger (exposed or protected)                              | Text  |

Table 2. Data descriptors.

Figure 3. Northeastern database showing dropdown menus. Users select Biomimic type (e.g., 8 cm epoxy logger); Country and Region (e.g., state); Site name; Intertidal zone (e.g., upper, mid, lower); Substrate type; Wave exposure, and Data statistic (raw, mean, maximum, or minimum over ranges of daily, monthly or yearly).
where multiple microsites meet the selected criteria, the program takes the average at each time point from the maximum number of loggers available before calculating summary statistics. Data from all microsites can be downloaded as raw data to avoid this averaging procedure.

Raw data in text file format as well as associated metadata are also archived in a public repository (Data Citation 1). Files are organized in to a series of subfolders organized by Country, Region and Site (Table 1 (available online only)). Metadata identical to those available at the Northeastern site are also included as a downloadable file. Each data file contains information specific to the microsite in its header, and follows a 10 letter/6 number naming convention as follows: BM (indicating biomimetic logger database); Logger type (RM for mussel loggers ['Robomussels'] or RB for unmodified loggers ['Robobarnacles']); 6 letter site code (Table 1 (available online only); Country, Region, Site); two-digit microsite ID and four digit Year.

Technical Validation
Comparisons of logger temperatures against tissue temperatures of adjacent live mussels made using thermocouples are presented in four publications44,45,54,59. The first compared temperatures recorded by a thermistor with the tip embedded in a silicone-filled shell against point measurements made from adjacent mussels in the field in Pacific Grove, California and found an average difference of ~0.75 °C (ref. 54). The second involved a more comprehensive set of tests of epoxy (polyester) loggers in both the field and in a wind tunnel45. In the laboratory experiments, the average difference between loggers and live mussels in artificial beds was ~2.2 °C (ref. 45). Notably, the average difference between live mussels and unmodified loggers (TidbiTs) in the same experiment was 14.6 °C. Field-tests yielded similar results, with an average error of 2.7 °C between robomussels and live mussels45. A follow-up study with additional laboratory tests over a wider range of temperatures (10–50 °C) reported a Root Mean Square Error (RMSE) of 3.84 °C with a correlation coefficient of 0.89 between loggers and live mussels44. Finally, iButton loggers placed in the middle of silicone-filled Geukensia demissa shells were tested in a wind tunnel in artificial beds under a range of wind speeds; results showed average differences of ~1.0–1.5 °C (ref. 59).

Usage Notes
Portions of the logger data presented here have been used in multiple field studies, and have provided context for laboratory studies. At small scales, biomimetic loggers (both loggers that we deployed as well as similar loggers made by other researchers) have been used to record differences in temperature among microhabitats (shaded and unshaded surfaces) and tidal elevations (Fig. 4) and the results compared to measurements of biochemical indicators of stress such as heat shock proteins54,60, gene expression61, reproductive condition62, and to the fine-scale distribution of native and non-native species63. At biogeographic scales, robomussels have been used to document thermal mosaics across large latitudinal gradients40,48 (Fig. 5) and the results related to patterns of mortality64, physiological stress65–67 and growth68,69, as well as interspecific differences in physiological stress39 and geographic distribution70.

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Figure 4. Monthly average daily maximum temperature at low, mid and upper intertidal elevations at a relatively wave-protected bench in Boiler Bay, Oregon.
Measurements from mussel biomimetics have been used to test heat budget models that estimate animal temperature using data from weather stations and satellites\(^71\)–\(^73\). Robomussels have also been used as part of controlled laboratory experiments that strive to replicate realistic field conditions\(^37,74\). Finally, robomussel data can be used to estimate wave splash and water temperature\(^56,57\), although in this regard they do not present a major advantage over unmodified loggers.

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**Figure 5.** Monthly average daily maximum temperature (for the hottest month of each year at each site) at mid intertidal elevations along the west coast of the United States (2007–2014).
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Author Contributions
Helmuth led the study for the entire duration of the record. Logistics of deployment, retrieval and data management were, at various times, overseen by Choi, Matzelle, Szathmary, Gilman, Mislan, Yamane, Tockstein and Strickland. All other authors managed instrument deployment and retrieval at field sites: Massachusetts (Choi, Torossian, Morella); Scotland (Burrows); Ireland (Power, Gosling); U.K. (Hilbish, Mieszkowska); British Columbia and Washington (Nishizaki, Carrington, Harley); Oregon (Menge, Petes, Foley, Johnson, Poole, Noble, Richmond, Robart, Robinson, Sapp); California (Denny, Mach,
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Additional Information
Table 1 is only available in the online version of this paper.

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Brian Helmuth1, Francis Choi1, Allison Matzelle2, Jessica L. Torossian2, Scott L. Morello2, K.A.S. Mislan3, Lauren Yamane4, Denise Strickland5,6, P. Lauren Szathmary5,6, Sarah E. Gilman6, Alyson Tockstein5,6, Thomas J. Hilbish5, Michael T. Burrows7, Anne Marie Power7, Elizabeth Gosling7, Nova Mieszkowska10,1, Christopher D. G. Harley11, Michael Nishizaki12,1, Emily Carrington12, Bruce Menge13, Laura Petes13,1, Melissa M. Foley13,1, Angela Johnson13, Megan Poole13, Mae M. Noble13,1, Erin L. Richmond13,1, Matt Robert13,1, Jonathan Robinson13,1, Jerod Sapp13,1, Jackie Sones14, Bernardo R. Broitman15, Mark W. Denny16,16, Katherine J. Mach16,16, Luke P. Miller13,16, Michael O’Donnell16,1, Philip Ross17, Gretchen E. Hofmann18, Mackenzie Zippay18,1, Carol Blanchette18,1, J.A. Macfarlan18,1, Eugenio Carpizo-Ituarte19,1, Benjamin Ruttenberg19,1, Carlos E. Peña Mejia19,1, Christopher D. McQuaid20, Justin Lathlean20, Cristián J. Monaco20, Katy R. Nicastro20,20 & Gerardo Zardi20

1Northeastern University, Marine Science Center, 430 Nahant Rd., Nahant, Massachusetts 01908, USA.
2The Downeast Institute, Beals, Maine 04611, USA. 3University of California, Davis, Department of Wildlife, Fish, and Conservation Biology, Davis, California 95616, USA. 4University of South Carolina, Department of Biological Sciences, Columbia, South Carolina 29208, USA. 5W.M. Keck Science Department of Claremont McKenna, Pitzer and Scripps Colleges, Claremont, California 91711, USA. 6Scottish Association for Marine Science, Oban, Argyll PA37 1QA, Scotland.
7Annie Marie Power, School of Natural Sciences, National University of Ireland Galway, Galway H91 TK33, Ireland.
8School of Life Sciences, Galway-Mayo Institute of Technology, Galway H91 T8NW, Ireland. 9Marine Biological Association of the United Kingdom, Plymouth, Devon PL1 2PB, UK. 10University of British Columbia, Department of Zoology and Biodiversity Research Centre, Vancouver, British Columbia, Canada V6T1Z4. 11University of Washington, Department of Biology, Seattle, Washington 98195, USA. 12Oregon State University, Department of Integrative Biology, Corvallis, Oregon 97331, USA. 13University of California, Davis, Bodega Marine Reserve, Bodega Bay, California 94923, USA. 14Centro de Estudios Avanzados en Zonas Aridas, Coquimbo 1780000, Chile.
15Stanford University, Hopkins Marine Station, Pacific Grove, California 93950, USA. 16University of Waikato, Environmental Research Institute, Tauranga 3110, New Zealand. 17University of California Santa Barbara, Marine Science Institute, Santa Barbara, California 93106, USA. 18Universidad Autónoma de Baja California, Instituto de Investigaciones Oceanológicas, Ensenada, Baja California 22860, Mexico. 19Rhodes University, Department of Zoology and Entomology, Grahamstown 6140, South Africa. 20Present addresses: Palmetto Health Richland, Columbia, South Carolina, USA (D.S.); Research Planning, Inc., Columbia, South Carolina 29201, USA (P.L.S.); The Maritime Aquarium Norwalk, Connecticut 06854, USA (A.T.); School of Environmental Sciences, University of Liverpool, Liverpool L69 7ZX, U.K. (N.M.); The Maritime Studies Program, Williams College and Mystic Seaport, Mystic, Connecticut 06355, USA (M.N.); Climate Program Office, National Oceanic and Atmospheric Administration, Silver Spring, Maryland 20910, USA (L.P.); U.S. Geological Survey, Pacific Coastal and Marine
