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Recommended Citation
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Climate Is Variable, but Is Our Science?

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Current climate shows significant variability across space (from kilometers spanning to terrestrial biomes and ocean basins) and time (spanning event, seasonal, interannual, and decadal timescales). For example, recurring climate events in specific locations in the World’s Oceans have been described as modes spanning interannual-to-decadal scales including: El Niño/Southern Oscillation (ENSO) which is triggered by changes in equatorial Pacific tradewinds, North Atlantic Oscillation (NAO) and Interdecadal Pacific Oscillation (IPO). This natural variability is superimposed on the general trend of global climate change. Recent studies highlight the importance of changes in the frequency of extreme climate events, i.e., changes in the maxima and minima of temperature or precipitation, which can lead to changes in the frequency of drought, extreme rain events, or heatwaves (Hartmann et al. 2013). Such extreme events can have disproportionate effects on ecosystems and society. Often these changes are neither spatially nor temporally uniform (Salinger 2005). Below we discuss in more detail how climate variability can be considered in observational and experimental aquatic ecology.

Climate variability on multiple scales is an inescapable reality. Aquatic ecologists must confront the challenges variability imposes on experimental and observational studies. Reducing or managing climate variability, both scientifically, in an attempt to tease apart ecological mechanisms, and societally, through human efforts to modify landscapes, requires great effort and has often produced mixed results. However, variability is a natural and important part of ecological systems: it can enhance biological diversity and influence the productivity, stability, and function of ecosystems (Connell 1978; Noguerra et al. 2012). By incorporating variability into our studies, we often gain a more detailed understanding of how ecosystems function (e.g., Benedetti-Cecchi et al. 2006; Vasseur et al. 2014). For example, Benedetti-Cecchi et al. (2006) found that temporal variance and mean intensity of aerial exposure often elicited opposite responses in algal and invertebrate assemblages. Furthermore, Vasseur et al. (2014) suggested that changes in temperature variation, rather than mean temperature, are a greater threat to species performance.

Currently, we lack a clear understanding of the function and consequences of variability in many systems (Thompson et al. 2013), and extrapolating what we do know across time or space can lead to bias and inaccuracies. This lack of baseline knowledge in many ecosystems is concerning, as many predictions suggest that patterns of climate variability are changing on all scales—regionally, globally, and seasonally (Salinger 2005). Our ability as aquatic scientists to predict the consequences of these changes is hampered by our limited understanding of the role of even contemporary variability in influencing ecosystems. Here, we explore the role of climate variability in the fields of limnology and oceanography and the importance of studying the intricacies of variability and its effects on aquatic ecosystems.

Variability has many facets

Researchers are becoming more aware of the importance of quantifying variability, yet observational and experimental science has often focused on a relatively narrow view of variability (e.g., mean, maxima, minima) (Thompson et al. 2013). Variability is inherently multi-faceted; building a comprehensive understanding of ecology in a variable world requires recognizing the different aspects of variability, understanding how they interact, and quantifying their effects. For example, variance, skewness, and the frequency and duration of extreme events are useful quantitative metrics describing different facets of climate variability across aquatic ecosystems (Table 1).

Views of variability are changing: comparisons of terminology in the first and most recent Intergovernmental Panel on Climate Change (IPCC) reports reveal that use of the term “extreme” increased 8× (standardized per page), “frequency” increased 2.1×, and “variance” increased 1.7× (IPCC WGI 1990, IPCC WGI 2013). However, mentions of other important aspects of variability either decreased between these years (i.e., “duration” decreased 0.7×) or were not referenced in either report (i.e., “skewness”). Each of these dimensions of variation can have different effects on the ecology and evolutionary trajectory of natural systems. For example, Gutschick and BassiriRad (2003) hypothesized that selection is virtually absent except during extreme events, thus with increased frequencies of extreme events we may expect a greater probability of natural selection. Therefore, quantifying and studying multiple facets of variability may be necessary to understand how ecosystems respond to future climate conditions.
TABLE 1. Properties of climate variation with examples from aquatic ecosystems. Each aspect can play an important role in determining the growth and persistence of populations, as well as influencing interactions between species.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Definition</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
<td>Measures how spread out the distribution of a climate variable is around its mean</td>
<td>El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO) are climate oscillations that reflect natural climate variability and have been shown to affect the abundance, species composition, and phenology of pelagic and benthic marine communities (Stenseth et al. 2005)</td>
</tr>
<tr>
<td>Skewness</td>
<td>Measures how asymmetric the distribution of a climate variable is</td>
<td>Some physical and biological oceanic variables have a spectral distribution that is red-shifted, such that unusually large changes in amplitude occur at low frequency. A red-shifted distribution will look skewed compared to a Gaussian distribution. Doney and Sailey (2013) provide an example of this when examining zooplankton abundance</td>
</tr>
<tr>
<td>Extremes</td>
<td>Measures include the minimum, maximum, or nth quantile of a distribution. Extreme events have most commonly been defined as a range of values exceeding some threshold. They can also be detected and defined using more sophisticated statistical approaches (Hartmann et al. 2013)</td>
<td>These include extreme weather events (e.g., droughts, extreme rain events, heat waves) or weather-mediated events (e.g., ice shelf calving)</td>
</tr>
<tr>
<td>Frequency</td>
<td>Measures the number of regular cycles or extreme events that occur within a given time period. Studied using spectral analysis or Fourier transformation (Legendre and Legendre 1998)</td>
<td>Frequency of anomalous events [e.g., number of record minimum ice extents in the Arctic in a decade (IPCC WGI 2013)]</td>
</tr>
<tr>
<td>Duration</td>
<td>Measures the length of specific events. Duration can be measured as the number of time steps (e.g., days, weeks) an event continues. An example of one index of duration (i.e., cumulative degree days, $\Delta D$) is described below: $\Delta D = \sum_{t} [T - T_0]$, where $T$ = temperature, $T_0$ = base temperature above which degree days accumulate, and $t$ = time step in days (Schwartz 2013)</td>
<td>Heat wave duration, length of growing season in temperate or high latitudes, cumulative degree-days</td>
</tr>
</tbody>
</table>

Examining the facets of variability: an example using global ocean models

The change in mean sea surface temperature (SST) provides a familiar example that nicely illustrates the effects of climate change in marine ecosystems. This change in mean SST shows a significant, positive directional trend over the vast majority of the ocean (Fig. 1). Here, we step beyond changes in the mean and also examine changes in several variability metrics (Table 1) to assess differences in intensity and spatial distribution of the response of ocean ecosystems to variability. In this example, we examined changes in four types of variability in global monthly SST and sea surface salinity (SSS). We used the Geophysical Fluid Dynamics Laboratory’s Earth System Model (GFDL ESM2M, Dunne et al. 2012; 2013) to examine projected changes between the years 1981–2000 and 2081–2100. This model shows warming across all regions of the globe, with the exception of part of the Southern Ocean and the area south of Greenland where there is a slowing of the Atlantic Meridional Overturning Circulation (AMOC) (Fig. 1), consistent with previous research (e.g., Collins et al. 2013).

However, metrics of variability exhibit quite different patterns than changes in mean variables. The number of months classified as “extremely warm” increases across the majority of the globe, with few regions exhibiting an increase in cool extremes. Changes in both temperature variance and skewness vary spatially. SST variance increases over parts of the Arctic and Northern Hemisphere subpolar gyres, but decreases in the Pacific equatorial region and the Southern Ocean. Our finding that there was relatively little change in SST variance is consistent with previous results (Hawkins and Suttons 2009), which also found relatively little change in variance of surface air temperature. Change in SST skewness is close to zero in most regions of the ocean, except for the Arctic where regions with both increases and decreases in skewness are projected. These changes in Arctic SST skewness may reflect polar amplification of warming, sea ice melt, and changes in ocean currents, although additional research is needed to investigate the mechanisms behind this pattern.

Compared to SST, changes in mean SSS are more spatially variable. Generally, climate change is associated with an increase in the salinity of the saltiest regions of the ocean and a decrease in salinity in the freshest regions (Fig. 1; Rhein et al. 2013). The geographic pattern associated with mean changes in salinity is amplified when examining salinity extremes. Low salinity extremes are projected to increase in frequency in the Arctic, Southern Ocean, subpolar gyres,
and the Western Pacific, while high salinity extremes will occur more frequently in the Mediterranean, subtropical Atlantic, and parts of other subtropical gyres. The variance and skewness of SSS do not change substantially on a global basis, although changes in these metrics may be locally important in some areas.

These results show strong regional differences in the magnitude and sign of changes when considering different types of variability. This highlights the complexity of climate change that would be missed if we ignore variability and focus solely on changes in mean values. Changes in temperature and salinity extremes are especially dramatic, which is concerning given the pronounced effect of such events on aquatic ecosystems. Several studies project extreme events to increase in frequency (e.g., Coumou and Rahmstorf 2012), and recent work by Donat and Alexander (2012) suggests that the greatest magnitude of changes in global daily temperatures are already occurring at the extremes of the distribution. In addition, increases in global mean temperature have been linked to changes in extreme daily precipitation worldwide (Benestad 2013).

The ecological impacts of extreme climatic events are disproportionate compared to their frequency and duration (Jentsch et al. 2007) and such events can also have economic repercussions. For example, coral bleaching events, most notably those which occurred in 1998 (Goreau et al. 2000), 2005 (Eakin et al. 2010), 2010 (Alemu and Clement 2014), and one that is currently ongoing, lead to large-scale increases in disease and massive die-off. Extreme cold events, such as the one that occurred in Florida in 2010, also lead to coral bleaching and mortality (e.g., Kemp et al. 2011). Extreme heat can also have profound effects on pelagic and demersal organisms of interest to commercial fisheries; in the Gulf of Maine, following a heat wave in 2012, the distribution of the longfin squid shifted northward and there was an advancement in the migration phenology of lobsters (Mills et al. 2013). This change in lobster phenology resulted in earlier and larger landings of lobsters by the fishery, flooding the market and reducing prices. Such extreme events clearly have notable impacts on ecosystems and socio-economic activities that rely on them, underscoring a continued focus on understanding the effects of climate variability.

How can we incorporate climate variability in observational and experimental studies?

Our simulation exercise examining changes in SST and SSS variability demonstrates that the patterns of response may differ depending on the metric examined, yet relatively few studies have actually incorporated this variability into aquatic ecosystem experiments (Thompson et al. 2013). In a review of studies involving temperature manipulations conducted between 2000 and 2012, Thompson et al. (2013) found that the majority of freshwater studies were increment studies along a temperature gradient in which the natural temperature variability is maintained by increasing the temperature by a fixed amount (e.g., +1°C above natural conditions). In marine systems, the majority of studies were fixed mean experiments (e.g., +1°C above mean temperature), which actually reduce natural variability (Thompson et al. 2013). The prevalence of fixed mean...
Controlled experiments are needed to determine how abiotic and biotic factors respond to changes in climate variability, and by what mechanisms. However, these experiments often do not reflect the natural complexity of climate variability at appropriate temporal and spatial scales. In addition, there are inherent difficulties in carrying out scalable experiments (Duarte et al. 1997) in aquatic environments (i.e., an experiment that takes place at the scale of centimeters-to-meters and days-to-weeks cannot easily mimic climate variability at the scale of tens-to-hundreds of kilometers or years-to-decades). This may lead some experiments to ignore the effects of climatic variability altogether. When studying the effects of climate change on aquatic ecosystems, it is common for studies to span natural gradients rather than to incorporate experimental manipulation. One such example is the PISCO program (Partnership for Interdisciplinary Studies of Coastal Oceans), which monitors climate variability and intertidal and subtidal communities along the U.S. West Coast (http://www.piscoweb.org). Along this coast, there are naturally occurring gradients in terms of temperature, precipitation, and wind (Checkley and Barth 2009). Climate variability is routinely included in many observational and process studies of marine and freshwater ecosystems (e.g., Lynn et al. 1998; Shimoda et al. 2011), although it is often done without the use of prior expectations thus allowing only for post hoc explanations for change with a limited basis for assigning causation (O’Connor et al. 2015). Furthermore, difficulties in applying experimental temperature and CO₂ treatments in aquatic environments at necessary scales may also lead to fewer manipulation studies in aquatic systems. For example, while experimental warming can be conducted on relatively small (plot-level) scales in terrestrial ecosystems, it is more difficult to manipulate an entire watershed to study the effects of warming on a small stream or to conduct manipulations in open-ocean ecosystems (Duarte et al. 1997). Acknowledging these limitations, there remains a need to incorporate variability in experimental studies to allow for a mechanistic understanding of how climate variability affects organisms and ecosystems.

Despite the challenges in addressing climate variability in aquatic ecosystems, some studies have successfully applied experimental manipulations and incorporated different forms of variability. For example, Benedetti-Cecchi et al. (2006) demonstrated that interactions of mean intensity and temporal variance of climate events affected rocky seashore algal and invertebrate assemblages. In their study, cores were translocated from low-shore habitat to one of three positions along the shore (low-shore, mid-shore, and high shore) at either regular or irregular intervals for 2 yr. The two intervals represented manipulations of temporal variance and the three landscape positions represented manipulations of intensity of aerial exposure (i.e., greater potential of desiccation in high-shore habitat). With regular intervals of temporal variance (low variance), there were negative effects on diversity and percent cover of filamentous and coarsely branched algae but these effects were reduced with greater temporal variance. The authors suggested that larger temporal variance may mitigate the effects of climate events in rocky seashore ecosystems.

In freshwater lakes, Carpenter et al. (2011) set out to test the hypothesis that rising variance and slowing return rates from perturbations could serve as an early warning of a regime shift. To test this hypothesis they induced a regime shift in a freshwater lake by gradually adding top predators and assessed variability in chlorophyll concentrations. In the last 2 yr of the 3-yr experiment a shift toward lower-frequency variance of chlorophyll concentration was observed in the manipulated lake compared with the control lake. Furthermore, skewness was elevated in the second year and exhibited low and high values in the third year of the study. Collectively, variability, return rates, autocorrelations, skewness, and shifts in variance spectra followed the theoretical hypotheses demonstrating these metrics can serve as early indicators of regime shifts in a lake food web (Carpenter et al. 2011).

Recent studies have shown that changes in climate variation can be more influential on species responses than changes in the mean (Campbell et al. 2012; Vasseur et al. 2014) and have provided a framework for utilizing long-term records, statistical metrics, and experimental design to study the impacts of climate (e.g., Carpenter et al. 2011). Campbell et al. (2012) found that some metrics of climate variance were more influential than the mean in affecting beaver survival and recruitment. Others have found that projections which incorporate both mean and variance can result in a wider range of responses than when only a single metric is considered. For example, Vasseur et al. (2014) used a combination of climate projections and thermal performance curves of ectotherms to demonstrate that merely increasing mean temperature generally resulted in a similar response among ectotherms (an increase in performance) but that the interaction of mean and variance of temperature yielded a wide range of responses. These examples illustrate that studying the connections between variability (in its many forms) and climate can provide important information about future climate and ecological responses in aquatic ecosystems.

It is not always necessary to collect new environmental data: in many cases we can also reanalyze data to obtain information on additional climate variability metrics. For example, a wide variety of monitoring networks (e.g., long-term ecological research stations, global sensor networks, federal monitoring networks, such as the United States Geological Survey stream gauge stations, remote sensing products, etc.), and citizen science monitoring provide valuable data spanning temporal and spatial scales that can be incorporated into observational or experimental studies. Re-examining these datasets can provide new insights into ecological processes. Even in the absence of large sensor networks, the increasing availability of automated sensors and remote sensing enhances our ability to measure high-resolution climate data at continental, regional, and local scales and incorporate analyses of climate variability into aquatic research. Automated, high-frequency monitoring through buoys, Argo floats, and gliders...
can also provide insight into episodic events in the ocean such as an internal wave, ephemeral blooms, die habitat variability, or migrations. Additionally, climate models can be used to understand changing patterns of variability in future projections for a range of variables (e.g., temperature, precipitation, oceanic primary production, nutrient concentrations), which can then be built into the design or analysis of experiments. For example, Thompson et al. (2013) proposed utilizing down-scaled global climate models to extract information on future climate variability and then using these predictions to drive realistic manipulations of the variance of stream water temperature.

Conclusion

To understand how aquatic ecosystems will respond to climate change, it is time to step beyond our focus on changing means and further incorporate variability into experimental and observational studies. As a discipline, we need to expand our perspectives and improve our methods, so that our science better reflects our need to understand the consequences of changing variability across scales and ecosystems. This will include a variety of scientific approaches (experimental, observational, modeling, etc.) that range in temporal and spatial scale. A more detailed understanding of where and how different facets of variability are responding to climate change and subsequently affecting aquatic ecosystems can enhance our ability to manage these ecosystems well. Accomplishing these goals requires continuing and extending long-term monitoring of both climate and ecological variables across a broad network of sites. In regions where those records do exist, we should utilize those data to design experiments that are as variable as the climate itself.

Acknowledgments

We thank Paul Kemp, Lydia Baker, and Cristian Monaco for valuable feedback on an earlier draft of this manuscript, and an anonymous reviewer for input which greatly improved this manuscript. This article originated from discussions that took place at the Ecological Dissertations in Aquatic Sciences (EcoDAS) XI Symposium in October 2014, which was hosted by the Center for Microbial Oceanography (C-MORE) and the University of Hawaii. Funding for EcoDAS XI was provided by the NSF biological oceanography program (award OCE-1356192) and the Association for the Sciences of Limnology and Oceanography (ASLO).

References


IPCC (Intergovernmental Panel on Climate Change). 2013. Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change, 1535 pp. In T. F. Stocker and others [eds.]. Cambridge Univ. Press.


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