# Memorandum: Climate Change Indicator Frameworks

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May 5, 2017 – revised

## Introduction

To complete Task 3 of the Statement of Work, ERG located, reviewed, and analyzed a variety of frameworks that could be adopted or adapted to support the development of a suite of climate change indicators for the Chesapeake Bay. Sources included existing suites of climate change indicators, compilations of other types of indicators, workgroup reports, other government publications, and journal articles and white papers from the resilience assessment community. Altogether, ERG reviewed 15 distinct sources. We plan to review an additional framework from the Chesapeake Bay National Estuarine Research Reserve's indicator project if it becomes available.

"Framework" is a loose term used in several different ways that relate to indicators. From the available sources, ERG identified three distinct types of frameworks:

- **Procedural:** A stepwise process for identifying and developing indicators.
- **Organizational:** A taxonomy for sorting indicators into categories or bins.
- **Criteria:** A set of requirements or desired characteristics that can be used to prioritize and select indicators for inclusion.

All three types of frameworks can add value to an effort such as the Chesapeake climate change indicators project. A procedural framework can help ensure that indicators are considered and developed in a consistent, objective, and repeatable manner. An organizational framework can help to align outcomes with project goals, promote a diversity of indicators, and shed light on causal relationships among indicators. Indicator criteria can help to establish the scope of the effort and standards for quality. These types of frameworks also work together; for example, the criteria might define boundaries by including or excluding indicators that fall into certain organizational bins.

This memorandum summarizes ERG's findings for all three types of frameworks, and it also provides ERG's initial recommendations of frameworks to apply to the Chesapeake project. We suggest solidifying these frameworks now, early in the project, as they will provide structure and focus for the subsequent tasks of identifying, prioritizing, and developing candidate indicators.

## Procedural Frameworks

### *Results*

ERG reviewed procedural frameworks from three sources recommended by the Chesapeake Bay Program (CBP) or ERG staff, as shown in Table 1.

**Table 1: Examples of Procedural Frameworks**

| Title | Source | Components |
|---|---|---|
| CBP Indicators Framework | CBP Status and Trends Workgroup | 1. Goal Implementation Team (GIT) Coordinator identifies and presents a monitoring, tracking, or other need related to adaptively managing or tracking progress toward the Chesapeake Bay Watershed Agreement to the Status and Trends Workgroup. Note: The Status and Trends Workgroup sits under STAR, and will have clear, defined criteria to help them maintain the integrity of the Indicators Framework and the products derived from it.<br>2. Status and Trends Workgroup Coordinator works with GIT Coordinator to identify metrics and indicator(s) to meet monitoring or tracking need.<br>3. Status and Trends Workgroup Coordinator informs Management Board and Communications Workgroup of new metrics and indicator(s).<br>4. GIT Coordinator and Staffer (with assistance from STAR as needed) collate and send monitoring and tracking data, analysis, and methods to Status and Trends Workgroup Coordinator.<br>5. Status and Trends Workgroup Coordinator quality checks data, analysis, and methods.<br>6. GIS Team uses data to create or update maps.<br>7. Web Content Specialist uses data, analysis and methods to create or update web content.<br>8. Communications and Web Teams determine whether, when, and how to promote indicator updates based on editorial calendar and newsworthy nature of information. Note: An indicator update may be embargoed on a case-by-case basis, but these cases are rare (with CBP erring on the side of transparency and timeliness). |
| Chesapeake Bay Report Card | UMCES | 2013 report card describes five steps that were going to be used to develop a climate resilience index:<br>1. Conceptualize.<br>2. Choose indicators.<br>3. Define thresholds.<br>4. Calculate scores.<br>5. Communicate results. |
| Aquatic Ecosystems, Water Quality, and Global Change: Challenges of Conducting Multi-Stressor Global Change Vulnerability Assessments | EPA | Stepwise process for developing vulnerability indicators:<br>1. Conduct literature search.<br>2. Identify indicators of water quality and aquatic ecosystem condition.<br>3. Delete duplicate indicators.<br>4. Classify indicators of vulnerability.<br>5. Assess data availability.<br>6. Create example maps. |

### *Discussion*

ERG's logical recommendation here is to follow CBP's existing indicator development framework (row 1 of Table 1). Our work plan follows the steps outlined by CBP in the Statement of Work, and our efforts on this project will naturally integrate with the first seven steps of CBP's indicator development process.

## Organizational Frameworks

An organizational framework can help to align outcomes with project goals—in this case, addressing the climate resiliency goal and associated outcomes in the 2014 Chesapeake Bay Watershed Agreement:

**Goal:** Increase the resiliency of the Chesapeake Bay watershed, including its living resources, habitats, public infrastructure, and communities, to withstand adverse impacts from changing environmental and climate conditions.

**Monitoring and Assessment Outcome:** Continually monitor and assess the trends and likely impacts of changing climatic and sea level conditions on the Chesapeake Bay ecosystem, including the effectiveness of restoration and protection policies, programs, and projects.

**Adaptation Outcome:** Continually pursue, design, and construct restoration and protection projects to enhance the resiliency of Bay and aquatic ecosystems from the impacts of coastal erosion, coastal flooding, more intense and more frequent storms, and sea level rise.

Ultimately, we want to ensure that the indicators we select are relevant to CBP's mission.

### *Results*

ERG reviewed seven organizational frameworks from sources recommended by CBP or ERG staff, as shown in Table 2.

**Table 2: Examples of Organizational Frameworks**

| Title | Source | Components |
|---|---|---|
| Indicator taxonomy proposed by CBP | Statement of Work for this project | • Physical climate trends<br>• Ecological and societal response (i.e., impacts)<br>• Programmatic progress toward resilience |
| CBP Indicators Framework | CBP Status and Trends Workgroup | • Influencing factor<br>• Output<br>• Performance |
| Framework for Implementing Climate Change Restoration and Adaptive Management for the Chesapeake Bay | Provided by CBP | • Institutional issues<br>• Drivers of change<br>• Monitoring change<br>• Impacts on restoration<br>• Adaptation strategies |
| DPSIR Framework | European Environment Agency | • Driving forces<br>• Pressure<br>• State<br>• Impact<br>• Response |
| Evaluating Urban Resilience to Climate Change: A Multi-Sector Approach (Final Report) | EPA | The report illustrates a conceptual framework for determining the type and breadth of indicators needed to assess a city's resilience condition and evolution over time. It includes the concepts of vulnerability, exposure, and hazards that present risks to urban environments, as well as feedbacks and evidence of learning or adapting over time. Indicators can be identified for each of these bins. |

| Title | Source | Components |
|---|---|---|
| Aquatic Ecosystems, Water Quality, and Global Change: Challenges of Conducting Multi-Stressor Global Change Vulnerability Assessments | EPA | 10 bins:<br>• Ecological<br>• Hydrological<br>• Chemical<br>• Land cover/use<br>• Socioeconomic<br>• Extreme weather events<br>• Air<br>• Soil<br>• Human populations<br>• Other |
| Resilience Engineering and Indicators of Resilience | International Risk Governance Council (IRGC) | The paper identifies several approaches that could help in classifying indicators. Examples include:<br>• Resilience analysis grid (measure the ability to monitor, anticipate, respond, and learn)<br>• Q4-balance framework (two dimensions: reactive-proactive and economy-safety) |

### *Discussion*

Our logical choice here is to use a framework that CBP has already established, for consistency with other CBP indicator efforts. The three-part taxonomy in the Statement of Work (physical climate trends, ecological and societal response/impacts, and programmatic progress toward resilience) is most closely aligned with the Chesapeake Bay Agreement: trends and impacts support the "monitoring and assessment" outcome, while programmatic progress supports the "adaptation" outcome. The "Framework for Implementing Climate Change Restoration and Adaptive Management for the Chesapeake Bay" overlaps somewhat with the other two frameworks, but it seems more focused on restoration and management, and less directly connected to the scope of this project, so we will just focus on the first two options listed in Table 2.

Both of the three-part CBP taxonomies collectively cover the "SIR" portion of the widely used DPSIR framework, although not a precise one-for-one match. It is probably not necessary to adhere strictly to DPSIR for this project, as the CBP taxonomy relates more directly to the Chesapeake Bay Agreement, and thus it is closer to the purpose of this project. As discussed below, we suggest largely excluding "D" and "P" indicators from this compilation.

The last three options in Table 2 are less relevant to this project because they cover a narrower scope or a different climate change subtopic (e.g., urban resilience or ecological vulnerability).

## Indicator Criteria

Part of Task 3 involves establishing a detailed set of criteria to define what constitutes an ideal indicator. As described in our work plan, we aim to select criteria that will give CBP a set of indicators that are scientifically defensible, feasible to measure, and relevant to the target audience(s).

### *Results*

ERG reviewed criteria from seven sources recommended by CBP or ERG staff, as shown in Table 3.

**Table 3: Examples of Indicator Criteria**

| Title | Source | Components |
|---|---|---|
| Climate Change Indicators in the United States | EPA | 10 criteria, divided into two tiers to guide the screening process:<br>*Tier 1:*<br>• Peer-reviewed data<br>• Feasible to construct<br>• Usefulness<br>• Understandable to the public<br>• Connection to climate change<br>*Tier 2:*<br>• Trends over time<br>• Actual observations<br>• Broad geographic coverage<br>• Uncertainty<br>• Transparent, reproducible, and objective |
| Climate Change Indicators for the Mid-Atlantic | EPA Region 3; provided by CBP | • Indicator informs important regional issues and addresses human or natural systems.<br>• Indicator can be calculated broadly across the region.<br>• Indicator compliments existing information.<br>• There is a documented connection to climate change, or a relationship to climate change can easily be explained.<br>• Data used in developing indicator are credible and have been peer-reviewed.<br>• Sources of uncertainty are known and understood.<br>• The data and methods used in developing the indicator are transparent, reproducible, and objective.<br>• The indicator provides a clear and understandable depiction of observations. |
| Guidance on Information Quality Assurance to Chapter Authors of the [Third] National Climate Assessment | USGCRP | • Utility: Is the particular source important to your chapter?<br>• Transparency and traceability: Are source materials identifiable and available?<br>• Objectivity: Why and how were the source materials created? (accuracy, reliability, bias)<br>• Information integrity and security: Will the source materials remain reasonably protected and intact? |
| Aquatic Ecosystems, Water Quality, and Global Change: Challenges of Conducting Multi-Stressor Global Change Vulnerability Assessments | EPA | Initial data quality criteria were borrowed from the Report on the Environment (ROE) (see below). Next, the list was narrowed to indicators of vulnerability: those that "could measure the degree to which the resource being considered (e.g., watershed, ecosystem, human population) is susceptible to, and unable to cope with, adverse effects of externally forced change." |

| Title | Source | Components |
|---|---|---|
| Recommendations for Assessing the Effects of the DOI Hurricane Sandy Mitigation and Resilience Program on Ecological System and Infrastructure Resilience in the Northeast Coastal Region | Department of the Interior (DOI) Metrics Expert Group | Definition of *resilience* established by Executive Order 13653 (issued November 2013; rescinded March 2017): "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions." This source also differentiates between **indicators** and **indices**.<br><br>Definition of *indicator*: "An ecological parameter for which we are able to measure its magnitude, extent, or trend using existing measurement techniques. A measurement must be measurable in the near term to be considered pertinent to the DOI assessment. Measurements which were either too costly or uncertain were not considered in the recommendations of the MEG."<br><br>Principles for metric development:<br>• Resilience of specific natural and artificial coastal features is dependent on different sets of controlling factors and stressors; thus, assessing resilience requires performance metrics that address those differences.<br>• Measurements of baseline conditions before project actions influence resilience are necessary to detect a resilience change.<br>• Detecting change in the resilience of coastal ecological systems and communities within the short timeframe needed to inform urgent resource management decisions will require utilizing existing and new data across a range of science disciplines and scales. No single agency or institution has the capacity to meet this challenge alone.<br>• The limited timeframe for implementing the Hurricane Sandy projects (three years) is not likely to allow for robust measurements of changes in resilience, so additional post-project monitoring will be needed to accurately assess changes to resilience attributable to these projects.<br>• The resilience of ecological systems and socioeconomic systems are not independent, and thus require methods to integrate metrics associated with each system.<br>• Establishing a set of performance metrics for effective data management and sharing across existing and new data collection programs is critical for a successful resilience assessment. |
| Resilience Engineering and Indicators of Resilience | IRGC | Within resilience engineering, resilience is defined as "the intrinsic ability of a system or organization to adjust its functioning prior to, during, or following changes, disturbances, and opportunities so that it can sustain required operations under both expected and unexpected conditions" (Hollnagel, 2014).<br><br>This source identifies several approaches that could apply to identifying and prioritizing indicators. Examples include:<br>• Weak signals (performance under adverse conditions).<br>• Margin of maneuver; slack (cushion/additional capacity).<br>• Functional analysis method (modeling dependencies within complex systems).<br>• SCALES framework (web tool to identify resilience indicators). |

| Title | Source | Components |
|---|---|---|
| Report on the Environment (ROE) | EPA | Definition of *indicator*: "An ROE indicator is a numerical value derived from actual measurements of a driver, stressor, state or ambient condition, exposure, or human health or ecological condition over a specified geographic domain, whose trends over time represent or draw attention to underlying trends in the condition of the environment."<br><br>The ROE excludes administrative indicators such as permits issued, regulations promulgated, and enforcement actions undertaken.<br><br>Indicator criteria:<br>• The indicator is useful. It answers (or makes an important contribution to answering) a question in the ROE.<br>• The indicator is objective. It is developed and presented in an accurate, clear, complete, and unbiased manner.<br>• The indicator is transparent and reproducible. The specific data used and the specific assumptions, analytical methods, and statistical procedures employed are clearly stated.<br>• The underlying data are characterized by sound collection methodologies, data management systems to protect their integrity, and quality assurance procedures.<br>• Data are available to describe changes or trends, and the latest available data are timely.<br>• The data are comparable across time and space and representative of the target population. Trends depicted in this indicator accurately represent the underlying trends in the target population. |

## *Discussion*

*Relevant Examples*

Some of the examples in Table 3 are more relevant to this project than others. We consider four of the projects listed—EPA's climate change indicators, EPA's Mid-Atlantic indicators, the USGCRP National Climate Assessment, and EPA's ROE—to be highly relevant to the Chesapeake climate indicators project in terms of objectives and focus. The DOI Metrics Expert Group has a more restricted focus on resilience, but it still offers some useful definitions and criteria to consider. The other two examples are less relevant because their criteria are designed for topics that are largely outside of our scope: vulnerability assessment (EPA's aquatic indicators) and resilience of engineered systems (IRGC). Thus, the remainder of this discussion will focus on the four highly relevant examples plus the DOI source.

*Commonalities*

The relevant examples in Table 3 have many criteria in common. We could either adopt one of these sets of criteria almost verbatim for the Chesapeake or we could create a hybrid from multiple sources; in either case, we would find ourselves in strong alignment with much of what these previous projects have established. The commonalities fall into four broad bins:

- **Utility.** Not surprisingly, many indicator projects have explicitly emphasized that data must be *useful* in terms of relevant topics, spatial and temporal coverage and resolution, and an understandable presentation. For temporal coverage, this means having multiple years of data, starting with a baseline if possible. Utility depends on the intended users and uses of the information. Thus, an important first step in establishing criteria for Chesapeake climate indicators will be to agree upon the purpose and target audience for these indicators. See "Target Audiences" below for current thinking.

- **Quality.** Data quality is another recurring concern. Most of the projects described above have expressed a need for credible data, characterized by consistent methods, high precision and accuracy, low uncertainty, and trust in the underlying science. Some indicator compilations, such as EPA's climate change indicators, explicitly require peer review to provide a stamp of quality.

- **Integrity.** Several of the projects described in Table 3 emphasize a need for traceable sources and thorough documentation that will allow each analysis to be reproduced independently if needed. The USGCRP guidance even goes so far as to prioritize data from sources that are publicly available and protected from tampering. These criteria might feel defensive, but they are arguably crucial when creating official government products on a topic as politically charged as climate change.

- **Feasibility.** Some of the criteria in Table 3 explicitly state that indicators must be feasible to develop. To make the investment worthwhile, indicators should also use data that will continue to be collected, which will allow the indicators to be updated in the future. We can often gauge the likelihood of future data collection based on data collection program documentation, the extent to which the data are mission-critical (for example, NOAA is unlikely to discontinue tide gauge monitoring, which has critical applications for commerce and safety), technical feasibility (for example, if data are collected by a satellite with many years of useful life remaining, or a successor in the works), and our understanding of funding sources.

Nearly all of these requirements are relevant to the Chesapeake climate change indicators project. Each of the examples has some specific concepts and wording that we find valuable, so we propose to create a hybrid set of criteria that takes the best ideas from every source, augmented with specific requirements that reflect the unique topical and geographic scope of this project. The new criteria can also be more specific about what constitutes peer-review validation, which is one of ERG's "lessons learned" from working on EPA's climate change indicators and ROE.

*Target Audience(s)*

The ideal criteria will depend on the target audience and the intended purpose of the indicators. Based on our initial discussions with CBP and our understanding of CBP's indicator efforts, we should consider a few distinct groups of users/uses for this project:

- The primary audience consists of technical users. As discussed in the Statement of Work, this project aims to develop indicators that can be used to "track and analyze trends, impacts, and progress towards advancing 'climate resiliency.'" We anticipate that scientists and policy analysts will use these indicators to support program evaluation and decision-making. This includes CBP staff and goal teams who can use climate-related indicators to inform management decisions under the Chesapeake Bay Agreement. For example, monitoring data can help to support adaptive management. Requirements for data quality, integrity, and length of record will be particularly important for these users.

- A secondary audience is the public or, more specifically, people who consume data from Chesapeake Bay websites and report cards, including educators and students. Some indicator data may be shared with these users. These users generally have at least a basic interest in the topic, but they do not necessarily have much scientific training. Extensive empirical evidence shows that they will be more receptive to information that is easy to understand—i.e., information that can be communicated through engaging graphics, clear terminology, familiar units (e.g., English units rather than metric), and no unnecessary and intimidating jargon. Requirements for understandability and relevance will be particularly important for these users.

*Absolute Requirements or Desired Characteristics?*

In establishing criteria for the Chesapeake indicators, it will be useful to differentiate between "must-have" and "nice-to-have" criteria. The examples reveal some must-haves: for instance, EPA's climate change indicators and ROE explicitly require indicators to be based on actual observations, not modeling or statistical inference. Some projects also require peer-reviewed sources. In a screening process, such criteria can be applied in a binary fashion to rule in or rule out a candidate indicator. Conversely, some other criteria express desired characteristics that can be graded on a scale. In a screening process, indicators can be prioritized for development after being scored on several such criteria—for example, an aggregated set of high/medium/low scores. We likely would not establish a hard rule that says an indicator must have at least 10 years of data, for instance, and we might prefer a source with 30 years of data over a source with only nine. Yet it is possible that the nine-year data set is more useful and more reliable than the longer-term option.

*Categorical Exclusions*

EPA's ROE presents some "driver" indicators ("D" in DPSIR) such as population and energy use. These drivers influence greenhouse gas emissions, which drive climate change. They can also lead to compounding stressors—for example, development pressures that accentuate the risks that climate change poses to ecosystems. However, it is probably not necessary to include driver or pressure indicators in this focused effort for the Chesapeake Bay. We can start with "state" indicators, which in this case will constitute physical climate conditions. We can refer readers to other sources for information about greenhouse gas emissions and the drivers behind them.

At the other end of the DPSIR spectrum, EPA's ROE explicitly excludes "administrative" indicators that track human actions, and EPA's climate change indicators implicitly have the same exclusion. An indicator such as "number of species listed as 'Endangered'" would not be allowed, as it reflects administrative (and often political) decisions rather than purely the physical condition of the environment. In terms of the DPSIR framework, this exclusion eliminates many possible "response" indicators. In contrast, the organizational framework for this Chesapeake project requires us to consider outputs or societal responses. Thus, we propose to allow administrative indicators where they add value. We will still seek indicators that are closer to physical measurements—for example, *acres or miles* of shoreline protected would be preferable to simply counting the *number* of shoreline protection projects—but we recognize that in some cases, a count is the best option available.

*Reliance on Actual Measurements*

Some indicator compilations allow future projections to be considered as indicators, but the ones that are most similar to this project, such as EPA's climate change indicators, do not. They require observed data in an effort to preserve the "purity" of the indicators, minimize uncertainty, and guard against public suspicion of modeling (whether it is warranted or not). We suggest holding Chesapeake climate change indicators to the same standard.

Modeling can also be used to interpolate or extrapolate within an observed data set. We suggest that the Chesapeake project prioritize measured data, but allow certain types of modeled observations where necessary to fill gaps and where supported by the peer-reviewed literature. This might mean interpolating between measurement stations to produce a gridded map, for example. Yet we would not feel comfortable extrapolating to locations outside the study area, and we would not feel comfortable with temporal interpolation (filling in missing years of data) or extrapolation (extending the time series forward or backward in time beyond the period when measurements were collected).

*Definitions*

A few of the examples in Table 3 provide definitions, including a definition of "indicator" that enumerates some of the must-have criteria. The indicator definition for EPA's ROE is closest to what we are looking for, and we suggest using it for this project with some minor adaptations, such as allowing administrative indicators. We also suggest defining "resilience" using the DOI definition, which is the closest we have to an official U.S. government definition of this term in a climate change context.

## Draft Recommendations

Based on the results and discussion above, ERG recommends the following approach:

- The indicator development process will follow CBP's procedural framework for "Creating and Maintaining a New Indicator." ERG's work plan provides more detail about the specific tasks we will perform to feed into this process.

- We will categorize indicators according to the three bins laid out in the Statement of Work: physical climate trends, ecological and societal response (i.e., impacts), and programmatic progress toward resilience. CBP has indicated a preference for this approach. If needed, indicators can be sorted into different bins in the future.

- In the prioritization process, we will seek a balance of indicators across all three bins. Input from CBP staff and workgroups can help us achieve this balance.

- We will establish definitions and criteria to prioritize the development of indicators that will be useful and relevant to the primary audience of technical users, which includes scientists and policy analysts involved in management and oversight. Where possible, we will also look favorably upon indicators that will work well for the wider secondary audience: members of the public who may see these data included in future Chesapeake Bay report cards and web products.

- We will use some of the criteria in a binary manner to screen candidate indicators in or out. We will use other criteria to score candidate indicators along a spectrum, and we will aggregate these scores to help prioritize indicators for development.

- We will use the following definitions for this project:

    1. An *indicator* is a numerical value derived from actual measurements of a state or ambient condition, ecological or societal response, or programmatic action, whose trends over time represent or draw attention to underlying trends in the condition of the environment or measure progress towards a desirable state or condition. This project focuses on indicators of climate change and progress toward climate resiliency in the Chesapeake Bay watershed.

    2. Indicators of *physical climate trends* are based on measurements of physical or chemical attributes of the environment, such as temperature, precipitation, extreme weather phenomena, water levels or flows, and salinity or nutrient concentrations.

    3. Indicators of *ecological and societal response* are those that measure a) attributes of ecological systems, particularly attributes that may be influenced by physical climate trends, or b) actions that people have taken to respond to physical climate trends. Attributes of ecological systems include their extent and condition, diversity and biological balance, and ecological processes such as nutrient cycling and food/energy flows. Social responses include management actions such as designating land for protection, as well as physical actions such as constructing systems to reduce combined sewer overflows into the Bay.

    4. *Resilience* is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions. This project focuses on the ability of the Chesapeake Bay watershed, including its living resources, habitats, public infrastructure, and communities, to withstand adverse impacts from changing environmental and climate conditions.

    5. Indicators of *programmatic progress toward resilience* are those that quantify resilience or show evidence of learning or adaptation over time.

- Every indicator must meet the following criteria:

    1. **Topical relevance:** The indicator provides information about physical climate trends, ecological or societal reponse, or programmatic progress toward resilience. The connection to climate change is documented or can be explained easily.

    2. **Spatial coverage:** The indicator provides information that is specific to the Chesapeake Bay, the Chesapeake Bay watershed, or geographic sub-units within the watershed.

3. **Temporal coverage:** Multiple years of data are available to describe changes or trends, and the latest available data are timely.

4. **Actual observations:** The indicator is based on observed data. Modeling and statistical inference (if any) is limited to spatial interpolation between data points, such as the process used to generate a gridded map.

5. **Credible methods:** The indicator is based on sound data collection and analytical methods that reflect the state of the science.

6. **Data quality and integrity:** The data provider uses quality assurance procedures to ensure data quality and management systems to protect the integrity of the data.

7. **Objectivity:** The indicator is developed and presented in a clear, complete, and unbiased manner that accurately represents the underlying trends in physical conditions.

8. **Uncertainty:** Sources of uncertainty are known and understood.

9. **Transparency and reproducibility:** The specific data used and the specific assumptions, analytical methods, and statistical procedures employed are clearly stated. Documentation is sufficient to allow the indicator to be reproduced independently.

10. **Feasibility:** The indicator is feasible to construct, and a program is in place to continue to collect data, thereby allowing the indicator to be updated in the future.

- Certain indicators must meet the following criterion:

    1. **Peer-review validation:** If an indicator is based on physical measurements of environmental conditions, it must use data from a peer-reviewed publication, a program that uses peer-reviewed methods to collect and analyze data, and/or a program whose data have been used and validated in peer-reviewed publications. This criterion will likely apply to all indicators in the *physical climate trends* bin and certain indicators in the other two bins (for example, a measure of benthic community condition). For indicators that are not based on physical measurements, peer review is ideal but not required.

- Every indicator will ideally meet the following additional criteria, which can be used to prioritize indicators for development:

    1. **Relationship to other indicators:** The ideal indicator will complement other indicators rather than duplicating them. It fills a vital role in the organizational framework. Where possible, an ideal indicator will have established causal relationships with other indicators, which can be evaluated.

    2. **Spatial coverage:** The ideal indicator will use data collected throughout the Bay and its major tributaries or throughout the watershed, as opposed to indicators that are only measured at a few locations.

    3. **Spatial resolution:** The ideal indicator will provide at least a total or an average for the Bay, the watershed, or the individual states that are part of the watershed. Where possible, the ideal indicator will support local-scale analysis by providing data that are downscaled further—for example, data for individual sampling sites, sub-watersheds (e.g., HUC-12), NOAA climate divisions (up to 10 per state), or a gridded map.

    4. **Temporal coverage:** The ideal indicator will have many years of data available. The best indicators will have at least 30 years of data, which is a common threshold for climatological analysis. The ideal indicator will also have a defined baseline, particularly if it is used to assess progress toward resilience.

5. **Temporal resolution:** The ideal indicator will have data with at least annual frequency, with sub-annual frequency if appropriate (e.g., where seasonal variations are important to consider).
6. **Consistency of methods:** The ideal indicator will be based on data collection and analytical methods that are comparable across time and space. In some cases, it may be appropriate to use data that were collected or analyzed using multiple methods—for example, supplementing short-term records with longer-term records from a different source. In such cases, the data visualization should distinguish between the different sources, such as by inserting a discontinuity in a time series or plotting multiple lines on a graph. The CBNERR indicators by UMCES and Chesapeake Data provide a good example of this approach.
7. **Uncertainty:** The ideal indicator will have low uncertainty—for example, small error bars or narrow confidence intervals.
8. **Other limitations:** The ideal indicator will have few counfounding factors or other limitations that make it difficult to interpret the data or draw conclusions.
9. **Understandability:** The ideal indicator will provide a clear depiction of observations that can be understood by both technical and non-technical users.

- We will not attempt to create our own *multi-metric indices* that combine multiple indicators. Multi-metric indices can be valuable for some uses, such as distilling large volumes of information into a single user-friendly number. They bring the user farther away from the actual measurements, though, and they may require careful development and peer-review validation that is beyond the scope of the present effort.