Synthesis Element 9: Synthesis of Information Supporting Development of and Options for a Tidal Bay Water Temperature Change Indicator

Abstract

There is interest by the Chesapeake Bay Program (CBP) to develop a Tidal Bay Water Temperature Change Indicator to assess the effects of rising water temperatures related to ecological impacts in Chesapeake Bay. The Rising Water Temperature STAC Workshop effort offers the opportunity to bring together experts in habitats, fisheries, and climate change assessment to identify potential habitat and fisheries management applications for a Tidal Bay Water Temperature Change Indicator and discuss available data, spatial and temporal needs, and monitoring gaps in relation to identified applications. The synthesis findings by the tidal fish (#2) and submerged aquatic vegetation (#3) teams and feedback from the workshop participants will be used to help inform options for the Tidal Bay Water Temperature Change Indicator to be presented to the CBP Management Board.

This synthesis paper focused on reviewing the CBP climate change indicator work to date, compiling examples of temperature-related climate change indicators to provide insights on methods to track long-term trends, presenting examples and conceptual ideas of temperature change indicators connected to ecological impacts, and identifying the strengths and limitations of available water temperature data in Chesapeake Bay. The following highlights the main findings from the synthesis:

- Assessing physical water temperature change methods exist, but connecting these changes to ecological impacts (e.g., habitats, living resources) to inform management responses is lacking.
- To work towards a Tidal Bay Water Temperature Change Indicator that has management utility related to assessing ecological impacts and tracking management responses, we need input from experts managing these resources on their application needs to identify the spatial and temporal requirements for the indicator.
- There is no one single data source that will likely meet all the desired criteria (accuracy, spatial resolution, temporal extent) to address management questions related to their responses to rising Bay water temperatures on habitats and living resources.
- Given likely data limitations, a multi-data source approach could allow for a more robust indicator (e.g., combining satellite data and monitoring data).
- It will be important to consider indicator longevity (e.g., agreements with data providers, maintenance plan) to ensure reliability of the indicator for decision-making needs.

A. Contributors

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B. Resources

The following resources were reviewed to inform workshop conversations related to the development of the Tidal Bay Water Temperature Change Indicator in connection with ecological impacts:

- 2018 CBP Climate Change Indicator Plan (Eastern Research Group, Inc. 2018)
- Climate Change Indicators on Chesapeake Progress
- 2021 CBP Prioritization of Climate Change Indicators Document
- Other Indicator and Trends Analysis Programs
    - Physical Change
        - United States Environmental Protection Agency (U.S. EPA) Climate Change Indicators (Mike Kolian, U.S. EPA)
        - Integrated trends analysis of Bay water temperature change (R. Murphy, University of Maryland Center for Environmental Science [UMCES], and J. Keisman, United States Geological Survey [USGS])
        - Indicator for the National Estuary Program extended to Chesapeake Bay (R. Vogel, NOAA, M. Craghan, U.S EPA, and M. Tomlinson, NOAA)
    - Physical Change in Connection with Ecological Impacts
        - Health Watersheds Assessment (Renee Thompson, USGS)
        - Forage Action Team seasonal warming indicator effort (Mandy Bromilow, NOAA Affiliate)
- Date Sources
    - In-Situ
        - CBP Long-term Monitoring Stations: 1985-present, Monthly
        - Chesapeake Bay Interpretive Buoy System (CBIBS): 2008-present, 5 buoys, 10-60 minute intervals
        - Chesapeake Biological Laboratory (CBL) pier: 1938-present
        - Thomas Point Lighthouse C-MAN station: 1985-present, hourly
    - Satellite
        - Multi-Satellite AVHRR: 2008-present, Daily, 1km - shorter record
        - Geo-Polar Blended: 2002-present, Daily, 5km - coarser spatial res
        - Landsat: 1982-present, Daily, 30m - less accurate
        - European Climate Change Initiative: 1981-2016, Daily, 5km - only avail to 2016

- Exploratory Analyses to Connect Water Temperature Data to Fish Impacts
  - Data needs and availability in relation to designated fish spawning grounds (S. Fadullon, NOAA-CRC intern)
  - Literature review on ecological-related indicators to inform conceptual ideas for the Tidal Bay Water Temperature Change Indicator (A. Foster, NOAA-CRC intern)

C. Approach

A Tidal Bay water temperature change indicator can be approached in different ways depending on the application need for the indicator and the management question being asked. Our synthesis approach was to look at information and data that could support the assessment of water temperature change in the Bay and begin evaluating considerations to connect these changes to impacts on living resources (e.g., fisheries) and habitat. During the synthesis evaluation, we focused on summarizing the temperature-related CBP climate change indicators to date, identifying examples of indicator methodologies related to assessing physical changes in water temperatures and options for connecting to ecological impacts, and evaluating relevant water temperature data sources, including an initial assessment of data strengths and limitations related to spatial and temporal coverage.

D. Synthesis

<u>Introduction</u>

The CBP is working towards developing indicators for all outcomes in the 2014 Chesapeake Bay Watershed Agreement[1] to track progress towards meeting respective goals. The Climate Resiliency Workgroup has been working on developing indicators for the Climate Monitoring and Assessment and Climate Adaptation outcomes under the Climate Resiliency Goal.

- **Climate Resiliency 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

[1]The 2014 Chesapeake Bay Watershed Agreement: www.chesapeakebay.net/what/what_guides_us/watershed_agreement

the impacts of coastal erosion, coastal flooding, more intense and more frequent storms and sea level rise.

The climate change indicator implementation strategy for the Chesapeake Bay Program (Eastern Research Group, Inc. 2018) outlined the following needs: (1) define the indicator and its metrics, (2) have a data collection program in place, (3) select methods to transform the data into an indicator, (4) process the data, and (5) have an available indicator for the Chesapeake Bay. Bay Water Temperature was one of the proposed indicators that was identified by the Climate Resiliency Workgroup to develop. The Eastern Research Group formulated an initial vision for the Tidal Bay Water Temperature indicator, including identifying potential metrics involving satellite data (i.e., temperature trends over a period of record, spatially averaged over 1-km grid cells) and in-situ data, (i.e., single Bay-wide trend in line graph or trends for each sampling location in a map).

Additionally, the CBP climate change indicator implementation strategy identified the following ecological-related values to consider when developing the Tidal Bay Water Temperature Change Indicator: frequency and extent of harmful algal blooms, submerged aquatic vegetation composition, and fish population distributions. The plan also mentioned that warming water temperatures effects on ecosystems could lead to economic impacts to fishing and crabbing industries and recreation in the Chesapeake Bay. It also emphasized the relationship of air temperature as a primary driver of Bay water temperature change and how changes in stream temperature could also play a role in relation to water flow into the Bay. Recent research by Hinson et al. (accepted for publication) also demonstrated that water temperature in the mainstem of the Bay were driven by changes in air temperature followed by changes in ocean circulation.

The development of the CBP climate change indicator strategy led to a partnership with the U.S. EPA Climate Change Program where they clipped their national indicators for the Chesapeake Bay. This led to seven indicators that are now on Chesapeake Progress,[2] including average air temperature increases, change in high air temperature extremes, stream water temperature change, change in total precipitation, river flood frequency, river flood magnitude, and relative sea level rise.

While the seven indicators on Chesapeake Progress was a critical first step, these indicators only represent physical change occurring on a broad spatial and temporal scale. They are not currently structured to inform resilience actions at a project implementation scale, which is needed to address the Climate Resiliency Goal in the Chesapeake Bay Watershed Agreement.

[2] Chesapeake Progress Climate Change Indicators: www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment

During 2020-2021, the Climate Resiliency Workgroup built into their management strategy[3] the goal to connect the climate change indicators to clear management purposes related to the Chesapeake Bay Watershed Agreement's water quality, habitat, and living resources goals. The Climate Resiliency Workgroup agreed on a framework where the physical change would be expressed in connection with ecological and community impacts to help identify and inform needed resilience actions (Figure IX-1).

Figure IX-1. Climate Change Indicator Framework by the Chesapeake Bay Program's Climate Resiliency Workgroup.

Using this framework, the Climate Resiliency Workgroup with approval from the Management Board prioritized the development of a Tidal Bay Water Temperature Change Indicator in connection with water quality thresholds for fish and submerged aquatic vegetation (SAV) habitat to inform adaptive management.[4] The warming effects on fish and SAV outlined in the corresponding synthesis papers for this STAC workshop effort (synthesis papers #2 and #3, respectively) and the eventual identified management responses from the workshop could be used to inform how to structure the indicator or indicators for changes in bay water temperature related to ecological impacts with clearly identified management purposes. It will be important to consider the spatial and temporal scales needed to inform the specific management application that the indicator is being designed for.

The following sections summarize the existing temperature-related climate change indicators, other indicator efforts related to assessing long-term trends in Bay water temperature, and water temperature indicators that are structured in connection with fish impacts. These indicator examples and methodologies can help inform conversations in identifying options for the Tidal Bay Water Temperature Change Indicator in connection with ecological impacts from climate change. The remaining sections summarize the available water temperature data

[3] Climate Resiliency Workgroup Management Strategy: www.chesapeakebay.net/channel_files/24283/2021-2022_climate_mgt_strategy_final_submit_4-30-21_edit_6-8-21.pdf
[4] Prioritized climate change indicators approved by the CBP Management Board: www.chesapeakebay.net/channel_files/41939/list_of_climate_change_indicators_for_mgmt_board_discussion_final.pdf

sources and provides an initial assessment of the spatial and temporal strengths and limitations and presents a couple of exploratory analyses looking at connecting this data with assessing fish impacts and conceptual ideas related to fish habitat suitability.

WATER TEMPERATURE-RELEVANT CLIMATE CHANGE INDICATORS ON CHESAPEAKE PROGRESS

There are currently three temperature-related climate change indicators on Chesapeake Progress:[5] average air temperature increases, change in high air temperature extremes, and stream water temperature change. These indicators have been adapted from broader regional indicators by the U.S. EPA Climate Change Indicator program.[6] **While these indicators are focused in the watershed, they could provide insights on methodologies and possible visual representations for the Tidal Bay Water Temperature Change Indicator**. Detailed documentation on the methods and analyses for these indicators can be found on Chesapeake Progress. These indicators are briefly described below.

Average Air Temperature Increases

The Average Air Temperature Indicator (Figure IX-2) is derived from temperature measurements collected from land-based weather stations. It calculates annual temperature anomalies from 1901 to 2017 using the average temperature from a baseline period of 1901 to 2000. A gridded analysis averages climate data over climate regions across the U.S., with the slope of each temperature trend calculated from the annual anomalies by ordinary least-squares regression and then multiplied by 100 to obtain a rate of change per century.

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[5] Chesapeake Bay Program Climate Change Indicators: www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment

[6] U.S. EPA Climate Change Indicators: www.epa.gov/climate-indicators

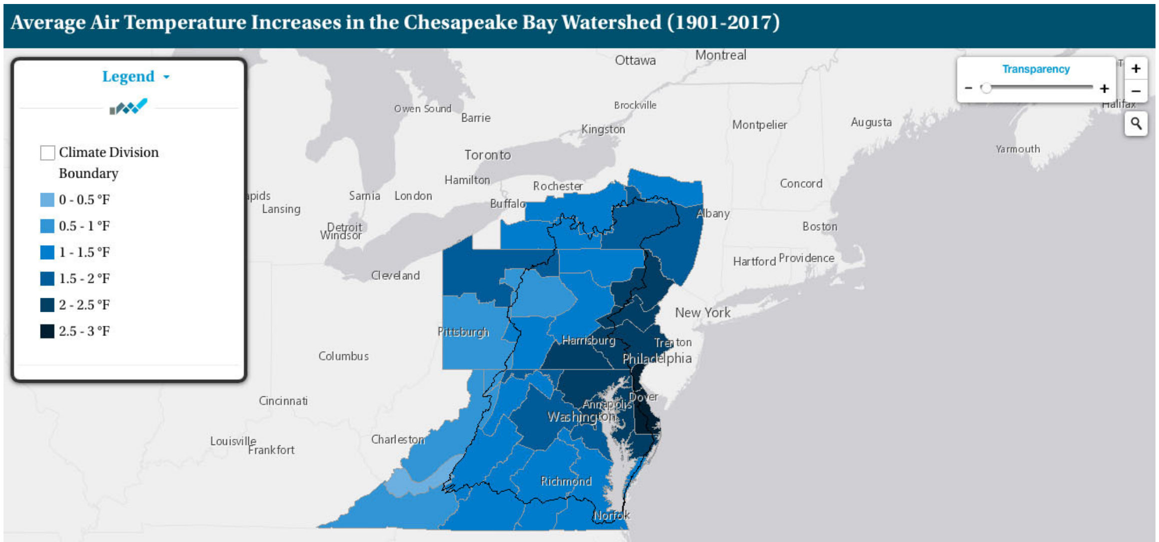

Figure IX-2. Climate change indicator showing the average air temperature increases in the Chesapeake Bay watershed in 2017 based on a baseline period of 1901-2000. Chesapeake Progress, *www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment.*

Change in High Air Temperature Extremes

The Change in High Air Temperature Extremes Indicator (Figure XI-3) also uses data from land-based weather stations. These data are compiled by the Global Historical Climatology Network, Daily edition (GHCN-Daily) overseen and maintained by NOAA. The method for this indicator calculates the 95th percentile daily maximum temperature of each station for the full time period and identifies exceedances above the 95th percentile (i.e., unusually hot days). Ordinary least-squares linear regression is used to determine the average rate of change over time in the number of > 95th percentile days. Regression coefficients for regressions significant at $p \leq 0.1$ are multiplied by the number of years in the analysis to estimate the total change in the number of annual > 95th percentile days over the full period record. Values, including zeros for insignificant trends, are mapped to show trends at each climate station.

Change in High Temperature Extremes in the Chesapeake Bay Watershed (1948-2017)

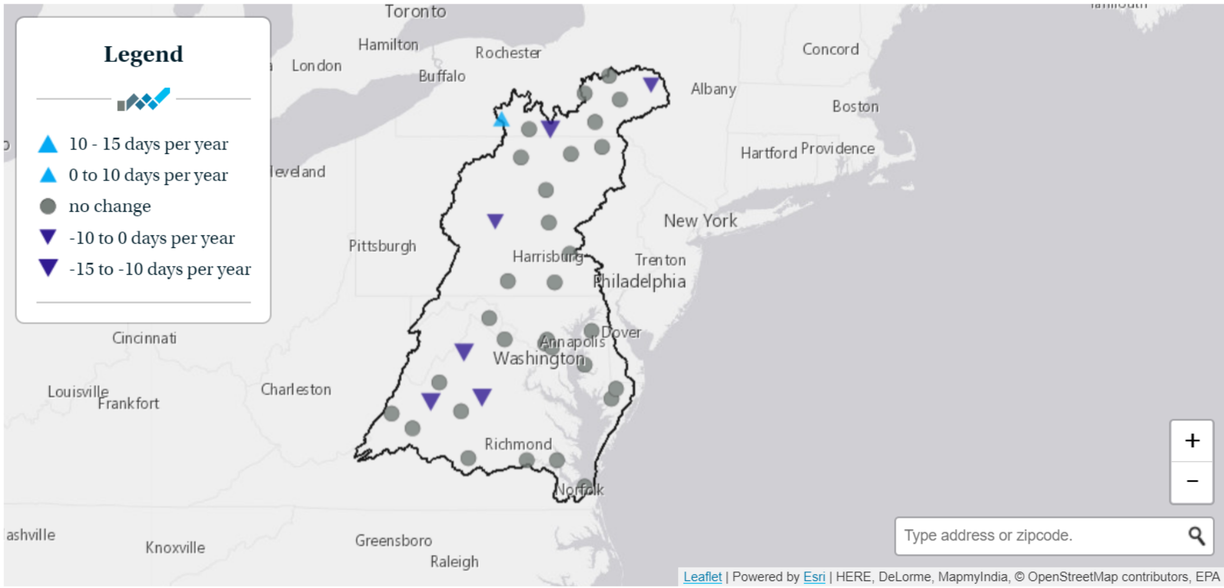

Figure IX-3. Climate change indicator showing the change in high temperature extremes in the Chesapeake Bay watershed in 2017 since 1948. Chesapeake Progress, www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment.

Stream Temperature Change

The Stream Water Temperature Change Indicator (Figure IX-4) uses data from the USGS stream gauge sites. Long-term monthly averages are calculated for each site and individual measurements are converted into anomalies (relative to the site-specific mean) to compare changes across sites. This indicator is currently not being updated given re-writing of data analysis and sharing protocols by USGS.

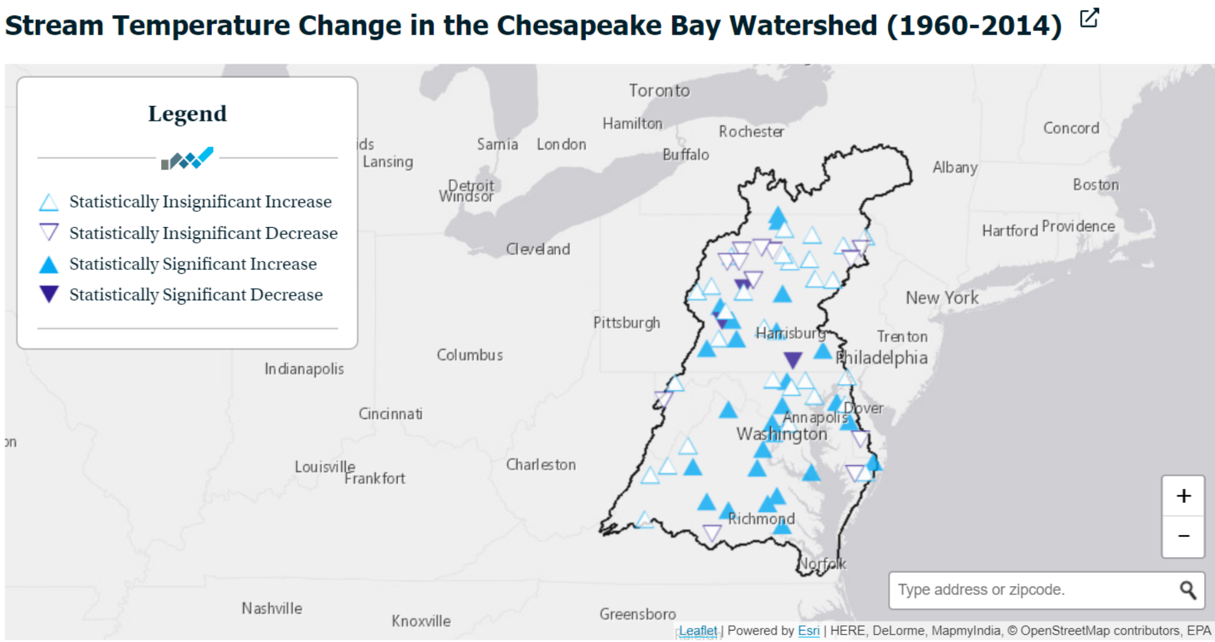

Figure IX-4. Climate change indicator showing the change in stream temperatures from 1960-2014 at USGS stream gauge stations in the Chesapeake Bay watershed. Chesapeake Progress, www.chesapeakeprogress.com/climate-change/climate-monitoring-and-assessment.

OTHER INDICATOR AND TRENDS ANALYSIS PROGRAMS

In addition to the climate change indicators on Chesapeake Progress, there are other programs that have developed climate change indicators ranging from national (i.e., U.S. EPA Climate Change Indicator Program) and regionally specific (i.e., Chesapeake Bay Integrated Trends Analysis, NOAA CoastWatch) indicators assessing long-term changes in water temperature to water temperature indicators specifically designed around ecological impacts (e.g., Healthy Watersheds Assessment climate change indicator related to brook trout occurrence, forage indicators related to seasonal warming and habitat suitability). The following sections describe these efforts with the goal to provide examples of indicator strategies that could help inform methodologies and application options for the Tidal Bay Water Temperature Change Indicator(s).

U.S. EPA Climate Change Indicator Program

www.epa.gov/climate-indicators

Program Point of Contact: Mike Kolian, U.S. EPA

The U.S. EPA Climate Change Indicator Program is a collaborative effort between EPA and 50 data contributors from government agencies, academic institutions, and other organizations to provide indicators reflecting climate change causes and effects. Summarized below are a subset of these indicators related to temperature. While these indicators focus on air temperatures, **the data and methods used for these indicators could provide insights on methodology approaches for the Tidal Bay Water Temperature Change Indicator**.

Global Air Surface Temperature

The EPA's U.S. and Global Temperature Indicator (Figure IX-5) synthesizes data from remote sensing, weather station surface measurements, and observations from buoys and ships on the ocean. It calculates annual temperature anomalies from 1901 to 2020 using the average temperature from a baseline period of 1901 to 2000. For example, an anomaly of 2.0 degrees means the average temperature was 2 degrees higher than the long-term average of the baseline. With the data as a time series, NOAA calculated monthly temperature means for each site and employed a homogenization algorithm to correct for error between the data types and regions. From there, averages were compounded and could be converted into monthly anomalies by comparing it to the long-term average.

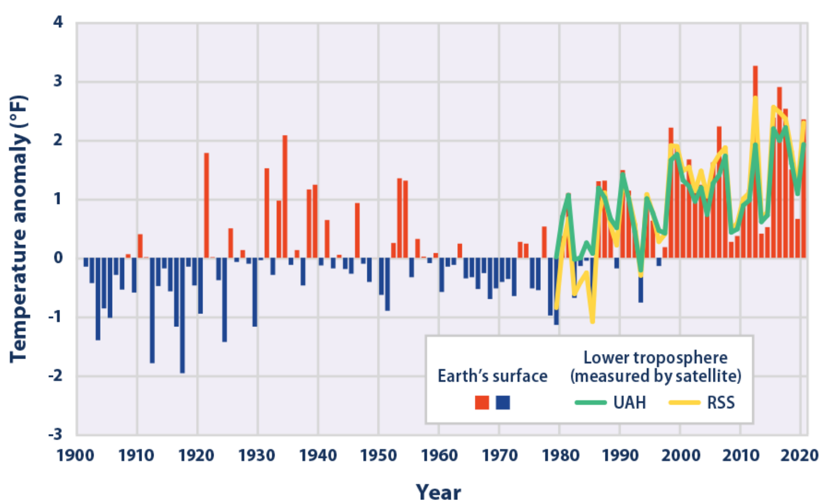

Figure IX-5. Temperature anomalies in the Contiguous 48 States, 1901–2020. U.S. EPA, www.epa.gov/climate-indicators/climate-change-indicators-us-and-global-temperature

Seasonal Air Surface Temperature

The Seasonal Temperature Indicator (Figure IX-6) serves to reflect the fact that while average air temperatures increase throughout the year, increases may be larger in certain seasons. This indicator examines changes in average air temperatures in each season based on daily temperature measurements from more than 10,000 weather stations across the U.S. Similar to the U.S. and Global Temperature Indicator, it calculates annual temperature anomalies from 1896 to 2020 using the average temperature from a baseline period of 1901 to 2000. Daily temperature measurements at each site were used to calculate monthly anomalies, which were then averaged for each season to find temperature anomalies for each year. Regional anomalies were then averaged together in proportion to their area to develop state and national results.

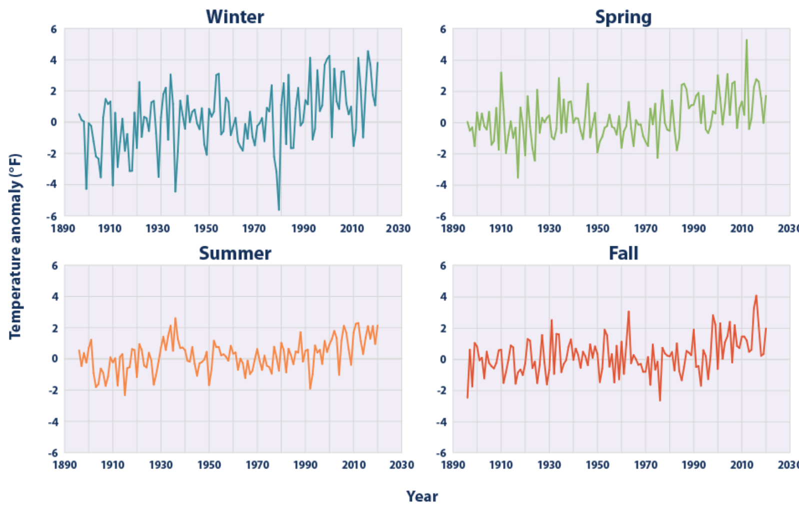

Figure IX-6. Average Seasonal Temperatures in the Contiguous 48 States, 1896–2020. U.S. EPA, [*www.epa.gov/climate-indicators/climate-change-indicators-seasonal-temperature*](www.epa.gov/climate-indicators/climate-change-indicators-seasonal-temperature)

Heat Waves

The Heat Wave indicator examines trends over time in four characteristics of heat waves in the United States: frequency (number per year), duration (length in days), intensity (how hot it is), and season length (days between the first heat wave of the year and the last) (Figure IX-7). Weather data was analyzed from 1961 to 2019 for 50 large metropolitan areas, where the most people are vulnerable. They used hourly air temperature and humidity measurements to calculate apparent temperature, which is more relevant to human health. For consistency across the country, this indicator defines a heat wave as a period of two or more consecutive days where the daily minimum apparent temperature in a particular city is higher than the 85th percentile of historical July and August temperatures for that city. Given that criteria, they were able to identify heat waves and collect data on frequency, duration, intensity, and season.

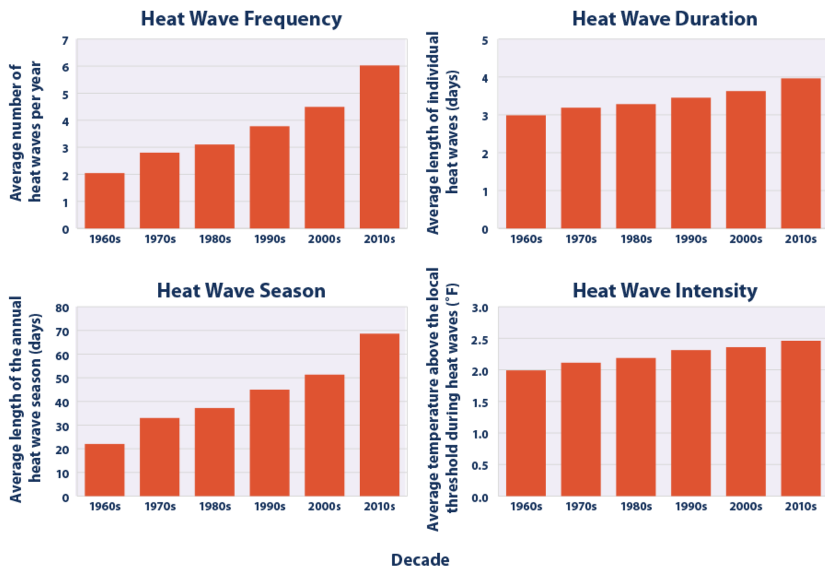

Figure IX-7. Heat Wave Characteristics in the United States by Decade, 1961–2019. U.S. EPA, www.epa.gov/climate-indicators/climate-change-indicators-heat-waves

Sea Surface Temperature

The Sea Surface Temperature indicator (Figure IX-8) tracks average global sea surface temperature from 1880 through 2020. While the early data was collected by inserting a thermometer into a water sample collected by lowering a bucket from a ship, today temperature measurements are collected more systematically from ships and buoys. NOAA reconstructed and filtered the data to correct for biases in the different collection techniques and to minimize the effects of sampling changes over various locations and times. It calculates annual temperature anomalies from 1880 to 2020 using the average temperature from a baseline period of 1971 to 2000. The data is averaged over 2-by-2-degree grid cells, with daily and monthly records averaged to find annual anomalies. A long-term trend was calculated for each grid cell using linear regression, where the slope of each grid cell's trend was multiplied by the number of years in the period to derive an estimate of total change.

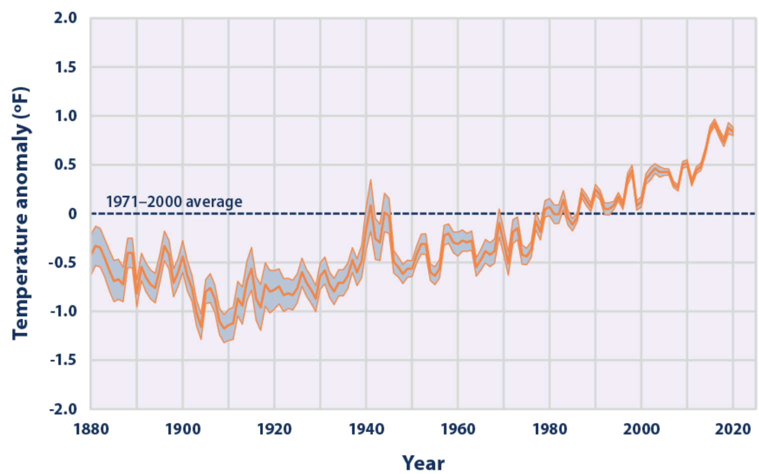

Figure IX-8. Average Global Sea Surface Temperature, 1880–2020. U.S. EPA, www.epa.gov/climate-indicators/climate-change-indicators-sea-surface-temperature

Chesapeake Bay Program Integrated Trends and Analysis Team
https://www.chesapeakebay.net/who/group/integrated_trends_analysis_team
Program Point of Contact: Rebecca Murphy, UMCES, and Jeni Keisman, USGS

The Integrated Trends Analysis Team (ITAT) aims to combine the efforts of the Chesapeake Bay Program analysts with those of investigators in governmental, academic, and non-profit organizations to identify collaborations that will enhance the understanding of spatial and temporal patterns in water quality. One of their annual partnership projects is to complete the Chesapeake Bay Tidal Trends Update. Maryland DNR, Virginia DEQ, DC and others have been sampling at 150+ stations since the 1980's 1-2 times per month for multiple parameters including water temperature (Figure IX-9). There is an extensive long-term coordinated tidal monitoring effort to analyze trends with this data. The data is collected and put into an R package called baytrends which has been designed to fit GAMs for the tidal Chesapeake Bay water quality data over time. A GAM is a statistical model in which a response of interest can be modeled as the sum of multiple smooth functions of explanatory variables (Murphy et al. 2019). These smooth functions can be constructed in many ways (Hastie and Tibshirani 1986, 1990), and GAMs allow for model shapes from linear to nonlinear – including patterns that change direction over time. The results from the different jurisdictions are submitted to the Chesapeake Bay Program and combined to show trends throughout the Bay through maps as demonstrated below.

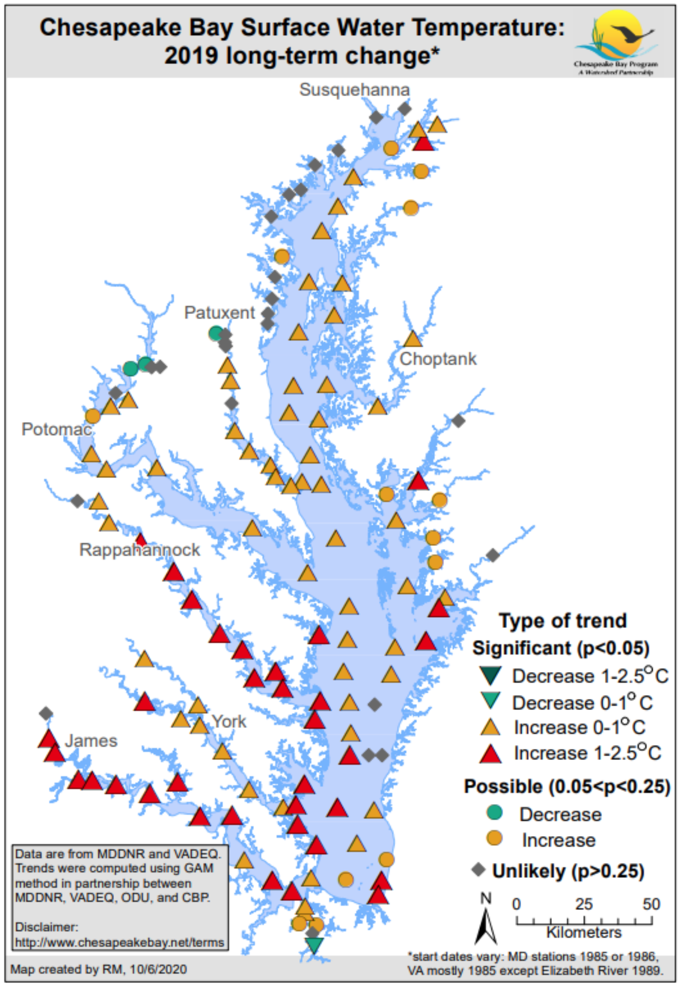

Figure IX-9. Long term flow-adjusted trends in bottom water temperatures at the Chesapeake Bay Mainstem and Tidal Tributary Water Quality Monitoring Program stations through 2019 from the Integrated Trends Analysis Team (ITAT).

The annual tidal trend results represent multiple parameters, different depths (surface & bottom), different temporal dynamics (observed conditions & flow-adjusted), and various time periods and seasons (1985 - present, last 10 years, spring & summer CHLA). Significant contributors to this work include Jennifer Keisman (ITAT Lead), Renee Karrh (MDDNR), Mike Lane (ODU), and Rebecca Murphy (UMCES).

The ITAT physical change indicator for long-term Bay surface water temperature change and corresponding methodology using GAMS for trends analysis provides robust information that should be considered when developing options for the Tidal Bay Water Temperature Change Indicator related to ecological impacts. **While this indicator shows water temperature change on an annual temporal scale, the method could be used to develop seasonal trends or other**

identified time periods of interest where the data are available (Rebecca Murphy, UMCES, personal communication), which could be more suited for assessing impacts to fish or SAV.

U.S. EPA National Estuary Program Indicator Extended to Chesapeake Bay
https://eastcoast.coastwatch.noaa.gov/time_series_sst_gen.php?region=cd
Program Point of Contacts: Ron Vogel, NOAA
Contributors: M. Craghan, USEPA, and M. Tomlinson, NOAA

The U.S. EPA National Estuary Program partnered with NOAA CoastWatch to develop a website tool that utilizes remote sensing satellite data from various sources to produce graphs (Figure IX-10) and maps of monthly and annual averages and statistical trends from 2008-2018 of water temperature change along the East Coast. This project was extended to the Chesapeake Bay where the temporal and spatial averaging methodologies were based on recommendations in the STAC 2008 CBP Climate Report (Pike et al. 2008) (Figure IX-11).

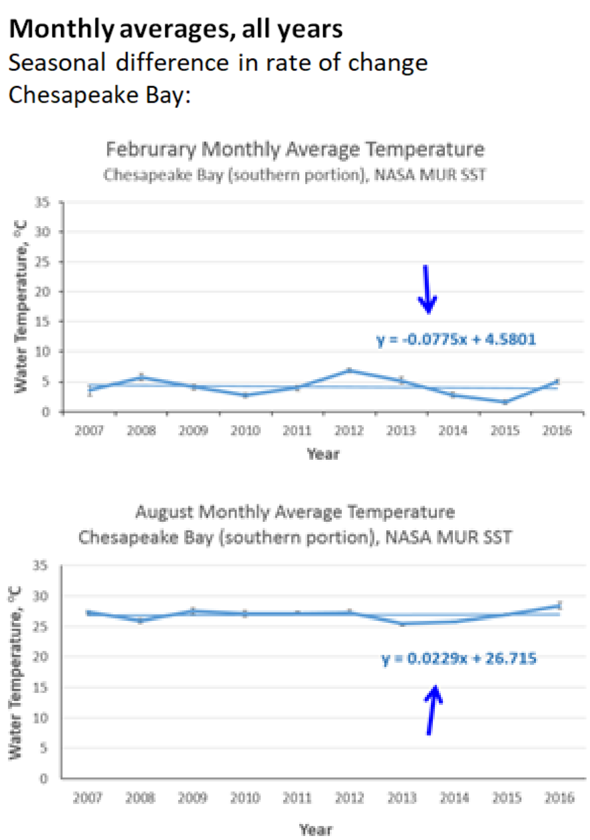

Figure IX-10. Example of graph outputs from the NOAA CoastWatch website demonstrating the seasonal differences in the rate of water temperature change from 2007-2016.

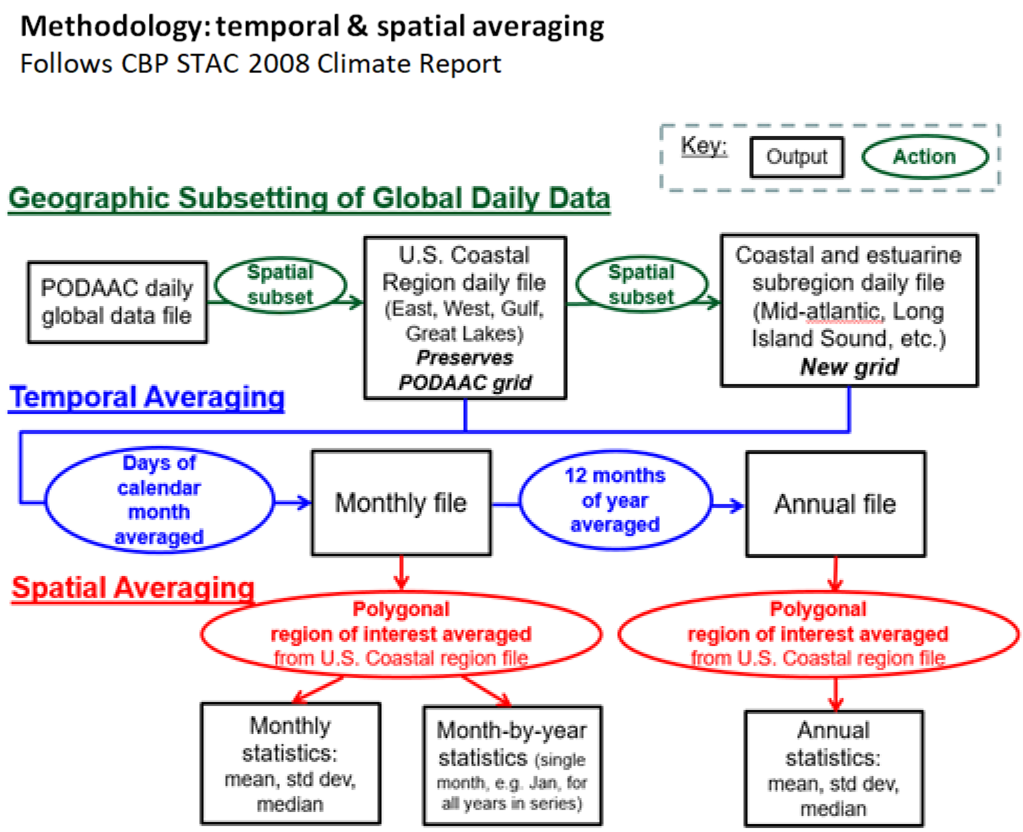

Figure IX-11. Flow chart demonstrating the temporal and spatial averaging methodologies for the NOAA CoastWatch water temperature change analyses based on recommendations found in the CBP STAC 2008 Climate Report (Pike et al. 2008).

The NOAA CoastWatch website is an interactive tool that allows users to select the monthly time period to run the trends analysis. **NOAA CoastWatch is an example of a customizable indicator that could be considered for the Tidal Bay Water Temperature Change indicator to allow the end user to select the time period of interest.**

Healthy Watersheds Assessment

The Healthy Watersheds Assessment (Roth et al. 2020) provides an example of how habitat conditions can be considered in assessing future probability of fish occurrence. Included in the assessment is the vulnerability metric, “Change in Brook Trout Probability of Occurrence with 6 degree Celsius Temperature Change” by catchment (Figure IX-12). This metric utilizes a model from Nature’s Network/USGS Conte Lab that predicts brook trout occurrence under present conditions and temperature increases from 2 to 6 degree Celsius scenarios. The 6-degree scenario provided the most sensitive signal of potential change across the Chesapeake Bay watershed regions. **Indicators developed with future scenarios in mind could support resilience planning by identifying areas to target conservation or restoration.**

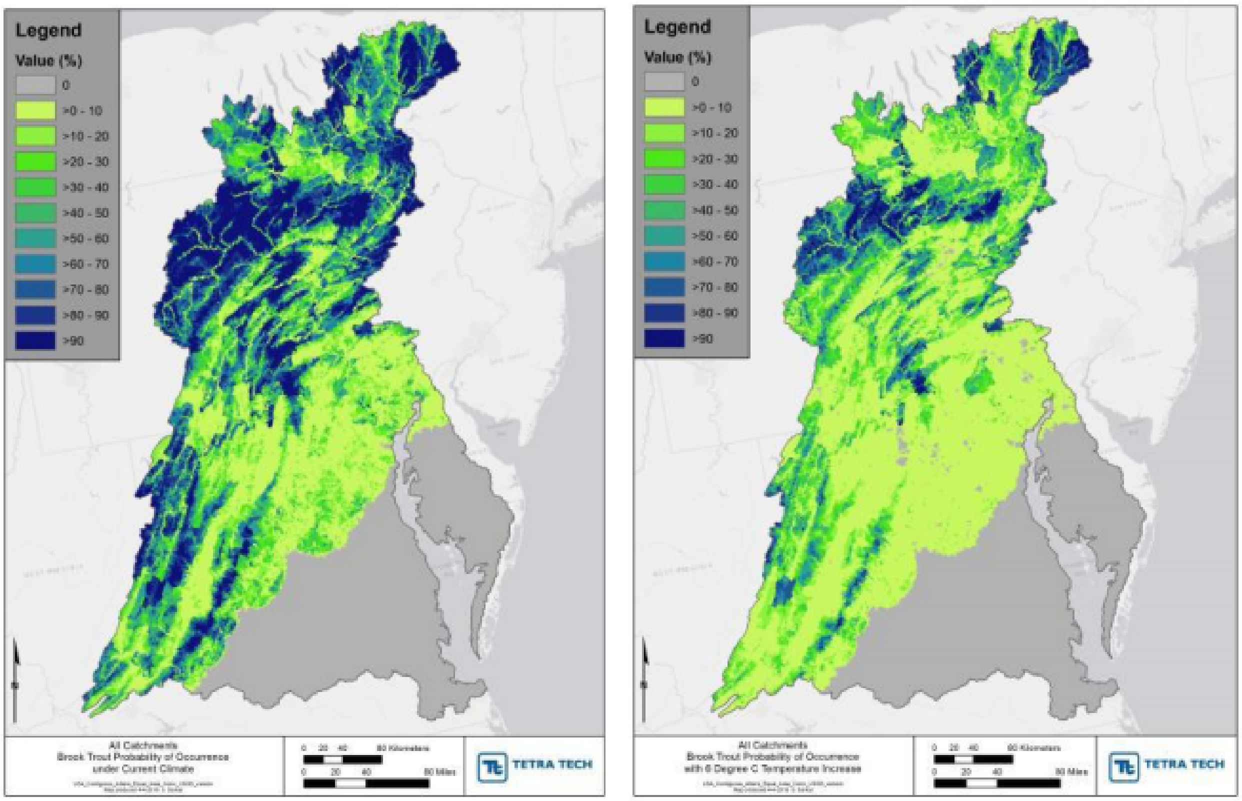

Figure IX-12. Probability of brook trout occurrence under current climate conditions (left) decreasing across much of the region with a 6 degree C increase in stream temperature (right) (Roth et al. 2020).

Forage Indicator Development Efforts

The goal of the Forage Outcome stipulated in the 2014 Chesapeake Bay Watershed Agreement is to “continually improve the partnership’s capacity to understand the role of forage fish populations in the Chesapeake Bay...and to develop a strategy for assessing the forage fish base available as food for predatory species.” The Forage Action Team (FAT) is currently developing an initial suite of indicators to assess the forage base in the Bay. This indicator suite is expected to operate as an assessment tool for tracking the health of the Bay and to eventually inform management. In 2020, the FAT created the Forage Indicator Development Plan to lay out a framework for indicator development which follows a tiered approach. The Tier 2 indicators, which use the relationships between environmental factors and forage abundance to track forage status over time, may provide insight for the development of a Chesapeake Bay water temperature indicator. There are currently two Tier 2 indicators that may be of interest: the Springtime Warming indicator and the Habitat Suitability Index.

The Springtime Warming indicator will use a phenological temperature index to determine the timing of warming water temperatures in the Chesapeake Bay. Woodland et al. (2017) determined that the rate of springtime warming (i.e., how quickly water temperatures reached a threshold in spring) has a negative relationship with summer forage abundance. That is, the earlier in the year that water temperature warms up, the less forage are available as prey in the Bay. The indicator will consist of a time series of the integer day each year at which 500 degree-days (DD) was achieved using 5°C as a threshold and will provide insight into the effects of climate change on the forage base. Bay anchovy are a key forage species that exhibited a significant negative relationship with the rate of springtime warming and will therefore be the initial focus of this indicator. Other finfish (e.g., YOY weakfish) and invertebrates (e.g., polychaetes, crustaceans) that exhibited a relationship can be used to develop indicators in the future.

The Habitat Suitability Index will consist of a time series of area (or percent area of the Bay) available as suitable habitat for various forage species in the Chesapeake Bay. This indicator will be developed from the results of a habitat suitability modeling project that was wrapped up in 2020, which uses hydrodynamic models and water quality parameters (e.g., water temperature, salinity, dissolved oxygen) to assess the extent of suitable habitat for four key forage species: bay anchovy, juvenile spot, juvenile weakfish, and juvenile spotted hake. With these models, researchers were able to examine the annual and seasonal variations in abundance and distribution of the four forage species. The model results indicated that seasonal variability was more pronounced than annual variability, and there was a significant correlation between suitable habitat extent and forage abundance for bay anchovy in winter and juvenile spot in summer.

These forage indicators under development provide examples of how water temperature data can be directly applied to understand ecological impacts by using thresholds to identify suitable habitat.

DATA CONSIDERATIONS

When evaluating a Bay Water Temperature indicator, the 2018 climate change indicator implementation strategy (Eastern Research Group, Inc. 2018) recommended the use of two metrics, *in situ* measurements and satellite data, allowing for multiple lines of evidence to adequately represent changing water temperature in Chesapeake Bay. While a method has been developed for remote monitoring (a system of averaging grid squares), no method has been selected to aggregate *in situ* data. **Discussions on how best to compile the data from multiple sources and structure it into a formal indicator that aligns with desired management applications will be needed**. Tables IX-1 and IX-2 summarize available *in situ* and satellite data sources, respectively, and provides information on their temporal and spatial attributes.

Table IX-1. In-situ data sources for water temperature and initial assessment of strengths and weaknesses.

Data Source	***Type***	***Temporal extent***	***Temporal sampling interval***	***Spatial sampling interval***	***Underlying agency***	***Access***	***Strength***	***Weakness***
CB Monitoring Network (CBP)	ship	1985 - present	monthly, bimonthly	89 stations in main stem & tributaries	Bay-wide cooperative effort	https://datahub.chesapeakebay.net	long record, bay-wide	infrequent sampling interval
Eyes of the Bay Continuous Monitoring	Various anchored instruments	1985 - present (varies by station)	15 min	Multiple stations	Maryland Department of Natural Resources (various partners contribute)	http://eyesonthebay.dnr.maryland.gov/contmon/ContMon.cfm	continuous data in shallow environments, long record, high frequency sampling interval	data gaps
CBIBS (NOAA)	buoy	2008 - present	hourly	varies year to year the number of operational buoys	NOAA	https://buoybay.noaa.gov/	continuous hourly data	surface data only, limited spatial coverage, frequent temperature data gaps
CBL Pier (UMCES)	various pier attached instruments	1938 - present		single point	UMCES Chesapeake Biological Lab	https://cblmonitoring.umces.edu	exceptionally long record, high frequency sampling interval	single point
Thomas Pt. Lighthouse (NOAA)	C-MAN station	1985 - present	hourly	single point	NOAA National Data Buoy Center	https://www.ndbc.noaa.gov/station_history.php?station=tplm2	long record, high frequency sampling interval	single point

Table IX-2. Satellite data sources for water temperature and initial assessment of strengths and weaknesses.

Data Source	***Type***	***Temporal extent***	***Temporal sampling interval***	***Spatial sampling interval***	***Underlying agency***	***Access***	***Strength***	***Weakness***
Multi-satellite composite SST (NOAA)	satellite	2008 - present	daily	1 km	NOAA CoastWatch	https://eastcoast.coastwatch.noaa.gov	bay-wide, high spatial sampling interval, temperature values confirmed against CBIBS buoys at seasonal scale	spatial gaps in daily record, shorter record than other satellite data sets, will be phased out in future, older algorithm and older data corrections than other satellite data sets
Geo-Polar Blended SST (NOAA)	satellite	2002 - present	daily	5 km	NOAA Center for Satellite Applications & Research	https://coastwatch.noaa.gov	bay-wide, no spatial gaps in daily record	coarse spatial sampling interval for a satellite data set
Coral Reef Watch SST (NOAA)	satellite	1985 - present	daily	5 km	NOAA Coral Reef Watch	https://coralreefwatch.noaa.gov	bay-wide, no spatial gaps in daily record	combines two separate data sets for 1985-2002 and 2002-present intervals, coarse spatial sampling interval for a satellite data set
Multiscale Ultrahigh Resolution SST (NASA)	satellite	2002-present	daily	1 km	NASA JPL/ PODAAC	https://podaac.jpl.nasa.gov/	bay-wide, high spatial sampling interval, no spatial gaps in daily record	inaccuracy exists currently for 2002-2006 period, improved accuracy for full temporal extent expected in future version

Landsat Surface Temperature (USGS)	satellite	1982-present (Landsat 4,5,7,8)	every 16 days	100 m (thermal data)	USGS	https://www.usgs.gov/core-science-systems/nli/landsat/data-tools	bay-wide, highest spatial sampling interval	spatial gaps in daily record, infrequent sampling interval compared to other satellites, less accurate than other satellite data products (see note below)
Climate-Change Initiative SST (European Space Agency)	satellite	1981-2016	daily	5 km	European Space Agency Climate Change Initiative	https://climate.esa.int/en/projects/sea-surface-temperature/data	bay-wide, no spatial gaps in daily record	coarse spatial sampling interval for a satellite data set, temporal extent not expected to be extended on routine basis

Additional information and considerations on the above satellite data sets:

1) Selected data sets have spatial sampling interval 5 km or less; coarser data sets are not suitable for Chesapeake Bay
2) Selected data sets have institutional support
3) All the above data sets combine data from multiple instruments on multiple satellites
4) Satellite SST data generally has accuracy of 0.3 degree C or less; accuracy assessment per specific data set may not be available; Landsat surface temperature has accuracy of ~ 1.1 degree C for estuaries (Schaeffer et al. 2018)
5) All the above data sets have weaknesses in temporal extent, temporal sampling interval, spatial sampling interval, spatial gaps in daily record, or consistent accuracy across the temporal extent
6) NOAA has formulated plans for best-of-all-products SST data set to address the above weaknesses. The new data set will cover 1981-present with a daily temporal sampling interval, 2 km spatial sampling interval, no spatial gaps, and consistency in accuracy across the temporal extent (availability TBD)

<u>Exploratory: Fish Habitat Applications for the Water Temperature Change Indicator</u>

With the goal to connect the Tidal Bay Water Temperature Change Indicator with ecological impacts, the NOAA Chesapeake Bay Office through the NOAA-CRC Summer Internship Program has supported two internship projects to date exploring data application and conceptual ideas related to water temperature change and fish habitat considerations. These projects involved evaluating temporal and spatial data considerations related to fish spawning and developing conceptual ideas for connecting the water temperature data to fish habitat suitability. **These exploratory analyses can help inform conversations to identify management application options for the Tidal Bay Water Temperature Change Indicator.**

Multi-Data Source Evaluation Related to Designated Fish Habitat in Chesapeake Bay
Work by Shalom Fadullon, NOAA-CRC Intern, Breck Sullivan, CRC, and Julie Reichert-Nguyen, NOAA (2020)

Supported by the NOAA-CRC internship program, this project evaluated existing, long-term data sources to support the development of a Tidal Bay Water Temperature Change Indicator for the Chesapeake Bay tidal waters. The project assessed the feasibility of combining satellite and individual site data as recommended in the CBP climate change indicator strategy (Eastern Research Group, Inc. 2018) in relation to fish spawning habitat grounds.

We evaluated datasets from the CBP Long-Term Monitoring stations and the Multi-Satellite AVHRR. Early in the project it was discovered that the daily satellite data did not typically reach narrow areas upstream in the tributaries where there are designated fish spawning habitats (Figure IX-13). While there are CBP Long-Term Monitoring stations in these areas, they only include monthly samples. Daily data are needed to better connect a water temperature change indicator to fish spawning effects (Jim Uphoff and Stephanie Richards, Maryland Department of Natural Resources, personal communication).

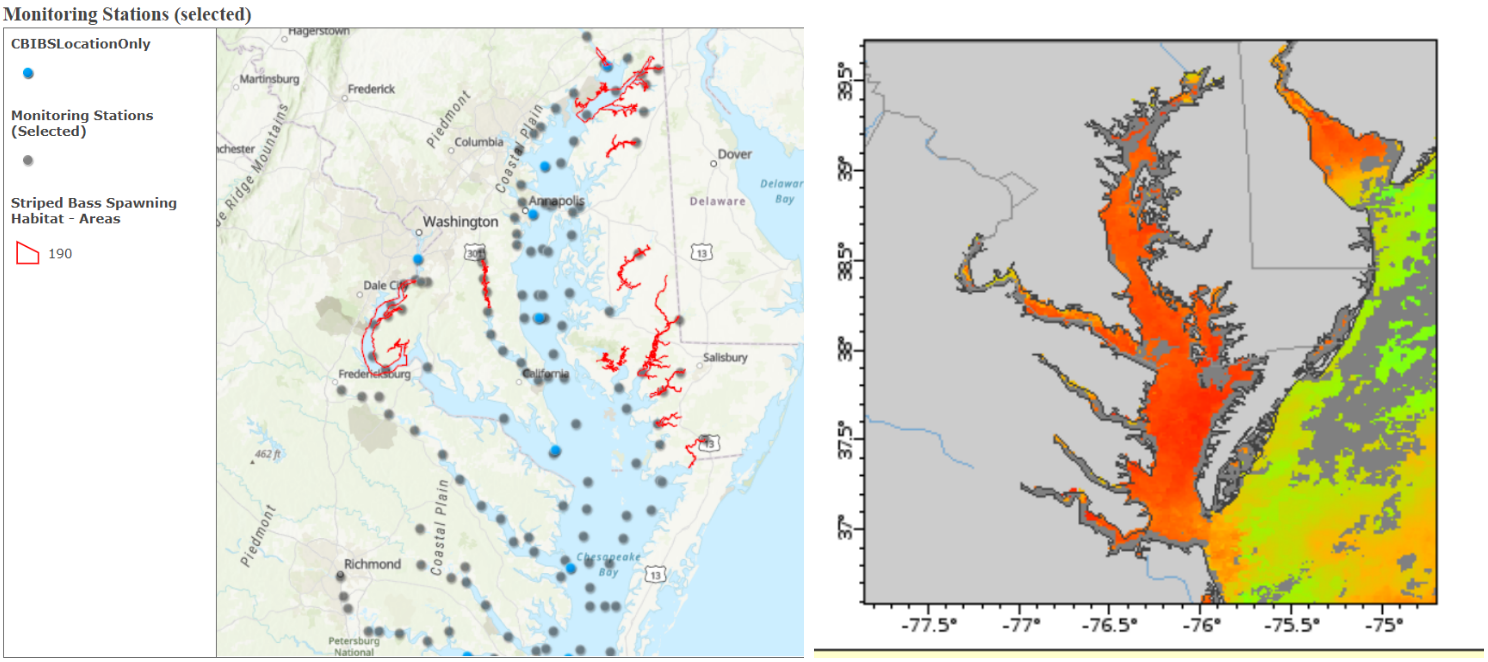

Figure IX-13. Location of designated fish spawning habitats (red), CBIBS buoys (blue), and CBP Long-Term Monitoring stations (grey) are shown in the map below (left). Example of spatial coverage from Multi-Satellite AVHRR data (right).

There were a few locations where the two different data sources did overlap within a designated fish spawning habitat, including an area in the Potomac River (Segment POTOH1_MD; Figure IX-14).

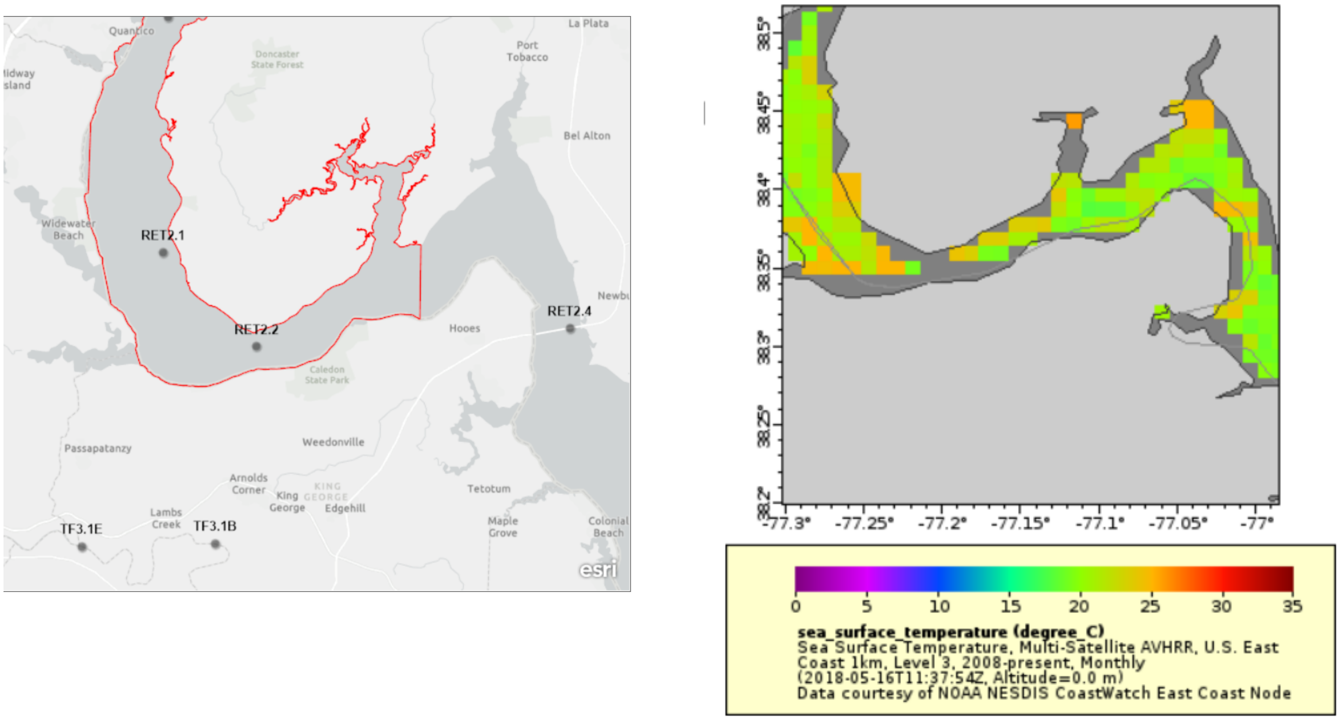

Figure IX-14. Long-term CBP Monitoring stations, RET2.1 and RET2.2, in the Potomac River segment POTOH1_MD (left) that align with Multi-Satellite AVHRR data (right)

Comparisons of the monthly averages from the long-term monitoring stations RET 2.1 with monthly averages from nearby daily Multi-Satellite AVHRR data from 2008-2019 were conducted to assess if the datasets produced similar results. Overall, the two datasets are comparable (Figure IX-15). Instances where the satellite or measured data are overestimating or underestimating the temperature should be further investigated.

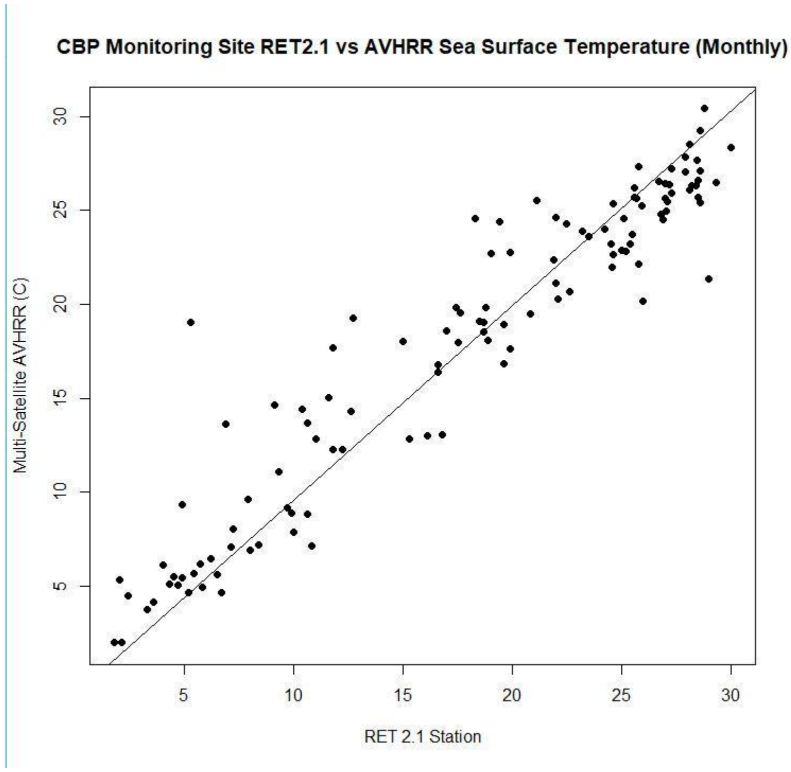

Figure IX-15. Comparison of CBP Monitoring Site RET2.1 data with Multi-Satellite AVHRR data from 2008-2019 in Potomac River segment POTOH1_MD.

A seasonal breakdown of the data could be explored to further assess the variability between the two datasets related to fish spawning cycles. Data gaps could be further evaluated to see if months with more cloud cover days demonstrate large differences from the measured values.

Depending on the management question being asked, there may be a data mismatch to fulfill all the spatial and temporal needs (e.g., preferred daily data unavailable in spawning location). Regarding satellite data, other sources should be explored beyond the Multi-Satellite AVHRR dataset, where daily data in the narrow tributaries may exist. **While there are data limitations in spawning areas, satellite and measured data are more abundant in the mainstem of the Bay and have shown to have a good fit. Combining these datasets to assess fish habitat requirements in the mainstem of the Bay related to latitudinal fish distribution could be feasible.**

Conceptual Ideas for the Tidal Bay Water Temperature Change Indicator Related to Fish Habitat

Work by Anissa Foster, NOAA-CRC Intern, Breck Sullivan, CRC, and Julie Reichert-Nguyen, NOAA, (2021)

Supported by the NOAA-CRC internship program, this project focused on compiling potential uses for a Tidal Bay Water Temperature Change Indicator related to fish impacts in Chesapeake Bay. **Concepts from the literature were reviewed to develop ideas for ecological impact indicators that connect water temperature change to fish habitat suitability. A persisting trend in the literature review is that climate-forced changes in species distributions are causing changes in both fishery operations and fisheries management (Link et al. 2015). Another is the increasing number of marine heatwaves.** Due to their severe negative impacts on coastal and ocean ecosystems, investigating resilience strategies with regards to these extreme events is crucial (Holbrook et al. 2020). Existing ecological metrics at NCBO provided insights into tools and concepts to build ecological indicators, such as temperature thresholds and seasonal change.

We developed two indicator concepts using information on striped bass habitat (Figure IX-16), but these concepts could be applied to other species of fish and even SAV where there are known habitat requirements. Spatially, to understand fish distribution change under a warming climate, water temperature data can be used to assess potential shifts in populations — particularly as the lower Bay warms faster than the upper Bay. For instance, striped bass prefer oxygenated, deeper areas, thriving in temperatures below 25°C (Thompson 2010). A water temperature change indicator that is structured related to fish habitat requirements could identify regions which serve as critical habitats to alleviate thermal stress during the summer months and ensure fish accessibility versus areas that are less optimal. Thompson (2010) outlines that striped bass require dissolved oxygen levels of at least 2 mg/L, thus a multi-metric approach (such as water temperature and dissolved oxygen) could allow for a more comprehensive assessment of available habitats.

The second concept was oriented towards striped bass survivorship. A heat wave indicator could track the characteristics of a heat wave related to fish habitat requirements to identify areas where fish may be exposed to more stressful habitat conditions affecting their survival. The indicator could examine trends in four key characteristics of heat waves (EPA 2021):

- Frequency: the number of heat waves that occur every year.
- Duration: the length of each individual heat wave, in days.
- Season length: the number of days between the first heat wave of the year and the last.
- Intensity: how hot it is during the heatwave.

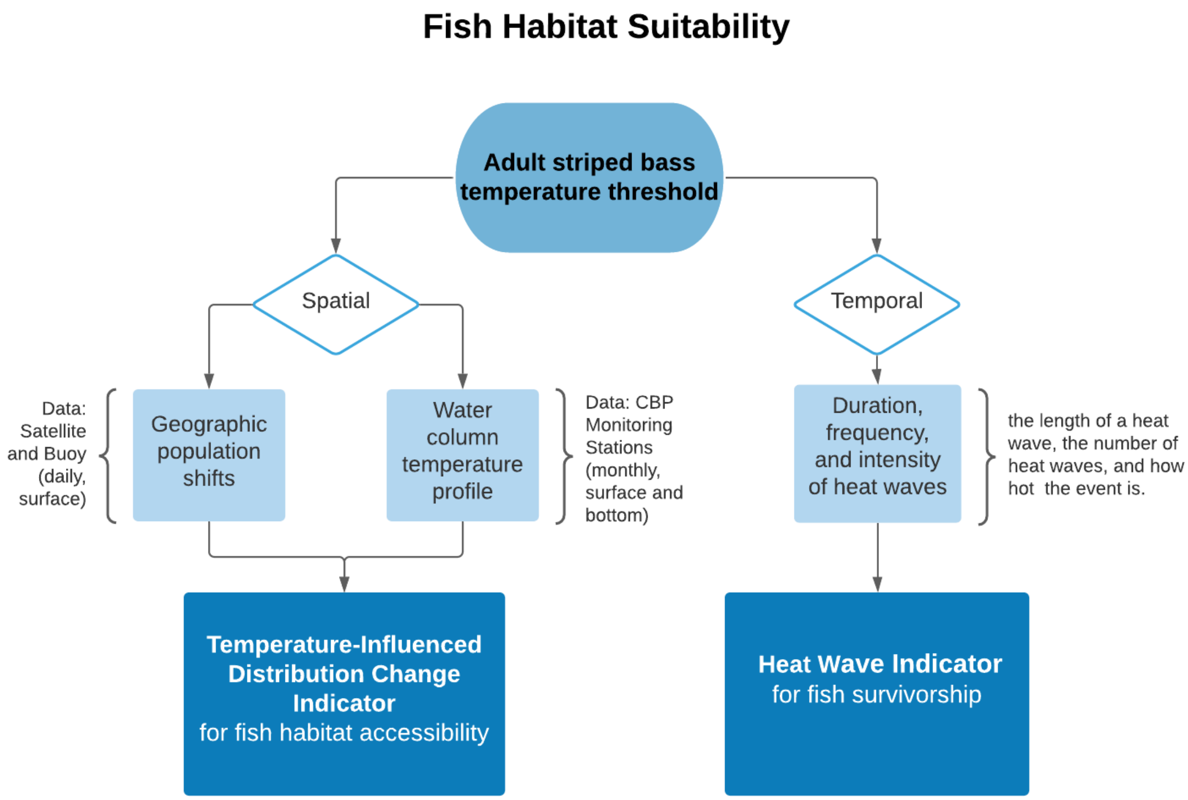

Figure IX-16. Conceptual ideas to connect Bay water temperature change with fish habitat suitability.

E. Evaluation

KEY FINDINGS

When just considering physical water temperature change in the Chesapeake Bay, indicators currently exist, including the ITAT water temperature trends analysis and the National Estuary Program's indicator extended to Chesapeake Bay using satellite data. However, to inform resilience management responses related to the water quality, habitat, and living resource goals, there is a need to connect the water temperature data to the ecological impacts at the appropriate temporal and spatial scales of the management question(s) being asked. Therefore, the indicator characteristics, methodologies and development depends on the specific management application that the indicator is needed to inform. Given that there could be multiple management questions around rising water temperatures, we may need more than one tidal Bay water temperature change indicator. Prioritizing the management needs will be important to identify which water temperature change indicators to pursue.

The review for the synthesis paper revealed that there is no one single data source that will meet all the desired criteria (temporal extent, temporal interval, spatial interval, accuracy, ongoing record, institutional support, etc.) to address management questions around habitats and living resources. Given the data limitations from individual data sources, a multi-data resource approach could allow for a more robust indicator by combining the advantages of different data sources: high temporal resolution from buoys and moorings; long-term data and bay-wide coverage from ships; bay-wide coverage with high spatial resolution from satellites (Table IX-3).

Table IX-3. Summary of advantages and limitations of different types of data sources (i.e., ship, buoy/mooring, satellite).

	SHIP	BUOY/MOORING	SATELLITE
Advantages	• bay-wide • vertical profile	• highest temporal sampling interval • surface-only or vertical profile	• bay-wide • highest spatial sampling interval • high temporal sampling interval
Limitations	• low temporal sampling interval • low spatial sampling interval	• lowest spatial sampling interval	• surface only

In reviewing the literature for potential uses of a Tidal Bay Water Temperature Change Indicator in connection with habitat and living resources, three common themes emerged: establishing habitat requirements, identifying critical thresholds, and evaluating the data from a seasonal standpoint. When considering fisheries management decisions, daily data are useful for decisions regarding spawning, while long-term monthly averages may be better suited for tracking adult distribution changes (Uphoff and Richards, Maryland Department of Natural Resources, personal communication). Indicators that incorporate future climate change scenarios could provide valuable information for resilience planning.

Figure IX-17 provides examples of management application options for a Tidal Bay Water Temperature Change Indicator depending on the management need. For instance, if the management need is to capture general long-term trends in changes to water quality, a coarser spatial (e.g., point data) and temporal (e.g., monthly) scale could be sufficient. However, if assessing changes to fish habitat to inform fisheries management decisions, a finer spatial (e.g., satellite) and temporal (e.g., daily) scale may be required.

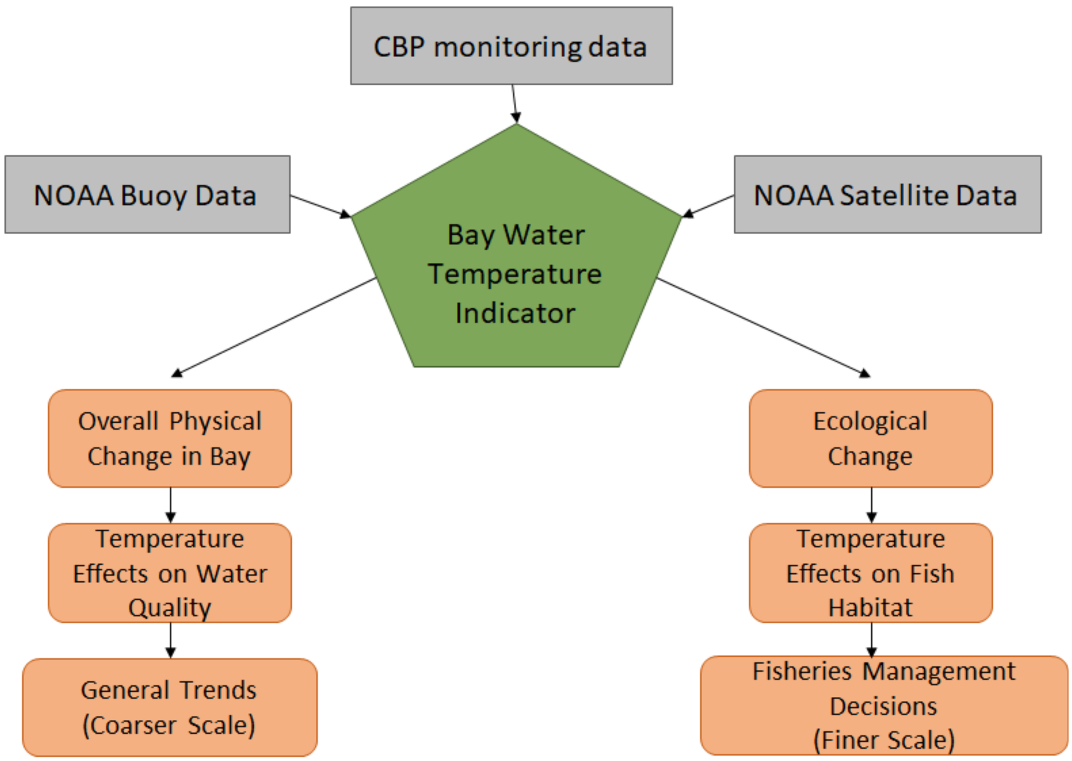

Figure IX-17. Flow chart demonstrating potential options for a Bay Water Temperature Indicator based on management applications.

The following are gaps in knowledge that need further assessment:

1) Better understanding of management needs to make decisions on resilience actions.
2) Scientific understanding to construct an indicator to meet the management need(s), i.e. development of a methodology, including selection of the specific data sources.
3) More linkages between environmental physical characteristics and biological suitability needs related to habitats and species of interest in relation to present and future conditions.

MANAGEMENT IMPLICATIONS

Given the time and effort to develop and maintain indicators, it will be important to get input from potential end users on the utility of any Tidal Bay Water Temperature Change Indicator before development. Doing this ahead of developing an indicator will better position the indicator to be useful in identifying and implementing strategies in managing affected resources from rising water temperatures in a strategic direction that optimizes resilience. Knowledge that is gained from the fish and SAV synthesis assignments should be considered when identifying options for the Tidal Bay Water Temperature Change Indicator. Additionally, information learned from the monitoring synthesis will be important to identify reliable data sources to support a Tidal Bay Water Temperature Change Indicator long-term.

A management criteria for any methodology for generating the indicator is flexibility to exchange the input data sets with new ones, as data sets lose funding, existing data sets' time series are reprocessed with new corrections applied, and new data sets with more desirable characteristics (accuracy, spatial resolution, temporal extent) become available. After replacement of the input data set(s), the indicator's entire time series will need to be recalculated. Infrastructure must be in place to accomplish this.

Overall, management considerations related to indicator longevity include:

- How and who will compile data from multiple sources in format that can be applied towards indicator development for the temporal and spatial management scales of interest?
- How and who will maintain and update the indicators after they have been developed?
- Does the indicator methodology allow flexibility if there is a change in data availability?

FURTHER FOLLOW-UP SYNTHESIS WORK PLANNED OR UNDER CONSIDERATION

- More synthesis of existing indicator methodologies
    - GAM trends analyses (R. Murphy et al., 2019)
    - Multimetric indicator (Q. Zhang et al., 2018)
- Incorporating climate change projection information from the CBP Modeling Workgroup and other sources. Range of future protections could be compared to present trends to inform management responses under a resilience lens.
- Consideration of indicators that include multiple stressors (e.g., temperature, dissolved oxygen, salinity, water flow) when making connections to ecological impacts. A multi-metric strategy that considers multiple of a species' habitat requirements (including water temperature thresholds) could allow for a more comprehensive

assessment of available habitats. However, the complexity of the indicator usually increases as more parameters are incorporated. Therefore, it will be important to gauge available resources to allow the inclusion of multiple metrics.

- Incorporate discussion on successor species - new species that are moving into Chesapeake Bay with the habitat changes (e.g., brown shrimp, cobia, red drum).
- Connect the Tidal Bay Water Temperature Change Indicator to societal impacts - CRWG looking to coordinate with Stewardship GIT.
- Consider the role of nature-based practices in reducing global air temperatures, which would ultimately benefit the mainstem of the Bay in the long-term. A recent modeling study in Nature (Girardin et al. 2021) demonstrated that nature-based solutions, such as forests and wetlands, contribute to lowering global temperatures in the long term. They emphasized that nature-based solutions must be designed for longevity, particularly developing strategies that protect long-term carbon-sink potential.

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ADDITIONAL RESOURCES

The recently NOAA-funded projects[7] incorporating climate change components related to fish distribution and abundance trends and indicators of habitat quality could offer valuable information in connecting the Tidal Bay Water Temperature Change Indicator to ecological impacts and provide insights on potential management responses. The principal investigators from these projects could be invited to the STAC workshops given their expertise in evaluating ecological effects from changing climate conditions. Summaries of their projects are described below:

Virginia Polytechnic Institute & State University (Virginia Tech) project titled, "Striped bass and summer flounder abundance trends and influencing factors in the Chesapeake Bay: an ecosystem-based evaluation" will:

- quantitatively assess the environmental, habitat variability and fishing intensity impacts on summer flounder and striped bass species abundance, distribution, and productivity in the Chesapeake Bay;
- assess fish community structure changes at long-term, interannual time scales and investigate trait and life history patterns that have similar or contrary trends with summer flounder and striped bass to better understand the mechanisms of their changes;
- detect or validate the potential climate change caused changes in habitat parameters for summer flounder and striped bass abundance and distribution in the Bay, and in fish community;
- investigate the environmental factor(s) and climate indices that can guide management caused by climate change.

This project aims to develop models to provide fishing communities and fishery managers with tools to better predict the key species of interest and viable fish communities during changing climate and habitat conditions. This project would addresses research priority #1 - synthesis and analysis of existing information that connects living resource responses to changing habitat, climate and other environmental conditions.

University of New Hampshire (UNH) project titled, "Leveraging multi-species and multi-year telemetry datasets to identify seasonal, ontogenetic, and interannual shifts in habitat use and phenology of Chesapeake Bay fishes" will analyze a variety of telemetry datasets for striped bass, river herring, cownose rays, dusky sharks, and horseshoe crabs, collected by the Smithsonian Environmental Research Center over the past ten years to identify species specific thermal and other indicators of habitat quality. The project plans to integrate telemetry data with habitat characteristics to develop species, season, and size based habitat distribution

[7] Past and Current Chesapeake Bay Fisheries Science Funded Research: https://www.fisheries.noaa.gov/past-and-current-chesapeake-bay-fisheries-science-funded-research

models in order to identify important indicators of habitat quality and use by fish in the Chesapeake Bay. This project addresses research priority #1 - synthesis and analysis of existing information that connects living resource responses to changing habitat, climate and other environmental conditions.

Another additional resource includes the Mid-Atlantic Fishery Management Council and partners' East Coast Climate Change Scenario Planning Initiative.[8] This effort includes fishery scientists and managers working collaboratively on identifying jurisdictional and governance issues revolving around climate change and effects to fisheries, such as shifting stocks.

[8] East Coast Climate Change Scenario Planning Initiative: https://www.mafmc.org/climate-change-scenario-planning