Synthesis Element 5: Past, Current and Projected Changes in Watershed and Tidal Water Temperatures and Implications for Ecosystem Processes Influencing Stream, River and Estuarine Health

May 17, 2021 DRAFT—Shared with Workshop Project Team as Example Synthesis Element

A. Contributors

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B. Resources

Published papers and Chesapeake Bay water quality monitoring network's long term trend analyses generated by Rebecca Murphy, Renee Karrh, and Mike Lane. EPA Climate Change Indicator development, PA Report on Climate Impacts, interviews with experts and draft

C. Approach

Synthesized evidence for long term changes in watershed and tidal Bay water temperatures, then engaged researchers and analysts currently involved in in-depth analysis and evaluation of both the trends and the likely underlining causes behind the observed trends and finished with accounting for the implications for the watershed and estuarine ecosystem. Will continue conversations with researchers as other temperature trends are analyzed to incorporate any upcoming publications.

D. Synthesis

Watershed and Tidal Bay Water Temperature Trends

Watershed and tidal Bay water temperatures are rising and have been for the past several decades. Preston (2004) reported an average water temperature increase of ~0.8-1.1°C from 1949-2002 as derived from direct observations and satellite measurements. Ding and Elmore (2015) found increases in surface water temperature of ~0.4-2°C from 1984-2010, also based on direct observations and satellite measurements. Chilrud (paper posted 01-07-20) cites USGS data in reporting that average non-tidal stream temperatures increased 2.52 °F from 1960 to 2010, while air temperatures increased 1.99 °F. Using estimates of changes from downscaled global climate models (GCMs) and the Chesapeake Bay Program Partnership's modeling framework, Tian et al. (2021) documented changes in Chesapeake Bay water temperatures of 0.85-0.9°C from 1995-2025. Hinson et al. (accepted for publication) used a combination of observations and model outputs to report that throughout Chesapeake Bay's mainstem, similar warming rates are found at the surface and bottom between the late 1980s and late 2010s of 0.02 °C per year, with elevated summer rates (0.04 °C per year) and lower rates of winter warming (0.01 °C per year) (Figure V-1). These annual rates yielded an annual average Bay-wide warming of ~0.7°C throughout the Chesapeake Bay's water column over the past 30-year period, with a 1.0 °C increase during the summertime and a 0.3°C during the winter months over the same three-decade period (Hinson et al. accepted for publication).

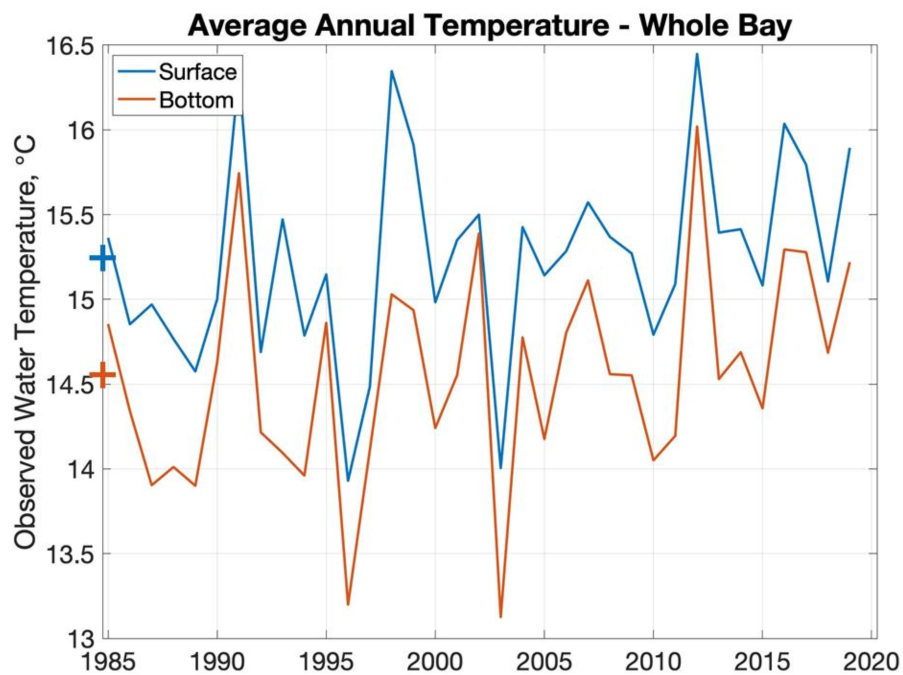


Figure V-1. Observed annual averaged surface and bottom water temperatures across Chesapeake Bay from 1985 through 2020.

Recent work by Murphy and colleagues (personal communication), using generalized additive model approach to evaluating water quality as described in Murphy et al. 2019, yielded annual estimates seen in Figures V-2 and V-3.

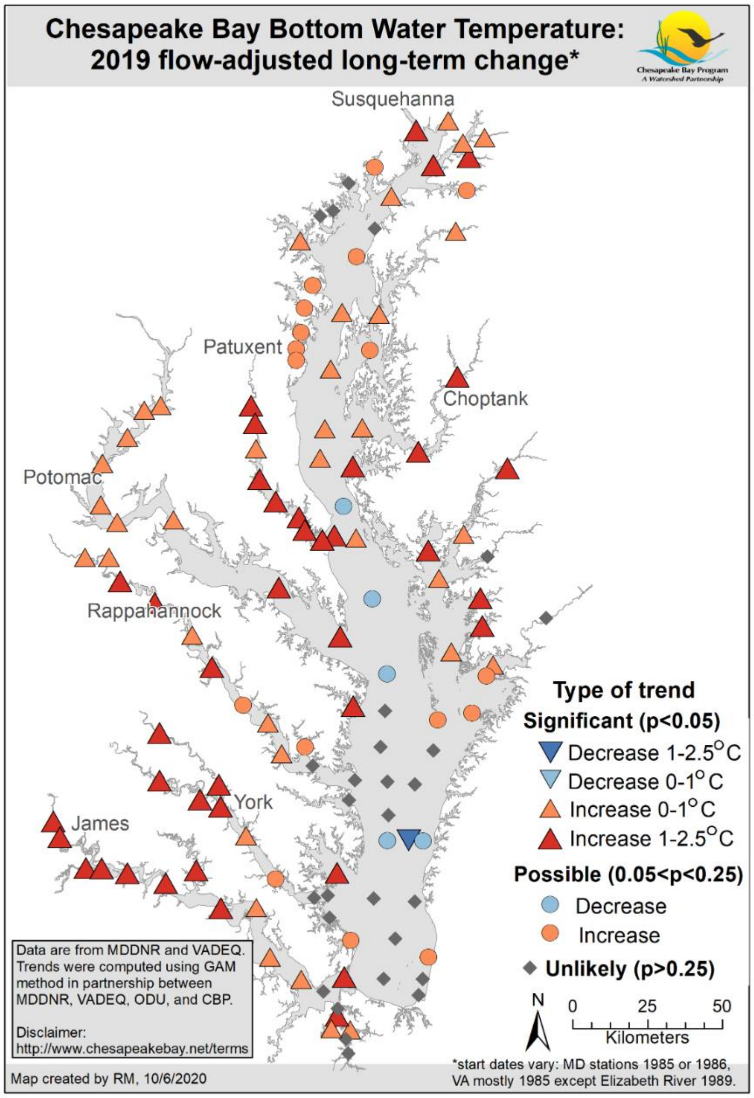


Figure V-2. Long term flow-adjusted trends in surface water temperatures at the Chesapeake Bay Mainstem and Tidal Tributary Water Quality Monitoring Program stations through 2019.

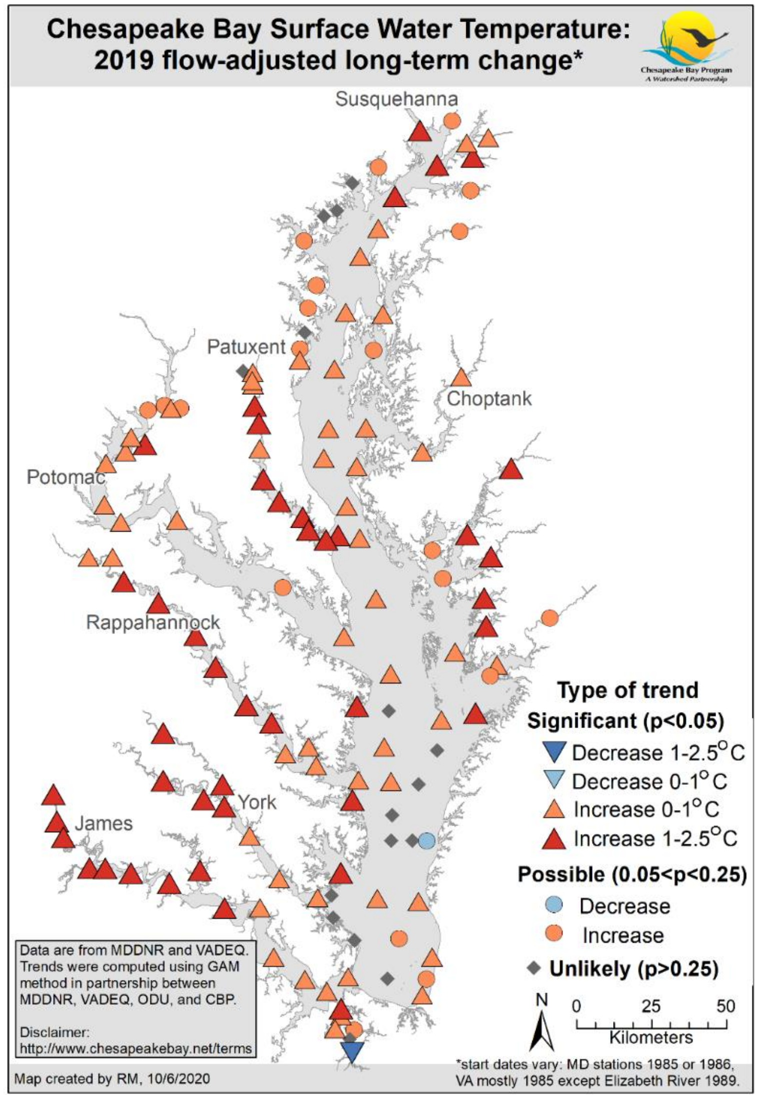


Figure V-3. Long term flow-adjusted trends in bottom water temperatures at the Chesapeake Bay Mainstem and Tidal Tributary Water Quality Monitoring Program stations through 2019.

Non-Tidal Water Temperatures

Key takeaways from trend analysis of instantaneous stream-water temperature (WT) at 129 sites within or near the Chesapeake Bay watershed from 1960 to 2014 (Rice and Jastram, 2015).

- From 1960 through 2014, WT increased significantly at 53 of 129 stations analyzed in the region. Stream-water temperature decreased significantly at 7 of those 129 stations over the same period.
- Regionally, the median of significant WT trends was 0.026 °C per year with a range of −0.08 to 0.08 °C per year.
- Increases in WT occurred at the greatest rates in the southern part of the study area.

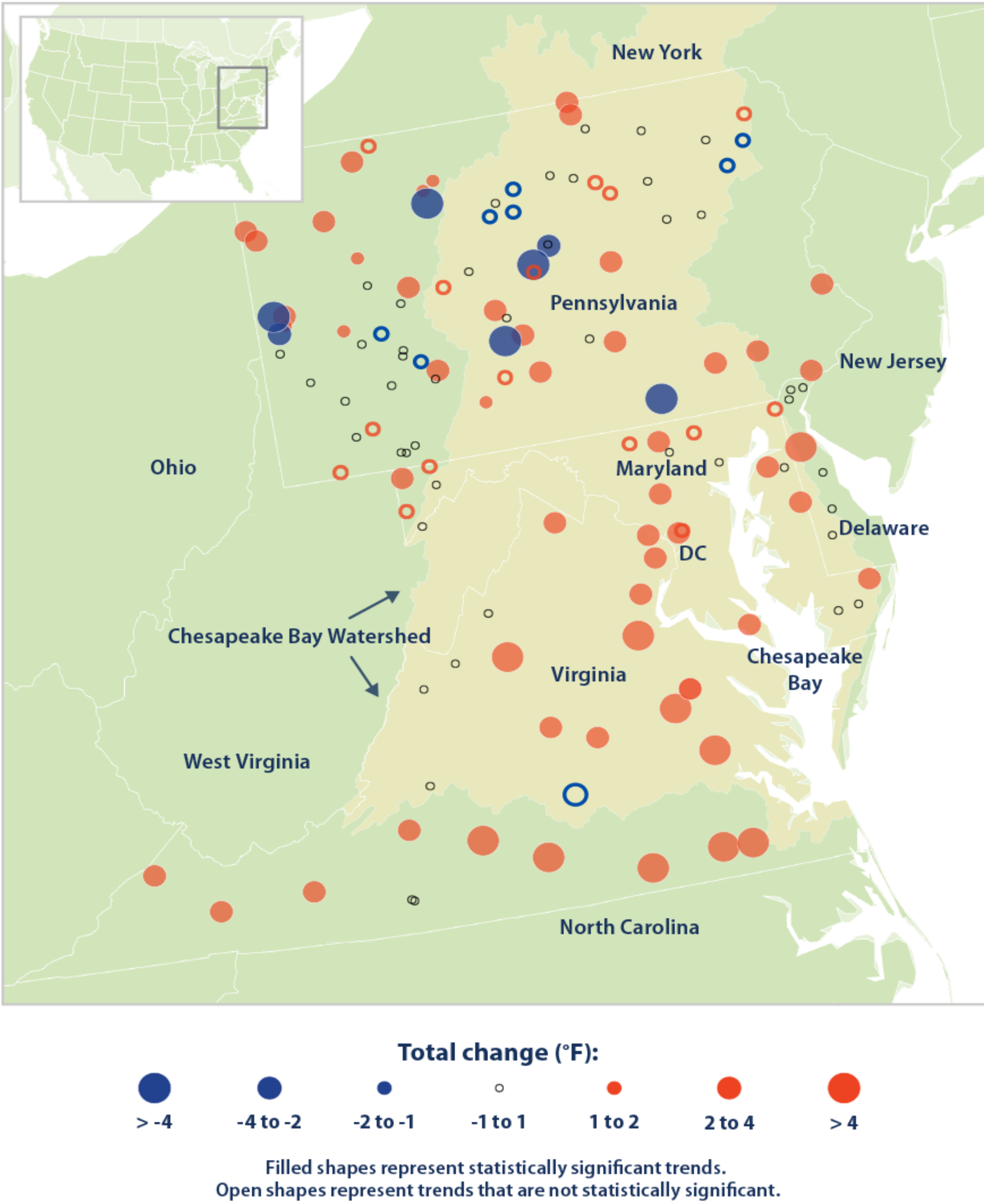


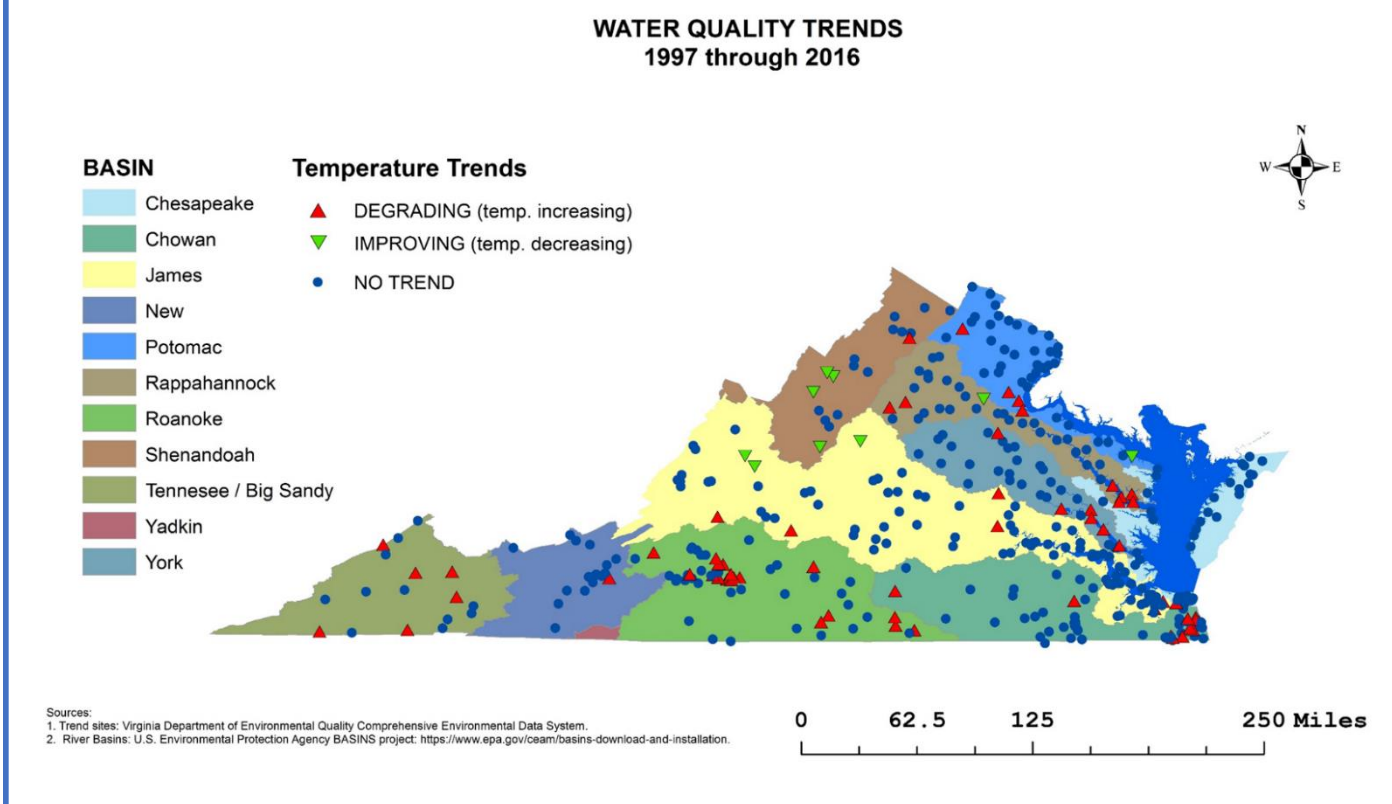
Figure V-4. Changes in Stream Water Temperatures in the Chesapeake Bay Region, 1960–2014

This map shows the change in water temperature at 129 stream gauges across the Chesapeake Bay region from 1960 to 2014. Red circles show locations where temperatures have increased; blue circles show locations where temperatures have decreased. Filled circles represent sites where the change was statistically significant (EPA Climate Indicator).

Water temperature in streams can be affected by factors other than climate, including industrial discharges, hydrologic alteration (for example, channelization, piping, and impoundment), land cover, location, and topography. A more detailed analysis of this data set found that water temperature tends to increase more quickly than air temperature in agricultural areas without major dams, but more slowly at forested sites and in areas influenced by dams (Rice and Jastram, 2015). For this indicator, WT measurements from all available stream gages with appropriate records within the study area were used, as described in Rice and Jastram (2015), regardless of potential influences from anthropogenic disturbances. A comparison, using the Rank-Sum test (Helsel and Hirsch, 2002), of relatively undisturbed reference stations (n = 35), as determined by Falcone (2011), with all other stations (n = 94) in the dataset demonstrated no significant difference (alpha = 0.05) in trends between the two groups of stations. Trends were determined using ordinary least-squares linear regression of sites-specific monthly water temperature anomalies, as described by Rice and Jastram (2015). The Cochrane-Orcutt method (Cochrane and Orcutt, 1949) was used to remove the effect of serial correlation, thus allowing determination of the statistical significance of water temperature trends at individual stations. Of the 129 stations analyzed, 60 (47 percent) had trends that were significant to a 95-percent level ($p \leq 0.05$), including 53 stations with temperature increases and seven with decreases.

Sources of variability include localized factors such as topography, geology, elevation, and natural land cover within individual watersheds. Variability between individual temperature measurements could result from variations in weather—for example, if a recent storm led to an increase in streamflow. Additionally, some sites may be more affected by direct human influences (such as land-cover and land use change or hydrologic modification) than others and does not include any sites that are affected by tides.

The Virginia Department of Environmental Quality (VADEQ) operates a network of 410 permanent trend stations where monthly or bimonthly data are collected for a variety of key water quality parameters. These fixed stations are located in areas of special interest including those near the mouths of our major rivers, along the fall line, near flow gaging stations, at designated non-tidal stations monitored to evaluate how rivers affect the Chesapeake Bay. In Roger Stewart’s 2018 Integrated Report on Water Quality Trends in Virginia from 1997-2016, water temperature was included in the trend analysis as a water quality indicator variable (Figure V-5). Temperature has an influence on regulating respiration rates, spawning, and the maximum concentration of dissolved oxygen in solution with the ambient water (increasing temperature reduces DO and therefore may limit respiration). In addition, animals and plants under thermal stress from abnormally high-water temperatures are at increased risk of adverse effects from other pollutants. Temperature standards exist for “the propagation and growth of a balanced indigenous population of aquatic life” as described in the clean water act (33 U.S.C. §1251 et seq; this is, more correctly, a balanced and indigenous community of aquatic life). Pollution events that cause harm to aquatic communities via water cooling are extremely rare in VA, and not known to exist at the stations in the trend network. Therefore, increasing trends in water temperature are considered degradation, and decreases in temperature are considered improvements (Stewart 2018).



SURFACE WATER TEMPERATURE	% NO TREND	% IMPROVING	% DEGRADING	STATIONS	N
	82	2	15	410	64,189

Figure V-5. Surface water temperature trends in Virginia 1977-2016

Driving Forces Behind Warming of Chesapeake Bay Tidal Waters

Hinson et al. (accepted for publication) have identified four principal mechanisms responsible for the observed increasing temperatures of Chesapeake Bay's tidal waters, listed here in the order of their relative influence: atmospheric forcings, warming ocean boundary, sea level rise and increasing river temperatures (Figure V-6).

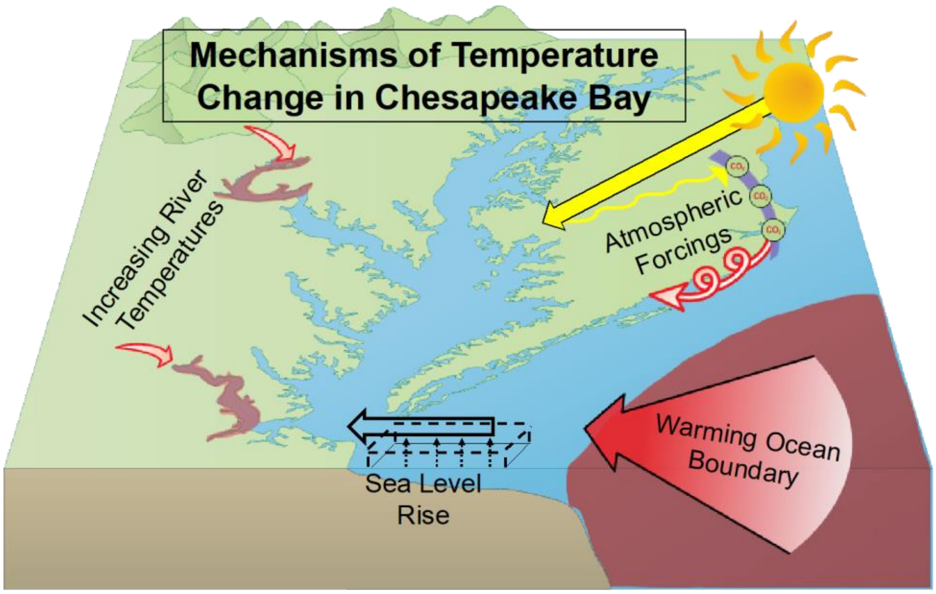


Figure V-6. Illustration of the four major mechanisms driving changes in water temperature throughout the Chesapeake Bay's mainstem, tidal tributaries and embayments.

[Briefly describe overall methodology used to quantify relative magnitudes of principal mechanisms causing temperature change in Chesapeake Bay here.]

Temperature changes were largely very similar at the Bay's and tidal tributaries' surface and bottom of the water column (Hinson et al. accepted for publication) (Figure V-7). Some regional differences in temperature changes were reported, with higher temperature changes estimated for the Susquehanna Flats and adjoining upper Bay mainstem, the lower Bay and mouth of the Bay, and the tidal fresh reaches of the major tidal tributaries (Figure V-8). There is evidence supporting river temperature influences in the upper tidal fresh reach of the major tidal tributaries and the upper Chesapeake Bay—Susquehanna Flats and the upper Bay mainstem reach down to about Back River on the western shore (see Figure V-7).

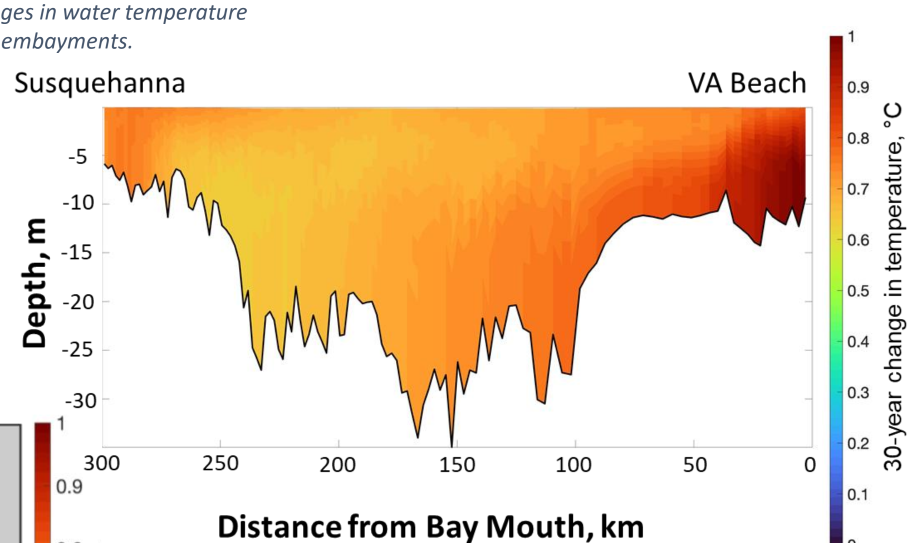


Figure V-7. Two-dimensional depth profile of the 30-year change in water column temperature along the Chesapeake Bay mainstem.

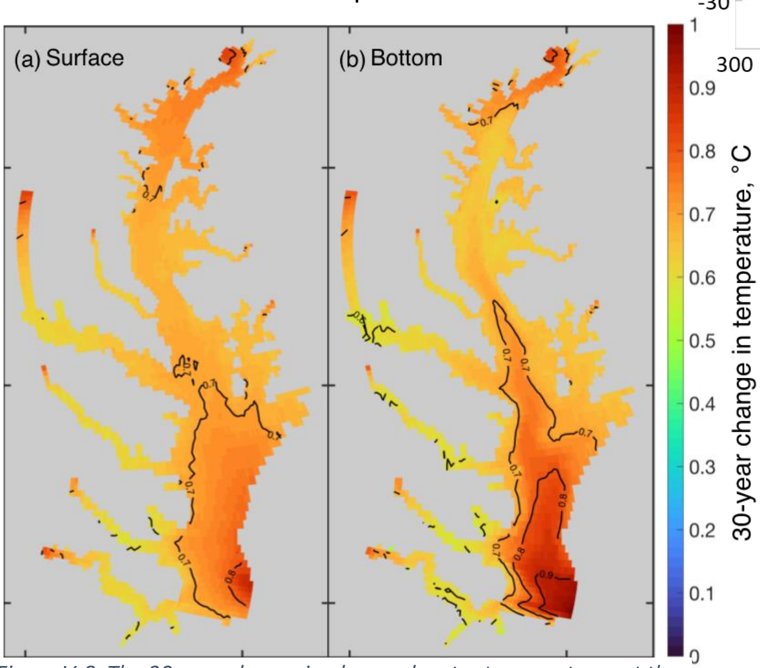


Figure V-8. The 30-year change in observed water temperatures at the surface and bottom across Chesapeake Bay.

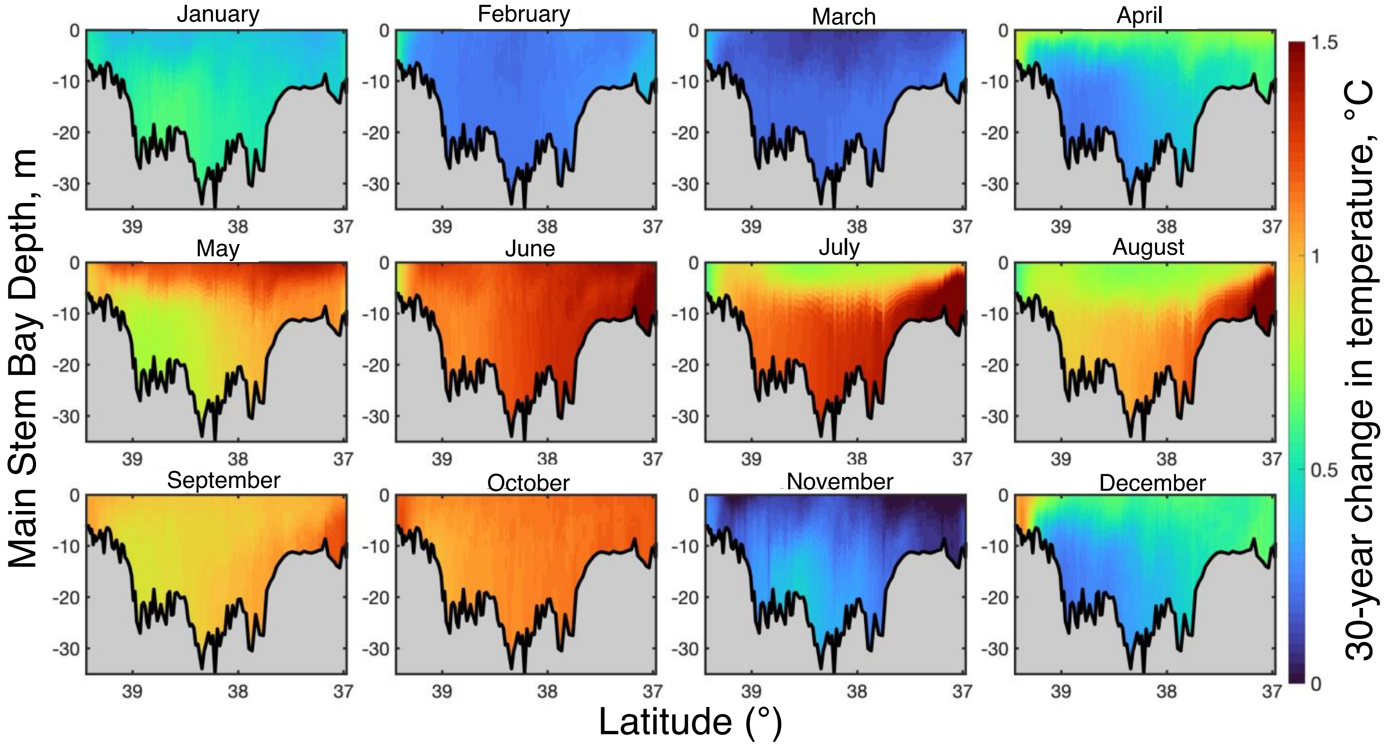


Figure V-9. The 30-year change in observed water column temperatures in depth profiles along the Chesapeake Bay mainstem by month from January through December.

There is substantial variation in the estimated water column temperature changes over the past 30 years between months, with generally more warming of water temperatures from May-October than November-April (Figure V-9). The observed increasing river temperatures are estimated produce little to no warming of water column temperatures in the Bay's mainstem (Hinson et al. accepted for publication) (Figure V-10).

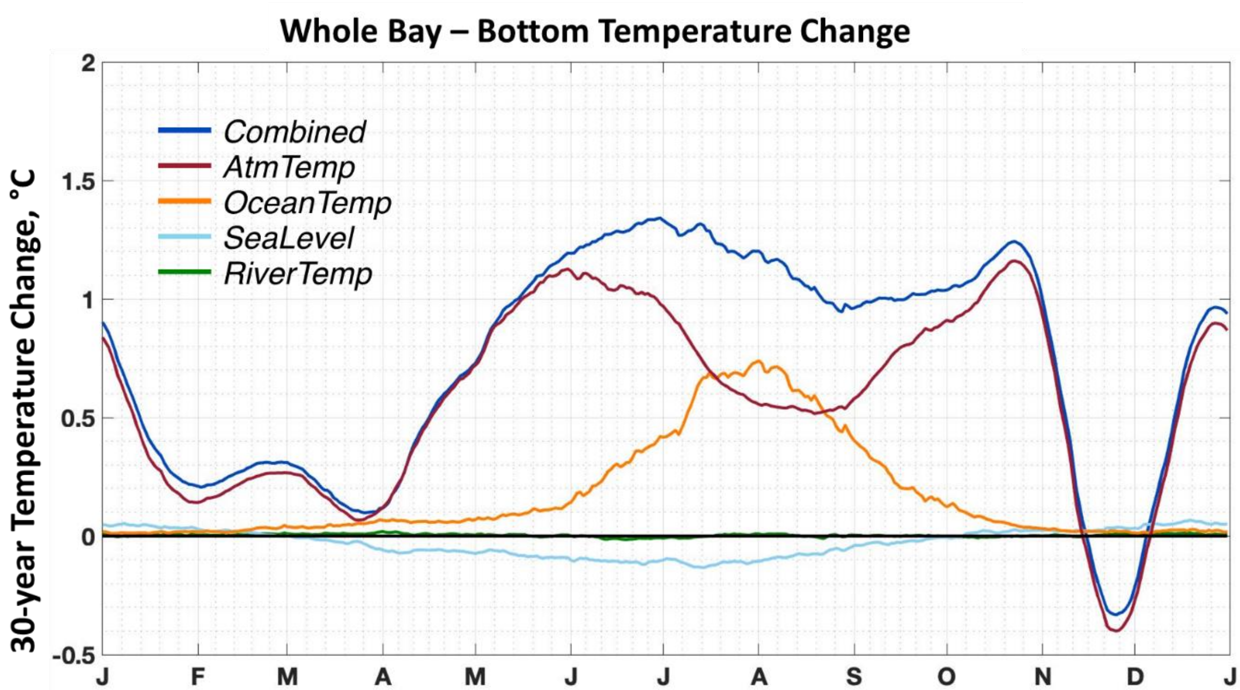


Figure V-10. Model-simulated 30-year bottom water temperature change throughout Chesapeake Bay by month compared with model-simulated bottom water temperature change estimated to be caused by river temperatures, sea level rise, ocean temperature and atmospheric forcings

Sea level rise is estimated to slightly cool Bay mainstem water column temperatures from April through September, and result in the warming of bottom Bay mainstem waters in the winter months (November through February) (Figure V-10). Increasing ocean temperatures are estimated to contribute significantly to the summer warming of the Bay water column temperatures between June and October, with a small effect on water column temperature for the remaining months of the year (Figure V-10). Atmospheric forcings are estimated to play biggest role in driving increasing water column temperatures throughout the Bay's tidal waters, but the effects on water temperatures are lessened during summer months of July through September and contribute to a cooling of Bay water temperatures during December (Figure V-10).

Atmospheric warming is the dominate influence on increasing Bay water column temperature almost everywhere across the tidal waters, contributing about 78% to the combined effect on changes in bottom Chesapeake Bay water temperatures observed by the past 30 years, equal to about a 0.6°C change over this timeframe (Figure V-11).

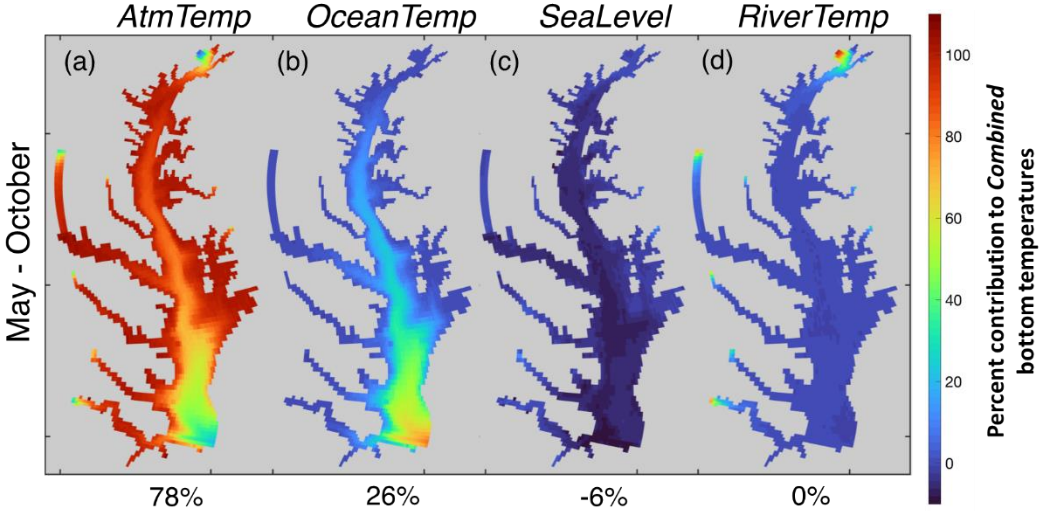


Figure V-11. The percent contribution to the model-simulated 30-year bottom water temperature change throughout Chesapeake Bay estimated to be caused by atmospheric forcing, ocean temperature, level rise and river temperatures. Source: Hinson et al. accept

The warming the adjacent Atlantic Ocean plays a large role in the changes in southern Chesapeake Bay's water temperatures, with about a 26% contribution to the overall Bay bottom temperatures over the past three decades. Ocean warming alone has contributed at least 50% or greater to the increased Bay water column temperature during the summer months over the past 30 years. The increasing temperatures in the rivers flowing into Chesapeake Bay only influence the water column temperatures of the immediate tidal fresh reaches of the tidal tributaries, making no measurable contribution to observed changes in bottom Chesapeake Bay water temperatures observed by the past 30 years. Sea level rise is estimated to slightly cool Bay water column temperatures across the tidal waters, contributing an offsetting 6% cooling contribution to the overall Bay bottom temperatures over the past three decades, about 0.1°C difference over this timeframe (Hinson et al. accepted for publication).

Implications for Ecosystem Processes

Watershed Ecosystem Processes

Water temperature affects all chemical and biological processes of aquatic organisms, as well as being directly linked to survival for temperature-sensitive organisms like brook trout. Water temperature integrates what is happening on the land (e.g. forested, open, urban impervious), and affects the way nutrients and other pollutants behave in the water column.

Temperatures can vary naturally along the length of a stream, from cold temperatures near a source of meltwater to higher temperatures near its outlet to the sea. The temperature at any given point is a product of many different factors, including sources of water (for example, melted snow, a recent rainstorm, or groundwater), the amount of water in the stream (streamflow), air temperature, plants along the bank (for example, trees that provide shade), and the amount of development within the watershed. Over time, however, an area's climate has the strongest natural influence on a stream's temperature. Higher temperatures reduce levels of dissolved oxygen in the water, which can negatively affect the growth and productivity of aquatic life. Persistently warmer temperatures in streams can accelerate natural chemical reactions and release excess nutrients into the water (EPA Climate Change Indicators).

Despite the wide variability of the streams with respect to watershed area, channel geometry, aspect, elevation, thermal capacity, the presence or absence of riparian buffers, microclimate conditions, and land cover, on the whole, WT increased from 1960 to 2010. For sites with significantly increased WT, 85 % of the variability could be explained by increased AT, despite increased streamflow at some sites. (Rice, Jostram 2015).

Estuarine Ecosystem Processes

Tian et al. 2021 reported that increasing Chesapeake Bay water column temperatures will result in reduced oxygen saturation, increased biological rates, and increased stratification of the water column. Their research focused on better understanding how changing oxygen solubility affects dissolved oxygen concentrations in the bottom waters of a stratified Chesapeake Bay.

Higher water temperature reduce the amount of oxygen which can become soluble in water, forming dissolved oxygen. The higher water temperatures will also increase the remineralization rate, that is the natural bacterial decomposition of organic matter into nitrogen, phosphorus and carbon, internally fueling growth of algae. Both of these processes lead to further expansion of and sustaining existing hypoxic and anoxic conditions in the deeper bottom waters of the Bay mainstem and lower tidal tributaries.

Running a series of scenario simulations using Chesapeake Bay Water Quality Model to determine the magnitude of various mechanisms controlling the effect of increasing water temperature on dissolved oxygen in the Chesapeake Bay, Tian et al. 2021 summarized the following findings. They estimated the average hypoxic volume in the summer would increase by 9% from 1995 to 2025 as air temperature increases by 1.06°C and water temperature by 0.9°C. Of the three major drivers of water temperature change impacts, the change in dissolved oxygen solubility contributes 55% of the change in hypoxic volume, biological rates 33%, and stratification 11%.

Off the mouth of the Rappahannock River, the abrupt change in bathymetry and “the convergence between seaward-moving freshwater and landward-moving saltwater causes downwelling and enhanced vertical mixing which introduces surface water of higher temperature to the deep channel and accelerates organic matter remineralization and oxygen consumption in deep waters” (Tian et al. 2021). As surface water dissolved oxygen concentrations will decrease under continued warming of the climate due to lower oxygen solubility, surface waters with even lower dissolved oxygen concentrations will flux to the deep channel further exacerbating development of low to no dissolved oxygen conditions in the deep channel of Chesapeake Bay.

E. Evaluation

Key Findings

There is significant evidence of widespread increases in Chesapeake Bay water column temperatures reported independently by an array of research teams over the past decade. And recently, a research team composed of scientists from the Virginia Institute of Marine Science and Penn State University published an in-depth evaluation of the major drivers for the observed increases in Chesapeake Bay water column temperatures, summarized as:

- Atmospheric forcings and warming ocean boundary most pertinent driving forces to future warming.
- Atmospheric forcings (air temp increases/decreases) main driver influencing Bay water temps year-round, but effects lessened during summer.
- Warming ocean boundary effects are important in summer (influenced =/> 50% warming), but small otherwise during the rest of seasons.
- Sea level rise slightly cools main stem from April-September and warms bottom waters in winter.
- River temperatures produce little to no warming in the Chesapeake Bay's mainstem.

Increasing Bay water temperatures will result in increased volumes of low dissolved oxygen due to direct effects on oxygen solubility, biological processes rates and stratification.

Management Implications

Reducing the water temperatures of the river flowing into Chesapeake Bay will have no to a very minimal to affect the continued warming of most of Chesapeake Bay’s water column temperatures. River water temperatures do influence the water temperatures of the tidal tributary reaches just down tide of the river inputs. These tidal fresh reaches provide for important spawning, nursery and year-round habitats for anadromous (e.g., striped bass), semi-anadromous (e.g., white perch) and resident (e.g., largemouth bass) fish populations which are directly affected by changes in water temperature.

Changing the magnitude of the two major influences on Bay water temperatures—atmospheric forcings and ocean warming—are clearly management and human behavioral challenges to be addressed at the global to local scales, collectively.

Warmer water temperatures could decrease the availability of water used for power plant cooling, could have other interactions with built infrastructure (PA Climate Impacts Assessment). For freshwaters, there are implications for potential shifts in floral and faunal species distributions. Streams at the upper end of the WT distribution may become unsuitable habitat for certain cool-water fish species (Eaton and Scheller 1996; Isaak et al. 2012). Increasing WT also may make some streams suitable for species not currently present, allowing warm-water species, including invasive species and pathogens, to move into previously cool-water habitats. Streams draining forested watersheds with major dams warmed more slowly than other watersheds and are likely to become even more important as refugia for cool-water species in a warming world. (Rice and Jastram 2015).

Further Follow-up Synthesis Work Planned or Under Consideration

- Need to continue to work with USGS scientists on their ongoing evaluation of long-term trends in water temperatures at the Chesapeake Bay Non-tidal Monitoring network stations. Stream temperature data is still being compiled and should be released by the end of 2021. USGS does not compute trends in water quality from non-tidal monitoring stations but is currently collecting all possible publicly available water-temperature data from multiple monitoring groups/agencies across the bay watershed. The objective of this data-collection effort is to (1) compute status of and trends in water temperature across a network of water-temperature data and (2) identify the linkages between changes in water temperature and changes in fish and benthic-macroinvertebrate habitat and health. John Clune is leading this effort.
- We could also reach out to municipal water intake facilities and their labs and ask for their long-term water temperature records.
- Need to continue to evaluate the major drivers for changes in water temperatures up in the watershed.

F. Bibliography

References Cited

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Additional Resources

Link to Kyle Hinson's presentation on Extent and Causes of Chesapeake Bay Warming as Presented to the Chesapeake Bay Program Partnership's Modeling Workgroup is: https://www.chesapeakebay.net/channel_files/42529/hinson_bay_warming_-_20210407.pdf

The "baytrendsmap" link that can be used to generate custom maps and explore the GAM trend analysis results is accessible at: https://baytrends.chesapeakebay.net/baytrendsmap/

Roger Stewart 2018 Integrated Report on Water Quality Trends in Virginia

EPA Climate change indicator- https://www.epa.gov/climate-indicators/climate-change-indicators-stream-temperature

PA Climate Impacts Report https://files.dep.state.pa.us/Energy/Office%20of%20Energy%20and%20Technology/OETDPortalFiles/Climate%20Change%20Advisory%20Committee/2020/12-22-20/2021_IA_Draft_Final_12-15-20.pdf

Stream temperature EPA technical documentation https://www.epa.gov/sites/production/files/2016-08/documents/stream-temperature_documentation.pdf