Summary of Recent Research on Effects of Climate Change on the Chesapeake Bay, Chesapeake Bay Program Partnership (Najjar, 2015)

A1. Introduction

Najjar et al. (2010) summarized research on historical and projected impacts of climate projections for the Chesapeake Bay region and the associated potential impacts on the circulation, biogeochemistry, and ecology of the Chesapeake Bay. The study concluded that climate change has the potential to dramatically alter the Bay with likely changes being: “(1) an increase in coastal flooding and submergence of estuarine wetlands; (2) an increase in salinity variability on many time scales; (3) an increase in harmful algae; (4) an increase in hypoxia; (5) a reduction of eelgrass, the dominant submerged aquatic vegetation in the Bay; and (6) altered interactions among trophic levels, with subtropical fish and shellfish species ultimately being favored in the Bay.” The main purpose of this appendix is to review research published over the past five years on the historical and projected effects of climate change on the Chesapeake Bay.

A2. Climate and hydrological processes affecting the bay

A2.1. Atmospheric composition

Najjar et al. (2010) utilized climate projections based on the Special Report on Emissions Scenarios (SRES), which were produced by the Intergovernmental Panel on Climate Change (IPCC) 15 years ago (Nakićenović and Swart, 2000). For the most recent IPCC climate assessment, a new family of greenhouse gas emissions scenarios, known as Representative Concentration Pathways (RCPs), was prepared (Moss et al., 2010; van Vuuren et al., 2011). Four RCPs have been developed—RCP8.5, RCP6.0, RCP4.5, and RCP2.6—where the numbers refer to the anthropogenic radiative forcing at 2100 in watts per square meter (Figure A1). Compared to the A2 and B1 SRES scenarios, which were in most common use, the RCP family captures a wider range in the forcing and the resulting simulated climate (Figure A2). The projected amount of total (natural plus anthropogenic) radiative forcing in terms of CO_2 equivalents is about 400 to 1200 ppm, which can be compared to the preindustrial CO_2 level of 280 ppm. Surface open-ocean average pH declines from the late 20th century to the late 21st century are between 0.06 and 0.32 pH units (Ciais et al., 2013).

A2.2. Water temperature

A new historical air and stream temperature analysis was conducted for the Chesapeake Bay watershed by Rice and Jastram (2014). Statistically significant trends over the 1960-2010 period of 0.23 and 0.28 °C per decade were found for air and stream temperature, respectively. Land use changes were found to explain differences in air and stream temperature trends.

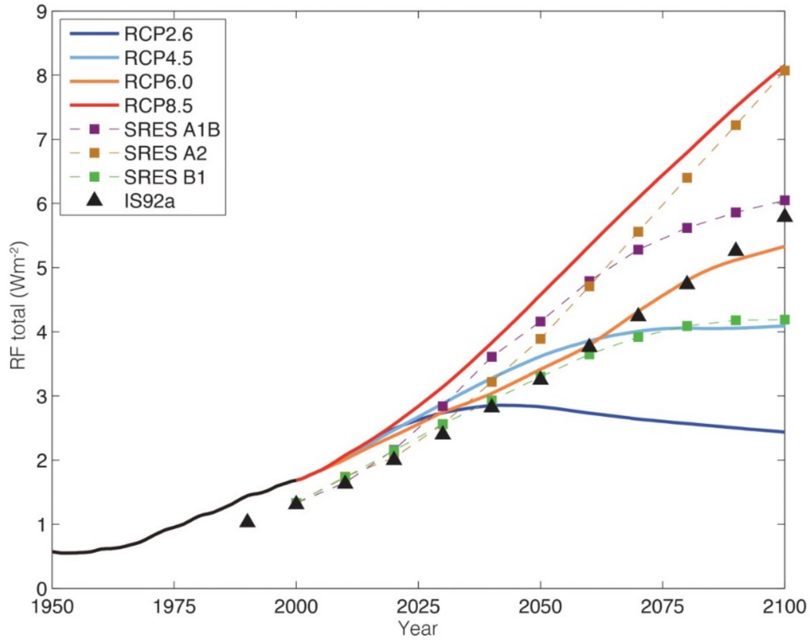

Figure A1. Anthropogenic radiative forcing from the Representative Concentration Pathways (RCPs) and the Special Report on Emissions Scenarios (SRES). Reproduced from Cubasch et al. (2013).

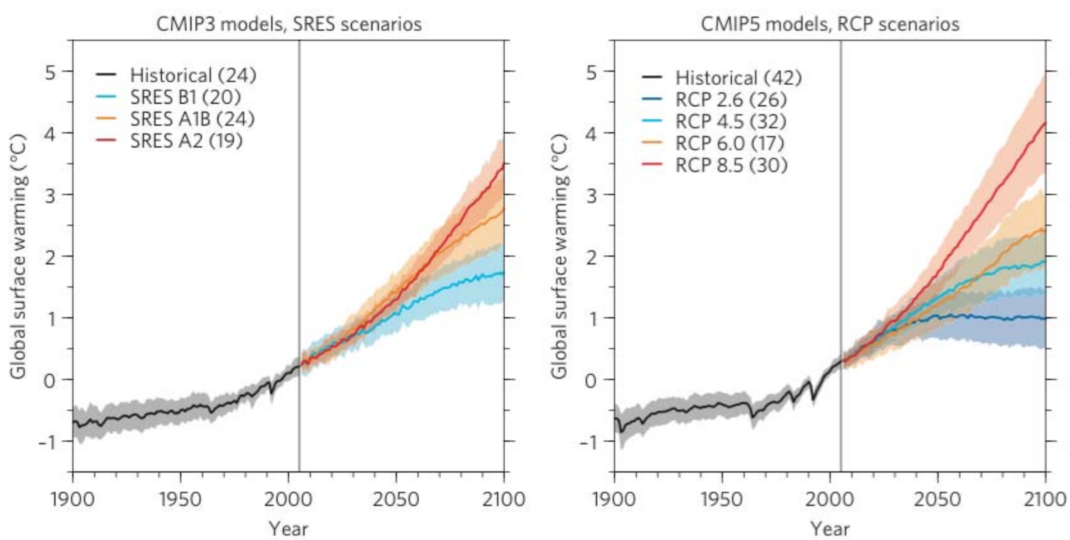

Figure A2. Historical and future simulations of global-mean surface temperature anomaly from the Coupled Model Intercomparison Project (CMIP). Left panel shows CMIP3 global climate models under the SRES emissions scenarios and right panel shows CMIP5 global climate models under the RCP emissions scenarios. Reproduced from Knutti & Sedláček (2013).

Projected changes in water temperature are expected to follow projected changes in air temperature (Najjar et al. 2010). Many new climate model simulations have been conducted over the past five years, which provide new estimates of air temperature change. Compared with previous work, these models may: (1) have higher spatial resolution, (2) utilize different emissions scenarios (Section A2.1), and (3) have been processed using statistical and dynamical downscaling techniques that provide projections on a finer spatial scale. One set of climate model simulations, known as the North American Regional

Climate Change Assessment Program (NARRCAP; Mearns et al., 2012; Mearns et al., 2009), uses regional climate models of relatively high spatial resolution (50 km) embedded in Global Climate Models (GCMs) of coarser resolution. One study of Pennsylvania, which is representative of the northern part of the Chesapeake Bay watershed, showed that NARCCAP simulations were quite similar to global climate model simulations in terms of temperature (Shortle et al., 2013); Kunkel et al. (2013) came to a similar conclusion for the Northeast U.S. in an analysis conducted for the National Climate Assessment.

Climate model projections for the Chesapeake Bay watershed have more confidence than they did five years ago because climate models can now successfully simulate the observed warming of the Northeast U.S. over the 20th century (Kunkel et al., 2013).

There has been great interest in winter climate over the past five years, with numerous studies suggesting a linkage between reductions in Arctic sea ice and increases severe winters over land in mid-latitudes (e.g., Francis and Vavrus, 2012; 2015; Liu et al., 2012). Winter temperature trends over the past 50 years were positive everywhere over land in the Northern Hemisphere, but for the past 20 years were actually negative over much of North America and Asia. In a recent review article, Cohen et al. (2014) conclude that "it is possible, in principle, for sea ice and snow cover to jointly influence mid-latitude weather" but "because of incomplete knowledge of how high-latitude climate change influences these phenomena, combined with sparse and short data records, and imperfect models, large uncertainties regarding the magnitude of such an influence remain." To emphasize this uncertainty, one recent study shows that Arctic amplification (greater warming in the Arctic than elsewhere) has actually led to a decline in sub-seasonal cold-season temperature variability (Screen, 2014). Despite these uncertainties, GCMs show a reduction in cold-air outbreaks over North America under enhanced levels of greenhouse gases (Gao et al., 2015). However, the reduction is about 20% smaller in a band that extends from Alaska to the Northeastern U.S. Thus, while winters are expected to become less severe in the future over the Chesapeake Region, the reduction in severity may be less than projections of mean temperature would suggest.

A2.3. Precipitation

Unlike mean temperature, there have been significant changes in projected mean precipitation for the Northeast U.S. Though models still project, on average, increases in annual precipitation, the higher-resolution models from NARCCAP show two important differences (Kunkel et al., 2013): (1) there is increasing consensus that summer precipitation will decline and (2) winter projections of increased precipitation are larger. Therefore, compared with earlier research, there is now a greater seasonality in the projected precipitation change. Increases in precipitation intensity, which are projected by GCMs, are also supported by the NARCCAP models (Kunkel et al., 2013).

A2.4. Streamflow

Whereas historical analysis of annual streamflow in the Chesapeake Bay watershed clearly indicates increasing trends, the question as to whether streamflow is becoming more extreme remains unresolved. An analysis in the Chesapeake Bay watershed for the 1930-2010 period by Rice and Hirsch (2012) used the annual seven-day low flow and one-day high flow as metrics of extreme flow. Low flows were found to have increased whereas high flows generally remained the same, meaning that flows have become less extreme with time. This is in contrast to previous work that suggested that high flows had increased in the Northeast U.S. (Groisman et al., 2001; 2004). Most recently, however, Armstrong and Collins (2014) found that annual maximum instantaneous discharge generally showed increasing trends throughout the Northeast U.S., including the Chesapeake Bay watershed. Similar results were found for another high-flow metric: the number of flow peaks exceeding a USGS-designated, station-specific threshold. The different conclusions among the studies may reflect the different metrics used for extreme flow and the choice of stations analyzed. For example, Armstrong et al. (2014) argue that the use of gauges in regulated watersheds compromised previous results.

Najjar et al. (2010) concluded that future changes in streamflow to the Chesapeake Bay, particularly the annual average, were highly uncertain because of the opposing effects of increases in temperature and precipitation. Major new work in this area was done by Johnson et al. (2012) and U.S. EPA (2013), who simulated changes in the hydrology of the Susquehanna River Basin using two watershed models and multiple sources of climate change projections, including GCMs, statistical downscaling, and dynamical downscaling (NARCCAP). Results in Table A1 are shown for one of the watershed models and six of the NARCCAP models for the middle of the 21st century under the A2 emissions scenario. In general, flow increases, as do peak flows, with median increases of 7% and 18%, respectively. The change in the magnitude of the lowest flows is equivocal. Global model results from Schewe et al. (2013), who used five watershed models in combination with 11 GCMs, indicate that warming will have very modest effects on mean streamflow in the Chesapeake region, with the projected change between -10 and +10% for a 2 °C warming. Modeling results from Hirabayashi et al. (2013) show an increased frequency of the 100-year flood in the lower Chesapeake watershed but a decreased frequency in the upper watershed.

Table A1. Results of Hydrological Model Simulations under Future Climate Change (US EPA, 2013).

	CRCM _ cgcm3	HRM3 _ hadcm3	RCM3_ gfdl	GFDL_ slice	RCM3 _ cgcm3	WRF _ ccsm	Median
Total streamflow	109	106	106	108	111	90	107
7-day low flow	91	120	104	89	107	86	98
100-year peak flow	107	130	106	128	172	100	118
Flashiness index	107	111	107	110	112	103	109
Sediment load	117	108	108	115	118	84	112
Phosphorus load	128	106	111	127	115	109	113
Nitrogen load	162	147	147	156	150	132	149

Results are reported for the time period 2041-2070 as a percent of the time period 1971-2000. Values greater than 100% represent an increase in the quantity being simulated. Results are shown for six different climate model configurations run under the A2 emissions scenario. The watershed model is SWAT (Soil Water Assessment Tool).

A2.5. Sea level

Numerous studies of sea-level rise at the global scale have been published over the past five years. There is strong consensus now that global-mean sea level is accelerating. Church and White (2011) found an acceleration of global-mean sea level consistent with numerous earlier studies. Problems closing the sea level budget before 1990 have been resolved by a reanalysis that indicates a mean sea-level rise of 1.2 ± 0.2 mm yr^{-1} for the 1901-1990 period, a rate substantially lower than previous estimates (Hay et al., 2015). For the 1993-2010 period, the same reanalysis estimated a global mean sea-level rise of 3.0 ± 0.7 mm yr^{-1}, similar to previous estimates, which indicates that sea level is accelerating more than previously thought.

Significant contributions have been made to our understanding of sea-level rise in the Chesapeake Bay region over the past five years. Despite initial indications of no acceleration of sea-level in the Chesapeake Bay (Boon et al., 2010), further study indicated acceleration larger than the global average and much of the U.S. east coast, which is possibly a result of changing ocean circulation (Boon, 2012; Ezer et al., 2013; Kopp, 2013; Sallenger et al., 2012). Global climate model simulations suggest that the Gulf Stream will weaken in the future, which will weaken the downward slope of the sea surface towards the east coast of the U.S., potentially adding another 0.2 m of sea-level rise to the Chesapeake Bay region by the end of the 21st century (Yin et al., 2009). Global sea-level rise projections that attempt to account for changes in global ice volume have not dramatically changed over the past five years, with typical projections by the end of the century between 0.3 and 1.3 m (Walsh et al., 2014). Boesch et al. (2013) suggest sea-level rise by 2100 of 0.5-1.4 m (best estimate 0.8 m) for the global mean and 0.7-1.7 m (best estimate 1.1 m) for Maryland.

The high rates of sea-level rise in the Chesapeake Bay are also due to land subsidence, caused by isostatic adjustment in response to the retreat of ice sheets as well as aquifer-system compaction resulting from groundwater withdrawals. Eggleston and Pope (2013) conclude that, in the southern Chesapeake Bay region, land subsidence currently contributes to approximately half of the relative sea-level rise and aquifer-system compaction contributes to about half of the land subsidence.

Rising sea level has increased the shoreward energy delivered to Chesapeake Bay's shorelines. Along the upper tidal shorelines of the lower Chesapeake Bay, the average shoreward energy flux for 1982-2010 was twice that for 1948-1981 (Varnell, 2014).

Rising sea level has dramatically increased flooding as well, including nuisance flooding, which is defined using a sea-level criterion determined by the local National Weather Service office (Sweet et al., 2014). For example, in Annapolis, Maryland, nuisance flooding occurred during only a few hours per year before 1940 whereas it is not uncommon over the past 10 years for it to occur for more than 200 hours per year.

Often ignored in historical sea-level rise analyses and projections is natural variability. Cronin et al. (2012, 2014) using a temperature-based reconstruction of sea-level for the Chesapeake Bay over the last 2000 years, notes that short-term rates of sea-level change have been frequently as large as they are now. These authors thus caution that the current acceleration in sea level may not be unusual or representative of a long-term average.

A2.6. Storms

Significant storms that impact the Chesapeake Bay are North Atlantic tropical storms and winter extratropical cyclones (including nor'easters). The most recent National Climate Assessment (Walsh et al., 2014) concluded that there is "high confidence that the intensity, frequency, and duration of North Atlantic hurricanes, as well as the frequency of the strongest (Category 4 and 5) hurricanes, have increased substantially since the early 1980s; low confidence in relative contributions of human and natural causes in the increases; and medium confidence that hurricane intensity and rainfall rates are projected to increase as the climate continues to warm." These conclusions are generally similar to the state of the science five years ago. Continued research on winter extratropical cyclone changes indicates little consensus on changes in the Northern Hemisphere, especially in the North Atlantic basin (Collins et al., 2013).

A3. Fluxes of nutrients and sediments from the watershed

Flow-adjusted concentrations of total nitrogen and total phosphorus at the mouths of the three largest rivers emptying into the Chesapeake Bay (Susquehanna, Potomac, and James Rivers) declined from 1985 to 2013 (Langland et al. 2012; Blomquist et al., 2014), with the exception of total phosphorus in the Susquehanna River, which showed no trend. Suspended sediment concentration trends for 1985-2013 were not significant, except for a decreasing trend in the Potomac. More recent trends (2003-2013) are negative for nitrogen (except for the James, which showed no trend), and not significant for phosphorus and sediment, except for an increasing phosphorus trend in the Susquehanna River.

High-flow events and their effect on the Conowingo Dam appear to play a disproportionate role in the delivery of nutrients and sediments from the Susquehanna River to the Chesapeake Bay. Hirsch (2012) Hirsch (2012) analyzed trends in flow-normalized fluxes at the Susquehanna River at Conowingo, Maryland, streamgage during 1996–2011 and found a 3.2-percent decrease in total nitrogen, but a 55-percent increase in total phosphorus and a 97-percent increase in suspended sediment. Upstream of the dam, however, concentrations declined for all constituents. Remarkably, Tropical Storm Lee, which contributed only 2% of the freshwater flow from the Susquehanna River to the Chesapeake Bay during 2002-2011, contributed 5%, 22%, and 39% of the nitrogen, phosphorus, and sediment loads. Zhang et al. (2013) reached similar overall conclusions. Both studies suggest that the Conowingo Dam is close to reaching its capacity to store particulate material and this fact has serious management challenges because of the decline in trapping capability influences the amount of N and P that reach the Bay. If the frequency distribution of streamflow conditions change as a result of climate change this would add another layer of complexity to this already difficult problem.

The fraction of net anthropogenic nitrogen inputs (NANI) to a watershed that is exported from that watershed is a function of the watershed’s climate, with some studies showing that this fraction increases with streamflow (e.g., Howarth et al., 2006) and others showing a decrease with temperature (Schaefer and Alber, 2007). In a recent analysis of a very large number of watersheds in the U.S. and Europe, it was found that the fraction of NANI exported varied significantly with temperature, precipitation, and streamflow, but the latter had by far the most predictive power (Howarth et al., 2012).

Modeling of future nutrient and sediment loads in the Susquehanna River Basin show increases in all quantities by mid-century under the A2 emissions scenario (Table A1). Median increases in sediment, phosphorus, and nitrogen loads are 12%, 13%, and 49%, respectively (Johnson et al., 2012; U.S. EPA, 2013).

A4. Bay physical response

Two modeling studies have been conducted over the past five years to estimate potential changes in the circulation and salinity of the Chesapeake Bay in response to sea-level rise. Rice et al. (2012) investigated changes in salinity in the James and Chickahominy Rivers resulting from sea-level increases between 0.3 and 1 m. They found that salinity was more sensitive to sea level during dry years, with salinity increases as large as 4 ppt for a 1-m rise in sea level. They also found that a local drinking water supply will be affected by saltwater intrusion resulting from sea-level rise. Hong and Shen (2012) explored similar sea-level scenarios for the whole of the Chesapeake Bay and found salinity and stratification to increase. In addition, they found an increased exchange flow, weaker downstream transport of fresh water, increased residence time, and increased vertical transport time. In addition, tidal currents were found to increase with sea-level rise, but not enough to negate the weakened vertical exchange associated with the stratification increase.

A5. Estuarine biogeochemistry

A5.1. Plankton

Harding et al. (2015) investigated historical changes in plankton composition in the Chesapeake Bay from 1985 to 2007. They found diatoms to be the predominant taxonomic group. Diatom abundance tended to be higher in wet years. Furthermore, flow-adjusted diatom abundance decreased towards the end of the time series, which was suggested to be a result of nutrient reductions; this suggests that future nutrient reductions could result in a more diverse phytoplankton population.

A5.2. Pathogens

We were unable to identify recent research on the impact of future climate change on estuarine biogeochemistry and plankton, with one exception: Urquhart et al. (2014) studied current models of ***Vibrio vulnificus*** and argued that these models are inadequate for predicting the effects of warming on this microbe.

A5.3. Dissolved oxygen

The processes driving interannual variations in summertime hypoxic volume in the Chesapeake Bay have been investigated in numerous studies over the past five years. Scully (2010a) found a correlation between observed wind direction and hypoxic volume, which was supported by numerical modeling results (Scully, 2010b). Murphy et al. (2011) found trends in the timing of summertime hypoxia, which were attributed to changes in stratification and nutrient loads. Testa and Kemp (2014) determined that higher Susquehanna River flows resulted in an earlier onset of hypoxia. Zhou et al. (2014) were able to account for 85% of the interannual variability in hypoxic volume using January-May total nitrogen load, April-August winds, and April-May precipitation as predictors. A numerical modeling study by Li et al. (2015) suggested that vertical mixing, vertical advection, and lateral advection are all important sources of dissolved oxygen to bottom waters. Hypoxic volume was surprisingly insensitive to river flow in this modeling study; this resulted from compensating changes in the lateral and vertical supply of dissolved oxygen to bottom waters. Li et al. (2015) also found that wind speed affected the timing and magnitude of hypoxic volume.

A6. Vascular plants

A6.1. Submerged aquatic vegetation

Orth et al. (2010) analyzed submerged aquatic vegetation (SAV) distributions in the Chesapeake and found support for the assertion that increases in nitrogen pollution reduce SAV abundance.

Jarvis et al. (2014) developed a model of *Zostera marina* and examined impacts of temperature and light stress. They found high sensitivity of established beds to consecutive years of stress and negative effects of multiple stressors on *Z. marina* resilience and recovery.

A6.2. Estuarine wetlands

Recent research suggests that sea-level rise continues to pose an uncertain but potentially significant threat to estuarine wetlands. Kirwan et al. (2013) used mesocosms to evaluate the hypothesis that sea-level rise would reduce organic matter decay rates, thereby providing a negative feedback loop that would help to reduce submergence. However, they found no effect of sea-level rise on decay rates, and concluded that enhanced organic matter production or mineral sediment supply would be needed in order for marshes to keep pace with accelerated sea level. Furthermore, temperature increases are expected to reduce net ecosystem production (Drake, 2014). However, elevated CO_2 was shown to enhance net ecosystem production of C3- and, to a lesser extent, C4-dominated communities in a Chesapeake Bay tidal wetland (Erickson et al., 2013).

A7. Fish and shellfish

A meta-analysis by Vaquer-Sunyer and Duarte (2011) showed that "ocean warming is expected to increase the vulnerability of benthic macrofauna to reduced oxygen concentrations and expand the area of coastal ecosystems affected by hypoxia."

A study of blue crabs along the east coast of the U.S. (Hines et al., 2010) concluded that warming may have positive and negative effects. The reduced severity of winters associated with global warming will increase winter survival and promote rapid growth and brood production. Warming, however, may increase juvenile mortality and size at maturity.

New research has been conducted on the impact of environmental factors on oysters. Levinton et al. (2011) found in a modeling study that projected increases in precipitation may lower salinities enough to be harmful to oysters. Kimmel et al. (2012) found that long-term variability in Eastern oysters in the Chesapeake Bay was related to salinity.

Waldbusser et al. (2011a), in laboratory studies of juvenile eastern oysters, found that biocalcification declined significantly with a reduction of ~0.5 pH units, but that increases in temperature and salinity reduced the sensitivity to pH. A related study using a flow-through control system found that pH declines increased shell dissolution rates (Waldbusser et al., 2011b).

Through a literature review, Jones (2013) examined the potential impact of climate change on finfish in the Chesapeake Bay through changes in seagrass and concluded that the uncertainty is too large to make reliable projections.

A8. Human systems

Some new research has been conducted on the human response to climate change in the Chesapeake region and in coastal areas in general. Paolisso et al. (2012) studied two African-American communities on the eastern shore of the Chesapeake Bay and found that community members recognize potential impacts and are organized through their churches to address some of those impacts. More generally, Moser et al. (2012) underscore multiple stressors that coastal systems face and the need for transformative changes in the science and management to address what appears to be an overwhelming challenge.

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