Revisiting climate-change impacts on the Chesapeake Bay

Raymond Najjar
The Pennsylvania State University

Chesapeake Bay Program Climate Change 3.0 Workshop
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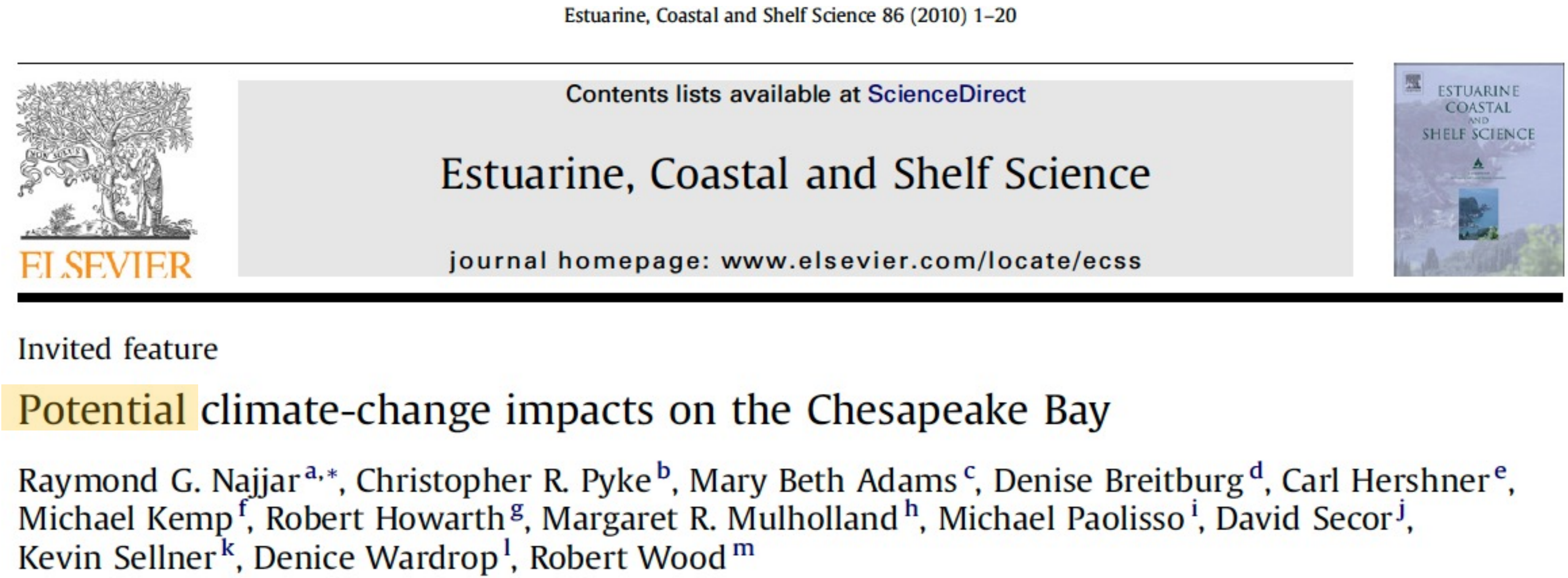
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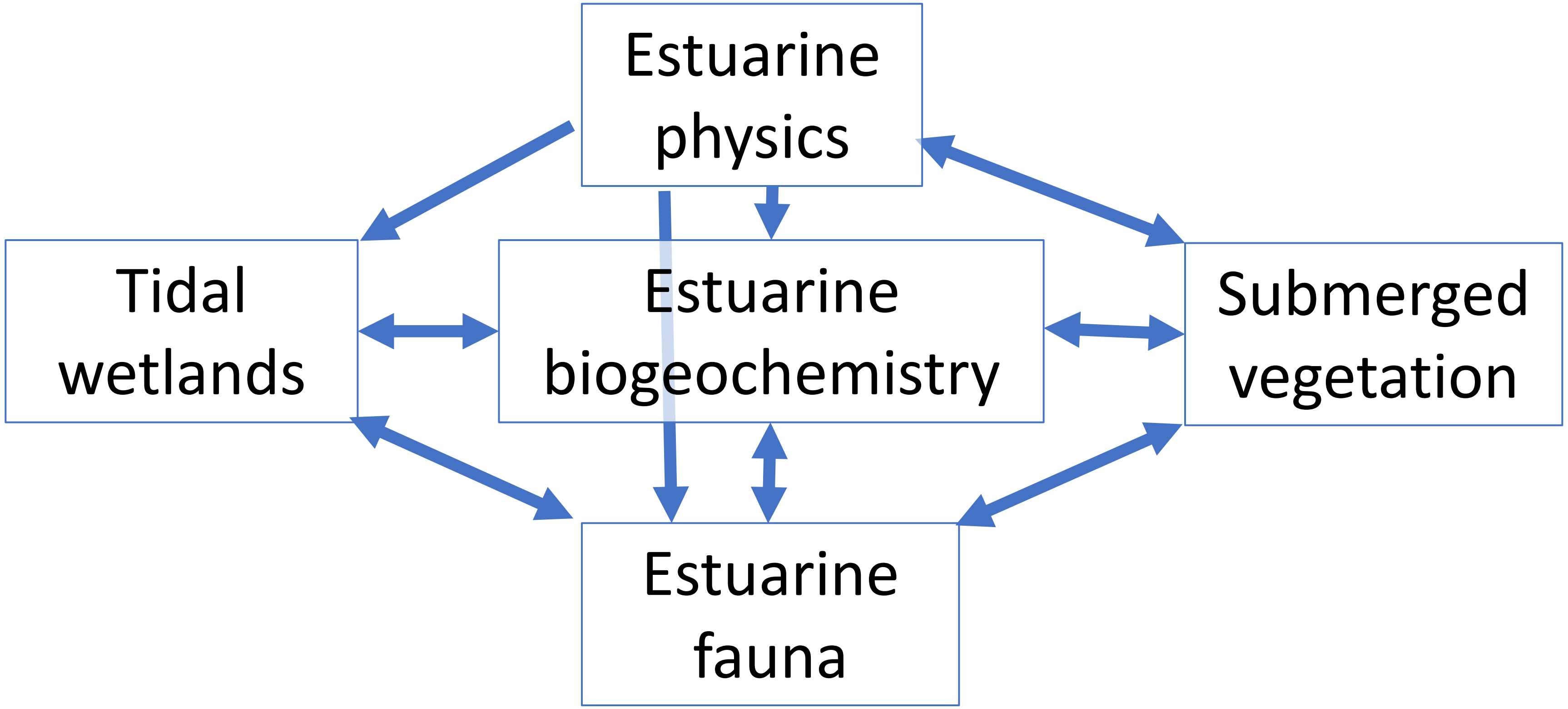
Invited feature

Potential climate-change impacts on the Chesapeake Bay

Raymond G. Najjar[a,*], Christopher R. Pyke[b], Mary Beth Adams[c], Denise Breitburg[d], Carl Hershner[e], Michael Kemp[f], Robert Howarth[g], Margaret R. Mulholland[h], Michael Paolisso[i], David Secor[j], Kevin Sellner[k], Denice Wardrop[l], Robert Wood[m]

- Followed 2008 CBP STAC report
- Still gets cited a fair bit, but a lot of research has been conducted in the past 15 years

The key components of an estuary are highly interconnected



Estuarine physics

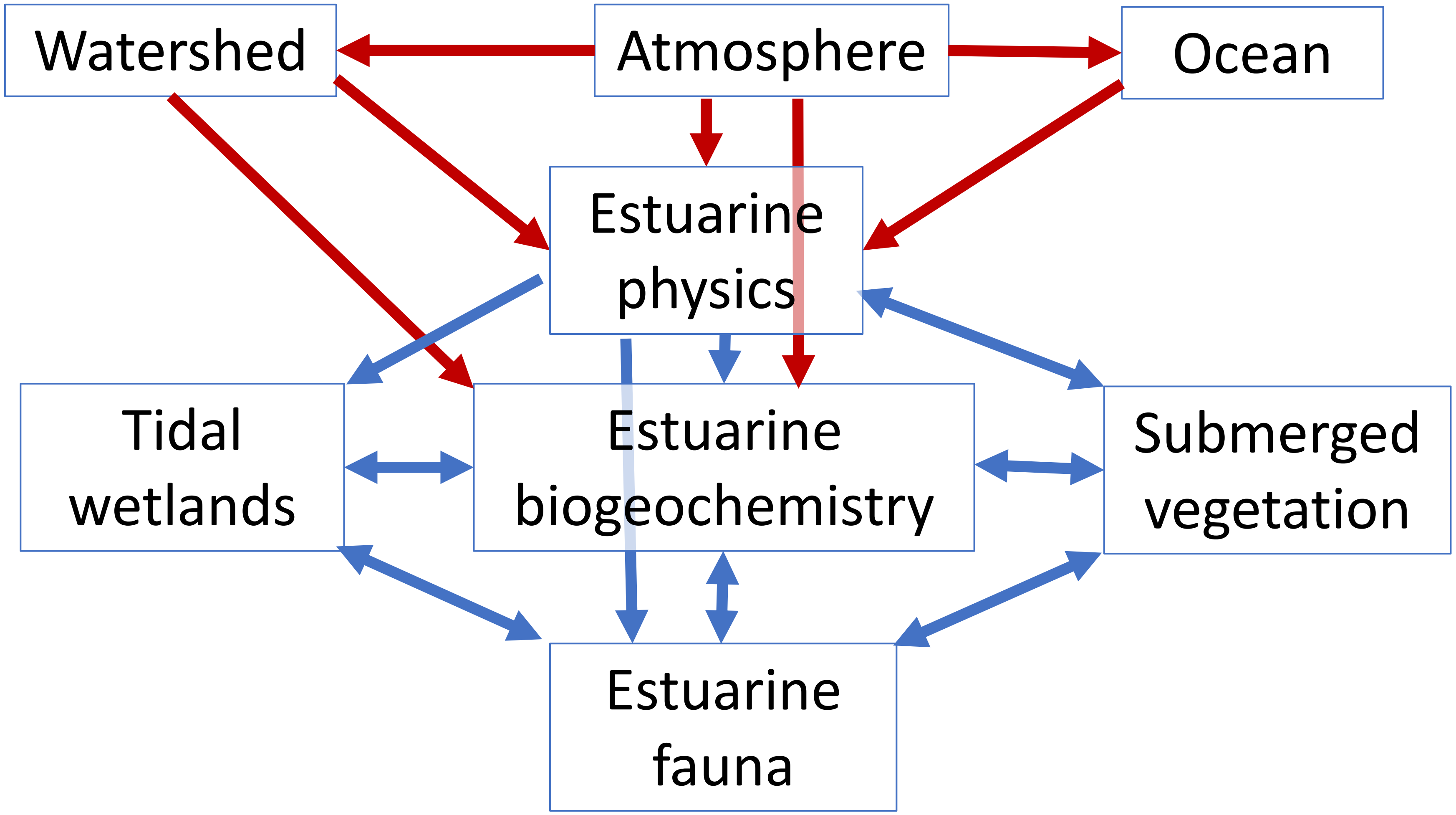
Tidal wetlands

Estuarine biogeochemistry

Submerged vegetation

Estuarine fauna

Thus, there is value in studying the response of an estuary to climate change at a system-wide level



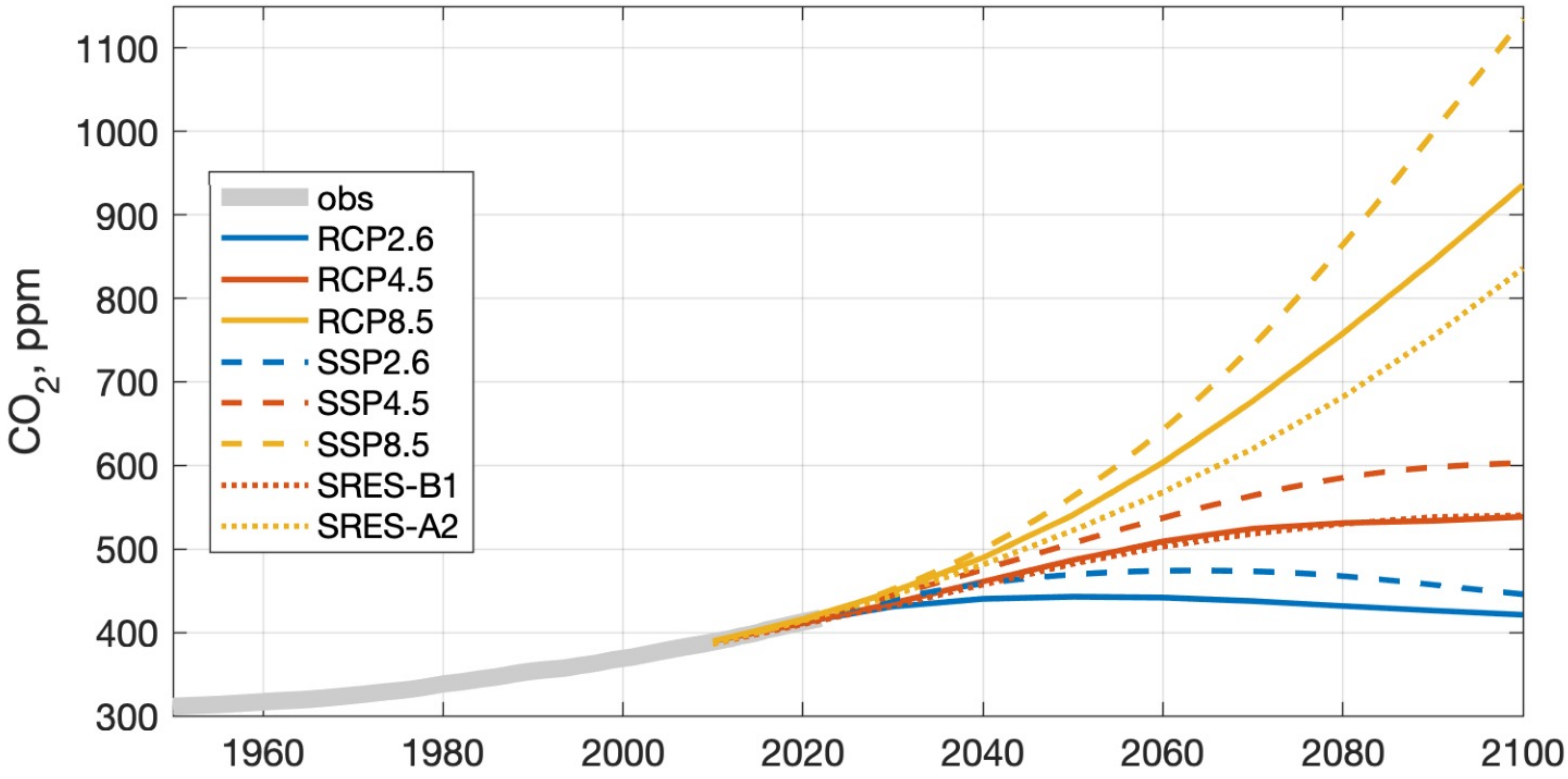
Paper outline

1. Introduction
2. Atmospheric conditions (R. Najjar, M. Herrmann)
3. Sea level (M. Mitchell)
4. Fluxes from the watershed (R. Najjar)
5. Bay temperature, salinity, and circulation (K. Hinson, M. Friedrichs, R. Najjar)
6. Hypoxia (K. Hinson, M. Friedrichs)
7. Carbonate system (F. Da)
8. Harmful algae and Vibrio (D. Horemans)
9. Submersed aquatic vegetation (C. Patrick)
10. Tidal marshes (M. Kirwan)
11. Fishes (M. Fabrizio, T. Tuckey)
12. Shellfish (T. Miller)
13. Other biota (R. Woodland)
14. Discussion
15. Conclusions

Each major section discusses observed trends and future projections

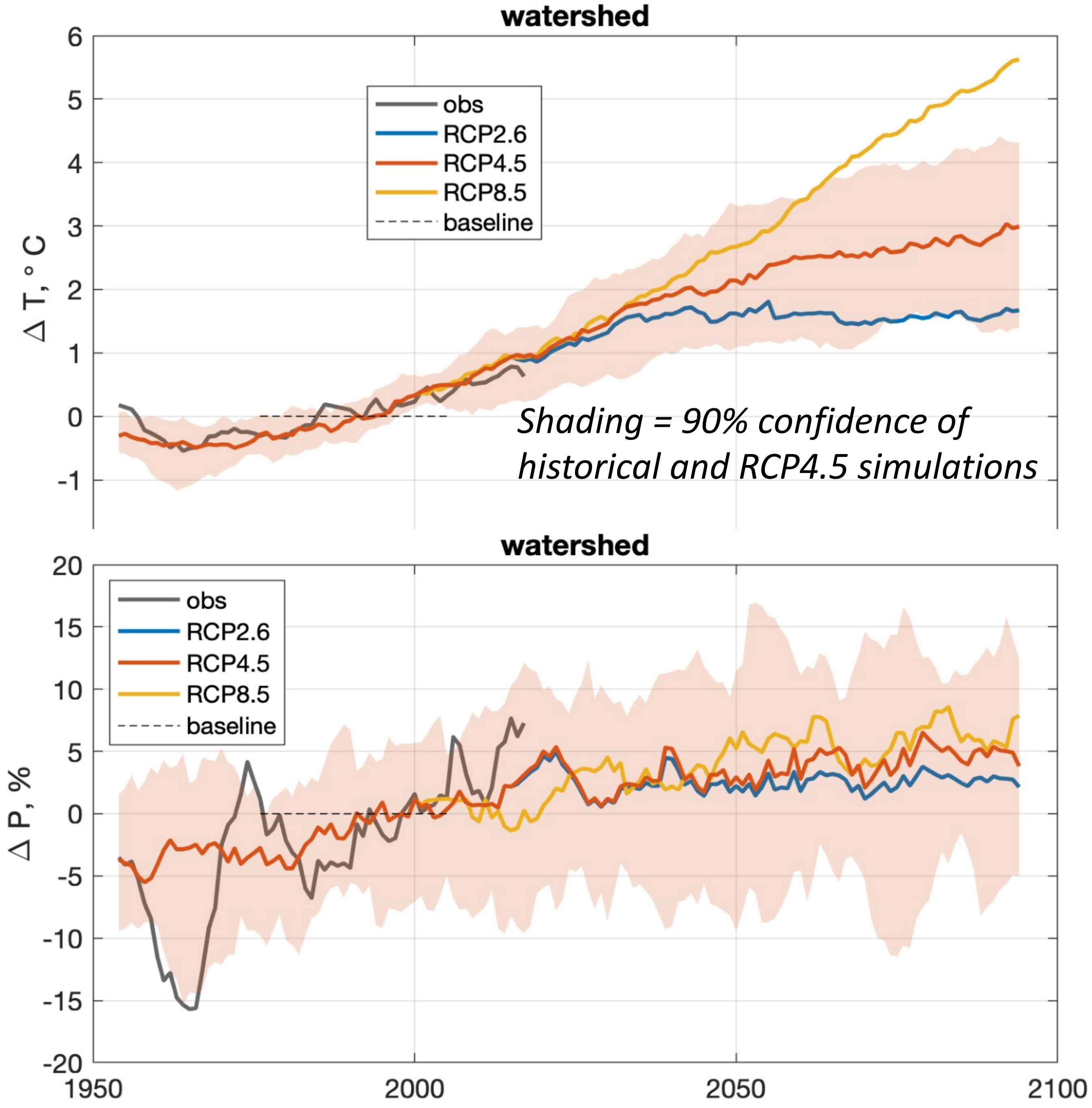
Atmospheric conditions

CO_2 scenarios vary widely



Observed and projected temperature and precipitation change averaged over the Chesapeake Bay watershed

- gridMET observations
- MACA downscaling of 20 GCMs
- 10-year running averages

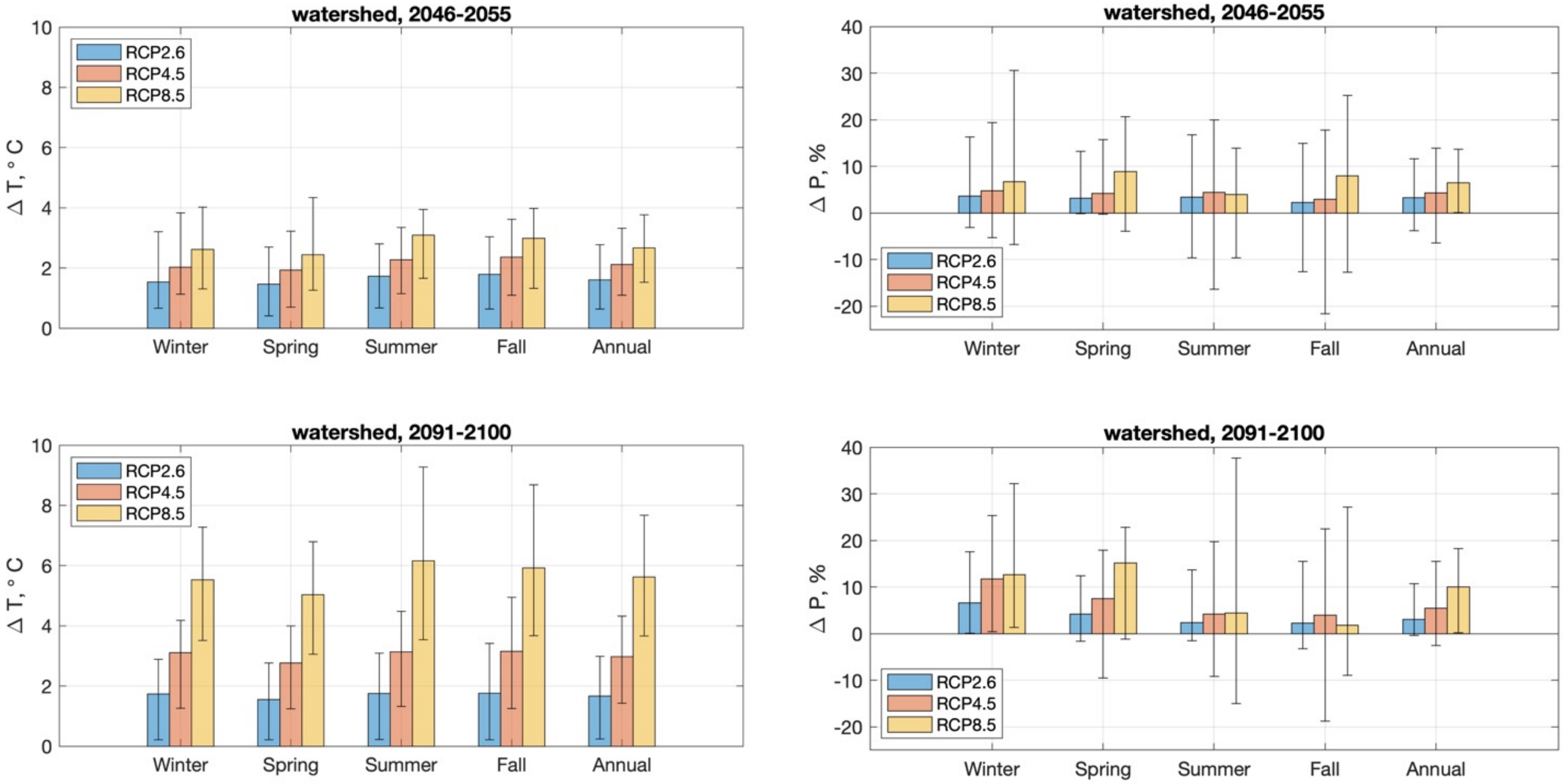


Shading = 90% confidence of historical and RCP4.5 simulations

Observed air temperature and precipitation trends

- Air temperature and precipitation have increased, in agreement with climate models
- Extreme temperature index trends around the Bay are consistent with warming (St.Laurent et al., 2022)
- Extreme precipitation index trends are equivocal around the Bay, even though large-scale regional trends of the northeast and southeast US are clearly increasing; poor agreement with models (St.Laurent et al., 2022)
- Climate modes (e.g., PDO, ENSO, NAO, and AMO) play an important role in interannual variability (Schulte et al., 2016)

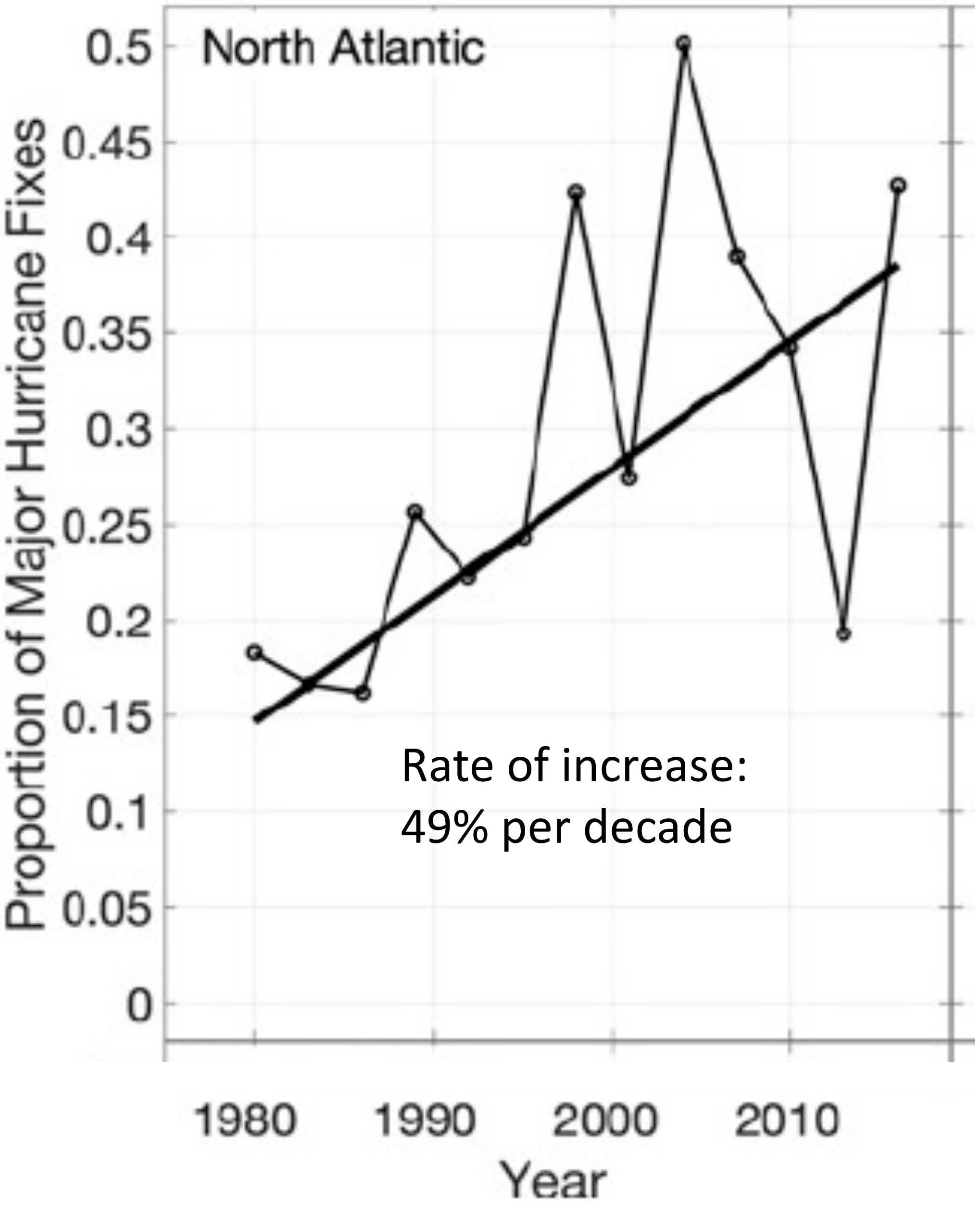
Seasonality of temperature and precipitation projections



Projections of air temperature and precipitation

- Climate zone of the Chesapeake Bay watershed will shift from *continental–warm summer* to *temperate–hot summer*
- Future warming is sensitive to emissions scenario
- Future precipitation is more uncertain, but multi-model average is consistently increasing; winter and spring are more certain and wetter than summer and fall
- Projections of temperature extreme indices are all consistent with warming (St.Laurent et al., 2022)
- Precipitation is projected to get more extreme (heavier downpours, longer dry spells) (St.Laurent et al., 2022)

The fraction of hurricanes that are major (category 3–5) is increasing in the North Atlantic Ocean



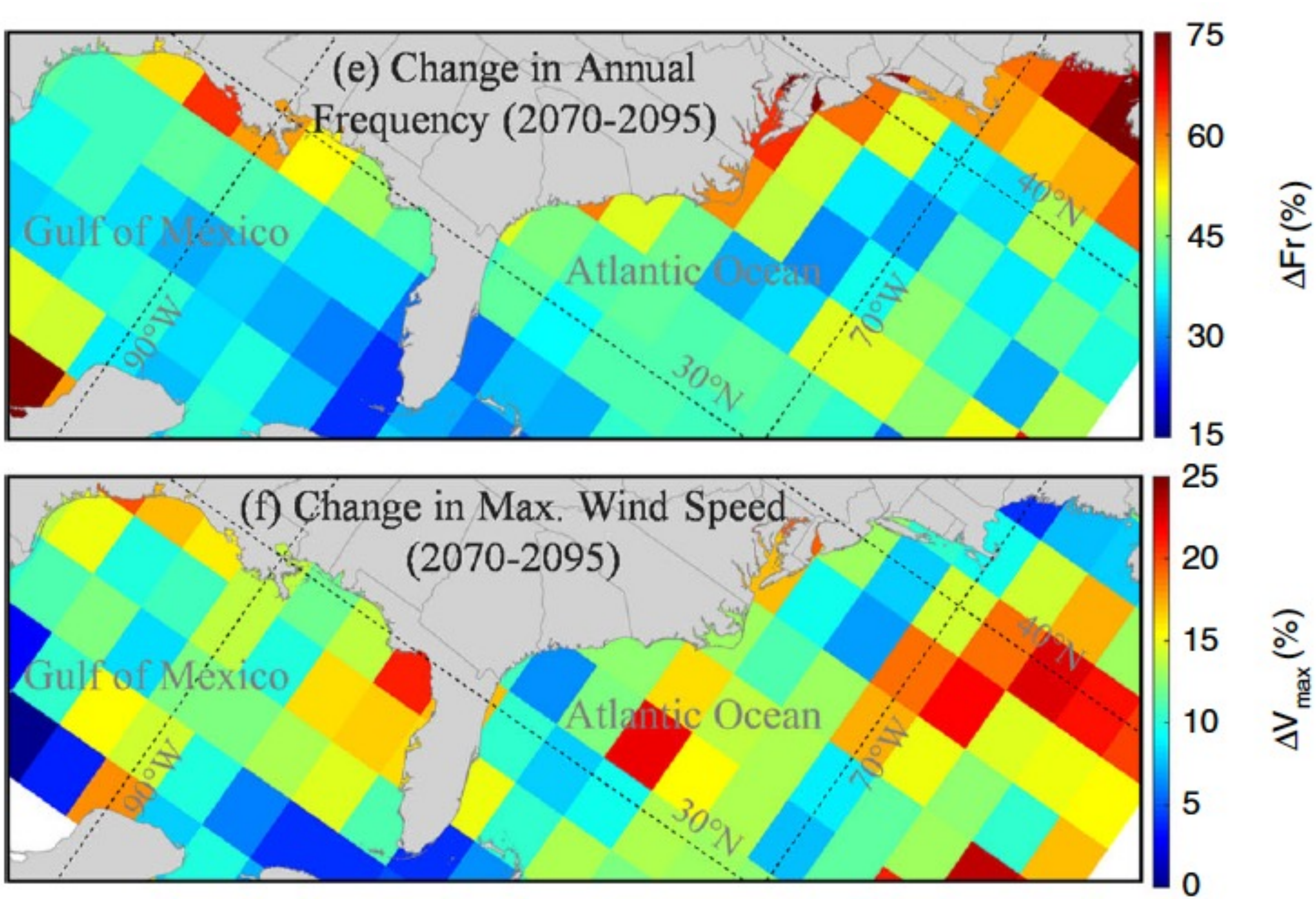
Rate of increase:
49% per decade

Kossin et al. (2020)

Observed trends in tropical cyclones (TCs)

- Track through Chesapeake Bay region about annually (Ingram, 2012)
- North Atlantic TCs have changed over the past several decades:
  - More frequent (Kossin et al., 2020)
  - More intense (Kossin et al., 2020)
  - Translating more slowly, increasing precipitation totals (Kossin, 2018)
  - Intensifying faster over the ocean (Garner, 2023)
  - Decaying more slowly over land (Li and Chakraborty, 2020)
  - Landfalling hurricanes shifting towards the US east coast (Li and Chakraborty, 2020)
  - More undergoing extratropical transition (Mokhov et al., 2020)
- Multiple causes of changes: increased greenhouse gases, reduced anthropogenic aerosols, natural variability
- Difficult to characterize centennial trends due to heterogeneous records

Marsooli et al. (2019) project increases in TC frequency and intensity for Chesapeake Bay and the Mid-Atlantic Region (RCP8.5)

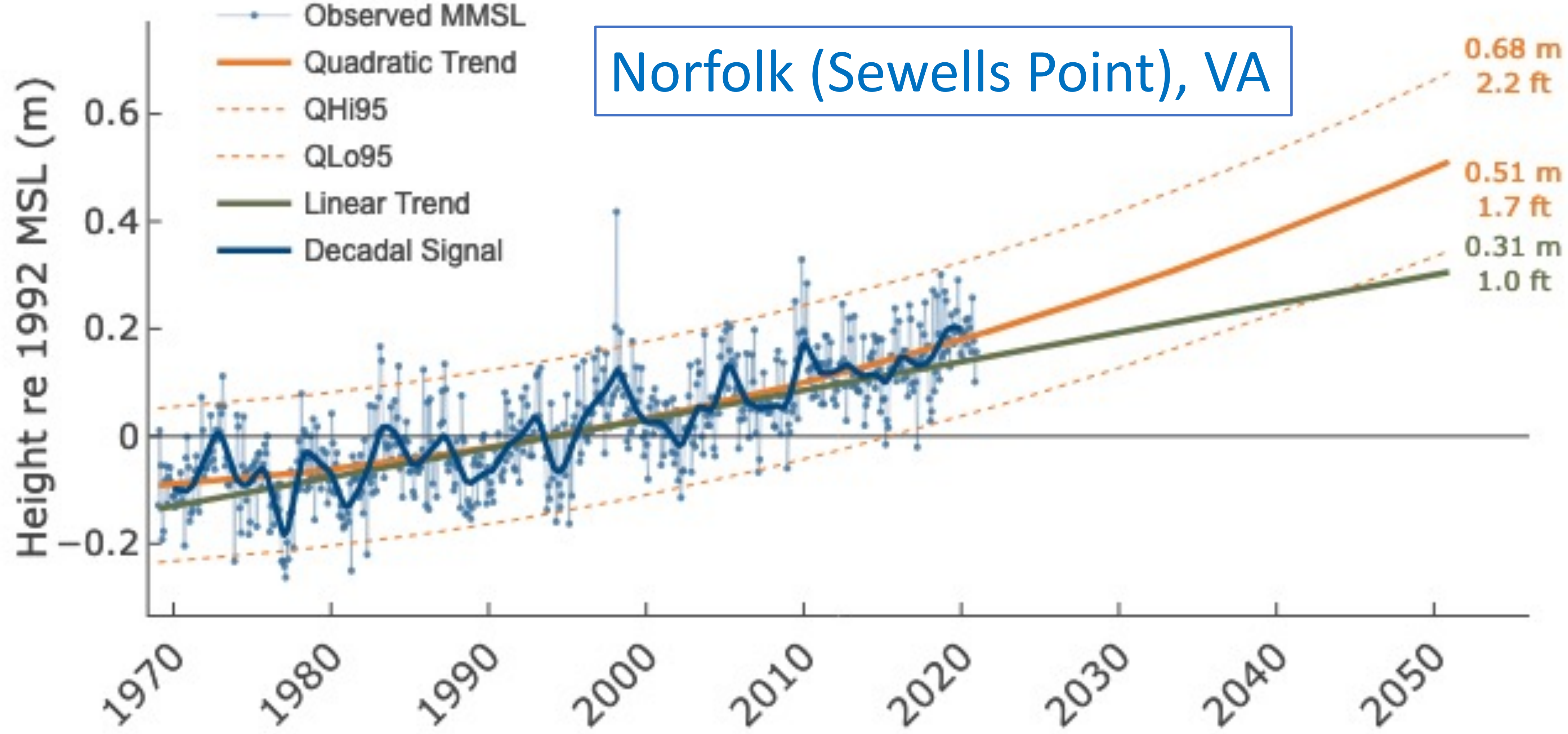


Tropical cyclone projections

- For North Atlantic:
  - TCs are expected to become more intense and produce more precipitation
  - Very low consensus on changes in TC frequency and fraction of TCs that are major
- For Chesapeake Bay and Mid-Atlantic region:
  - Statistical-dynamical approaches generally show increasing TC threat
  - TC frequency projections using dynamical approaches show mixed results

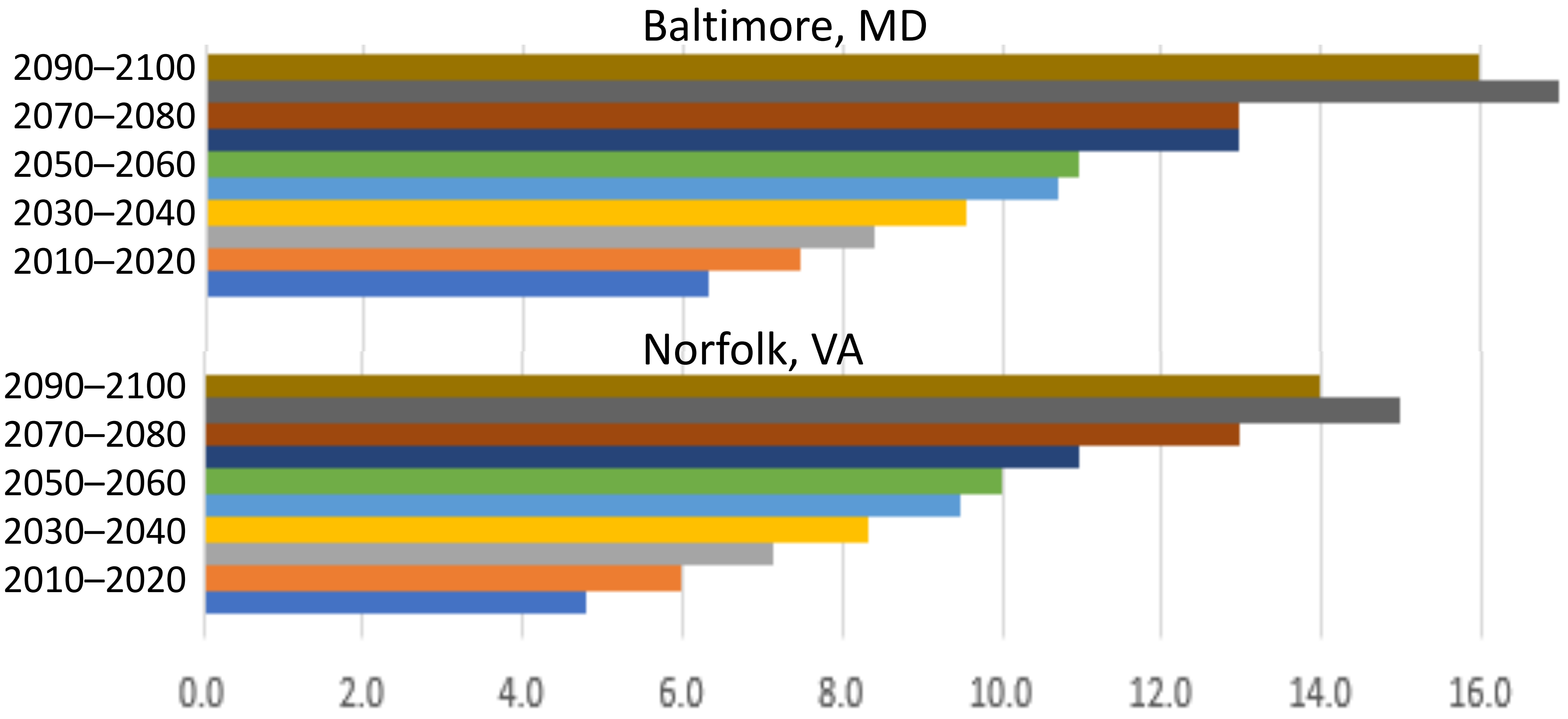
Sea level

Sea level acceleration is significant



Boon et al. (2018)

Sea level rise rates are projected to double by mid-century

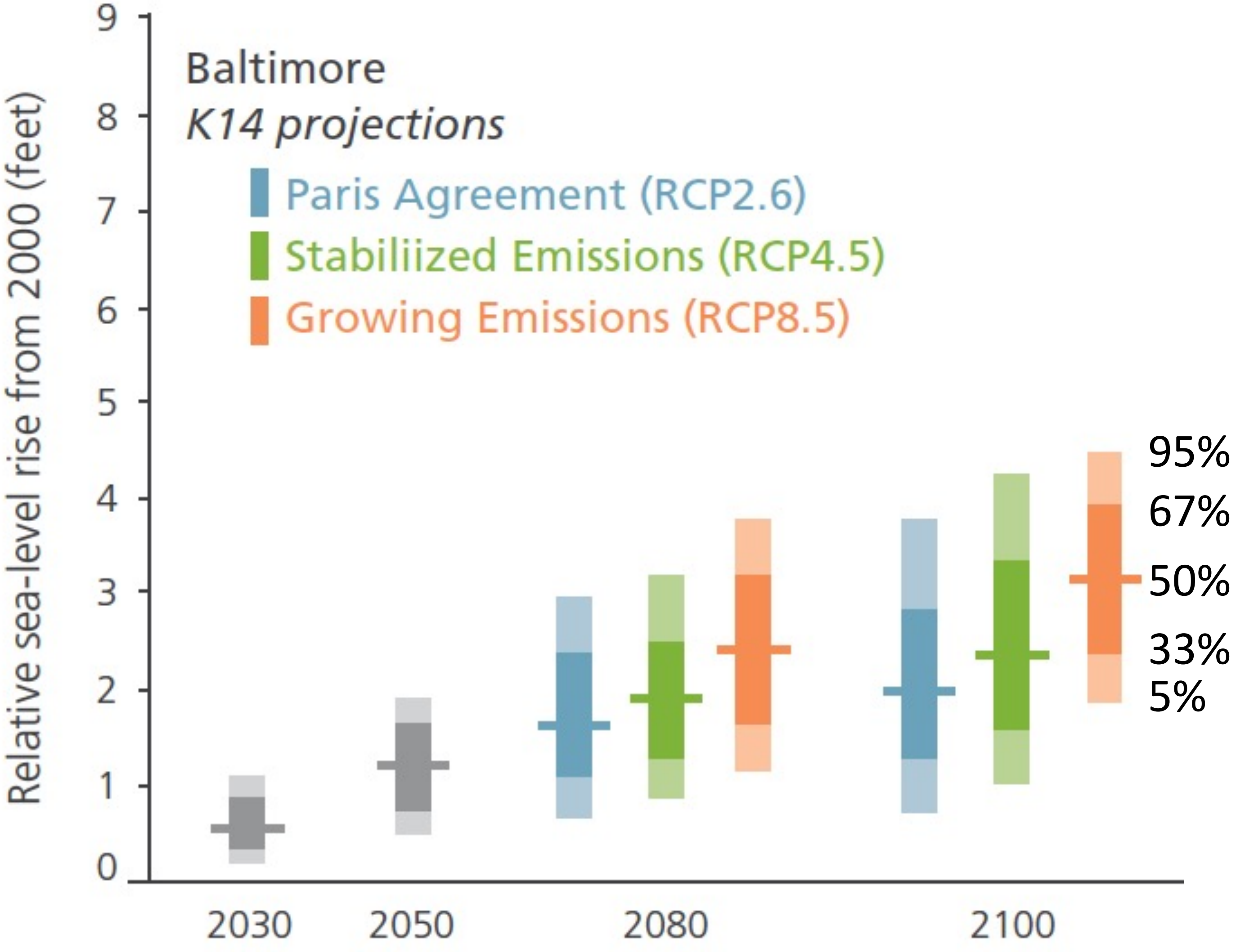


Average decadal rates of sea level rise (mm/yr)

Source: Molly Mitchell

Emissions are important in sea level projections, particularly by late century

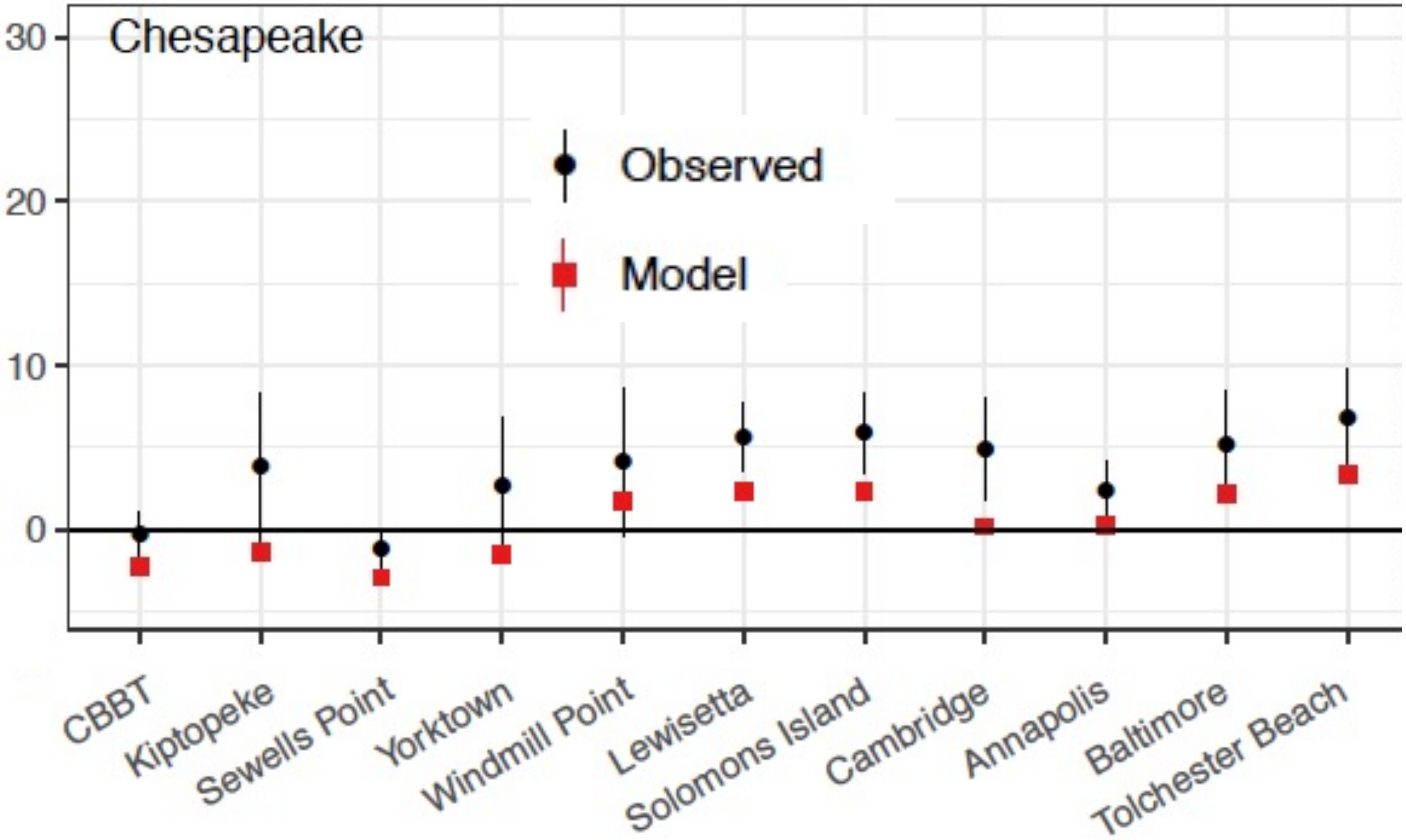
Kopp et al. (2014) model accounts for spatial variations due to ice sheets, glaciers, ocean warming, ocean dynamics, land water, and non-climate (e.g., tectonic effects)



Boesch et al. (2018)

Tidal range is changing, in part due to sea-level rise

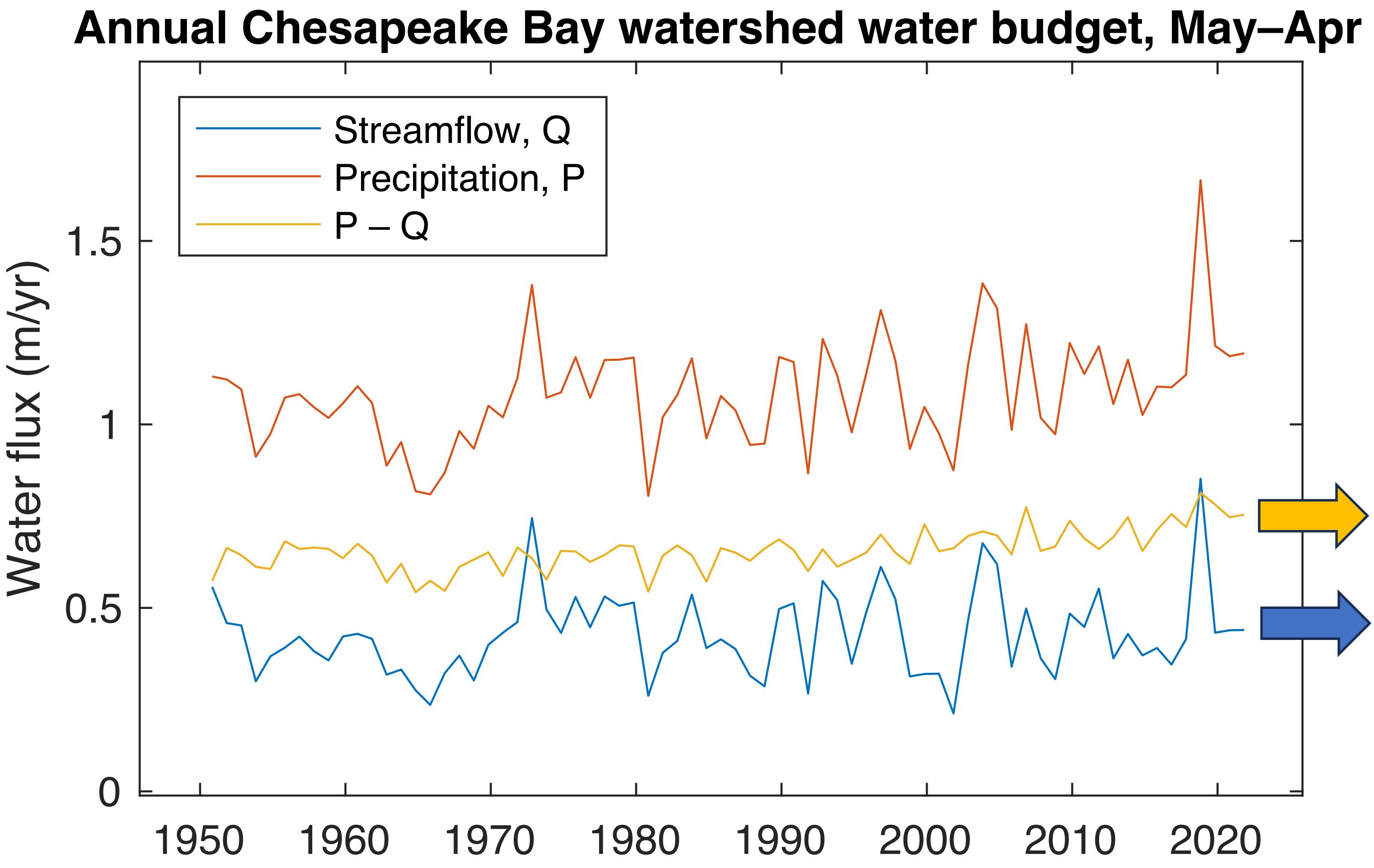
Change in tidal range per change in sea level (cm/m)



Ross et al. (2017)

Fluxes from the watershed

All water fluxes (precipitation, estimated evapotranspiration, and streamflow) of the Chesapeake Bay watershed are increasing



Estimated evapotranspiration correlated with temperature (r = 0.34)

Streamflow well-modeled from precipitation and temperature (r^2 = 0.89)

Observed trends in fluxes from watershed

- Precipitation, streamflow, and estimated evapotranspiration are increasing
- Streamflow is positively correlated with temperature during colder months and negatively correlated with temperature during warmer months (Schulte et al., 2016)
- Climate already influencing TN load: precipitation increasing TN load with modest offset from warming (Ballard et al., 2019)
- But flow-normalized TN sources (Sabo et al., 2022) and loads (Zhang et al., 2023) are decreasing
- Susquehanna River sediment input to Bay has decreased during low flows due to management and increased during high flows due to dam infilling (Russ and Palinkas, 2020)

10 studies show widely different results for annual flow changes from the watershed

Reference	Domain	Time period	Emissions scenarios	Climate models; down-scaling	Watershed model(s)	Annual streamflow change
Johnson et al. (2015)	Sus	1971–2070	SRES A2	CMIP3; NARCCAP	SWAT	–10 to 11% Median: 8%
Hawkins (2015)	CBW	1950–2099	SRES B1, A1b, A2; RCP 2.6, 4.5, 8.5	CMIP3, CMIP5; BCCA, BCSD	Distributed water balance	2020–2039: –1.1 to 3.3% 2050–2059: –6.6 to 4.4% 2080–2099: –13.5 to 3.9%
Seong and Sridhar (2016)	CBW	1950–2099	RCP 4.5, 8.5	CMIP5; BCCA	CBP Phase 5.3	2070–2099: –21.8 to 6.3%
Ross and Najjar (2019)	Sus	1950–2099	RCP 8.5	CMIP5	VIC	1 to 49% Median: 14%
Ni et al. (2019)	Sus	1971–2070	SRES A2	CMIP3; NARCCAP	Internal	Not reported
Modi et al. (2021), Modi (2020)	Sus	1976–2090	RCP 4.5, 8.5	CMIP5, MACA	Noah-MP	Multi-model averages RCP 4.5 2021–2050: 1.1% RCP 8.5 2021–2050: –0.8% RCP 4.5 2061–2090: 2.2% RCP 8.5 2061–2090: –5.4%
Ator et al. (2022)	CBW	1995–2025	RCP 4.5	CMIP5 Median	SPARROW	2.4%
Botero-Acosta et al. (2022)	CBW	1970–2099	RCP 8.5	CMIP5, BCCA	SWAT	Not reported
Hinson et al. (2023)	CBW	1991–2055	RCP 8.5	CMIP5; BCSD, MACA	CBP Phase 6, DLEM	2046–2055: –12 to 15%
Bhatt et al. (2023)	CBW	1995–2055	RCP 4.5	CMIP5; BCSD	CBP Phase 6	2025: 2.4% 2055: 6.2%

Projections of watershed fluxes

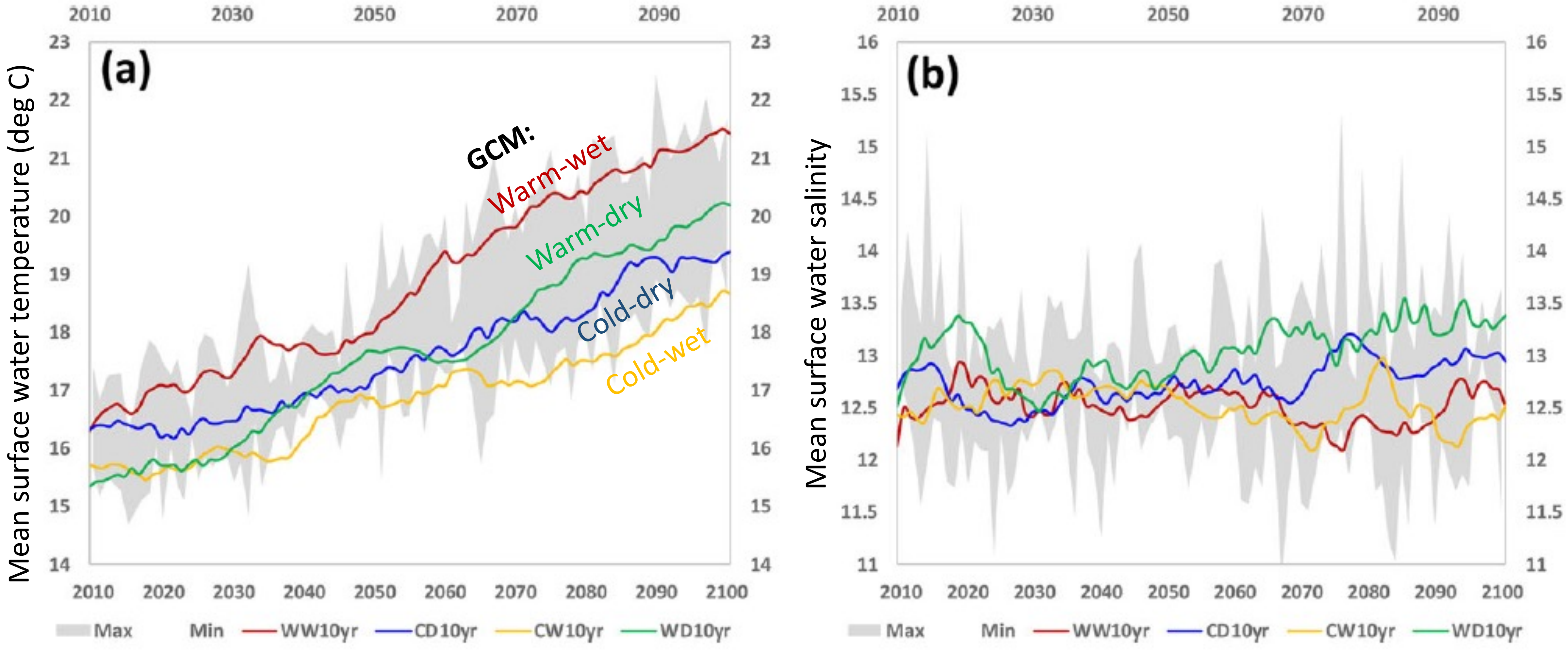
- Annual flow projections highly uncertain
  - Due, in part, to offsetting impacts of precipitation and temperature (Simple model of annual Q vs. P and T applied to RCP4.5 MACA average: –9.3% due to temperature and +8.2 due to precipitation)
  - PET formulations still being worked out (Shenk et al., 2021)
- Winter (Dec–Feb) projections consistent and increasing (8 of 9 of studies)
- % total nitrogen changes = % streamflow changes (Shenk et al., 2021)--but see Sabo and Elmore presentation for more comprehensive view
- Climate should increase TSS loading due to increased precipitation intensity

Bay temperature, salinity, and circulation

Observed trends in Bay temperature, salinity, and circulation

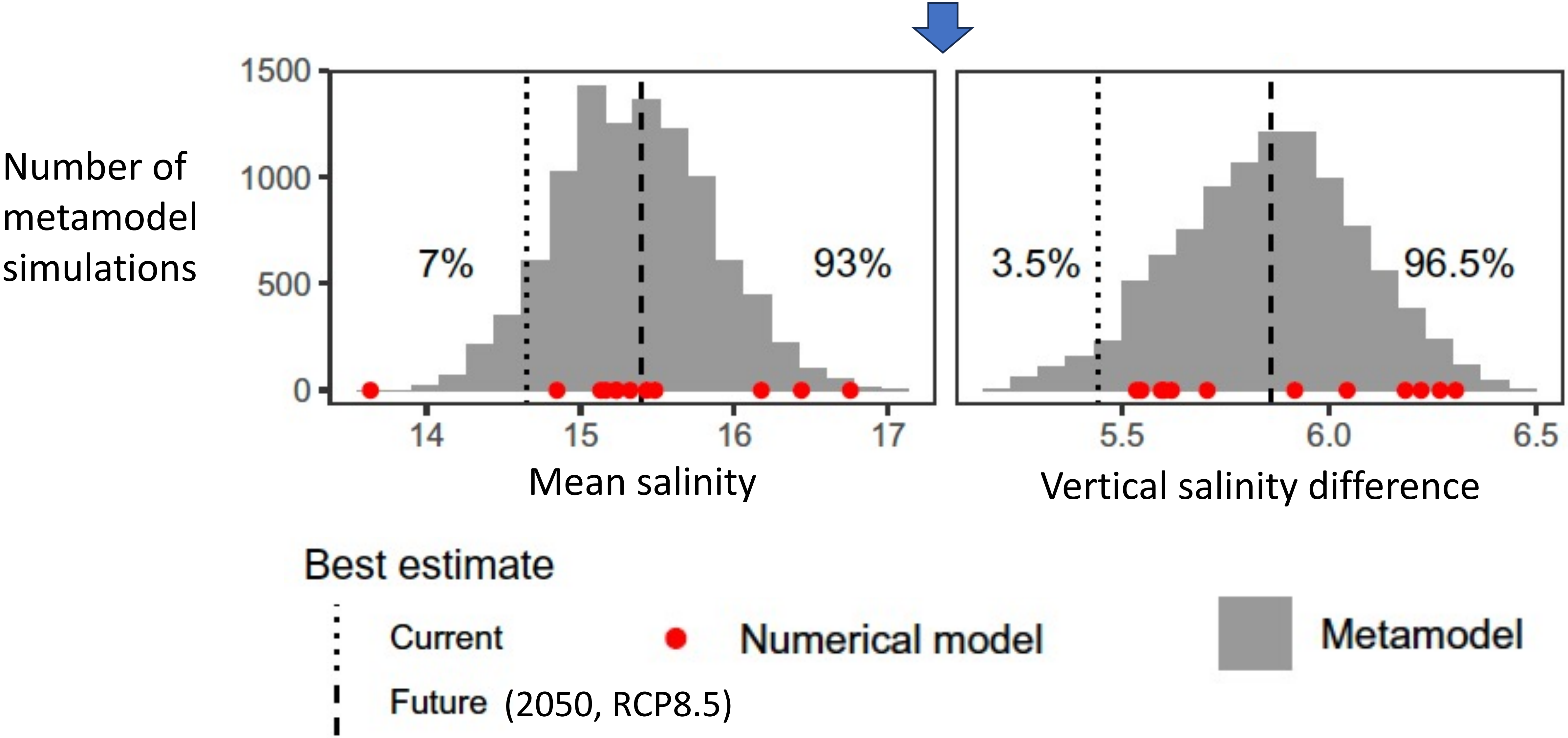
- Warming and increase in heat waves (Mazzini and Pianca, 2022; Shunk et al., 2024)
- Signal of sea-level rise in salinity (Hilton et al., 2008)
- Stratification mostly unchanged (Testa et al., 2018)

Bay waters will continue to warm, but future salinity change due to streamflow change is highly uncertain



Muhling et al. (2017)

Sea-level rise increases salinity and stratification (Hilton et al. 2008; Rice et al., 2012; Hong and Shen, 2012) and are larger than streamflow and tidal range impacts in future projections (Ross et al. 2021)



Projections of temperature, salinity, and circulation

- Warming
- Sea level to increase salinity by 1.2 to 2.5 per m
- Spring salinity should decline due to projected increases in winter streamflow
- Changes in tidal fresh and oligohaline regions highly uncertain, particularly in summer
- Stratification and circulation changes uncertain, though sea-level rise alone likely to increase them

Hypoxia

Hypoxia trends and projections

- Climate has already influenced hypoxia, primarily through warming (Du et al., 2018; Frankel et al., 2022; Ni et al., 2020)
- Warming will be the dominant climate change factor directly affecting future hypoxia (Irby et al., 2018; Lake and Brush, 2015; Ni et al., 2019; Testa et al., 2022; Tian et al., 2022)
- The positive impact of planned nutrient reductions can overwhelm negative impacts of warming on hypoxia (Frankel et al., 2022; Hinson et al., 2023; Irby et al., 2018)

Carbonate system

Carbonate system trends

- River and bay alkalinity increasing (Kaushal et al., 2013; Najjar et al., 2020)
- pH increasing in upper Bay, decreasing in lower Bay (Da et al., 2021)
- Carbonate system variables are changing due to changes in atmospheric CO_2, temperature, and river carbon, alkalinity, and nutrients (St-Laurent et al. 2020; Da et al., 2021)

Projections of the carbonate system

- Elevated atmospheric CO_2 and temperature, along with changes in streamflow and continental shelf conditions, will decrease Chesapeake Bay pH by 0.1 to 0.3 units and nearly double atmospheric CO_2 uptake (Li et al., 2023)
- Elevated atmospheric CO_2, temperature, and sea level decrease calcite saturation state; oyster tissue weight and shell weight are projected to decrease by 16% and 25%, respectively, over the next 50 years (Czajka, 2024)

Harmful algae and Vibrio

Observed trends in harmful algae and Vibrio

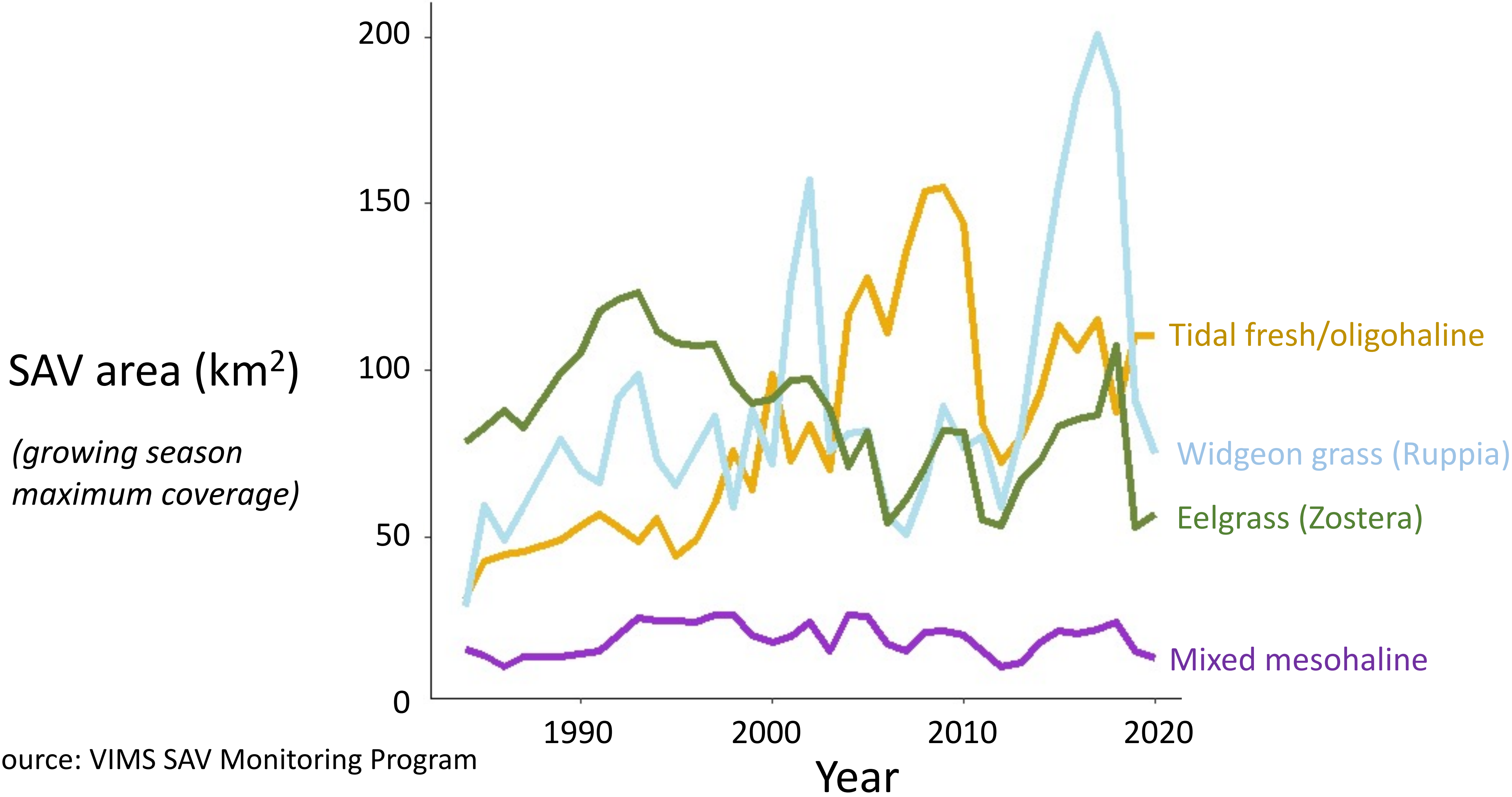
- Warming partly explains increase in reported *Vibrio* human infections (Urquhart et al., 2015), and *K. veneficum* and *M. polykrikoides* blooms (Li et al., 2015; Marshall et al., 2009)
- Warming may have contributed to the emergence in the Bay of new cyanobacteria, *Lyngbya* and associated saxitoxin (MDE, 2004; Wozniak, 2024)

Projections of harmful algae and Vibrio

- A variety of modeling studies indicate that climate change will result in shifts of harmful algae and Vibrio abundance in time and space, and changes of the community composition (Jacobs et al., 2015; Muhling et al., 2017; Li et al., 2020, 2022; Hofmann et al., 2021)
- Warming and eutrophication tend to increase HABs

Submersed vegetation

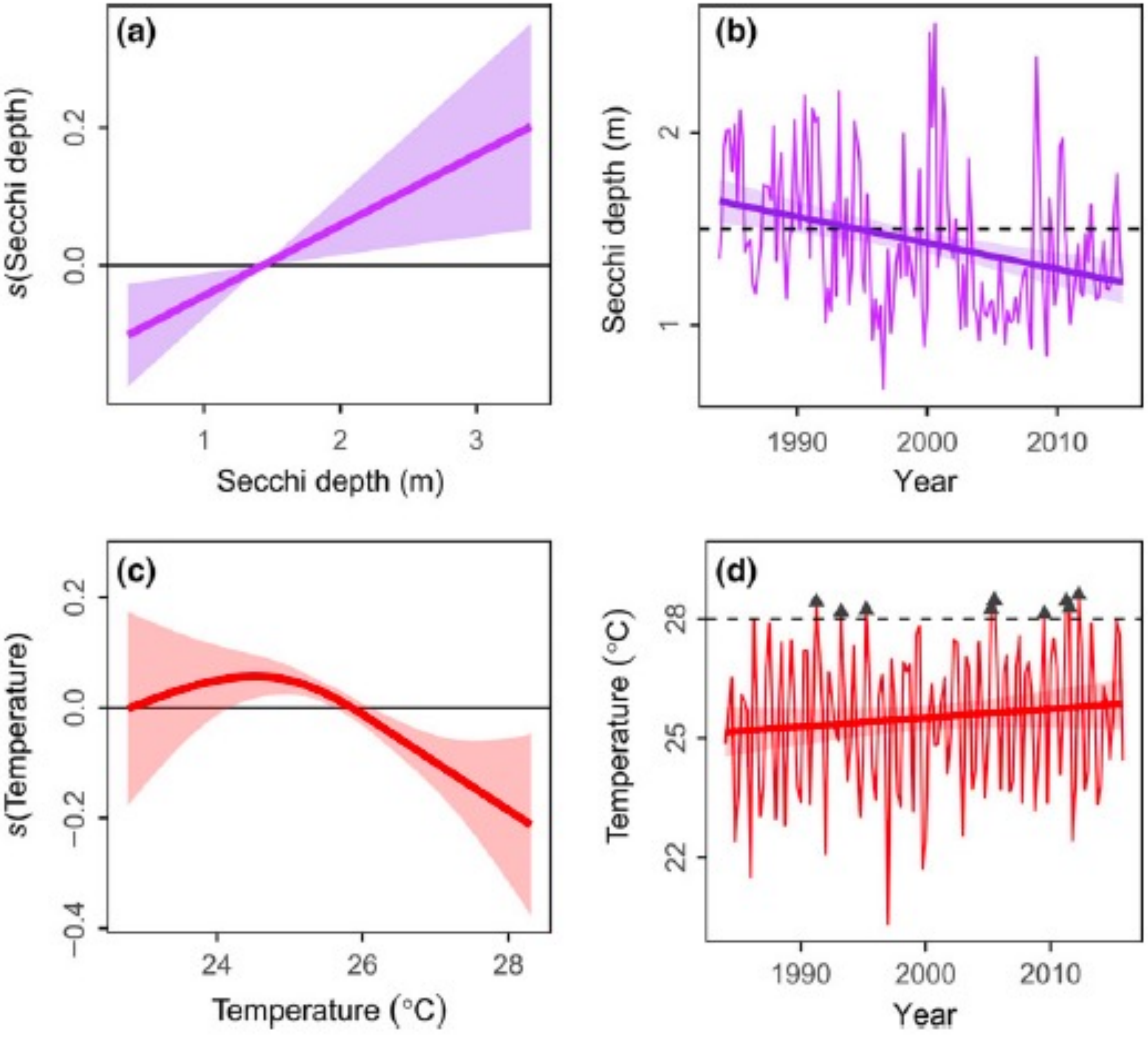
SAV area by community has varied a lot over the past several decades



Source: VIMS SAV Monitoring Program

SAV area responds to environmental variables

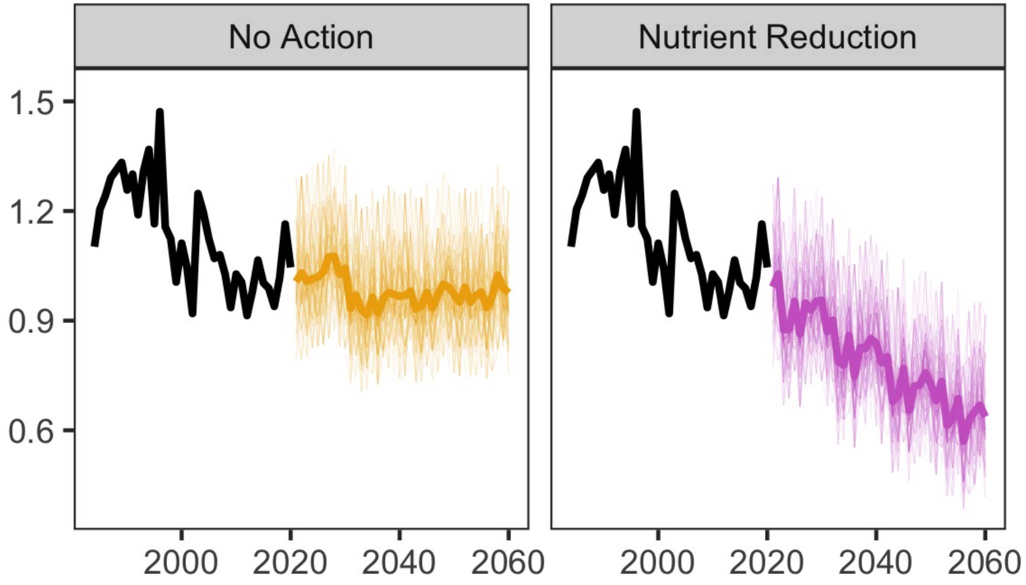
Here, eelgrass declines over the past several decades due to clarity decrease and temperature increase



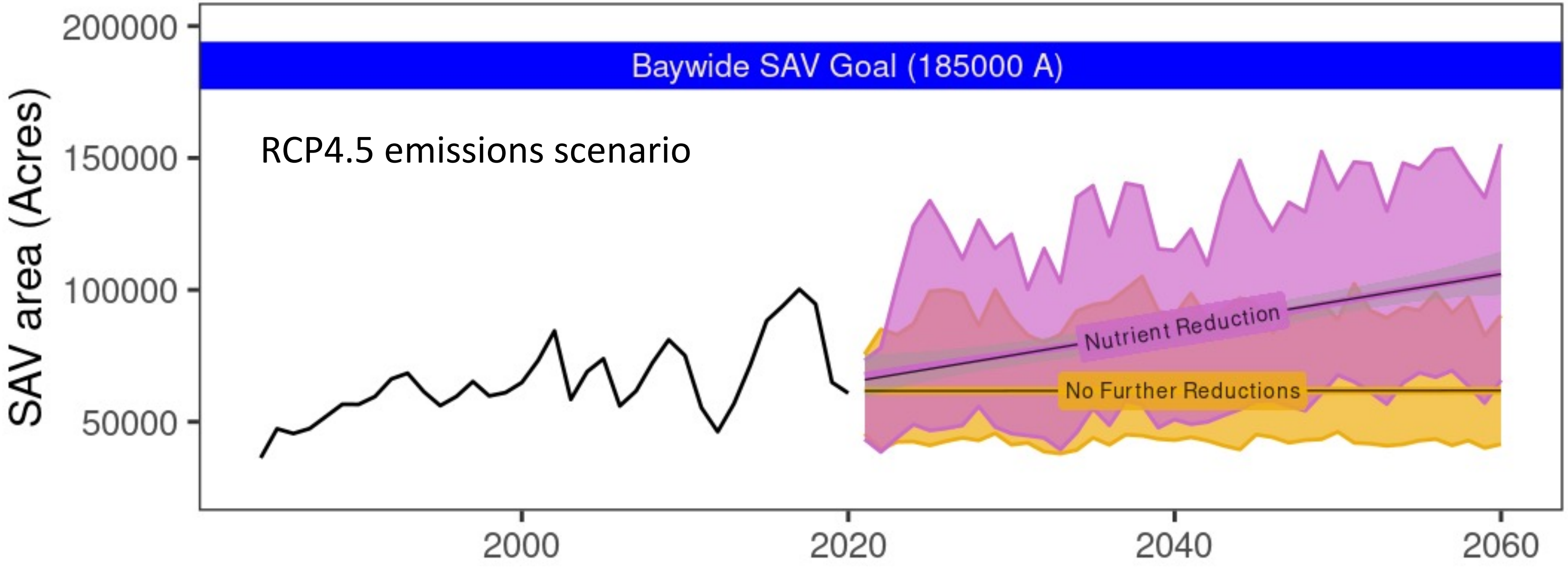
Lefchek et al. (2017)

Total SAV projections show large impact of nutrient management

Mean springtime total nitrogen (mg/L)



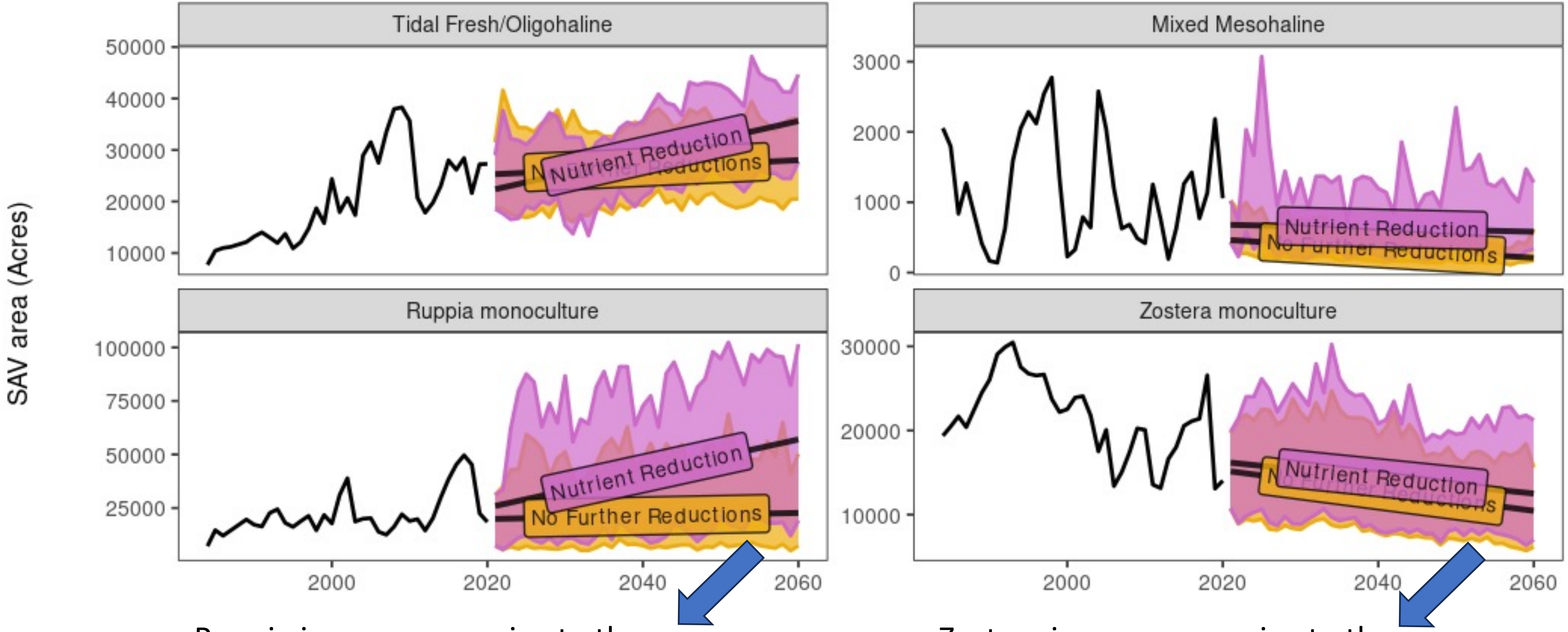
From CBP modeling suite



Community-specific statistical models using water quality inputs

Patrick et al. (2023) Scope 6 Final Report: Modeling Climate Impacts on SAV in the Chesapeake Bay

But results are community specific



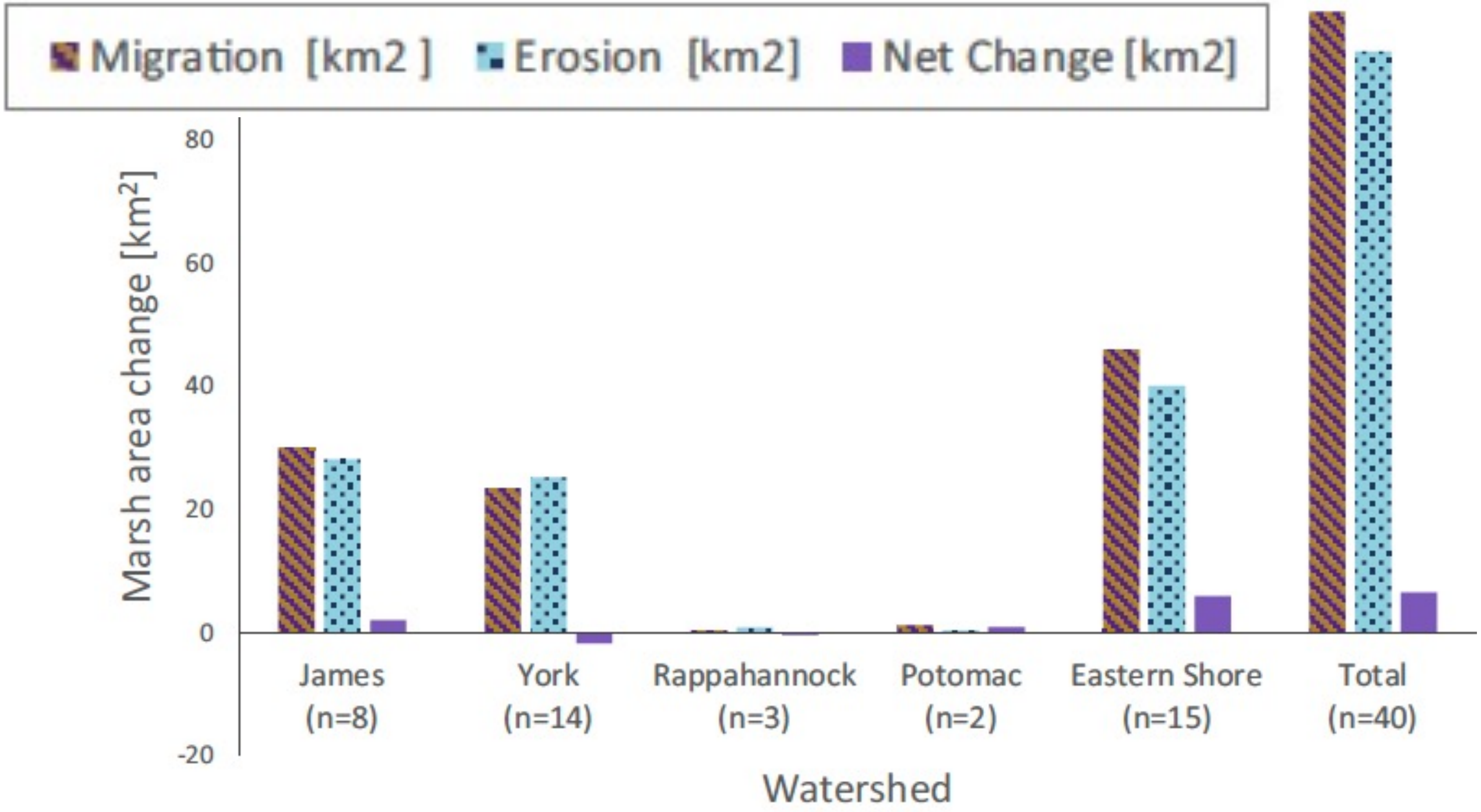
Ruppia is very responsive to the nutrient reduction and less affected by warming

Zostera is very responsive to the warming and less affected by the nutrient reduction

Patrick et al. (2023)

Tidal marshes

- <u>Tidal wetlands</u> not keeping up with sea-level rise (Beckett et al. 2016)
- But migration compensates for loss (Schieder et al. 2018)
- Migration constrained by topography (Molino et al. 2022)



Tidal marsh projections

- 60% of marsh units in the Chesapeake Bay region have unvegetated-vegetated ratios of less than 0.15, suggesting widespread degradation of existing marshes under faster sea level rise rates (Ganju et al., 2024)
- Nevertheless, there is potentially 1050–3748 km^2 of land available for marsh migration across the Chesapeake Bay, similar to the total area of tidal marsh in the Bay
- Warnell et al. (2022) project 12% loss for 0.6 m of SLR and 69% loss for 1.2 m of SLR of MD and VA marshes by end of century
- While CO_2 and temperature are important drivers of marsh processes, there are numerous compensating effects, leaving sea level as the dominant driver

Fishes

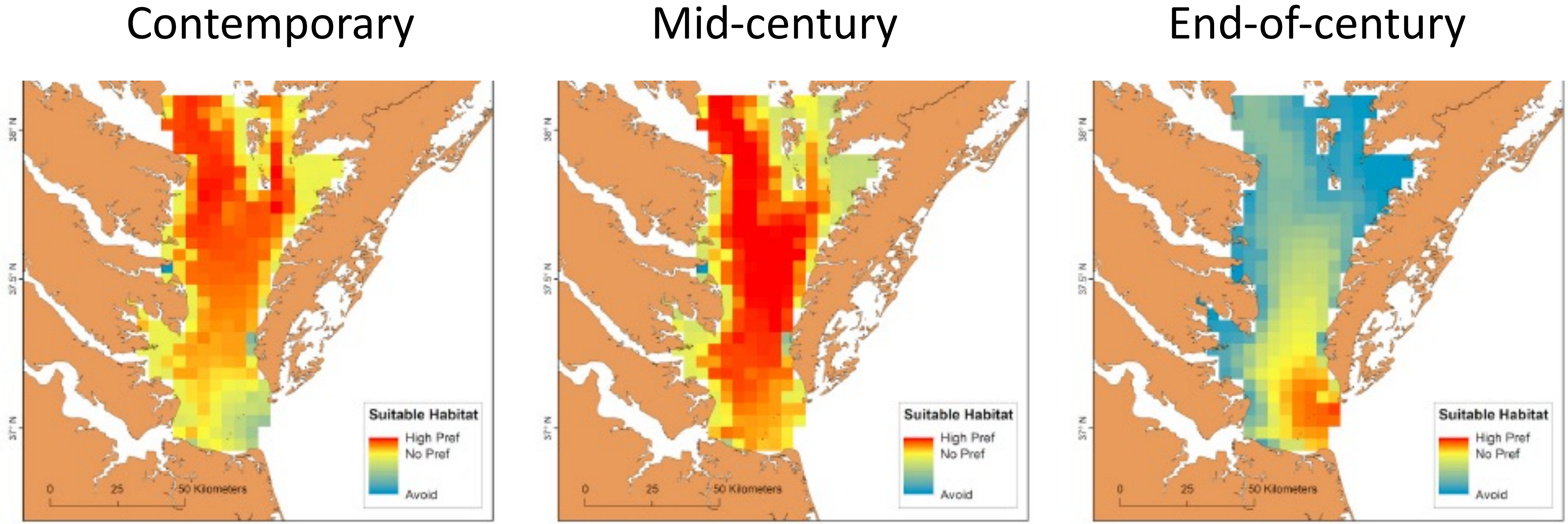
Key message

Climate-related increases in water temperature (high confidence) and salinity (low confidence), and decreases in DO (without TMDL) forecasted for mid-century and end of century for Chesapeake Bay will affect fish through a variety of mechanisms that are species and life-stage (egg, larva, juvenile, and adult) dependent

Examples of climate-related responses noted from the Chesapeake Bay in recent years:

- Alterations in the spatial distribution of individuals (Crear et al., 2020a and b),
- Fluctuations in abundance that mirror the availability of suitable habitats (Fabrizio et al. 2021)
- Changes in the phenology of key life-history processes such as spawning migrations (Peer and Miller, 2014)
- Facilitation of the spread of invasive species (Nepal and Fabrizio, 2019, 2021)

Simulated Cobia suitable habitat (May 15 – Sep 30) response to climate is nonlinear


Contemporary

Mid-century

End-of-century

(Crear et al. 2020)

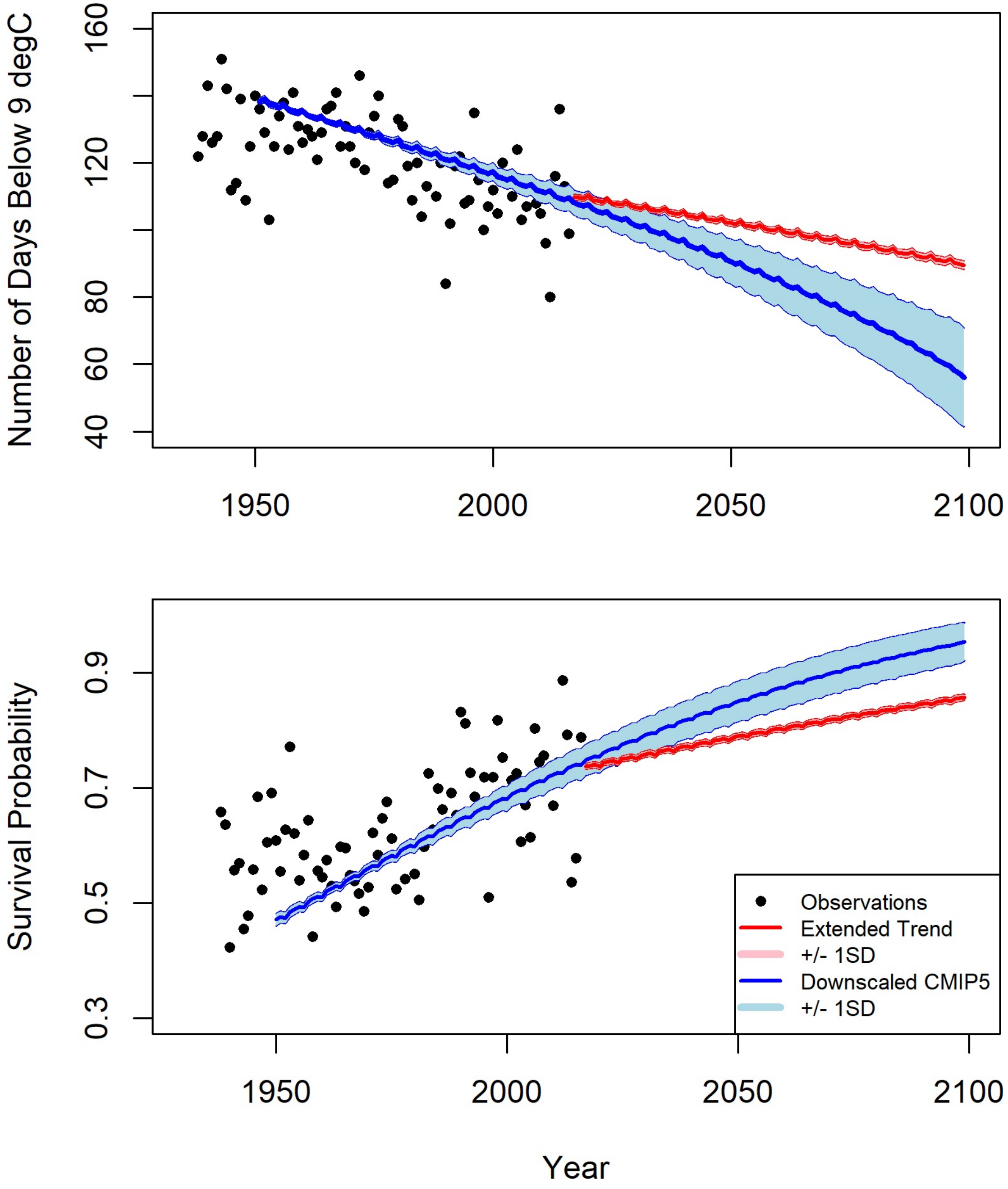
Shellfish

Climate change and shellfish

- Principal drivers
  - Changes in thermal regime alter phenology of key life history events
  - Changes in acidity and saturation state alter the carbonate system
- Interactive effects
  - Changes in thermal regime alter ecological roles – e.g., extension of growing seasons increase trophic demand by consumers
  - Reductions in saturation states lead to corrosion of shells which diverts energy to shell replacement from other ecological processes.
- 2 examples

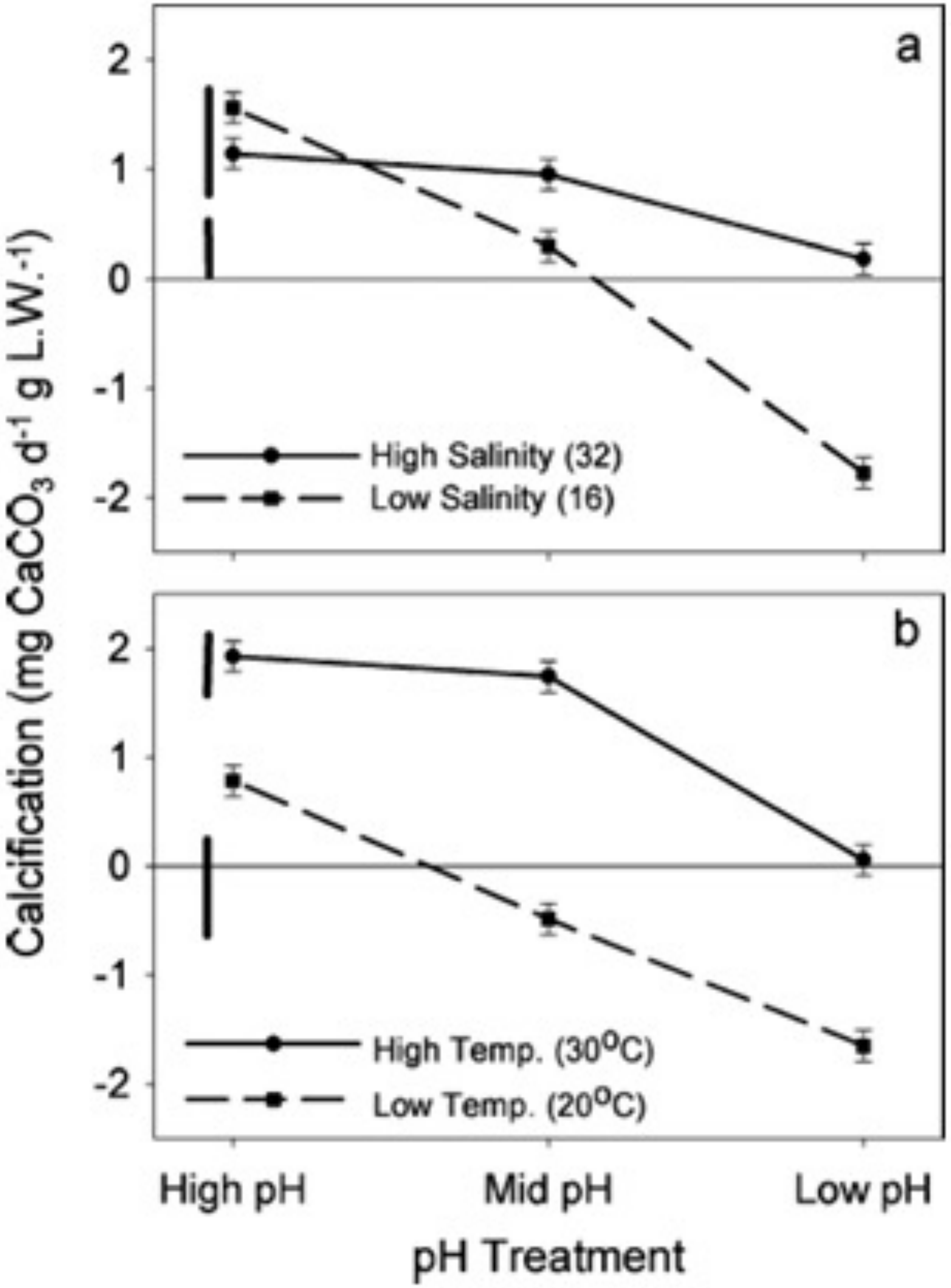
Blue crab

- **Direct drivers**: Glandon et al. (2019) extended experimental results to show that increased winter temperature will greatly reduce (eliminate) overwintering in blue crab
- **Indirect effects**: Shortened overwinter will extend periods of crab predation in the benthos, potentially shifting community composition and productivity



Eastern oyster

- **Direct driver**: Waldbusser et al. (2010) showed that increased acidity and temperature interact to reduce calcification rates of Eastern Oyster, leading to thinning shells
- **Indirect effects:** Oyster with thinner shells experience higher rates of mortality, and have to divert energy from growth to shell maintenance



Other biota

Observed trends in other biota

- A diverse community of birds, mammals, reptiles, insects, and other invertebrates inhabit or use Chesapeake Bay habitats
- Evolving land use, water quality, harvest pressure, and climate over the past decades have all led to changes in the populations of many of these species
- Erosion and armoring of fringing marsh and low beach nesting habitats have led to declines or extirpation of some birds
- 14 species of seabird now arrive earlier during their northward migration, arriving later during their southward migration, or both, relative to the middle of the 20th century (Reese and Weterings, 2018)
- Benthic biodiversity related to temperature, streamflow, DO, and phytoplankton (Woodland and Testa, 2020)

Some overall findings thus far

- Climate impacts no longer potential—climate is already expressing itself in nearly every aspect of the Bay
- Climate is likely to emerge as a first-order driver of Bay health
- We have agency locally to mitigate the negative impacts of climate change (examples from hypoxia, SAV, maybe HABs, …)
- Emissions really matter for impacts beyond mid-century and we need to keep communicating that to the public (tidal marsh example)

Some areas that really need work

- Reducing uncertainty in streamflow projections—salinity and nutrient loading are are strongly influenced by streamflow
- Development and application of a hierarchy of models of living resources (tidal wetlands, SAV, fish, shellfish, etc.)