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## Research Article

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# On the Influence of Synoptic Air Masses on Water Conditions in the Chesapeake Bay

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## ABSTRACT:

The Chesapeake Bay is one of the largest estuaries in the world and serves as a major port of the United States, a major source of economic stability in the region, and is home to a unique ecosystem. The bay's ecological health and resiliency is highly dependent upon the physical and chemical makeup of the water, which in turn, is largely influenced by changes in weather and climate conditions typical of the midlatitudes. In this research, we examine the relationships between multiple water characteristics of the Bay and a unique, multivariate index of the local climate – air masses (AMs). Daily AM data were retrieved from version 2 of the gridded weather typing classification (GWTC2) from 1985-2023, and compared with six water characteristics from the Regional Ocean Modeling System (ROMS) within the Bay: temperature, salinity, dissolved oxygen (DO), sea-surface height (SSH), and the u- and v-components of ocean volume transport. Specific AMs have the strongest association with water temperature, meridional volume transport, and sea surface height (SSH) throughout most of the Bay and portions of the inner shelf, with a humid-warm AM causing a 6.6x risk in an extreme warm-water event, while warm front passages increase the likelihood of a spike in northward ocean volume transport by a factor of 6.5. While SSH, salinity and DO showing fairly weak Bay-wide correlations with AMs, significant sub-regional relationships are notable, especially with salinity around the Bay entrance. In general, the three warm GWTC2 AMs and the three cool GWTC2 AMs have the largest (and opposing) influences on the multivariate water conditions of the Bay.

## KEYWORDS:

air masses, Chesapeake Bay, weather-water relationships, GWTC

## I. INTRODUCTION AND BACKGROUND

The Chesapeake Bay is the largest estuary in the United States, and the third largest in the world. Due to its sheer size and proximity to major urban centers of eastern North America, it is a vital resource for the US and the world. Over \$100 billion per year of economic activity is provided from within the Bay, its tributaries, and the watersheds encompassing it (Webber et al., 2025), which includes two of the largest shipping ports on the North Atlantic Ocean (Chesapeake Bay Program, 2026). The seafood industry alone provides over 500 million pounds of seafood each year, worth \$2-3 billion annually in sales to the local economy and the 18 million people living in the Bay's watershed (Chesapeake Bay Foundation, 2026, NOAA Fisheries, 2026). The Bay is also home to thousands of plant and animal species, including hundreds of species of fish and shellfish, keystone species such as the blue crab (*Callinectes sapidus*) and the striped bass (*Morone saxatilis*), and is also a major stopover point or wintering ground for waterfowl along the Atlantic Flyway (NWF, 2025).

The Bay's ecological health – and thus, our benefit from the Bay – is inherently dependent upon the water conditions and attributes that directly influence the biology; these include aspects of temperature, salinity, sea levels, and circulation influencing water movement. Likewise, pollution-related chemical constituents, including dissolved gases, nutrients, and other organic and inorganic materials are as important, influencing trophic-level interactions, growth, distribution and abundance of ecologically important organisms throughout the bay. Collectively, these abiotic factors are important catalysts to the movement and migration, recruitment and survival of species. Consequently, marked changes in key water conditions that shape the ecology in the bay are largely driven by weather- and climate-related factors (e.g., Harding et al. 2019; Easton et al., 2025; Scully, 2013; 2010; Garzon et al., 2018; Lee et al., 2013). While temperature and precipitation are two atmospheric factors found most often in climate model projection studies in the bay (Hanson et al., 2022; Easton et al., 2025), wind speed/direction, humidity, insolation, and other meteorological variables can have considerable influence as well (Easton et al., 2025). Moreover, upon the backdrop of anthropogenic climate change, trends in these meteorological forcing agents have altered key physical and biogeochemical aspects of the Bay in recent decades (Najjar et al., 2010; Easton et al., 2025; Hinson et al., 2022).

The bay and adjacent continental shelf system are subjected to a variety of land to sea, weather- and ocean-related processes which drive water exchange at the bay entrance, circulation patterns inside and outside the bay and overall water conditions. In particular, wind is the primary driver of short-term water movement, sea height, and circulation in the bay (Boicourt, 1981). Winds can move surface water in and out of the bay and cause localized sea level fluctuations, while prolonged winds along the shelf can push surface waters shoreward (seaward) via direct onshore (offshore) flow, and via Ekman circulation. Similarly, coastal upwelling events are fundamental drivers of temperatures changes and water column mixing along the coast, driven by southerly winds and Ekman-induced flow (Glenn et al. 2004).

Estuarine circulation in the bay is highly dynamic, consisting of a two-layer flow: an upper layer of lower salinity water from river discharges onto the continental shelf, and a lower

layer that moves more saline waters into the bay. Mean flow along the shelf is southward and flow increases towards the shelf break (Pritchard, 1955, Boicourt, 1981, Johnson et al. 1983).

From a seasonal perspective, mean flow in summer is typically toward the north along the shelf (Boicourt, 1981). Stratification occurs in the bay and shelf systems via spring runoff and surface warming, peaking in summer. Finally, among these known factors influencing bay water conditions, temperatures in the bay can change dramatically as a result of air-sea flux, moisture and heat exchange, driving extremes in surface temperatures, and in certain situations, thermally stressed conditions impacting many bay species, including juvenile and adult blue crabs, red drum, Atlantic menhaden, and speckled trout, among other fish species and invertebrates (Najjar et al., 2010; WMRA, 2026).

Multiple studies have used individual weather variables for evaluating environmental effects on coastal systems. These methods have advantages particularly when the effects are driven by circulation patterns, multi-scale interactions and processes. For example, in the case of elevated water levels impacting flood conditions along the Atlantic and Southeast coast, the combined, additive effects of atmospheric pressure variability (i.e., the inverse barometer effect), wind-driven Ekman-induced setup, direct offshore/onshore flow, and steric effects have been evaluated and modeled using assemblages and aggregates of multiple weather classes to evaluate impacts (Sheridan et al., 2017; 2019; Lee et al., 2023; Pirhalla et al., 2022). However, research examining how the *combinatorial* (i.e., multivariate) atmosphere impacts water conditions, including flow patterns and circulation, surface temperatures, salinity, dissolved oxygen, and nutrients in this estuary, is lacking.

In order to address this gap in the research, and in conjunction with a larger project investigating weather-water impacts on blue crab in the Chesapeake Bay, the simple aim of this research is to leverage a recently developed air mass classification system – version 2 of the Gridded Weather Typing Classification (GWTC2, Lee, 2020) – and gridded water quality data from the Regional Ocean Modeling System (ROMS) to investigate how multivariate air masses impact a variety of water characteristics in the Chesapeake Bay.

## II. DATA & METHODS

Daily air mass (AM) data were retrieved from the GWTC2, for the 1985-2023 study period, within a 4° x 4° latitude/longitude domain encompassing the Chesapeake Bay and vicinity (from 36°N to 40°N latitude, 78°W to 74°W) at a 0.5° spatial resolution, resulting in 81 sample points. Additionally, for each point, the probability that each day was classified into each of the 11 air masses was obtained from GWTC2 archives (and can be found at Lee and Pirhalla, 2026). The probabilities of each AM on each day were then averaged across these 81 GWTC2 locations in the domain, and the AM with the highest probability of occurrence was chosen as the regional AM for the day.

The GWTC2 is a multivariate surface air mass (or weather typing) classification scheme. Developed by Lee (2016) and updated and revised by Lee (2020), the GWTC2 combines data from the Climate Forecast System version 2 (CFS) and the CFS-Reanalysis (Saha et al., 2014) to produce globe-wide, daily-scale historical classifications of every location's weather into

one of 11 different types of weather, or air masses (AMs; Figure 1). Incorporated CFS data include: 2-meter temperature, 2-meter dewpoint, 10-meter zonal and meridional wind components, sea-level pressure (SLP) and total cloud cover at 3-hour increments, from 1979-2025. Separately at each location, each of these variables at each 3-hourly timestep is subjected to deseasonalized standardization (i.e., transformed into seasonally-relative z-scores), in an effort to identify air masses that represent the spatiotemporally-relative, multivariate departures from ‘normal’ – resulting in every air mass being possible at any time of year (Table 1). Despite the multivariate nature of AMs, temperature and humidity characteristics are the most deterministic of the six variables, and thus, the nine ‘core’ air masses are named according to whether they are above-, near-, or below-normal in that regard. Finally, two categories in the classification are reserved for transitional weather (e.g., when one air mass yields to another), such as when a cold front or warm front pass through the domain. The full GWTC2 methodology is detailed in Lee (2015) and Lee (2020).

All water data are retrieved from the Chesapeake Bay Environmental Forecast System (CBEFS). The CBEFS is based on the Regional Ocean Modeling System (ROMS) Estuarine Carbon Biogeochemistry (or ROMS-ECB) computer model, which simulates hydrodynamics (volume transport, salinity, temperature) and ecology (algal growth, nutrients, dissolved oxygen, among others). ROMS-ECB is an implementation of ROMS (Shchepetkin and McWilliams, 2005) designed for process-based modeling of systems such as the Chesapeake Bay. ROMS data are validated using historical data corresponding to the period of the hindcast simulation to evaluate the model skill. The *in-situ* validation data set originate from the Water Quality Monitoring Program (WQMP, USEPA, 2023) from 1984 to present. Direct physical measurements of temperature, salinity, sea surface height and dissolved oxygen (DO) have the best coverage throughout the bay and consistently showed high model skill (St-Laurent and Friedrichs, 2024).

Daily averaged water temperature, salinity, dissolved oxygen (hereafter, DO), sea-surface height (SSH), and the zonal (across-bay; u-transport) and meridional (along-bay; v-transport) components of ocean volume transport (downloaded as Huon and Hvom in units of  $\text{m}^3/\text{s}$ ) data were gathered for the domain encompassing  $36.5^\circ\text{N}$  to  $39.6^\circ\text{N}$  latitude and  $75^\circ\text{W}$  to  $77.5^\circ\text{W}$  (corresponding to the entire Chesapeake Bay, some of its major tributaries, and the immediately adjacent Atlantic Ocean), excluding land. These ROMS data were collected for the layer nearest the ocean surface, and the bottom-most layer of the water column at  $0.00540^\circ \times 0.00684^\circ$  (latitude x longitude;  $\sim 600\text{m} \times 600\text{m}$ ) spatial resolution, at daily-scale, from 1985-2023. The majority of the focus herein is on the *surface* level water characteristics.

In addition, to aid in the interpretation of the physical mechanisms linking AMs to anomalous water characteristics in the Bay, the synoptic-scale patterns of deseasonalized air temperature, daily precipitation and wind speed/direction associated with each of the AMs are composited in Figures 2-4. For these composite maps, daily mean data were retrieved from the European Center for Medium Range Weather Forecasting’s ERA-5 reanalysis (Hersbach et al., 2020) at  $0.25^\circ$  resolution for the domain  $23^\circ\text{N}$  to  $50^\circ\text{N}$  latitude, and  $86^\circ\text{W}$  to  $60^\circ\text{W}$  longitude for the same time period as the GWTC2 data.

Both the ERA5 and ROMS data were transformed into deseasonalized z-scores, by subtracting a smoothed curve of day-of-year means from each individual value, and then dividing the difference by a smoothed curve of day-of-year standard deviations. Composites of deseasonalized z-scores of ROMS data and ERA5 data for each AM were then mapped.

Two metrics were used to quantify the relationship between AMs and ROMS data: eta-correlations, and relative risks ( $RR$ ). Eta-correlations ( $\eta$ ), also known as categorical correlations, measure the strength of association between a categorical variable (e.g., AMs), and a continuous variable (e.g., ROMS data). As a derivative of a simple one-way ANOVA,  $\eta$  is equal to the positive square root of the between-group sum of squares over the total sum of squares.  $RR$ s quantify the probability of an event happening given an exposure, over the probability of that event happening without that given exposure. Herein an 'extreme event' is defined as any day when the deseasonalized z-score is greater than the 95%-ile (for an extreme high event) or less than the 5%-ile (for an extreme low event) of the distribution, and is calculated separately for each ROMS gridcell. Thus, for example, if an 'extreme event' is a sea-surface temperature (SST) > 95%-ile, and this event happened on 100 of the 400 days (25%) on which a Humid-Warm (HW) AM occurred, and happened on 600 of 14,000 days (4.3%) that HW did NOT occur, then the relative risk for HW is  $RR = 5.81$  ( $25\%/4.3\%$ ), meaning that there is a 5.81x increased risk of an extreme high-SST on days when HW occurs, compared to other days.

### III. RESULTS & DISCUSSION

#### 3.1 – Synoptic Setup Associated with GWTC Air Masses

The GWTC2 AMs are broadly characterized as groupings of cool to warm, dry to humid, seasonal and transitional patterns (Figure 1). The three cool GWTC AMs (HC, C, DC) all exhibit colder than normal air temperatures throughout much of the synoptic-scale domain centered on the Chesapeake Bay (Figure 2), along with northerly wind directions, especially with C and DC (Figure 4). Humid cool (HC) exhibits a particularly unique synoptic setup, with a pronounced north-south SLP gradient across the Mid Atlantic (supplementary material), colder than average temperatures over land, but warmer than average temperatures over ocean; distinctly northeasterly winds, and precipitation within, and just offshore of, the study region (Figures 2-4). The warm GWTC AMs (HW, W, DW) generally exhibit opposite 10-meter wind characteristics to those exhibited by the three cool AMs, with notable southerly components to the wind fields, and higher than normal pressure generally centered off the Atlantic Coast of the US. Warmer than normal air temperatures and anticyclonic flow, particularly with HW, are notable throughout the domain, with slight precipitation falling in association with both HW and W, but not with DW.

Both the Humid (H) and Dry (D) AMs exhibit more nebulous 10-m wind patterns than either of the two sets of AMs noted above. The Humid AM is ushered in via southerly winds with a fetch over the open ocean, while the Dry AM is more a product of offshore, westerly wind directions. The Humid AM shows notable precipitation in the Bay and just offshore, while the Dry AM has little to none within the Bay's watershed. The Seasonal (S) AM tends to show weakly westerly mean air flow, and neutral temperature, pressure, and precipitation

patterns. While the two transitional AMs (CFP, WFP) are less frequent than the other types, they are indicative of a dynamic atmosphere, with CFP showing strong cyclonic flow (associated with a low-pressure center over New England) and offshore wind direction over the Atlantic coastline, while WFP exhibits onshore flow and the greatest amount of average precipitation over the Bay of any of the AMs.

### 3.2 – Air Mass Impacts on Water Characteristics

Across the domain on the whole, AMs are good predictors of surface ocean temperature ( $\eta \approx 0.5$ ) and ocean volume transport ( $\eta \approx 0.4$ ), but poorer predictors of salinity, dissolved oxygen, and SSH, which each exhibit fairly weak domain-wide eta correlations (all  $\eta < 0.29$ ; Table 2). The highest eta-correlations between ROMS water temperatures and AMs are exhibited in the tributaries of the Bay, with  $\eta > 0.6$  throughout most of the higher-order river systems (e.g., the Potomac River, James River, Choptank River), and in the middle to upper bay (Figure 5). These spatial temperature patterns of association inversely mimic water depth; the shallowest regions of the Bay – where the entire water column can interact with the atmosphere above it – are correlated with AMs the most, while deeper regions become increasingly impacted by oceanic processes, and less so by the immediate overlying AM on a daily time scale.

Of the various AMs, HW poses the highest relative risk of any extreme water event, with occurrences of HW being associated with a 6.6x increased risk of an extreme warm water event basin-wide, with W ( $RR = 2.7$ ) and DW ( $RR = 1.7$ ) also showing elevated risks of such events (Table 3) when averaged across the domain. Figure 6 shows that, as would be expected, the three warm AMs are associated with substantially positive anomalous water temperatures, while the three cool AMs are opposite. Generally, the greater anomalies (positive or negative) are exhibited in the upper Bay, though they are still substantial in the southern Bay and into the Atlantic.

The Humid AM and the Dry AM show nearly ubiquitous warm and cool anomalies, respectively, though of much lesser magnitude than the cold or warm AM groups. However, the Humid AM has an interesting dichotomy when examining their associated risk of *extreme events*, with  $RR > 1.0$  out in the Atlantic, but  $RR < 1.0$  in the Bay and its tributaries (Figure 7). The relative shallowness of the Bay likely plays a role in this result, as Humid AMs are accompanied by significant cloud cover and precipitation which likely cool a large percentage of the water column in the shallower Bay, which would lower the risk of extreme spikes in surface water temperatures. While these atmospheric conditions are also present in the open Atlantic with a Humid AM, here, slightly warmer ocean waters from the south are being advected northward, while high-humidity simultaneously prevents evaporative cooling of the surface, and thus, slightly raises the risk of spikes in water temperatures.

While decreasing in frequency in recent decades, cold water events do still occur, and can have severe ecological impacts (Wang et al., 2022; Pirhalla et al., 2015). Interestingly, unlike with the warm types which have varying risk profiles among them, the risk of extreme *cold-water* events are nearly *equally* the result of the three cool AMs: HC ( $RR = 3.2$ ), C ( $RR = 3.5$ ) and DC ( $RR = 3.6$ ). This difference between causes of warm-water events and cold-water events highlights the added value of using the multivariate air mass-based approach herein. For example, during DW AM days, the increased rate of evaporative cooling can offset some

of the radiative heating of the ocean surface, leading to fewer extreme warm-water events with DW by comparison to HW (especially in the shallower bay). However, with cold-water events, while DC has the largest *RR* due to both evaporative cooling and sensible heat loss, HC (and C) also cause a large number of these events via a two-step process: 1) direct conduction of ocean heat to the cooler atmosphere, which then warms the atmosphere; and 2) that slight atmospheric warming lowers the relative humidity below saturation, and induces some additional evaporative cooling of the surface waters as well. The result is anomalously cold water (and risks of cold extremes) across the three cool types is fairly uniform, while anomalously warm waters (and risks of warm water extremes) are much more intense in HW than they are in either of the other two warm AMs.

The spatial distribution of associations between GWTC2-AMs and surface water transport (Figures 8-9) is more spatially nuanced than those with surface water temperatures. The greatest correlations ( $\eta > 0.6$ ) between AMs and v-transport (meridional/along-bay) are noted along the coastline of the Delmarva Peninsula, but the strongest correlations with u-transport (zonal/cross-bay;  $\eta \approx 0.5$ ) are relegated mostly to the shelf. Throughout the domain, all cool and/or dry AMs are associated with anomalously southward v-transport, while, all warm and/or humid AMs are associated with an anomalous northward v-component to water movement (Figure 8). This aligns with the composited 10-m winds associated with each of these AMs: northerly winds with cool AMs, and southerly components of the winds with warm AMs (Figure 4). Extreme northward components of surface transport are most likely with the occurrence of the WFP (*RR* = 6.5) which is the only AM with strong southeasterly winds associated with actual south-to-north flow in the Bay and along the shelf.

Surprisingly, sea-surface heights were only moderately correlated with GWTC-AMs across the domain, with an average eta-correlation of  $\eta \approx 0.3$  when examined across the domain as a whole. However, this fairly low overall correlation belies notable associations with specific individual AMs, and is irrespective of any spatial heterogeneity (Figure 10). For example, one of the highest *RR* of any AM with any water characteristic is that between HC and extreme high SSH events, with *RR* = 4.1. As noted above, the HC air mass is the only AM associated with northeasterly winds on average. Such a wind direction, parallel to the coastline, forces onshore Ekman-induced transport, leading to piling water (as noted with the strong north to south and westward transport association with HC in Figures 8-9) and anomalously high SSH throughout the domain. Combined with ample precipitation that usually accompanies HC (Figure 3), the Ekman-induced high SSHs can also be supplemented with additional mass both via direct rainfall and coastal runoff. Meanwhile, the DC air mass is associated with the greatest risk of extreme *low* SSH events (*RR* = 3.15), which is most notable in the upper Bay. Not only is DC associated with little to no rainfall and strong southeasterly (offshore) winds (coinciding with strong upper-to-lower bay transport that lacks a westward component), but it is nearly always under higher-than-average SLP, which suppresses the ocean water via the inverse barometer effect.

As noted above, other water variables show more irregular correlations with AMs, though region-wide relative risks of some AMs with extreme water events are notable (Table 3), as are nuances of spatial variability. For example, though salinity has a low basin-wide eta correlation with AMs ( $\eta \approx 0.16$ ), there is a notable signal of moderate correlations ( $\eta \approx 0.4$ )

between AMs and salinity gradients extending from just inside the Bay eastward to the shelf. In this area, some AMs (e.g., HW and DC; Figure 11) exhibit average deviations that are  $\approx 1$ -sigma from the mean. Moreover, the three dry AMs (D, DC, and DW) all tend to be associated with an increased risk of extreme high-salinity events (with the DW AM associated with a 62% increase chance of extreme salinity), while the HW ( $RR = 1.67$ ) and H ( $RR = 1.42$ ) air masses are associated with extreme low-salinity events in the Bay (Table 3). Obarein et al. (2023) show that humid GWTC2 AMs are associated with an increased likelihood of rainfall, which would lead to freshwater input into the Bay tributaries and seaward spreading of lower salinity plume water during such weather, while dry AMs would lead to little freshwater input along with substantial evaporation, leaving behind abundant dissolved salts. Indeed, composite analysis of ERA5-based precipitation data (Figure 3) shows HC air masses with nearly 14mm of precipitation on average over the Bay watershed, while DW (and the other two dry) AMs have virtually none. HC is particularly interesting – although it is associated with near-average to anomalously low surface salinity in the upper Bay (especially near the shoreline), HC conditions produce markedly higher-than-average surface salinity near the Bay entrance and over portions of the adjacent shelf. Near the Bay mouth, favorable northeasterly winds promote downwelling-favorable conditions and elevated SSH, driving rapid westward transport of saltier offshore Atlantic surface water into the Bay. Concurrent unseasonably cold air and water temperatures may enhance vertical mixing and the upward entrainment of saltier bottom shelf water, further increasing surface salinity within and near the Bay entrance.

Dissolved oxygen's low basin-wide eta-correlations ( $\eta \approx 0.18$ ) mask substantial regional associations with different AMs (Figure 12). The most notable relationship is somewhat counterintuitive: the cool AMs (especially HC and DC) and CFP are associated with low DO levels throughout much of the Bay, while the warm AMs, (especially W and DW) have higher DO levels. However, due to the seasonally-relative nature of both the AMs and the water characteristics examined herein, these patterns should not be interpreted as simple temperature–oxygen-solubility responses. Instead, AM-related effects on biological activity, circulation, and vertical mixing appear especially important. Notable is the dichotomy between the coastal DO levels and those further into the main stem of the Bay when HW occurs. HW is associated with anomalously low surface DO across some parts of the lower Bay and shorelines, with positive anomalies primarily over the adjacent shelf. HW's warm air temperatures may heat shallow water and sediments while the high humidity limits evaporative cooling, which both act to warm surface waters, reduce oxygen solubility and increase respiration, sediment oxygen demand, and microbial decomposition, thereby lowering surface DO (Breitburg et al., 2018) in these shallower areas. Conversely, the widespread positive anomalies associated with W and DW likely reflects greater solar radiation and photosynthetic oxygen production, together with stronger surface-layer stability that limits entrainment of lower-DO water from below. HC produces the most spatially extensive negative surface-DO anomalies among the core AMs. With HC, extensive cloud cover may suppress photosynthetic oxygen production (via phytoplankton), while the elevated SSH and anomalous Atlantic-to-Bay currents associated with HC may advect the relatively salty/low-DO Atlantic water into some parts of the southwestern Bay, and/or promote upward entrainment from beneath the surface layer. CFP produces an even stronger negative response than HC. Although strong (northwesterly) winds would enhance

atmospheric oxygen exchange, they also increase waves and turbulence, potentially entraining lower-DO subsurface water into the surface layer faster than atmospheric exchange and photosynthesis can replenish it.

#### IV. SUMMARY AND CONCLUSIONS

GWTC2-AM associations with key water conditions in the Chesapeake Bay are significant across many of the water variables analyzed. The three warm GWTC AMs (HW, W, DW) show significant relationships with multiple water variables, including surface volume transport, surface temperature, salinity, and general circulation features, including bay outflow characteristics. Southerly dominant flow is evident in both winds and surface water volume transport along with higher than normal SLP centered off the Atlantic Coast with these three AMs. Pronounced northeastward surface outflow from the Bay to the shelf and increased southwestward bottom flows (supplementary material, Figure S12) are indicative of enhanced Ekman-induced transport and two-way flow circulation. These AMs also suggest some northward dispersal of lower salinity Chesapeake Bay plume water (Figure 11). Moreover, warmer than normal air temperatures associated with HW leads to expected warmer surface waters of the shelf and in the Bay proper (Figure 6).

Meanwhile, the three cool AMs (HC, C, DC) generally exhibit opposite flow characteristics to those of the warm AMs in terms of ocean volume transport, with northerly winds forcing southward volume transport in the surface waters in the Bay. Along the immediate coast, however, westward surface flows (and eastward bottom flows) are noted, indicative of Ekman-transport, especially with HC (Figure 9). As a result, outflow of Bay plume waters is suppressed to the south along the coast (supplementary material, Figure S11). These patterns also suggest reduced dispersal of lower salinity plume water and increased influence of higher ocean salinity in surface waters (Figure 11). Colder than normal air temperatures lead to expected cooler waters along the shelf and in the Bay proper (Figure 6), especially with DC. The unique spatially heterogeneity of HC (versus that of C and DC) is due to the distinct north-to-south, high-to-low pressure gradient across the Mid-Atlantic. This distinct pressure pattern and elongated temperature gradient promotes the stronger than normal westward and southward flow patterns in both winds and ocean volume transport, indicative of downwelling favorable transport, with an increased risk of higher ocean salinity water being advected into the bay. The other two cold AMs (C and DC) are also associated with a strong southward wind component (which promotes some eastward volume transport in surface waters and opposing westward transport in bottom waters via Ekman transport), but also substantial eastward/offshore winds (Figure 4) which act to offset any enhanced saltwater shelf intrusions entering the bay that might otherwise be expected.

The Humid AM and Dry AM exhibit generally weak associations with most variables, with the exception of general volume transport characteristics. Under Humid AM conditions, surface flow tends to be weak or slightly up-Bay, but with moderately enhanced outflow at the Bay mouth. Contrastingly, the Dry AM conditions show stronger down-Bay flow patterns, yet slightly suppressed outflow into the shelf. These AMs (and the Seasonal AM) generally show minimal influences on water temperatures, salinity, DO, or SSH.

The two transitional/frontal AMs (CFP, WFP) of the GWTC2 are much less frequent than the other AMs, but have strong short-term influences on Bay circulation and specific water conditions. These patterns are indicative of strong dynamics of direct offshore and onshore flow for CFP and WFP occurrences, respectively. WFP exhibits the strongest deviations of northward surface volume transport, indicating increased volume and sea surface heights in the upper Bay. CFP exhibits some of the strongest southward surface flow and fairly muted bottom flow characteristics. CFP also has a strong association with (low) DO, as strong winds mix oxygen-rich surface water through the water column. Associations with other water conditions for these transitional types are generally minimal.

Using GWTC2-derived combinations of atmospheric variables as assemblages of *weather situations* has distinct advantages over univariate approaches when evaluating water conditions in the bay, particularly when the drivers have multi-temporal, or co-contributing effects. Considering the strong relationships uncovered herein between AMs and water characteristics in the Chesapeake Bay, planned future work will utilize artificial neural networks (ANNs) in order to model these characteristics throughout the Bay at daily to monthly scales. Once these ANNs are validated, then such models will form the basis for hindcasting physical water characteristics back through 1979 (the start of the GWTC2 dataset), projecting climate change-related influences on the Bay, and eventually, for real-time forecasting. Ultimately, our goal is to merge this weather-water research with historical blue crab data throughout the Chesapeake Bay, including abundance, winter dredge data, summer trawl data, and harvest datasets to help further our understanding of the complex and multivariate associations between atmospheric/oceanic states these vital blue crab population metrics.

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## DECLARATIONS

### Ethics approval and consent to participate

Not applicable. This study did not involve human participants, human data, or animals.

### Consent for publication

Not applicable.

### Availability of data and material

All data necessary to reproduce the analyses presented in this study, along with descriptions of the datasets, are publicly available through Zenodo: Lee, C. and Pirhalla, D. (2026), *GWTC-2 Air Masses & Water Characteristics in Chesapeake Bay*. Zenodo. <https://doi.org/10.5281/zenodo.21462307>.

### Competing interests

The authors declare that they have no competing interests.

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### Author Contributions

C.C.L. conceived and designed the study, conducted the research and analyses, prepared the figures and tables, interpreted the results, and wrote the original manuscript draft. D.E.P. contributed to the scientific background and interpretation of the results and provided substantive review and editing of the manuscript. D.E.P. also served as the primary point of contact for the NOAA-funded project. Both authors reviewed and approved the final manuscript.

# TABLES

**Table 1** – Average monthly frequency of each GWTC2 air mass, 1985-2023.

|      | HC   | H     | HW   | C     | S     | W     | DC   | D     | DW   | CFP  | WFP  |
|------|------|-------|------|-------|-------|-------|------|-------|------|------|------|
| JAN  | 2.8% | 7.8%  | 5.3% | 14.6% | 29.5% | 14.6% | 6.9% | 10.7% | 3.5% | 3.3% | 1.0% |
| FEB  | 3.3% | 6.8%  | 5.6% | 13.4% | 28.9% | 13.8% | 6.7% | 11.8% | 5.9% | 2.9% | 0.9% |
| MAR  | 3.9% | 7.3%  | 6.0% | 11.9% | 27.9% | 15.0% | 6.6% | 11.3% | 5.5% | 3.8% | 0.8% |
| APR  | 3.8% | 11.5% | 5.4% | 10.1% | 30.5% | 15.3% | 4.0% | 11.6% | 4.7% | 2.8% | 0.3% |
| MAY  | 5.3% | 13.1% | 5.4% | 8.5%  | 30.4% | 17.2% | 3.6% | 10.4% | 4.0% | 1.7% | 0.3% |
| JUN  | 5.5% | 17.6% | 5.4% | 8.1%  | 29.6% | 13.9% | 3.0% | 12.6% | 2.9% | 1.3% | 0.2% |
| JUL  | 4.8% | 20.7% | 4.7% | 5.4%  | 28.8% | 15.9% | 3.2% | 10.6% | 4.8% | 0.9% | 0.1% |
| AUG  | 5.3% | 17.8% | 5.7% | 7.1%  | 31.2% | 13.2% | 3.3% | 10.8% | 4.8% | 0.9% | 0.1% |
| SEP  | 2.8% | 19.0% | 5.6% | 10.4% | 31.7% | 13.1% | 3.2% | 8.3%  | 3.2% | 2.7% | 0.0% |
| OCT  | 3.9% | 10.9% | 5.1% | 13.9% | 32.6% | 13.7% | 2.8% | 9.2%  | 4.3% | 3.1% | 0.5% |
| NOV  | 2.8% | 10.2% | 4.9% | 16.5% | 29.8% | 14.2% | 4.2% | 8.4%  | 3.8% | 4.4% | 0.8% |
| DEC  | 3.4% | 8.6%  | 5.8% | 14.2% | 30.2% | 13.8% | 4.9% | 11.3% | 3.3% | 3.2% | 1.3% |
| YEAR | 4.0% | 12.6% | 5.4% | 11.2% | 30.1% | 14.5% | 4.4% | 10.6% | 4.2% | 2.6% | 0.5% |

**Table 2** – Domain-wide averaged eta-correlation ( $\eta$ ) between GWTC air mass and each of the ROMS water variables of interest at the surface water layer.

| ROMS        | eta-corr |
|-------------|----------|
| Temp        | 0.467    |
| Salinity    | 0.158    |
| Oxygen      | 0.184    |
| U-transport | 0.354    |
| V-transport | 0.432    |
| Zeta        | 0.277    |

**Table 3** – Domain-wide averaged relative risk (RR) of extreme high (top; >95th percentile) and extreme low (bottom; <5th percentile) water events, by air mass (columns) and water variable (rows). Increasingly darker shades of red indicate greater RRs (RR=1.00 is unity), and increasingly darker shades of green indicate lower RRs.

|             | HC   | H    | HW   | C    | S    | W    | DC   | D    | DW   | CFP  | WFP  |
|-------------|------|------|------|------|------|------|------|------|------|------|------|
| Temp        | 0.10 | 0.98 | 6.63 | 0.07 | 0.37 | 2.73 | 0.12 | 0.43 | 1.74 | 0.87 | 0.00 |
| Salinity    | 1.13 | 0.82 | 0.92 | 1.17 | 0.84 | 0.83 | 1.35 | 1.30 | 1.62 | 0.91 | 0.85 |
| Oxygen      | 0.64 | 1.09 | 0.92 | 0.77 | 1.31 | 1.33 | 0.60 | 0.82 | 1.10 | 0.36 | 0.46 |
| U-transport | 0.54 | 0.77 | 2.67 | 0.94 | 0.47 | 1.72 | 1.35 | 0.76 | 1.38 | 3.41 | 0.35 |
| V-transport | 0.51 | 1.76 | 4.84 | 0.15 | 0.52 | 1.92 | 0.09 | 0.35 | 0.87 | 0.55 | 6.49 |
| Zeta        | 4.14 | 1.38 | 0.35 | 1.88 | 1.05 | 0.38 | 0.69 | 0.36 | 0.14 | 0.62 | 0.79 |

|             | HC   | H    | HW   | C    | S    | W    | DC   | D    | DW   | CFP  | WFP  |
|-------------|------|------|------|------|------|------|------|------|------|------|------|
| Temp        | 3.16 | 0.59 | 0.10 | 3.54 | 0.67 | 0.17 | 3.66 | 0.81 | 0.17 | 0.57 | 0.74 |
| Salinity    | 1.03 | 1.42 | 1.67 | 0.81 | 0.99 | 1.24 | 0.54 | 0.55 | 0.72 | 1.03 | 1.07 |
| Oxygen      | 1.82 | 1.18 | 1.48 | 1.21 | 0.79 | 0.75 | 1.25 | 0.90 | 0.72 | 1.73 | 0.72 |
| U-transport | 3.63 | 1.29 | 0.23 | 1.63 | 1.13 | 0.42 | 0.93 | 0.66 | 0.19 | 0.19 | 3.01 |
| V-transport | 2.28 | 0.46 | 0.12 | 2.57 | 0.79 | 0.20 | 3.45 | 1.16 | 0.42 | 1.82 | 0.06 |
| Zeta        | 0.26 | 0.68 | 0.87 | 1.21 | 0.59 | 1.39 | 2.99 | 1.28 | 1.55 | 0.88 | 1.15 |

FIGURES

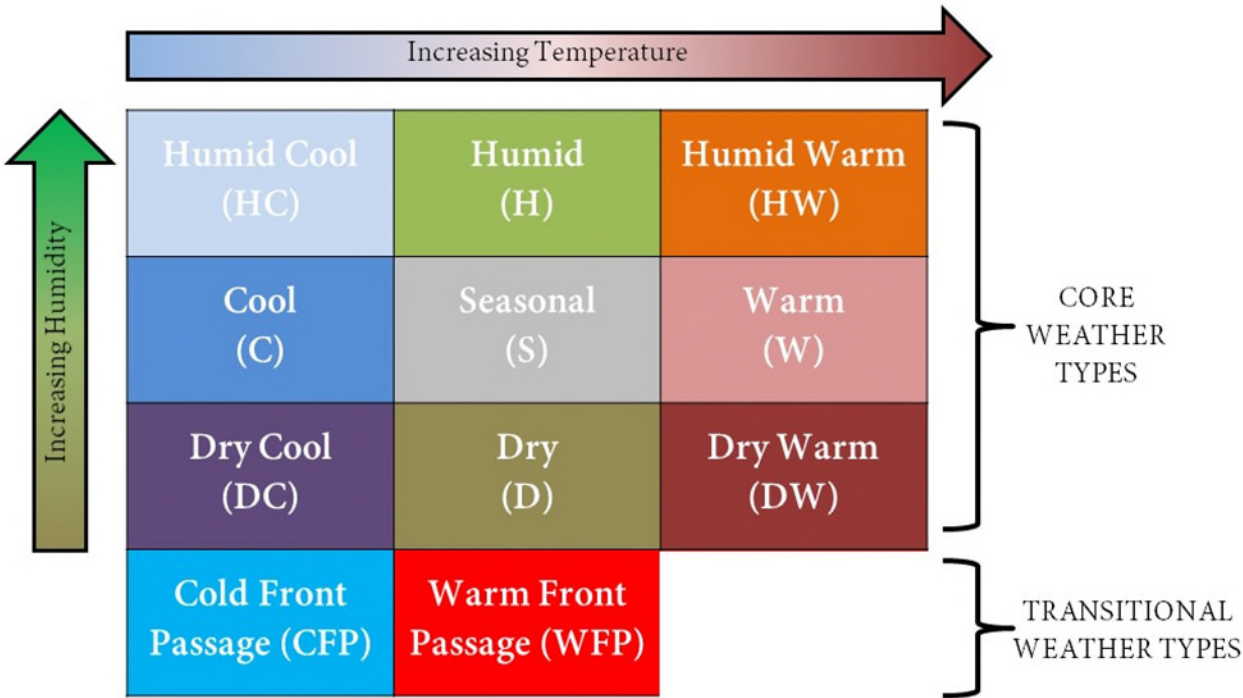
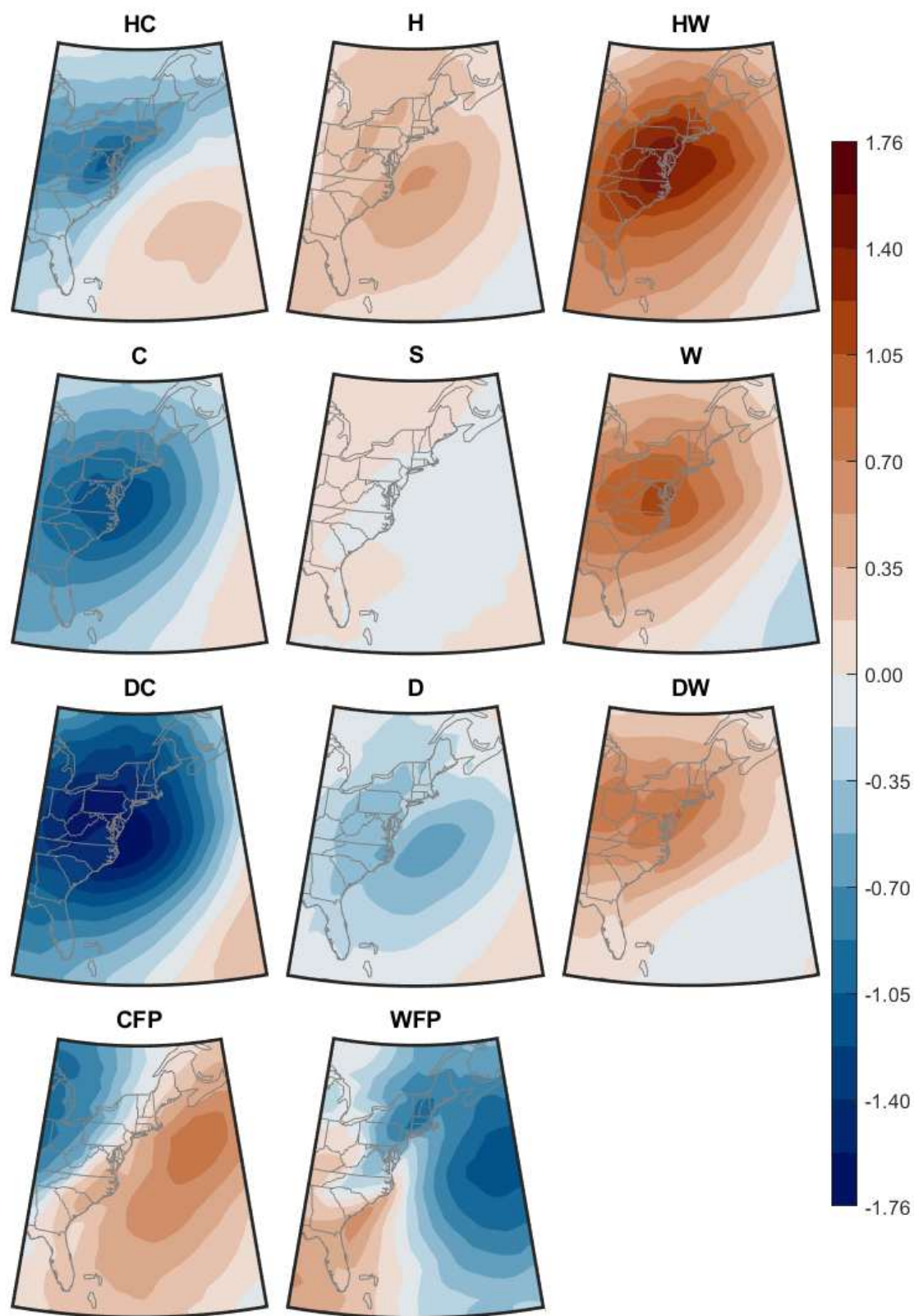


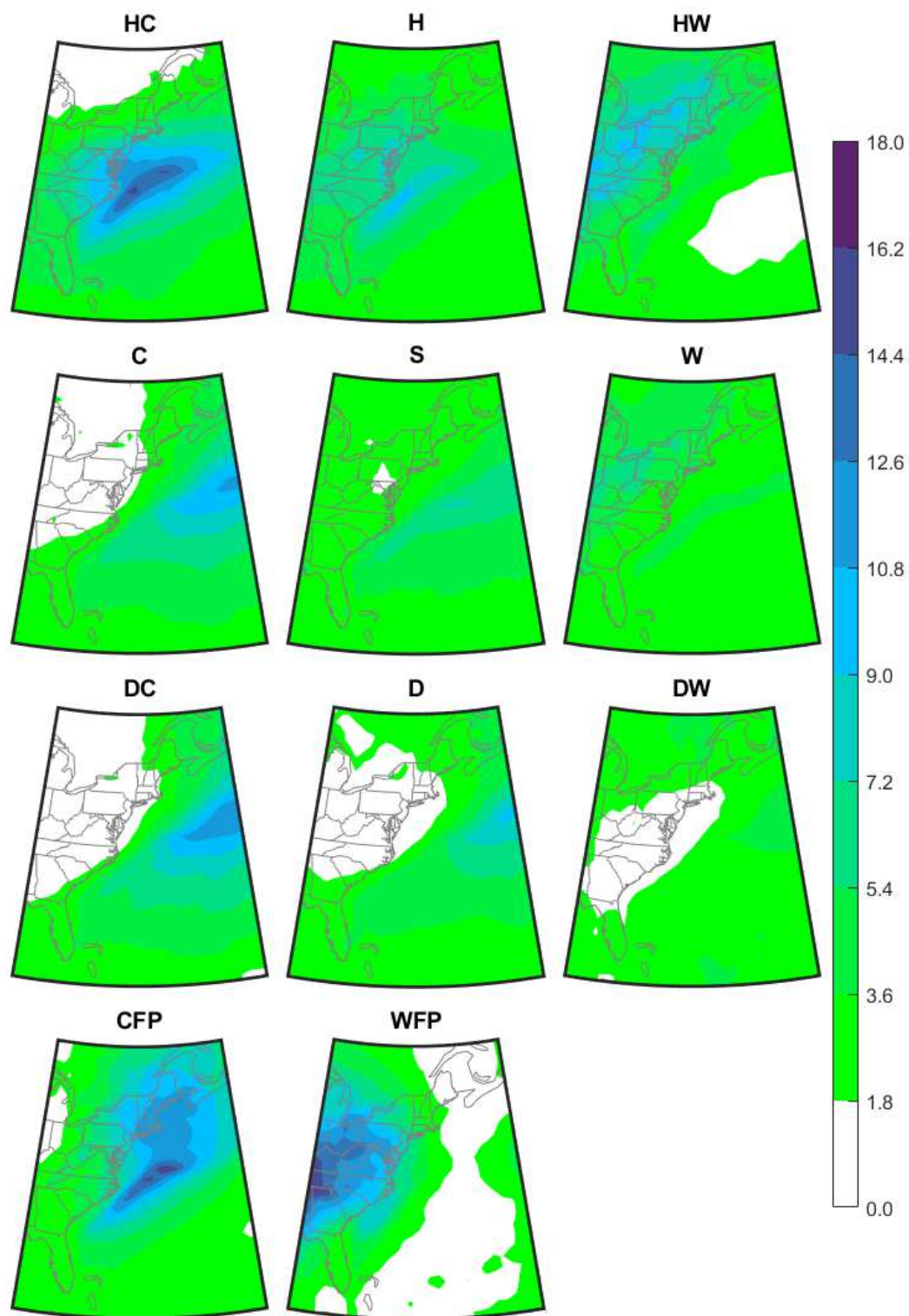
**Figure 1** – GWTC2 air masses (modified from Lee 2026 website) and common abbreviations.



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568 **Figure 2** – Average standardized deseasonalized anomalies (i.e., deseasonalized z-scores) for 2m  
 569 temperature for each of the GWTC air masses.

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571

572 **Figure 3** – Average daily precipitation (in millimeters) for each of the GWTC air masses.

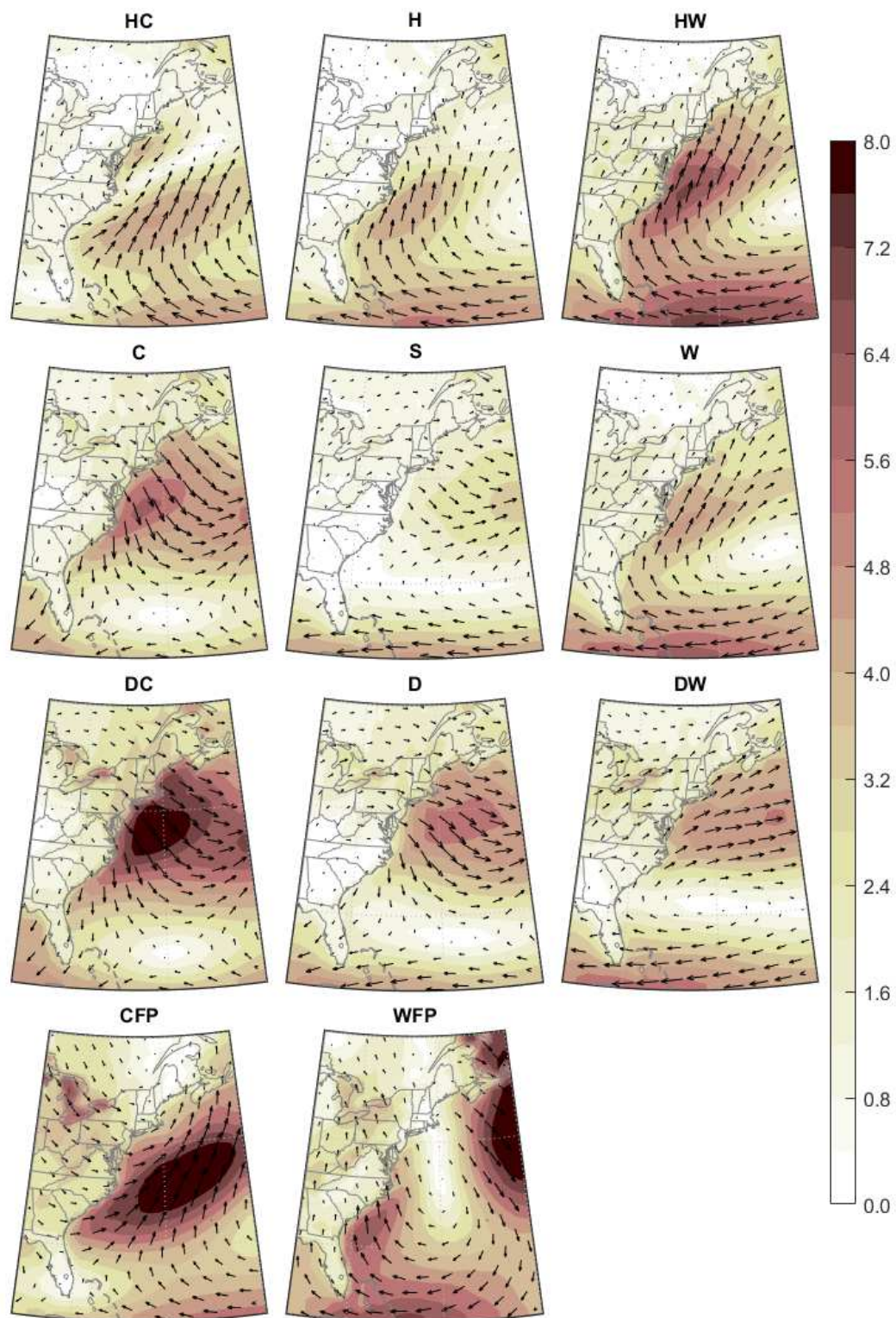


**Figure 4** – Average 10m wind speed (colors, in m/s) and direction (arrows) for each of the GWTC air masses.

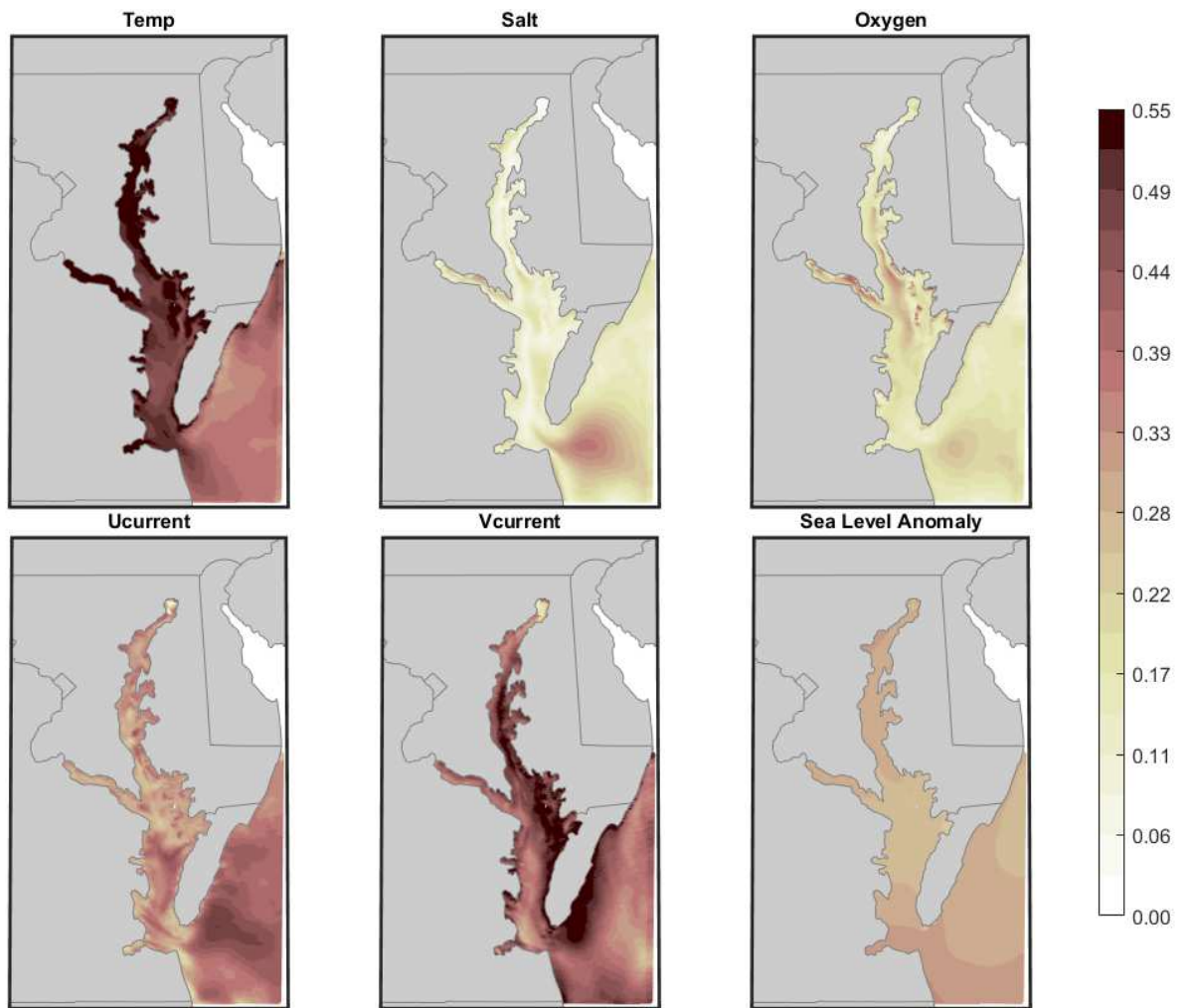


**Figure 5** – Average eta-correlation ( $\eta$ ) between GWTC air masses and each of the deseasonalized anomalies of the surface water variables

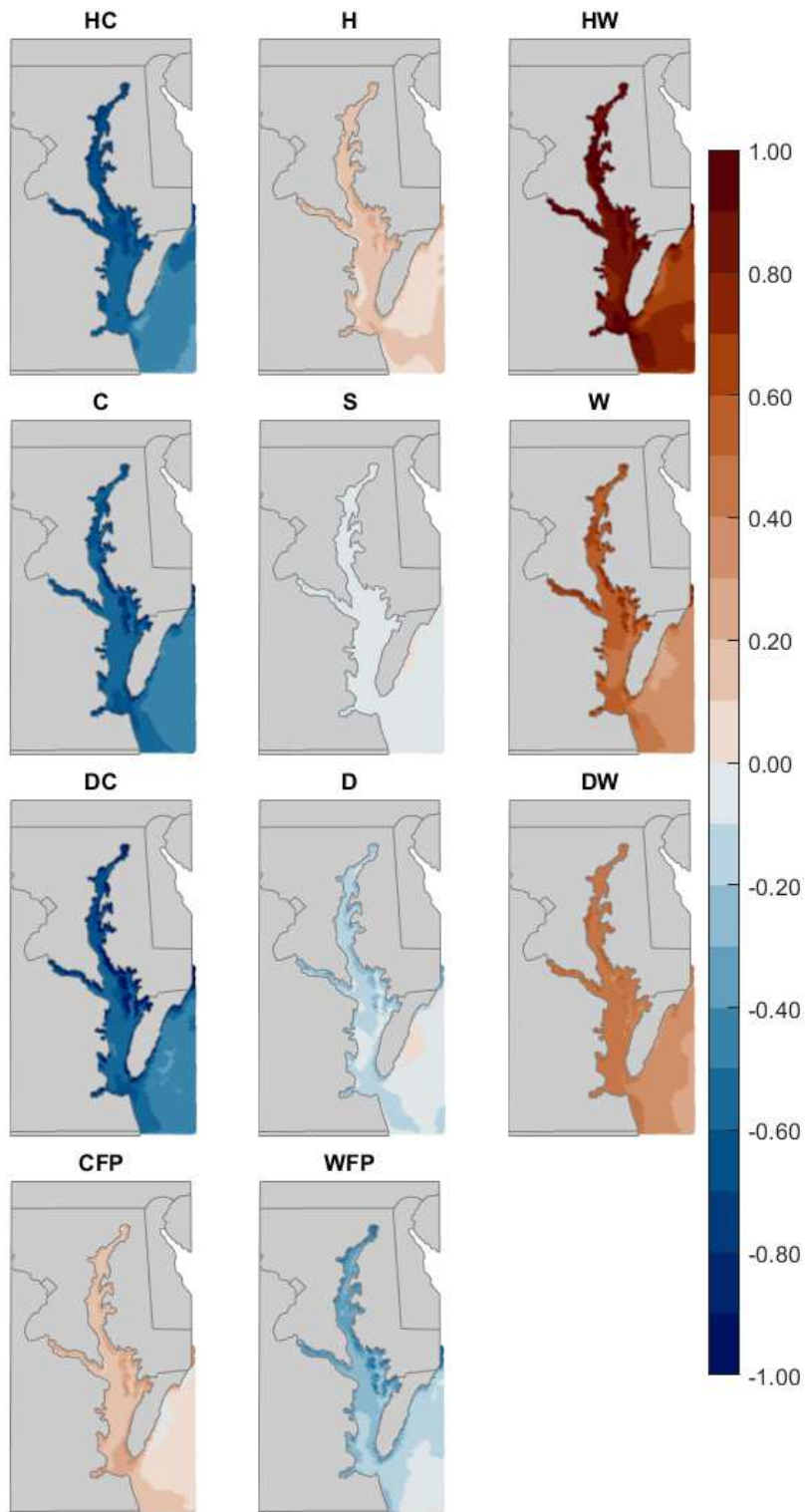


**Figure 6** - Average standardized deseasonalized anomalies (i.e., deseasonalized z-scores; in sigma units) for surface water temperature for each of the GWTC air masses.

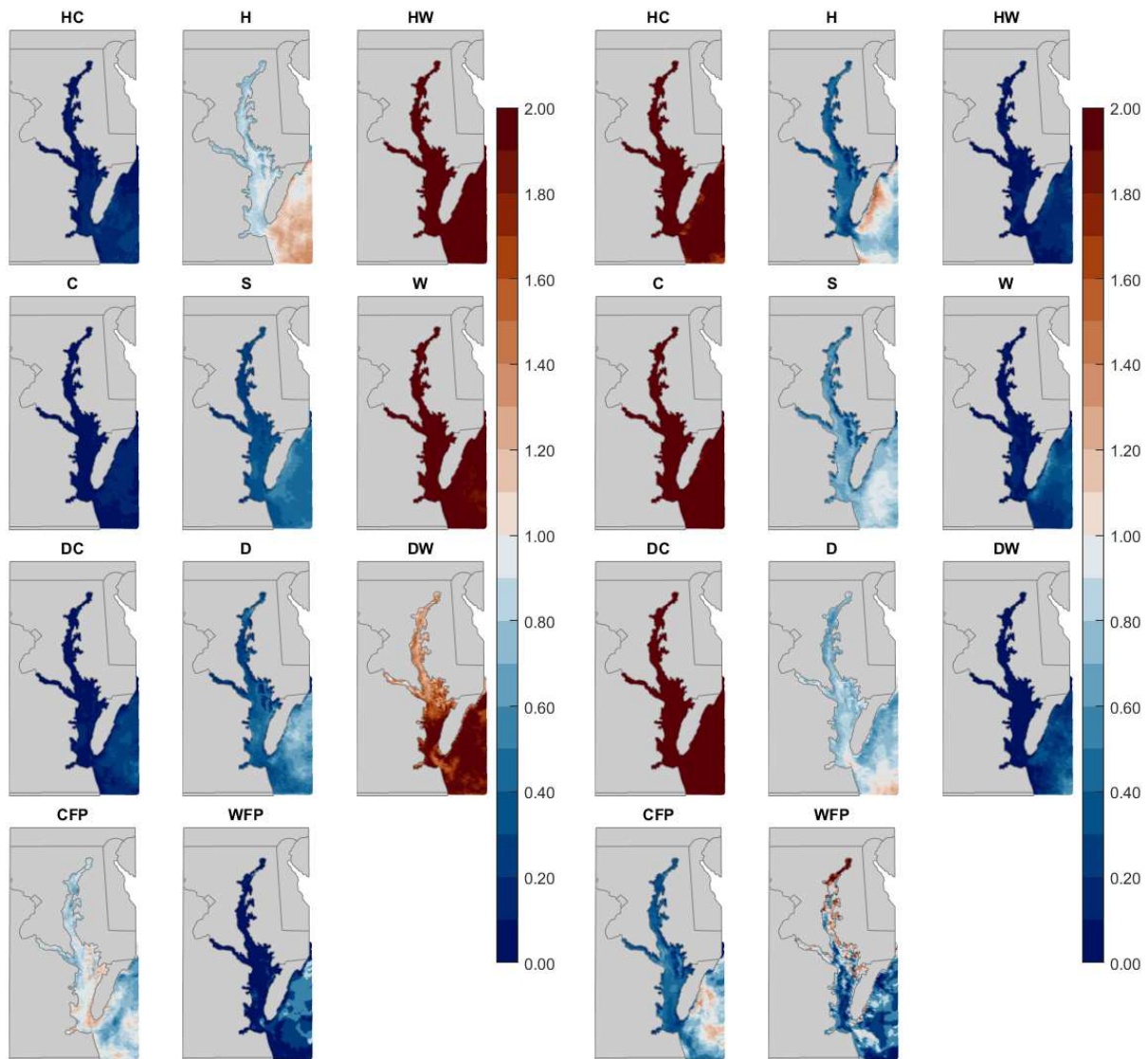


**Figure 7** - Relative risk (RR) of an extreme high (left; >95th percentile) and low (right; <5th percentile) surface water temperature event when each of the GWTC air masses occurs.

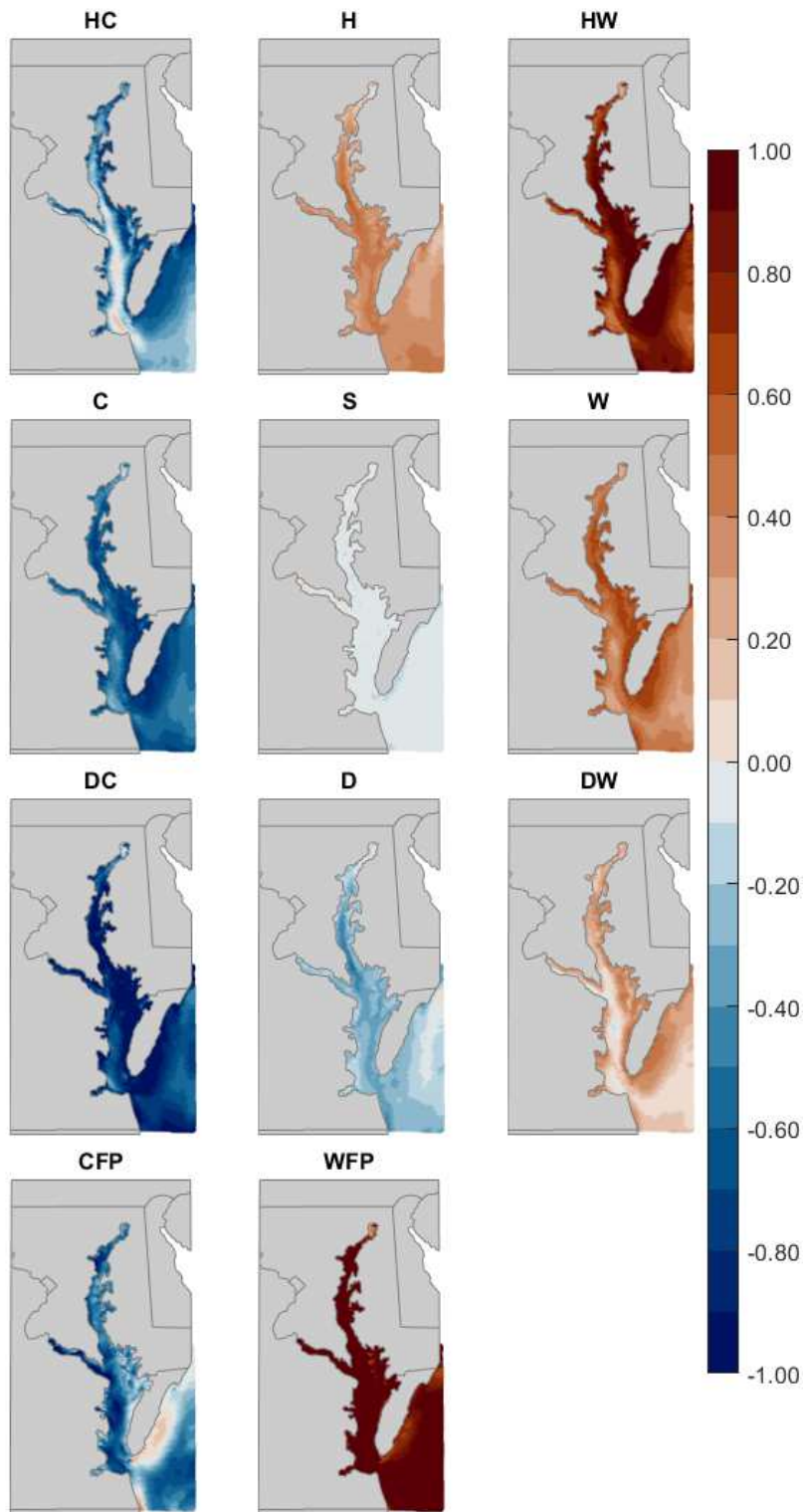


**Figure 8** – Same as Figure 6, except for meridional ( $v$ ) surface ocean volume transport.

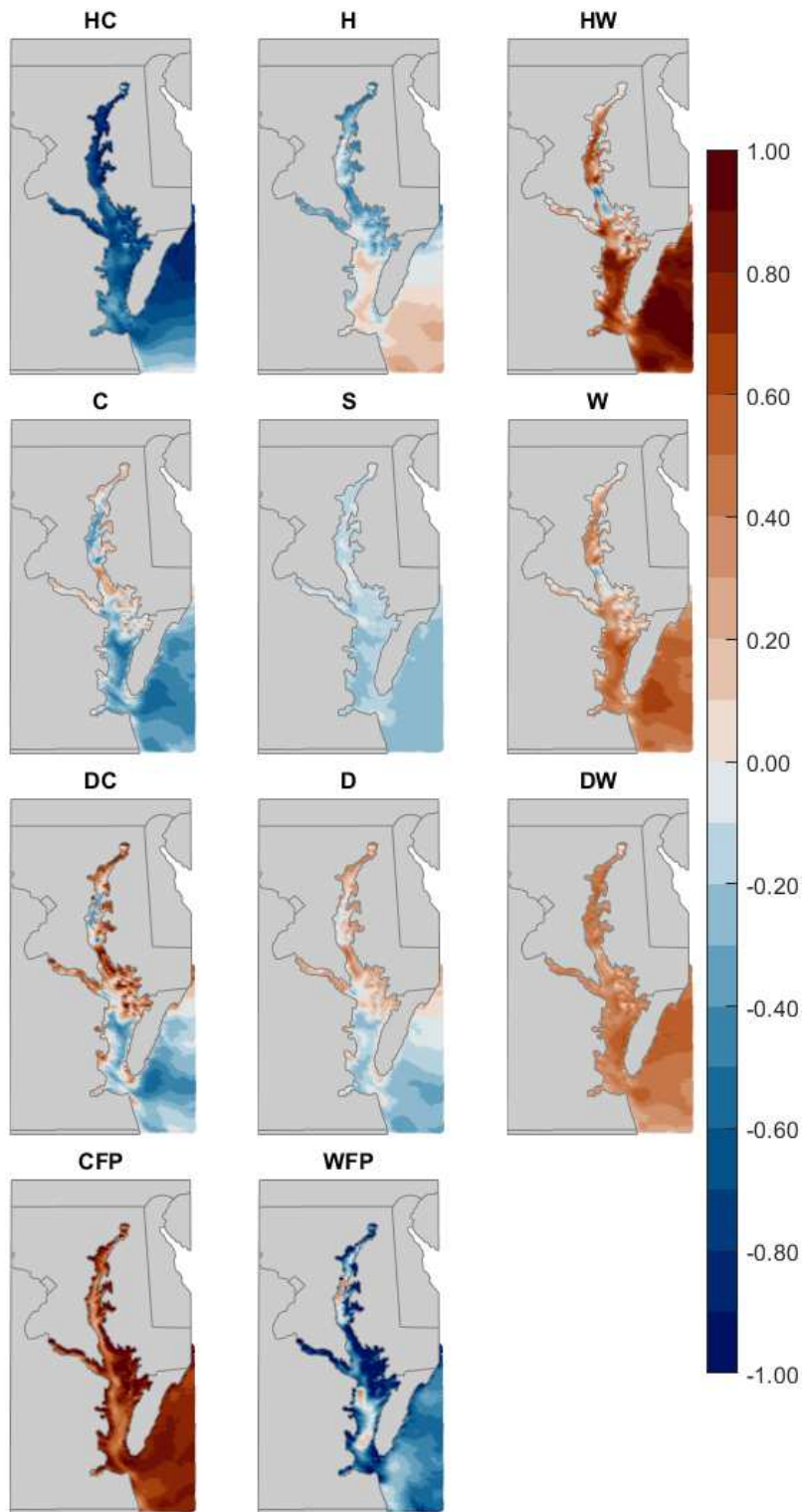


**Figure 9** – Same as Figure 6, except for zonal ( $u$ ) surface ocean volume transport.

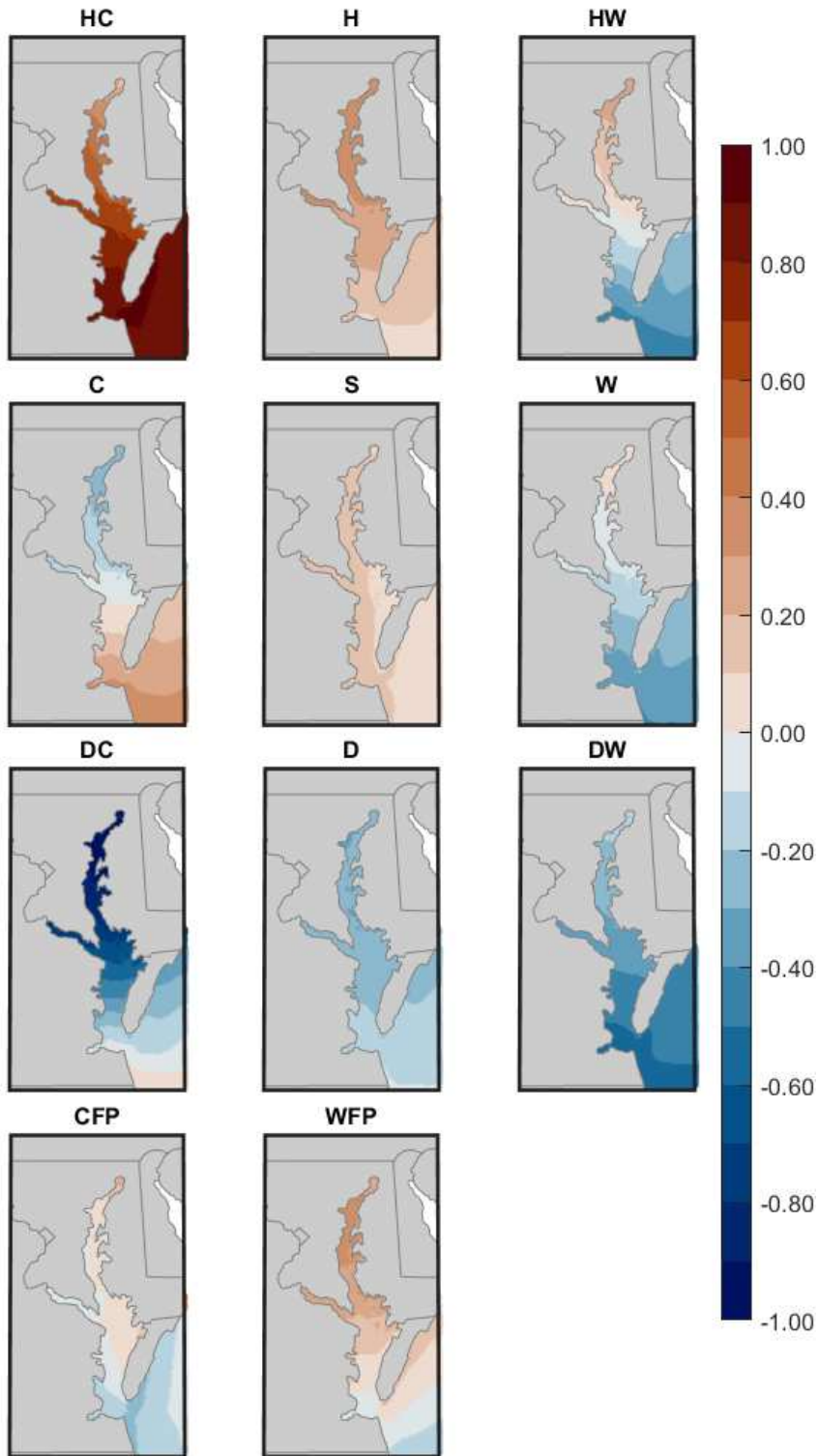


**Figure 10** – Same as Figure 6, except for sea surface height (zeta).

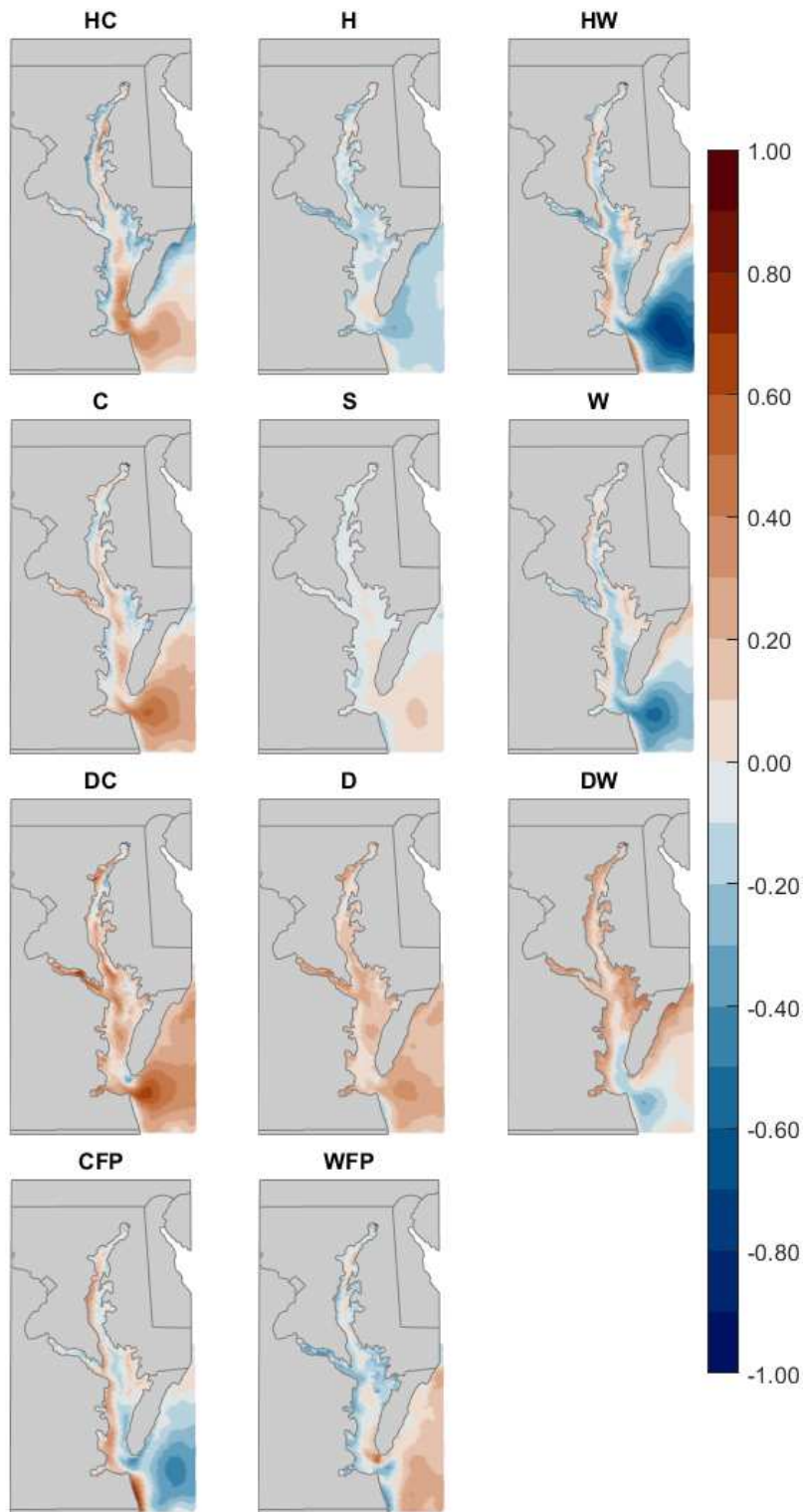


**Figure 11** – Same as Figure 6, except for surface salinity.

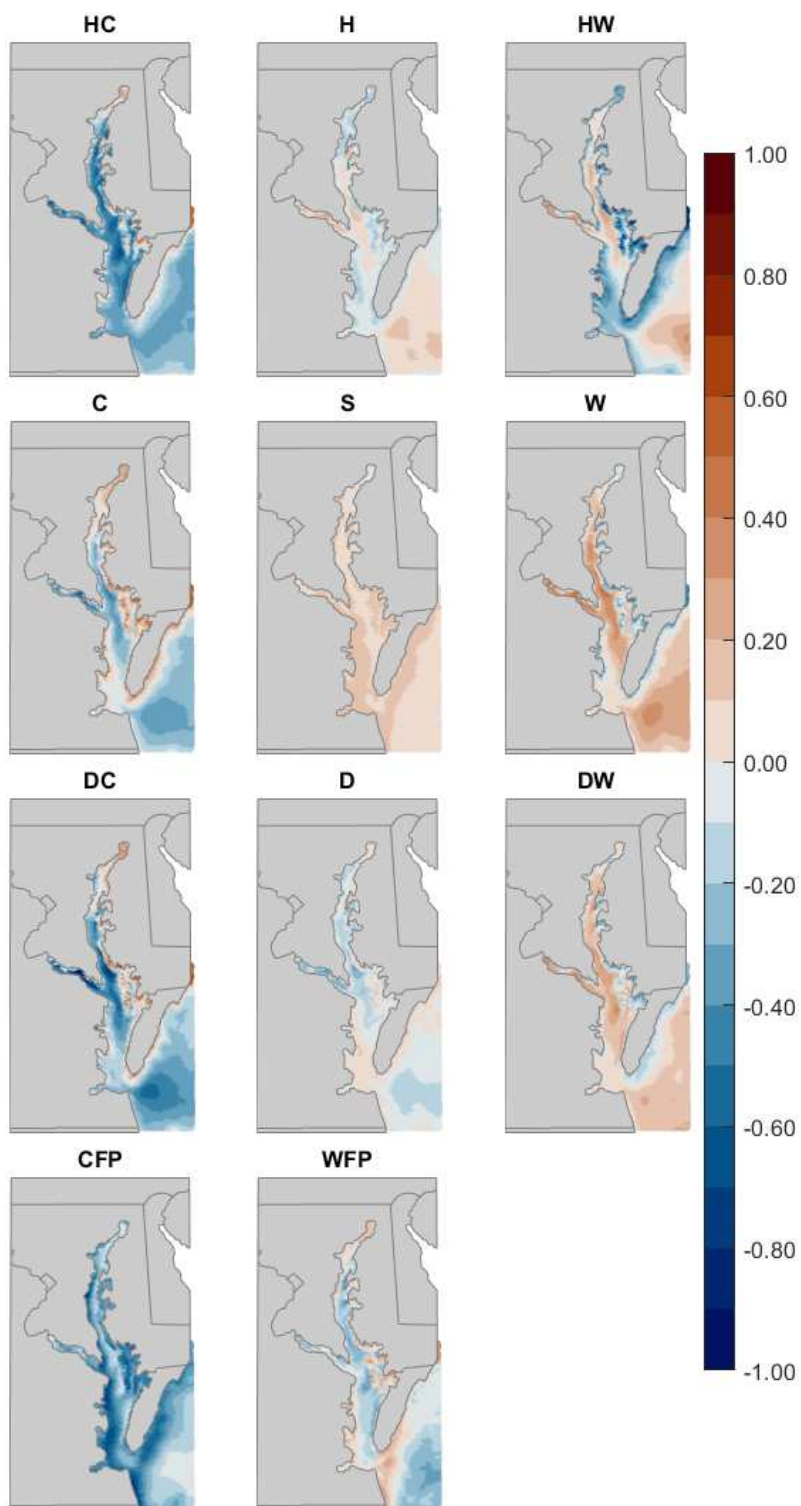


**Figure 12** – Same as Figure 6, except for surface dissolved oxygen.