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Climate relationships to fecal bacterial densities in Maryland shellfish harvest waters

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ABSTRACT

Coastal states of the United States (US) routinely monitor shellfish harvest waters for types of bacteria that indicate the potential presence of fecal pollution. The densities of these indicator bacteria in natural waters may be related to climate in several ways, including through runoff from precipitation and survival related to water temperatures. The relationship between interannual precipitation and air temperature patterns and the densities of fecal indicator bacteria in shellfish harvest waters in Maryland's portion of the Chesapeake Bay was quantified using 34 years of data (1979–2013). Annual and seasonal precipitation totals had a strong positive relationship with average fecal coliform levels ($R^2 = 0.69$) and the proportion of samples with bacterial densities above the FDA regulatory criteria ($R^2 = 0.77$). Fecal coliform levels were also significantly and negatively related to average annual air temperature ($R^2 = -0.43$) and the average air temperature of the warmest month ($R^2 = -0.57$), while average seasonal air temperature was only significantly related to fecal coliform levels in the summer. River and regional fecal coliform levels displayed a wide range of relationships with precipitation and air temperature patterns, with stronger relationships in rural areas and mainstem Bay stations. Fecal coliform levels tended to be higher in years when the bulk of precipitation occurred throughout the summer and/or fall (August to September). Fecal coliform levels often peaked in late fall and winter, with precipitation peaking in summer and early fall. Continental-scale sea level pressure (SLP) analysis revealed an association between atmospheric patterns that influence both extratropical and tropical storm tracks and very high fecal coliform years, while regional precipitation was found to be significantly correlated with the Atlantic Multidecadal Oscillation and the Pacific North American Pattern. These findings indicate that management of shellfish harvest waters should account for changes in climate conditions and that SLP patterns may be particularly important for predicting years with extremely high levels of fecal coliforms.

1. Introduction

Shellfish harvest in many coastal areas may be restricted due to high levels of fecal bacteria in the surrounding waters or shellfish tissues. Although these fecal indicator bacteria may rarely be pathogenic themselves (Walters et al., 2007; Wilkes et al., 2011), their presence in shellfish waters acts as an indicator of fecal pollution and an increased risk of shellfish being contaminated with human pathogens (Ashbolt et al., 2001; EPA, 1986; Wilkes et al., 2011), though the strength of this relationship has been questioned (Wade et al., 2003).

Bivalve shellfish (such as oysters and clams) contaminated with human pathogens represent a significant risk to humans. For example, the consumption of shellfish contaminated with pathogenic *Vibrio* bacteria has caused documented illnesses in Japan, Canada, Australia and the US, and likely many more undocumented cases worldwide (FAO, 2011) Estimates for the annual number of *Vibrio parahaemolyticus* cases specifically from oyster consumption range from 66 in Japan to 186 in Canada (FAO, 2011). In the US, *Vibrio* bacteria in shellfish accounted for thousands of human illnesses over the period of 1996–2010, including hundreds of hospitalizations and about 70 deaths (Newton et al., 2012). The economic impact from these waterborne and foodborne related illnesses is significant, with total annual costs for the US estimated

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at roughly $350 million (Ralston et al., 2011). These are also relevant concerns in the Chesapeake Bay where pathogens of human health concern, such as species of *Vibrio*, *Clostridium*, *Klebsiella*, and *Salmonella* have been isolated from Bay waters and shellfish (Sayler et al., 1975; Morgan et al., 1976). *Vibrio* species found in the Bay are naturally occurring aquatic pathogens and generally are not considered aligned with land-based sources.

To prevent consumption of shellfish contaminated with human pathogens, US coastal states conduct sanitary surveys and monitor surface waters in shellfish harvest areas for bacterial indicators of fecal pollution, in accordance with the National Shellfish Sanitation Program Guide for the Control of Molluscan Shellfish, 2013 revision, the federal/state cooperative program recognized by the US Food and Drug Administration (FDA) (FDA, 2013), and the Interstate Shellfish Sanitation Conference. With more than 1000 historic oyster beds and numerous areas of clam harvest, Maryland officials routinely conduct shoreline surveys for roughly 5650 km of shoreline, looking for and assessing pollution sources, and monitor over 5000 square kilometers of waters for indicator bacteria. In Maryland, the Department of Environment (MDE) measures fecal coliform bacteria densities at several hundred shellfish harvesting and sewage outfall areas, at least once per month. If the bacterial densities exceed the criteria, the State will close the shellfish beds for harvest and work to identify ways to mitigate fecal bacterial levels in those waters. Currently, most Maryland tributaries to the Chesapeake Bay have at least some portion of their shellfish grounds restricted to harvest (MDE, 2014).

The density and distribution of fecal indicator bacteria and associated pathogens in natural waters, such as shellfish harvest waters, may be linked to climate through regional weather patterns, especially rainfall. The relationship between precipitation, indicator bacteria, and pathogens has been noted in a number of other studies (Mallin et al., 2001). Curriero et al. (2001), for example, found that most waterborne disease outbreaks in the US follow large precipitation events. In addition, fecal coliform concentrations at beaches are often related to rainfall (Ackerman and Weisberg, 2003; Kelsey et al., 2004). In a study of fecal coliform densities at shellfish areas in Galveston Bay, Texas, years with higher amounts of precipitation tend to have higher fecal coliform counts (Jensen and Su, 1992). Because of this relationship between rainfall and fecal bacteria, in US coastal states, rainfall greater than a specified height (e.g. one inch) is a standard that may be used to trigger the closure of shellfish beds in waterbodies where the runoff of fecal bacteria appears to coincide with rain events (FDA, 2013).

Other important factors that affect the presence and survival of indicator bacteria in coastal waters are water temperature (Howell et al., 1996) and salinity (Goyal et al., 1977), which both may be related to climate variability. For example, a small number of studies found water temperatures were negatively correlated with fecal bacterial levels (Chigbu et al., 2005; Burkhardt et al., 2000) and salinity (Chigbu et al., 2004). In addition, fecal bacteria have been found to survive in benthic sediments (Anderson et al., 2005; Davies et al., 1995) and have a positive relationship with total suspended solids, suggesting that winds can act to resuspend benthic sediments and increase fecal coliform densities in shallow waters (Howell et al., 1996).

These linkages of indicator bacteria levels to regional (i.e. synoptic (Barry, 2005)) climate patterns may be described, in part, by larger scale climate phenomena. For example, Lipp et al. (2001b) found that fecal indicator organisms in a Florida estuary became more widespread during winter and fall when precipitation rates increased and noted that this trend occurred during an El Niño event. In the Chesapeake Bay, large-scale climate patterns have been reduced to synoptic climate patterns which have been statistically linked to dynamics in nutrients and phytoplankton (Miller and Harding, 2007), zooplankton communities (Kimmel et al., 2006), and fish populations (Wood, 2000). In addition to effects from climate variability, the potential for climate change to impact important ecological conditions in the Chesapeake Bay appears likely (Najjar et al., 2010), including changes to factors that may influence the introduction of indicator bacteria, such as the magnitude and timing of precipitation, streamflow, and storm-related runoff.

The goal of this paper is to better define the potential relationship of climate and fecal bacteria in Maryland waters of the Chesapeake Bay. The focus is not on the ability to predict individual observations of surface water fecal coliform concentrations or to define as many drivers of fecal pollution as possible, but to understand the more global impact of climate patterns on densities of these indicators bacteria. The specific objectives of this study are to 1) assess the relationship of annual and seasonal precipitation and air temperature patterns to average annual and seasonal fecal coliform densities in shellfish harvest waters of Maryland's portion of the Chesapeake Bay, 2) examine climate relationships to indicator bacteria concentrations within individual rivers and bays, 3) identify within-year patterns of precipitation associated with years of high fecal coliform concentrations, and 4) identify dominant climate patterns corresponding to periods of high precipitation and fecal coliform concentrations.

2. Materials and methods

2.1. Station and time period selection

The Maryland Department of Environment (MDE) has collected surface water samples at shellfish harvest areas since the 1950s. However, monitoring stations for shellfish waters in Maryland have been added and removed over time. Therefore, a subset of monitoring stations that have been continuously sampled were selected for our analysis. A significant change in the number and locations of sampling stations occurred in 1978 and 1979, making that a necessary time period to begin our analysis. Although the Maryland Department of Environment attempts to sample each station twice a month, year-round, weather and other logistics often result in missed sampling events. For the purposes of this study, we considered any station as continuously monitored if it had been sampled at least four months out of each year from 1979 to the 2013, with at least six samples for each year. Even within this subset, there were a number of stations missing several years of data, though these gaps did not tend to overlap for a large number of stations in any particular year. Therefore, stations were included that had no more than four non-contiguous years in which no samples were collected. These criteria resulted in the selection of 355 continuous sampling stations, which included most of the rivers and bays of Maryland Chesapeake Bay waters (Fig. 1).

2.2. Fecal indicator bacteria data

Surface water estimates of fecal coliform bacteria densities from the selected stations were obtained from an existing MDE database. These data were generated in a consistent manner for the entire period of sample collection, using the three-tube broth dilution protocol as recommended by the American Public Health Association (APHA, 1998) and FDA (FDA, 2013). Data were excluded from the analysis if they were from targeted sampling around specific weather events or samples collected from more than 1 m below the surface of the water.

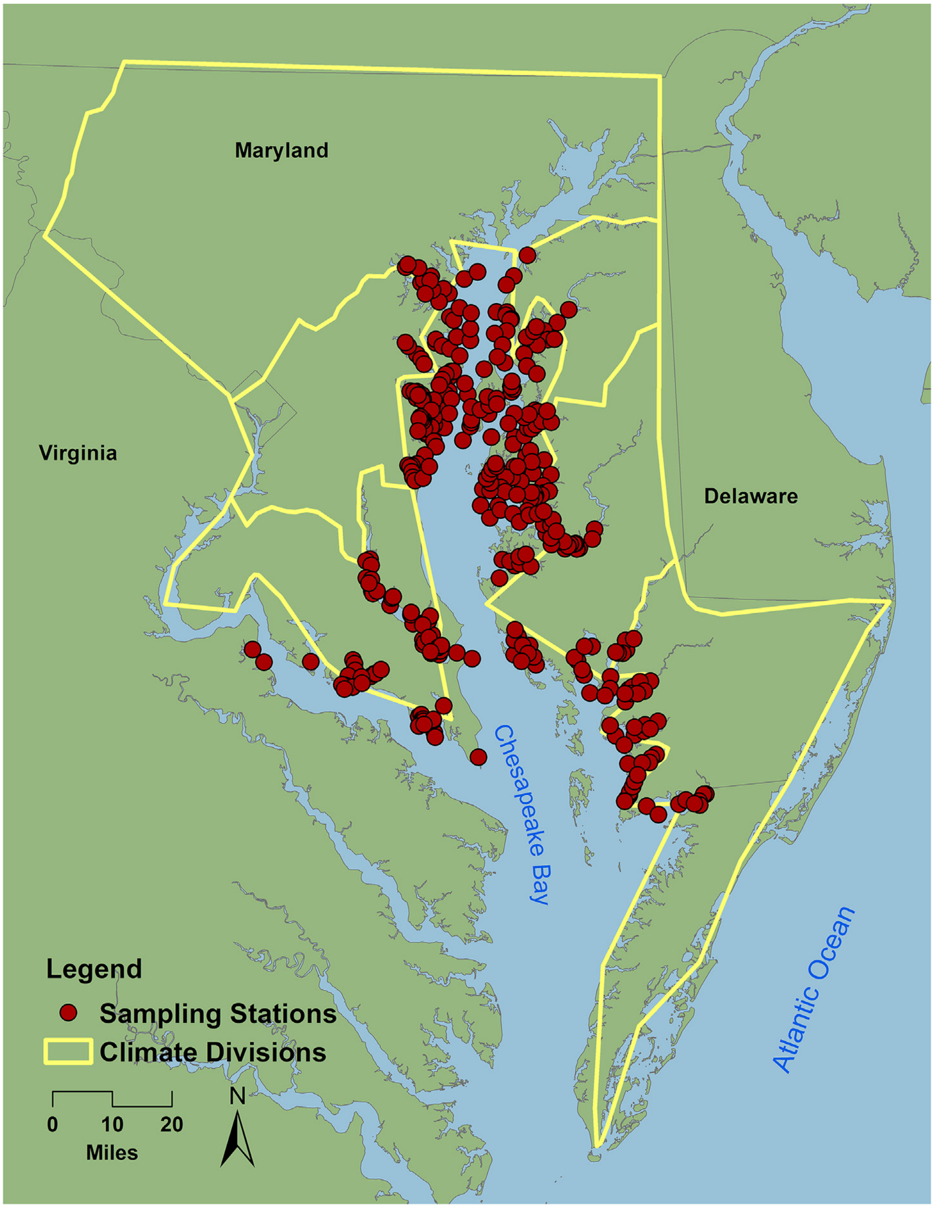

Fig. 1. Climate divisions (polygons) and sampling stations (circles) used in our analyses.

2.3. *Climate data*

Precipitation and air temperature data were obtained from the National Climatic Data Center (NCDC) (www.ncdc.noaa.gov) for the same time period as the fecal coliform data. Monthly NCDC Climate Division data, aggregated from national weather service stations, were used because they capture weather conditions within geographic regions, called divisions. The data represent aggregated information from multiple National Weather Service stations within each division. The five climate divisions that cover Maryland's portion of the Chesapeake Bay were selected (Fig. 1). NCDC reports climate division data as monthly total precipitation in inches and monthly average air temperature in degrees Celsius. In order to summarize conditions over the region, precipitation and air temperature values were first averaged between the five geographic divisions by month. For each year and season, the sum of monthly precipitation values, the average of monthly air temperatures, and the maximum of the monthly air temperatures were then calculated.

2.4. *Sea level pressure patterns and teleconnections*

Monthly sea level pressure (SLP) data were obtained from the Earth System Research Laboratory (ESRL) (www.esrl.noaa.gov) in the form of 'reanalysis' data, which has undergone a quality control process (Kalnay et al., 1996). Values for climate teleconnection indices, such as the North Atlantic Oscillation, were obtained from the National Centers for Environmental Prediction (www.ncep.noaa.gov). In order to identify differences in the SLP between years with very high fecal coliform counts and rainfall amounts and the long-term average for SLP, the three years with both the highest precipitation levels and highest fecal coliform concentrations were each compared to the average condition for all other years (1979–2013). These three years (1979, 1996, and 2003) were selected because the fecal coliform levels were notably higher than other years and therefore of the greatest relevance to natural resource managers. Average annual SLP data for each year of the three years of greatest rainfall were compared to the long-term average for the base period 1979–2013 to generate climate anomalies.

2.5. Analysis

2.5.1. Comparison of interannual variability in fecal coliforms and climate factors

In order to examine the relationship of fecal coliforms in surface waters to precipitation and air temperature patterns, three endpoints for evaluation of trends in fecal coliform densities were selected. Densities were reported in Most Probable Numbers (MPN) which represents an estimate of the number of viable fecal coliforms in a particular volume of water based on replicated culture methods (APHA, 1998). The average fecal coliform MPN/100 mL of water, within the geographic region and time period of interest, the proportion of samples with densities exceeding the FDA criteria (FDA, 2013) of 14 MPN/100 mL, and the proportion exceeding the FDA criteria of 49 MPN/100 mL were examined. The 14 and 49 MPN/100 mL criteria were established to compare against the geometric mean and 90th percentile, respectively, of fecal coliform densities from individual monitoring stations over time (FDA, 2013). Both FDA criteria were considered in order to compare the effect of climate variables on both high and low level exceedances. Because average air temperature has increased over this region during the time period examined, annual air temperature and fecal coliform densities were compared with and without their long term trends. Detrending was accomplished by regressing fecal coliforms and air temperature separately against year and then using the residuals associated with each for further comparison.

2.5.2. Seasonal comparison of fecal coliforms and climate variables

Because data from times of the year are considered when regulating shellfish harvest, we examined seasonal trends. Seasons were classified as follows: December through February as winter, March through May as spring, June through August as summer, and September through November as fall.

2.5.3. Comparison of fecal coliforms and climate variables within different rivers

When considering geographic trends, bacterial monitoring stations were grouped within geographic regions as defined by MDE, and regions that contained less than five sampling stations were excluded from our analysis in order to limit the potential influence of single stations and the inherent spatial variability of environmental data. Each MDE region was compared to the nearest NCDC climate division, except for the stations in the mainstem of the Bay which were compared to aggregated climate data for all five divisions.

2.5.4. Statistical and geospatial methods

All tests for correlation were Pearson tests, as opposed to Spearman correlations, because plots of the raw data suggested that approximately linear relationships existed between fecal coliform levels and the climate variables. Linear regression models using various combinations of total annual precipitation, average annual air temperature, and air temperature of the hottest month against average annual fecal coliform densities, the proportion of samples over the 14 MPN/100 mL criteria and the proportion of samples over the 49 MPN/100 mL criteria were compared using adjusted R^2 values. Akaike's Information Criteria (AIC) and AIC weight were also calculated to inform model selection (Wagenmakers and Farrell, 2004). A visual comparison of residuals versus predicted values, and a visual comparison of predicted and observed values were used to evaluate the linearity and heteroscedasticity of each model. Cluster analysis was conducted using Ward's minimum-variance method, which attempts to assign observations to clusters by minimizing the within-group variance (Ward, 1963). All statistical test results were considered significant with a p-value of 0.05 or less.

ArcGIS (ESRI, Redlands, CA) was used to produce layered maps of monitoring stations and NCDC climate divisions. All statistical tests were done using SAS (SAS Institute, Inc., Cary, NC). Analyses of sea level pressure and wind vector data, and the generation of climate anomaly maps were conducted using NCAR (National Center for Atmospheric Research) Command Language (NCL) (www.ncl.ucar.edu).

3. Results

3.1. Annual comparison of indicator bacteria to climate factors

Interannnual trends between fecal coliform densities (Fig. 2, Panel A) and the proportion of samples exceeding the FDA criteria (Fig. 2, Panel C and D) are well correlated ($p < 0.001$) to patterns of total annual precipitation (Table 1). The average annual air temperature and the average air temperature of the warmest month (Fig. 2, Panel B) were inversely correlated (Table 1) to annual average fecal coliform densities, as seen both in the opposing peaks and valleys of the late 1980's and mid-1990's and in the long-term trend of decreasing fecal coliforms and increasing air temperatures. Annual total precipitation explained considerable amounts of variability for both the proportion of samples per year with fecal coliform densities above the 14 MPN/100 mL and the proportion with densities over 49 MPN/100 mL (Table 1). Long-term annual average air temperature and the average temperature of the hottest month followed a significantly positive trend, while fecal coliforms followed a significantly negative trend. However, detrending the data did not affect the strong negative correlation between air temperature and fecal coliform densities. Linear regression analysis showed that the combination of total annual precipitation and the average air temperature of the warmest month provided a significant linear model ($p < 0.001$) of average annual fecal coliform densities (Table 2; adjusted $R^2 = 0.60$). However, the model comparing the proportion of samples exceeding the 49 MPN/100 mL criteria per year to both the total annual precipitation and average air temperature of the warmest month proved to be the strongest model out of those tested (Table 2; adjusted $R^2 = 0.72$) and was able to reasonably predict observed values (Fig. 3).

3.2. Seasonal and geographic comparisons

Fecal coliform densities were highest during the fall (September through November), though there was considerable variability within season for the 34 years of data (Fig. 4, Panels A, and B). In contrast, total precipitation was highest in spring and summer, slightly lower on average in the fall, and lowest in winter, showing a mismatch in the timing of peak precipitation and fecal coliform levels seasonally (Fig. 4, Panel C). The comparison of fecal coliform densities to precipitation and air temperature between years and by season showed that for all seasons, total seasonal precipitation was significantly correlated to average seasonal fecal coliform densities and to the proportion of samples exceeding 49 MPN/100 mL, with the highest correlation coefficients occurring in the summer and spring (Table 3). Average and maximum monthly air temperature, although always negatively related to fecal coliform densities, was only significantly related in summer (Table 3).

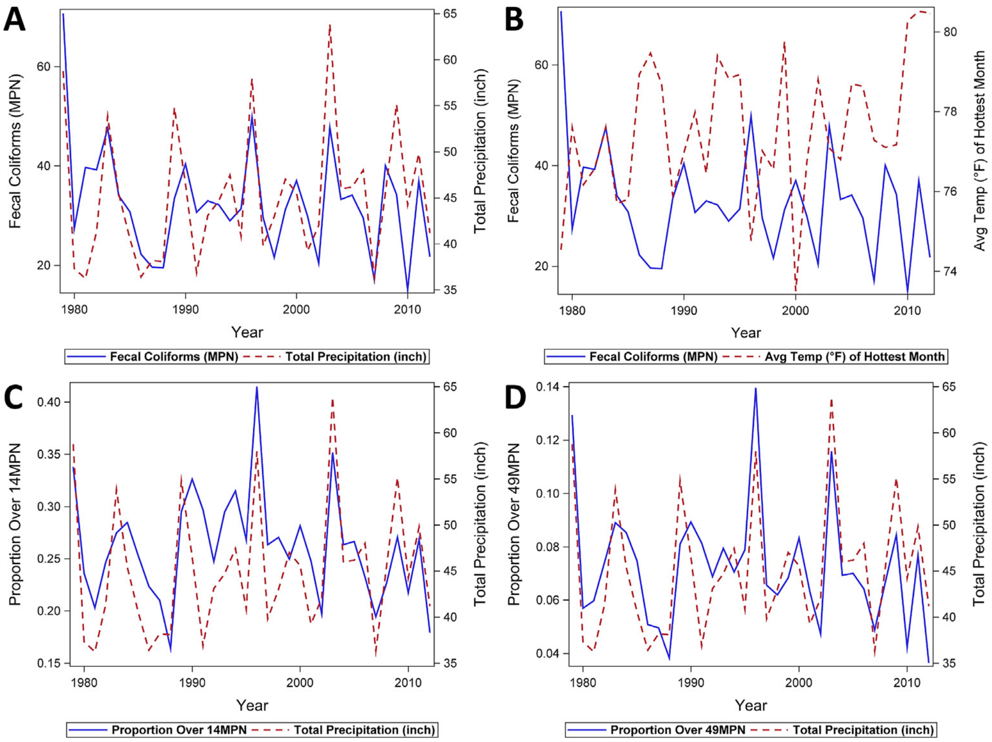

Fig. 2. Plot of annual average fecal coliform levels (solid line) and total annual precipitation (dashed line) by year (Panel A), annual average fecal coliform levels and the average air temperature (dashed line) of the hottest month by year (Panel B), the proportion of samples with fecal coliform densities exceeding the 14 MPN/100 mL criteria and total annual precipitation by year(Panel C), the proportion of samples with fecal coliform densities exceeding the 49 MPN/100 mL criteria and total annual precipitation by year (Panel D).

Table 1
Correlation coefficients between fecal coliform densities (MPN) and climate variables. Numbers in parantheses are p-values. Numbers in bold are considered significant ($p < 0.05$).

		Climate		
		Total annual precipitation	Average Monthly air temperature	Air temperature of hottest Month
Fecal Bacteria	Annual Average	0.690 (<0.001)	−0.469 (0.005)	−0.554 (<0.001)
	Proportion Above 14 MPN	0.711 (<0.001)	−0.302 (0.083)	−0.459 (<0.001)
	Proportion Above 49 MPN	0.771 (<0.001)	−0.430 (0.010)	−0.572 (<0.001)

Table 2
Fit statistics for regression models comparing the proportion of samples over 14 MPN/100 mL (P_{14}), the proportion over 49 MPN/100 mL (P_{49}) or the average annual fecal coliform density (X_{fc}) to total annual precipitation (Σprecip), average annual air temperature (X_{temp}), and average temperature of the hottest month (H_{temp}). AIC = Akaike's Information Criteria.

Model		Adjusted R^2	R^2	AIC	AIC weight	Delta AIC
P_{49}=	Σprecip + H_{temp}	0.72	0.74	−297.5	0.99	0.0
	Σprecip + X_{temp}	0.64	0.66	−288.9	0.01	8.6
	Σprecip	0.60	0.60	−284.7	0.00	4.2
	H_{temp}	0.33	0.33	−267.4	0.00	17.3
	X_{temp}	0.19	0.19	−260.9	0.00	6.5
P_{14}=	Σprecip + H_{temp}	0.56	0.58	−226.5	0.79	0.00
	Σprecip	0.49	0.53	−222.7	0.12	3.79
	Σprecip + X_{temp}	0.49	0.51	−222.1	0.09	0.56
	H_{temp}	0.19	0.21	−206.8	0.00	15.30
	X_{temp}	0.06	0.09	−202.1	0.00	4.79
X_{fc}=	Σprecip + H_{temp}	0.60	0.62	134.2	0.86	0.0
	Σprecip + X_{temp}	0.55	0.58	138.0	0.13	3.8
	Σprecip	0.48	0.48	143.4	0.01	5.3
	H_{temp}	0.31	0.31	152.8	0.00	9.5
	X_{temp}	0.22	0.22	156.9	0.00	4.1

Geographically, the relationship of annual precipitation and maximum monthly air temperature varied notably between different rivers (Figs. S1,S2). Total annual precipitation within river tended to explain more variability in the fecal bacteria values than did air temperature. The proportions of samples exceeding the 49 MPN/100 mL criteria within several rivers on the eastern side of

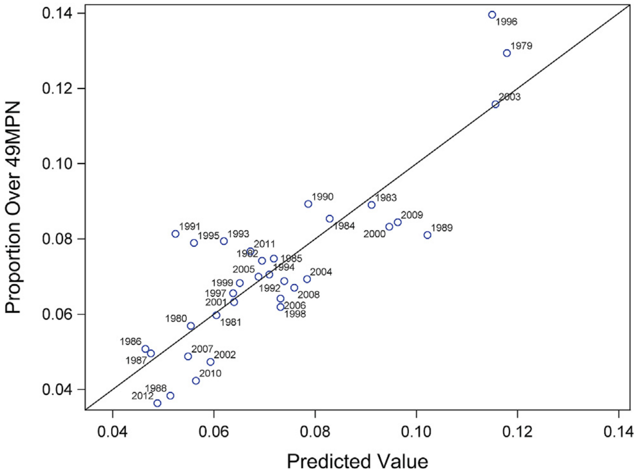

Fig. 3. Plot of the proportion of samples with fecal coliform densities exceeding the 49 MPN/100 mL criteria (y axis) versus the predicted values (x axis). Predicted values are based on the regression model: predicted = 0.0022 * (total annual precip) - 0.0052 * (air temp of hottest month) + 0.38 (adjusted $R^2 = 0.729$, $p < 0.001$).

the Chesapeake Bay, as well as the two rivers on the western side of the Bay were moderately correlated to annual precipitation levels (correlation coefficients between 0.5 and 0.7) (Fig. S1). However, fecal coliform exceedances in the remaining rivers and regions of the Bay were either not significant ($p \geq 0.05$) or had very low correlations to precipitation. Only a few rivers showed a low level of correlation between the proportion of samples exceeding the 49 MPN/100 mL standard and the average air temperature of the hottest month (Fig. S2).

3.3. *Characterization of synoptic precipitation patterns*

Using cluster analysis to examine the timing and magnitude of monthly precipitation totals, we were able to characterize several types of precipitation patterns (Fig. S3). Monthly precipitation profiles for many of these clusters (Fig. 5) showed distinct profiles that differed from ‘normal’ (average monthly values from 1979 to 2013) precipitation patterns. For example, Cluster A (Fig. 5) tended to have above average precipitation in the late summer and fall, while Cluster C featured above normal precipitation throughout much of the year, particularly between May and September. Cluster B contained only one year, 2006, which had a very distinct below average pattern of precipitation for much of the year and large peaks in June and September. A large number of years were clustered together that generally contained low precipitation values throughout the year. Comparison of the annual proportion of samples exceeding the 49 MPN/100 mL criteria by cluster (Fig. 6) shows that Clusters A and C contained years with very high exceedances relative to all other years. Despite having two months with precipitation totals well above average, fecal coliform levels (based on the 49 MPN/100 mL exceedance criteria) for 2006 were relatively low.

The precipitation-temperature regression model derived in this work accounted for a majority of the observed variance (72%) among annual fecal coliform exceedances of the 49 mpn/100 mL criteria from 1979 to 2013, and highlighted three years with extremely high precipitation and fecal coliform levels (1979, 1996, and 2003) relative to the other years (Fig. 3). In order to better understand climate and weather conditions that may be common to years with high fecal coliform exceedances, a focused examination of the precipitation patterns and regional atmospheric circulation for these three years was conducted. The monthly

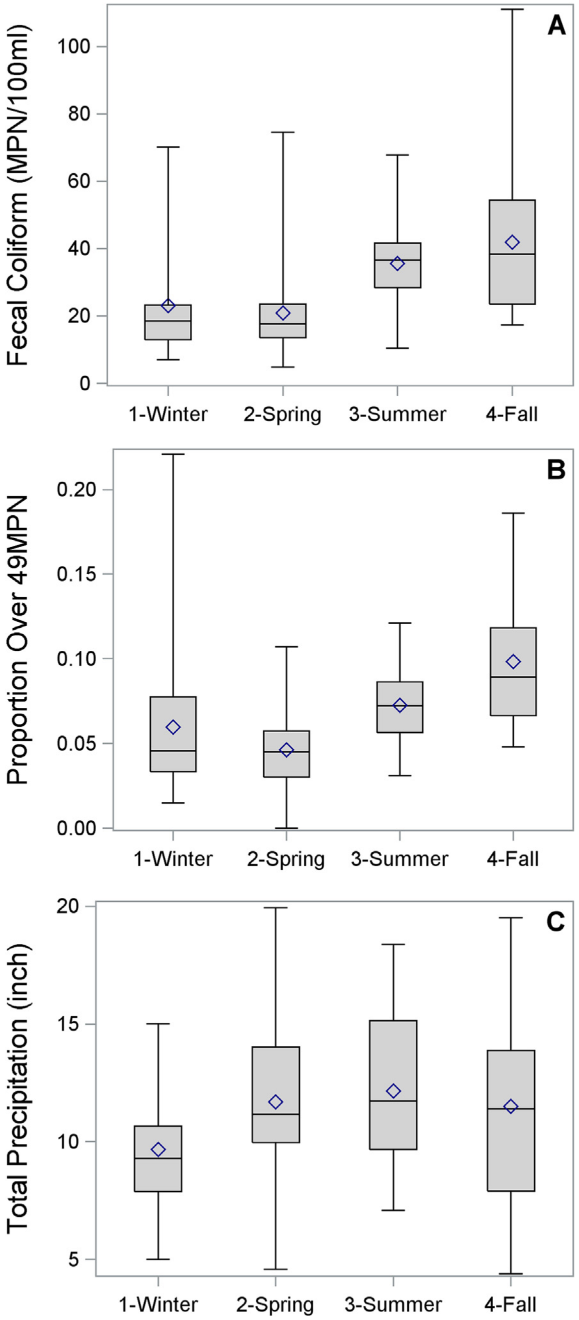

Fig. 4. Boxplots of average fecal coliform densities (panel A), the proportions of samples with densities over 49 MPN/100 mL (panel B), and total precipitation amounts (panel C) by season. Boxes represent the range between the 25th and 75th percentiles of values. Whiskers extend to extreme values. Horizontal lines bisecting boxes indicate the median value and diamonds represent the mean value.

Table 3
Correlation coefficients for the proportion of measurements over 49 MPN/100 mL compared to total precipitation and the average air temperature of the hottest month by season. Bold text indicates a significant relationship ($p < 0.05$).

	Total precipitation	Maximum temperature
Winter	**0.547 (0.001)**	−0.034 (0.850)
Spring	**0.687 (<0.001)**	−0.138 (0.438)
Summer	**0.607 (<0.001)**	**−0.500 (0.003)**
Fall	**0.520 (0.002)**	−0.181 (0.307)

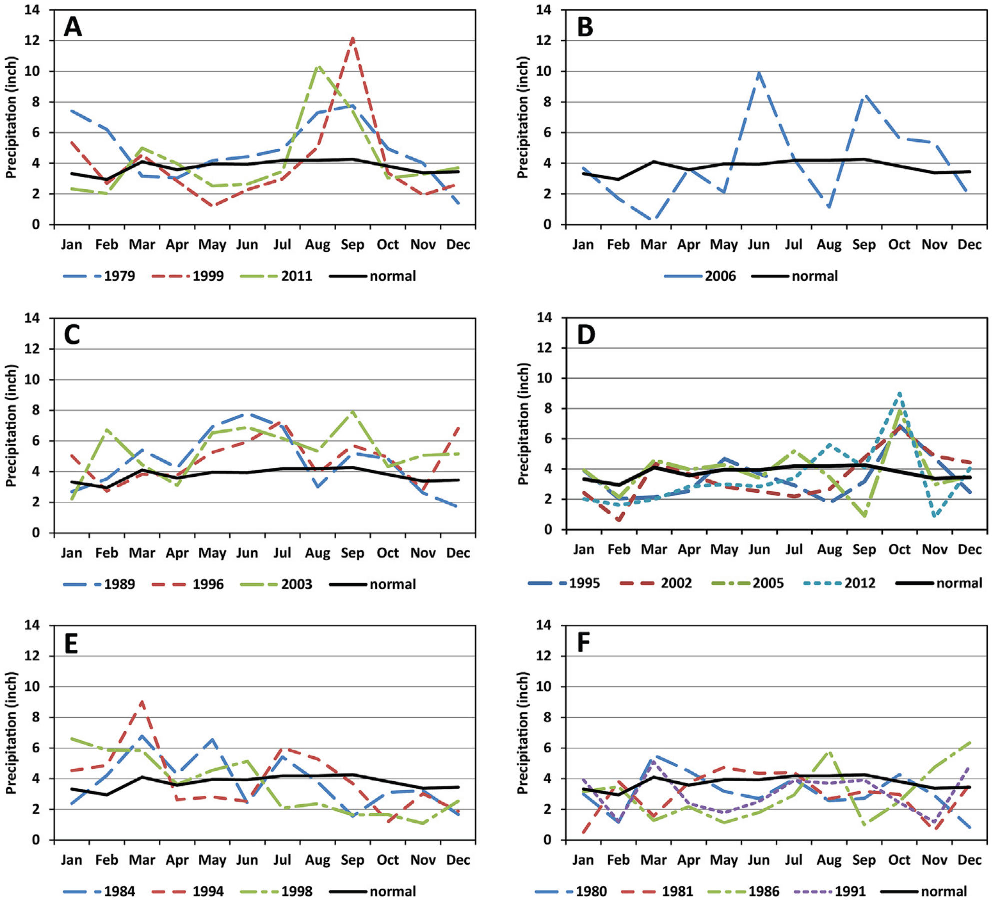

Fig. 5. Monthly total precipitation values compared to the normal (the long term average for that month over the base period of 1979–2012). Panels A–E represent years from individual clusters corresponding to Fig. 8. Cluster F includes a subset of years from those years not included in clusters A-E.

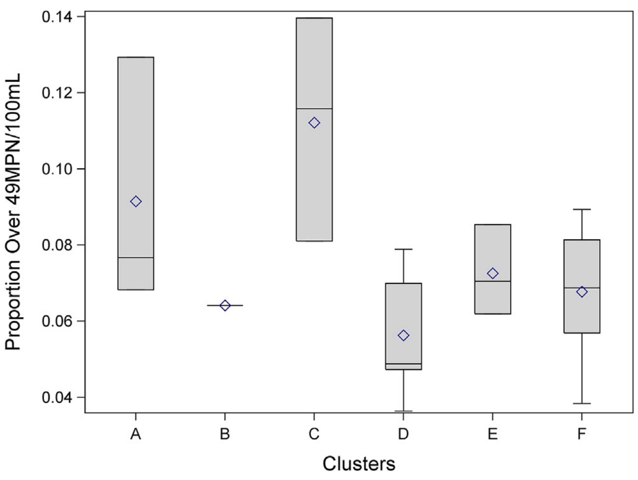

Fig. 6. Comparison of the annual proportion of samples with fecal coliforms exceeding the 49 MPN/100 mL criteria for clusters of years, as defined by the cluster analysis.

precipitation and fecal coliform levels for these three years showed a delay in timing between some peaks of precipitation and fecal coliform exceedances (Fig. 7). Also, there were both similarities and differences between precipitation patterns when comparing 1979, 1996, and 2003. For all three of these very high fecal coliform years, precipitation was generally high from May–October. However, in 1979 precipitation peaked in late summer through early fall (August–September), while 1996 featured very high spring precipitation (May–June) with an exceptionally high early summer peak (July). In 2003, precipitation was very high throughout most of the growing season (May–September).

3.4. Comparison of climate variables to climate indices and synoptic climatology

Precipitation patterns for the climate divisions included were significantly, though weakly correlated to annual average index values for the Atlantic Multidecadal Oscillation and the Pacific–North American Oscillation (Table 4). No discernible relationship emerged between precipitation patterns in these climate divisions and either the El Niño Southern Oscillation (ENSO) or North Atlantic Oscillation.

Comparison of sea-level pressure patterns for the years with extremely high precipitation and fecal coliform densities (1979,1996, 2003) to the average SLP conditions for the period 1979 to 2013, revealed climate patterns consistent with the precipitation patterns observed in these three years (Fig. 8). Precipitation in May through June was very high in 2003, high in 1996, and moderately high in 1979. This pattern was inversely related to SLP over the mid-Atlantic, which was anomalously low in 2003, higher in 1996 as a result of intersecting high pressure areas centered to the Northwest and Southeast of the mid-Atlantic, and very high over the North American mid-latitudes in 1979. Anomalous SLP patterns for the three years with very high precipitation and fecal coliform levels were also consistent with observed precipitation patterns from July

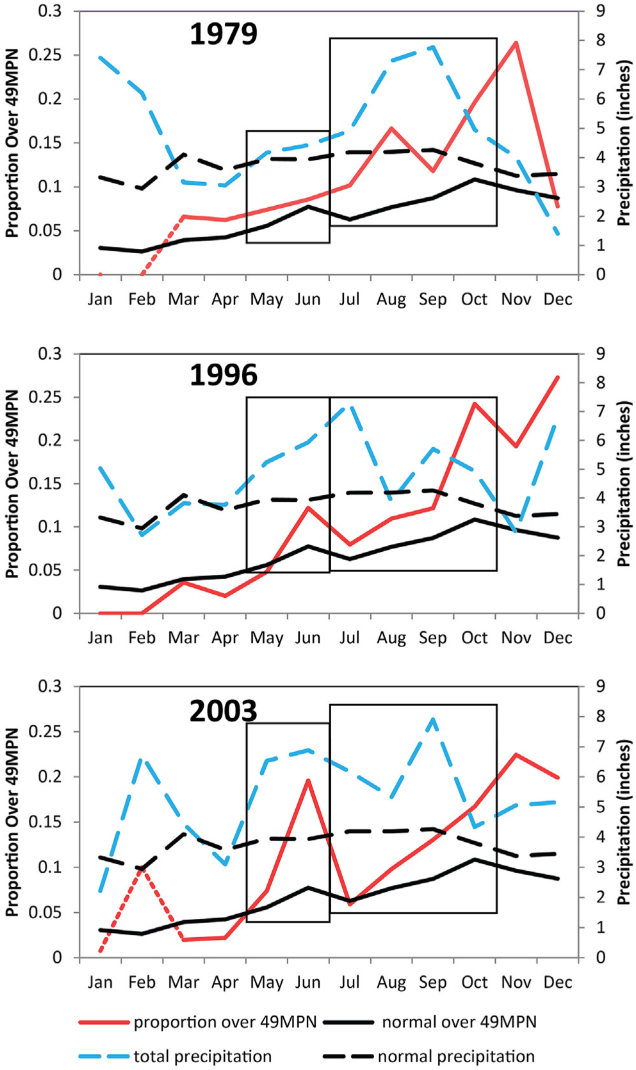

Fig. 7. Monthly values for the proportion of samples above the 49 MPN criteria (solid gray line) compared to the normal conditions (average monthly value for base period of 1979–2013; solid black line), and total precipitation levels (dashed gray line) compared to normal conditions (dashed black line), for 1979, 1996, and 2003. Dotted lines in January and February of 1979 and 2003 indicate low numbers of samples (<100) for those months due to icy conditions. Black boxes indicate the time periods targeted for sea-level pressure analysis.

through October, when cold fronts from the west or northwest and tropical storms generally account for very high monthly precipitation levels. In 1979, when July–October precipitation was moderate to very high in all months, SLP was very high across the Atlantic basin, indicative of a stronger than normal Azores-Bermuda high (ABH), while low pressure existed over the western Caribbean, much of the US and the Gulf of Mexico, and also over most of the area from eastern Canada to Iceland. A distinctive high SLP anomaly over the western Atlantic Ocean was present in 2003 coinciding with very high precipitation amounts. In 1996, only a weak and small high SLP anomaly existed off of the eastern US, corresponding to slightly less precipitation for August through October of that year, compared to 1979 and 2003.

4. Discussion

Precipitation and air temperature patterns explain a large percentage of the inter-annual variability in bacterial levels at shellfish harvest areas in Maryland waters. A small number of previous studies have demonstrated similar relationships, for other geographic areas and shorter time periods, between annual estimates of climate variables and levels of fecal indicator bacteria in estuarine and river waters (Chigbu et al., 2005; Huang, 2010; Lipp et al., 2001a), though a positive relationship between fecal coliforms and air temperature was noted for Virginia waters (Huang, 2010).

In Maryland shellfish waters, total annual precipitation was more strongly correlated to the proportions of samples over 14 and over 49 MPN/100 mL than to average fecal coliform density. This finding may be related to the skewed distribution of both precipitation and fecal coliform data such that median and 90th percentile values are more representative than the average. This finding also supports the management approach of classifying shellfish beds as ‘conditionally closed’ based on the magnitude of precipitation events (FDA, 2013). In Virginia waters, the density of fecal coliforms was strongly influenced by the amount of precipitation within a given rain event and the time period between the rain event and the sample collection (Huang, 2010). Future work in Maryland should attempt to better define the relationship between climate patterns and the frequency and magnitude of individual precipitation events.

The inverse relationship between air temperature and fecal coliform levels may be related to summer heat waves along the eastern US resulting in relatively low precipitation and fecal coliform levels. This interpretation is supported by the weak negative correlation between summer air temperatures and total summer precipitation amounts, and the more continental influence of air masses in summers with lower precipitation amounts. This finding also agrees with the relationship that other studies have noted for decreased indicator bacteria levels with increasing water temperatures (Chigbu et al., 2005; Burkhardt et al., 2000). Rhodes and Kator (1988), for example, showed that increasing water temperatures leads to increased predation on *Escherichia coli* (a type of fecal coliform bacteria) and may be correlated with increased stress from physical factors such as solar radiation. In contrast, the weak, positive relationship between fecal coliforms and air temperature found for Virginia rivers (Huang, 2010) was hypothesized to result from reduced physical stress and lower mortality rates of fecal coliforms in warm waters.

In this study, seasonal differences were also detected in the relationships between fecal bacteria and climate variables, which may be important to managers since data from all seasons are typically treated the same when determining whether or not to close shellfish beds to harvest (FDA, 2013). The relationship between climate and fecal coliforms was stronger from spring through fall than in winter, with the strongest relationship

Table 4
Correlations (and p-values) for comparisons of climate variables and established climate indices.

	North Atlantic oscillation	Atlantic multidecadal oscillation	Pacific North American oscillation	Multivariate ENSO Index
Total Precipitation	0.187 (0.283)	0.232 (0.210)	**−0.424 (0.011)**	−0.137 (0.434)
Average Air Temperature	−0.116 (0.507)	**0.525 (0.002)**	−0.254 (0.142)	−0.117 (0.505)
Maximum Air Temperature	−0.060 (0.731)	0.189 (0.309)	0.129 (0.459)	0.013 (0.940)

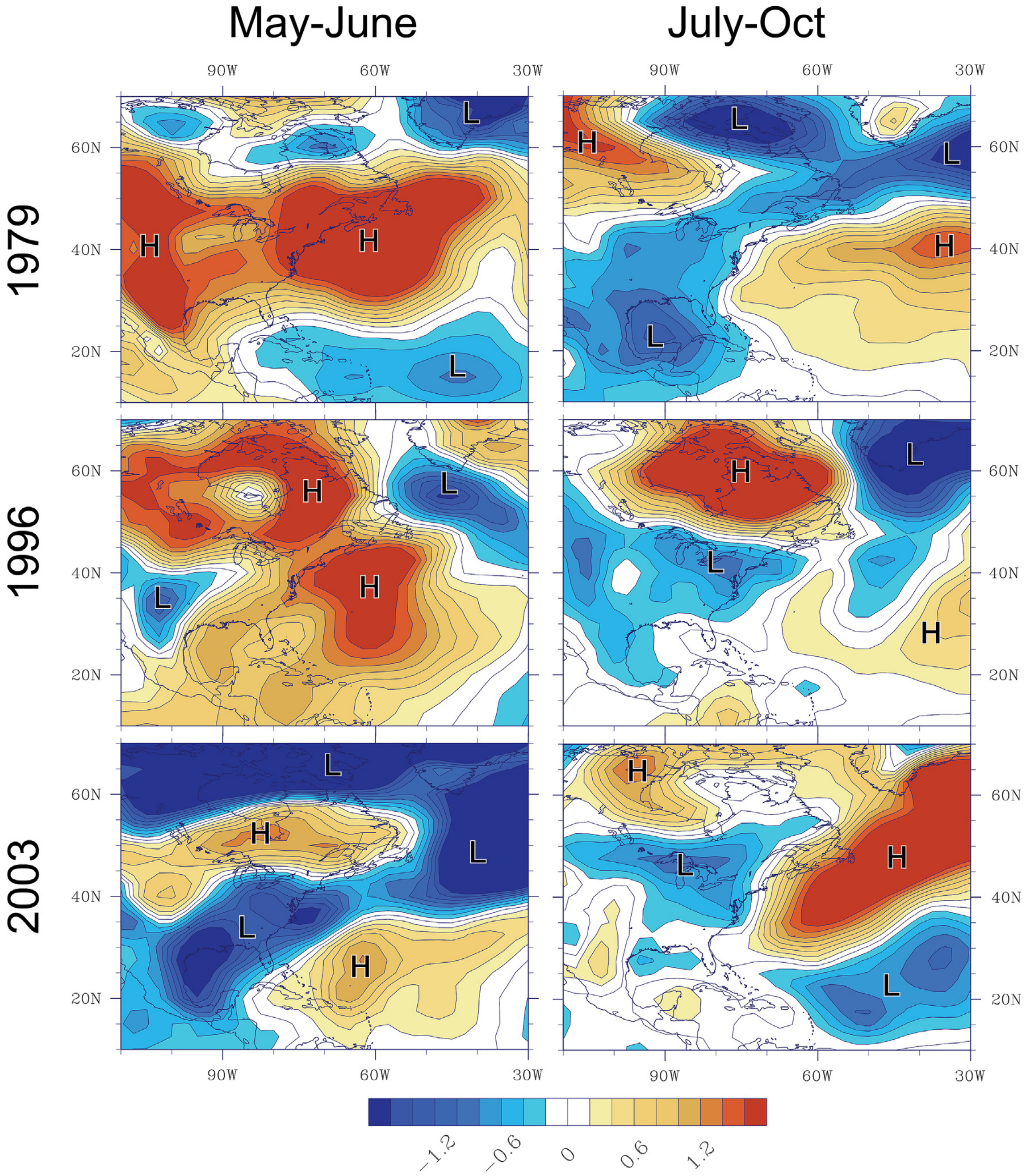

Fig. 8. Maps of sea level pressure anomalies (in millibars; base period 1979–2013) for select months of the three years with very precipitation and fecal coliform levels. Panels in the left column show pressure patterns for May through June, while the right-hand column shows patterns for July through October.

occurring in summer when both precipitation and air temperature patterns were significantly related to average annual fecal coliform densities and the proportion of samples above the 49 MPN/100 mL criteria (FDA, 2013). In contrast, Lipp et al. (2001a) found for an estuary in Florida that fecal coliform levels increased in fall and winter and hypothesized that the seasonality related to ENSO driven wintertime precipitation patterns.

The classification of within-year precipitation patterns, in our study, further defined the relationship between precipitation and fecal coliform presence in Maryland waters by identifying two distinct types of years that tend to lead to high fecal coliform levels, years with high precipitation in the late summer and fall and those years with above normal precipitation throughout much of May through September. The separation in time between periods of extremely high precipitation and elevated fecal coliform levels helps describe the linkages between climate, weather, and fecal coliform levels. The delayed response in fecal coliform levels that was observed in late fall of some years, suggests that periods of high precipitation for those years may create conditions that indirectly lead to elevated fecal coliform levels. Although fecal indicator bacteria levels in surface waters are often linked to runoff from individual precipitation events, elevated bacterial concentrations in months after the bulk of precipitation suggests that either conditions in the summer and early fall associated with highest rainfall levels are not favorable to the survival of fecal coliforms in surface waters or that periods of above normal precipitation set up conditions that support the subsequent introduction of fecal coliforms. It may be that solar radiation and stratification of waters are lower in fall and early winter than earlier in the year resulting in conditions more supportive of fecal coliform survival and distribution throughout the water column following rain events. Another related possibility is that intense rain events in the summer and early fall result in stormwater overflows and intense runoff of water from land, which loads benthic sediments with fecal coliforms. Subsequent wind events could pull these benthic sediments and associated fecal bacteria up into the water column.

Precipitation and air temperature patterns within a geographical region may be described and predicted by large scale climate patterns. Climate indices have been developed to assess the state of these climate patterns and may be used to explain annual and seasonal variability in fecal bacteria levels. For example, Lipp et al. (2001a) found significant seasonal differences for levels of fecal indicators and pathogenic bacteria in waters and sediments of Charlotte Harbor, Southern Florida, and hypothesized that these differences were being driven by weather conditions resulting from changes in the ENSO. Lipp et al. (2001b) also found significant differences in fecal bacteria for tributaries of Tampa Bay, Florida, which correlated to patterns of the ENSO. Chigbu et al. (2004) found seasonal and annual patterns in fecal indicator densities in Mississippi waters over 11 years of field sampling that corresponded to changes in the ENSO.

In contrast to ENSO effects along the Gulf Coast, regional climate conditions in the Chesapeake Bay have been linked to the North Atlantic Oscillation (NAO) (Cronin et al., 2003) and American Multidecadal Oscillation (AMO) (Nye et al., 2014), with winter climate conditions being related to biological endpoints, such as the abundances and predation patterns for jellyfish (Purcell and Decker, 2005). In this study, the weak but significant correlation of fecal coliform levels above the 49 MPN/100 mL to the AMO was surprising given the multidecadal cycle of the AMO contrasted with the relatively short time frame and large interannual variability of the fecal coliform levels. As time goes on and more years of data are added, a more robust test of this relationship can occur. Some summer climate patterns for the Chesapeake Bay region have also been described. For example, Zhu and Liang (2013) defined an index of the Bermuda High for summer, where high SLP rover the Gulf of Mexico and low SLP over the southern Great Plains of the US correlated with precipitation and air quality patterns over the central and eastern US. However, the interannual summertime anomalies of their Bermuda High Index (BHI) (Zhu and Liang, 2013) do not appear to correspond with the patterns of total annual precipitation that we present in this study.

Analysis of SLP for the three years with very high precipitation and fecal coliform levels highlighted large scale climate patterns capable of affecting precipitation over the Chesapeake Bay by influencing the generation of storms (cyclogenesis), storm tracks, storm durations, and storm intensity. That analysis suggested that high precipitation and high fecal coliforms result from storm generation and tracks that stretch from the western Gulf of Mexico, across the eastern US to the Canadian eastern coastline. That same analysis showed patterns of high pressure off the east coast of the US, sometimes characteristic of a stronger than normal Azores-Bermuda High, which can lead to tropical storm tracks that traverse the eastern US, bringing very high precipitation (Elsner, 2003; Herbert, 1980). In fact, the SLP patterns during the three years of extreme fecal coliform abundances corresponded to years with notable tropical storm seasons for Maryland. For example, tropical storms David and Frederic tracked across the Chesapeake Watershed in September of 1979. Additionally, the presence of high pressure over the western Atlantic in the summer and fall of 1996 occurred when Tropical Storms Bertha, Fran, and Josephine impacted the eastern US with heavy rainfall and storm surges. Similarly, the fall of 2003, when anomalously high pressure occurred over the northwestern Atlantic, was marked by Tropical Storms Bill, Grace, and Henri; with Hurricane Isabel causing historic flooding along the eastern US in September. Additional research into SLP anomalies for years with more moderate amounts of precipitation and fecal coliform levels and for the small set of years where the relationship of fecal coliforms, precipitation, and air temperatures was weaker (Fig. 3) would help describe potential links between large-scale climate variability and the synoptic patterns of climate over the upper Chesapeake Bay.

The effect of climate on fecal coliform densities is also especially important for cases where a particular climate pattern occurs for consecutive years. This can be seen most distinctly in the late 1980's (Figs. 2 and 4) when a drought over much of the United States resulted in sustained decreases in average annual fecal coliform densities and the proportion of samples exceeding both FDA criteria. Without taking climate into account, managers might come to the conclusion that decreases in bacterial densities during that period was linked exclusively to other factors, such as best management actions implemented as a result of the Clean Water Act.

The goal of sustaining environmental and public health involves not only the assessment of current risks, but an understanding of how risks change over time and why. Another finding from this study is that the evaluation of long-term trends in fecal coliform densities, both retrospectively and in projections of future conditions, should both account for climate variability and climate change. In retrospective analysis, the influence of climate variables needs to be considered when examining long-term trends. For projections of future conditions, the linear relationship that we describe between fecal indicator patterns and climate variables may provide a predictive tool for forecasting broad-scale fecal coliform conditions in future years. In addition, the indirect link of fecal coliform levels to years with notable tropical storm activities calls for a robust analysis of future storm projections and the concurrence of fecal bacteria in shellfish harvest waters.

Our study suggests that a combination of climate variability and climate change forecasts with estimates of the effectiveness of practices and structures designed to reducing bacterial pollution could be used to help predict the success of management actions. For example, the State of Maryland continues to support and strengthen its activities in stormwater management (Md Code §4-201 (LexisNexis 2015)), with the goal of reducing the amount of various pollutants entering the Chesapeake Bay. Improvements in the management of stormwater, through the implementation of best management practices that are designed to reduce the direct runoff of rain water and stormwater overflows, should lead to lower inputs of fecal bacteria. Because these practices target precipitation-related runoff, the link between precipitation and fecal introduction may be lessened over time, as other drivers become more important, or may shift in nature, as low volume rain events become less important and large scale rain events that overwhelm stormwater controls become more influential in indicator bacteria densities.

Our findings also indicate that the relationship between rainfall and fecal coliforms may be influenced by other environmental factors within each river. By focusing our analysis on annual averages and the proportions of samples exceeding FDA criteria, our goal was to describe the relationship between fecal bacteria in Maryland waters to climate on a large geographic and temporal scale. However, this approach limits the interpretation of our results to annual, seasonal, and river scale dynamics, and does not attempt to predict bacteria levels within individual samples or sample stations. Although the approach in this study of looking at annual data is in keeping with the practice by managers of aggregating data (typically 15 or more samples from each station are considered when making decisions about harvest closures; FDA, 2013), building models that can predict fecal coliform levels in individual samples might help explain drivers of fecal pollution at the local scale.

In both Maryland (this study) and Virginia (Huang, 2010) waters, the strength of the relationship between precipitation and fecal coliform levels weakened as the analysis focused on smaller time and spatial scales. This phenomenon likely results from the influence of factors other than rain and temperature when considering bacterial concentrations in surface waters at finer temporal and spatial scales, such as land-use and local hydrodynamics (Huang, 2010). For example, several studies have found an increased level of fecal bacteria in areas of increased human development (Interlandi and Crockett, 2003; Mallin et al., 2001) and impervious surface (DiDonato et al., 2009; Glasoe and Christy, 2004), presumably from increased overland runoff of fecal matter related to precipitation events. In this study, the aggregate influence of precipitation on fecal coliform levels in various rivers appears to be weaker for watersheds with high development, such as Baltimore, Washington D.C. and other highly developed areas, than for the agriculturally and more sparsely developed lands, primarily on the eastern side of the Chesapeake Bay. Further research into the sources of fecal coliforms found in Maryland shellfish waters is needed to better describe the relationship between source type and runoff potential. One approach would be to conduct a regression analysis using as many locally-relevant factors (e.g. land use status and change, hydrodynamics, fecal sources, etc.) to help describe the suite of factors that influence fecal coliform densities on smaller time and spatial scales.

5. Conclusions

- Climate variables, particularly annual rainfall, play a substantial role in large-scale fecal coliform trends for Maryland shellfish waters, and should be considered when evaluating conditions for management of shellfish beds.
- The strength of these relationships is not uniform seasonally or geographically, suggesting that management criteria may be altered by season and location.
- The timing of rainfall within a year can influence fecal coliform levels for that year, with patterns of sustained spring through fall and intense early fall rains leading to the highest coliform levels.
- In several years, there was a delay in timing between peak rainfall and peak fecal coliform levels indicating that either the high rainfall sets up conditions for later appearance of fecal coliforms or is predictive of some later climatological conditions.
- Large scale sea-level pressure patterns are indicative of years with very high fecal coliform levels and correspond to climate conditions that direct storms over the region or that produce storms.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2015.11.055.

Disclaimer

The scientific results and conclusions, as well as any opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce. The mention of any commercial product is not meant as an endorsement by the Agency or Department.

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