RESEARCH ARTICLE

Seasonal trends and phenology shifts in sea surface temperature on the North American northeastern continental shelf

Andrew C. Thomas*, Andrew J. Pershing†, Kevin D. Friedland‡, Janet A. Nye§, Katherine E. Mills†, Michael A. Alexander‖, Nicholas R. Record¶, Ryan Weatherbee* and M. Elisabeth Henderson§

The northeastern North American continental shelf from Cape Hatteras to the Scotian Shelf is a region of globally extreme positive trends in sea surface temperature (SST). Here, a 33-year (1982–2014) time series of daily satellite SST data was used to quantify and map spatial patterns in SST trends and phenology over this shelf. Strongest trends are over the Scotian Shelf (>0.6°C decade^{-1}) and Gulf of Maine (>0.4°C decade^{-1}) with weaker trends over the inner Mid-Atlantic Bight (~0.3°C decade^{-1}). Winter (January–April) trends are relatively weak, and even negative in some areas; early summer (May–June) trends are positive everywhere, and later summer (July–September) trends are strongest (~1.0°C decade^{-1}). These seasonal differences shift the phenology of many metrics of the SST cycle. The yearday on which specific temperature thresholds (8° and 12°C) are reached in spring trends earlier, most strongly over the Scotian Shelf and Gulf of Maine (~ –0.5 days year^{-1}). Three metrics defining the warmest summer period show significant trends towards earlier summer starts, later summer ends and longer summer duration over the entire study region. Trends in start and end dates are strongest (~1 day year^{-1}) over the Gulf of Maine and Scotian Shelf. Trends in increased summer duration are >2.0 days year^{-1} in parts of the Gulf of Maine. Regression analyses show that phenology trends have regionally varying links to the North Atlantic Oscillation, to local spring and summer atmospheric pressure and air temperature and to Gulf Stream position. For effective monitoring and management of dynamically heterogeneous shelf regions, the results highlight the need to quantify spatial and seasonal differences in SST trends as well as trends in SST phenology, each of which likely has implications for the ecological functioning of the shelf.

Keywords: sea surface temperature; trends; phenology; seasonal cycles; US northeastern continental shelf

Introduction

Sea surface temperatures (SST) on the North American continental shelf from Cape Hatteras to Nova Scotia (**Figure 1**) (hereinafter referred to as the northeastern shelf) exhibit one of the strongest warming trends of the global ocean (Burrows et al., 2011; Pershing et al., 2015; Saba et al., 2015), and the region has recently been subjected to a strong heat wave (Mills et al., 2013; Scannell et al., 2016). The warming trend has been implicated in shifts in the distribution of marine species (Lucey and Nye, 2010; Pinsky et al., 2013), many of which are of commercial importance (Nye et al., 2009; Pinsky and Fogarty, 2012), and some of which are invasive species able to exploit new ranges (e.g. Maynard et al., 2016; Stephenson et al., 2009). Such trends impose serious challenges for fisheries and fisheries management (e.g. Pinsky and Fogarty, 2012; Pershing et al., 2015). However, temperature interactions with species distributions and behaviors occur not only through trends in temperatures, latitudinal shifts in isotherms, or even in episodic events such as heat waves, but also through shifts in phenology, the timing within temperature seasonal cycles (Asch, 2015; Burrows et al., 2011). Friedland and Hare (2007) show increasing annual SST ranges over the northeastern shelf in the later years of their 1854–2005 time series. Such changes in SST phenology can drive changes in species phenology that potentially have large ecosystem ramifications when shifts among functionally linked aspects of the food web

* School of Marine Sciences, University of Maine, Orono, Maine, US
† Gulf of Maine Research Institute, Portland, Maine, US
‡ National Marine Fisheries Service, Narragansett, Rhode Island, US
§ School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, New York, US
‖ NOAA Earth System Research Laboratory, Boulder, Colorado, US
¶ Bigelow Laboratory for Ocean Sciences, East Boothbay, Maine, US
Corresponding author: Andrew C. Thomas (thomas@maine.edu)

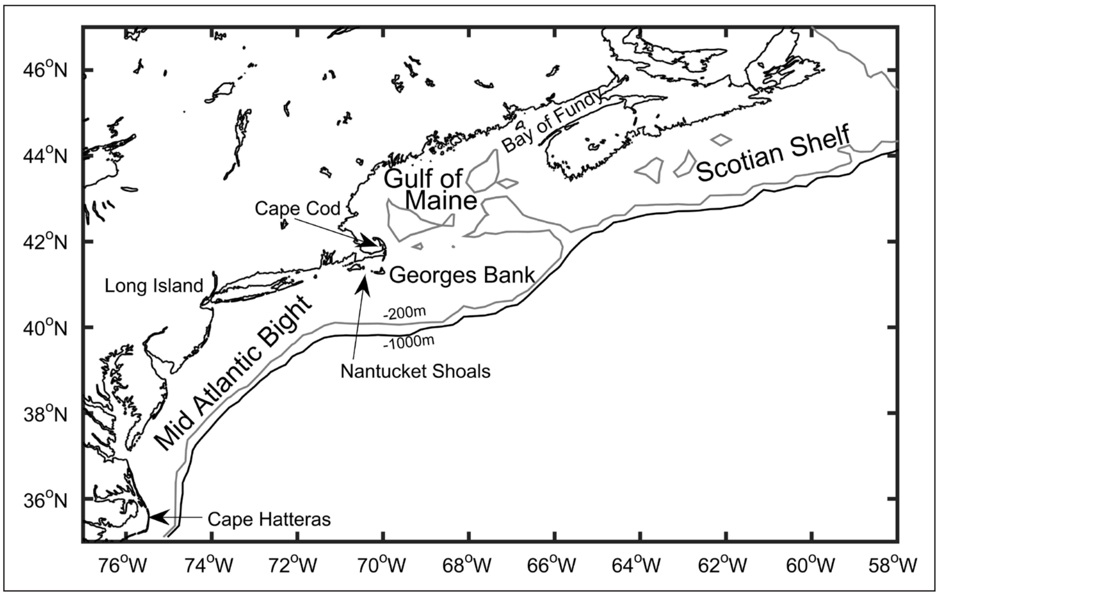

Figure 1: The study area. The northeast North American continental shelf study area from Cape Hatteras to Nova Scotia, showing major geographic locations and two relevant bathymetric contours. DOI: https://doi.org/10.1525/elementa.240.f1

cause them to become dissociated in time (e.g. Edwards and Richardson, 2004; Ji et al., 2010). Different species, and even different life stages of the same species, can have varying susceptibilities to temperature variability in different seasons (e.g. Pörtner and Peck, 2010; Friedland et al., 2014). In this study, we separated the strong multi-year warming trends in SST over the northeastern shelf into months, to document strong seasonal diversity in the strength of these overall trends and map their regional differences. We then used a series of metrics of the SST annual cycle to quantify changes in SST phenology to more fully characterize the nature of SST changes that are being imposed on the northeastern North American shelf ecosystem.

Although clearly part of global warming trends (Levitus et al., 2009; Karl et al., 2015), drivers of the very rapid change in SST on the northeastern North American shelf remain a subject of investigation. Residual circulation and water mass analysis show that shelf water as far south as Cape Hatteras is linked to equatorward flow of subarctic water masses along and on the North American shelf (Loder et al., 1998; Townsend et al., 2006). Water of higher latitude origin flows south along the Scotian Shelf, circulates cyclonically around the deeper basins of the Gulf of Maine, and then anti-cyclonically around Georges Bank before flowing south into the Mid-Atlantic Bight (MAB) (Mountain, 2003; Pettigrew et al., 2005; Townsend et al., 2006). The canonical view, based on observed phase-lagged temperature anomaly signals at latitudinally separated buoy locations along the shelf, is that major changes in SST and hydrographic structure over the shelf are predominantly driven by advection of anomalous properties from higher latitudes upstream (Loder et al., 2001; Shearman and Lentz, 2010). In these higher latitudes serving as potential source waters, the Labrador-Newfoundland shelf and Labrador Sea are also among the most rapidly warming regions of the global ocean (Belkin, 2009; McGregor et al., 2014; Larouche and Galbraith, 2016). Oceanographic anomalies related to the North Atlantic Oscillation (NAO), the dominant basin-scale climate signal of the North Atlantic, are advected into the region from higher latitudes with a 2–4 year lag (Greene et al., 2013; Xu et al., 2015). However, changes in the proximity of the Gulf Stream to the shelf also impact shelf temperatures, at least in the MAB region (e.g. Gawarkiewicz et al., 2012; Zhang and Gawarkiewicz, 2015) and Gulf of Maine (Pershing et al., 2015), and interannual variability in equatorward flow along the Scotian Shelf appears to be modulated by local wind forcing (Li et al., 2014). Galbraith et al. (2012) show that the trends in SST in spring-summer-fall over the Gulf of St. Lawrence, immediately to the north of our study area, have a strong correlation to changes in local surface air temperature. Recent work by Chen et al. (2014, 2015) shows that the extreme 2012 SST anomalies over the entire study area were not phase-lagged, and their model simulations suggest that the synchronous anomalies were driven by anomalous heat flux linked to changes in atmospheric patterns that began the preceding fall. They show that fall-winter advective processes work against these heat flux anomalies to cool the water column, but that air-sea heat flux associated with shifts in jet stream position in both fall and winter–spring overwhelmed the advective processes and resulted in an anomalously warmer water column leading to the strong 2012 SST anomalies. Long-term trends in Pacific SST have been shown to contribute to warming at high latitudes in the Atlantic through atmospheric teleconnections (Ding et al., 2014), and Pershing et al. (2015) show correlations between Gulf of Maine temperature variability and the Pacific Decadal Oscillation as further evidence of atmospheric teleconnections from the Pacific into the northwestern

Atlantic. Shelf temperature variability might also be modulated by salinity changes that change stratification and convective mixing (e.g. Taylor and Mountain, 2009). Time series of salinity data show a distinct decrease between the 1980s and 1990s over Georges Bank (Mountain and Kane, 2010) and in the MAB (Mountain, 2003). Balch et al. (2012) document decreasing salinities in the surface waters of the Gulf of Maine in the 1998–2010 period, and using a satellite bio-optical proxy for salinity, Geiger et al. (2013) show decreasing salinities in the MAB over the 2003–2008 period that are most spatially widespread in summer. Each of these mechanisms can result in temperature anomalies in the region that in turn can impose ecologically important changes in temperature phenology.

The study area is characterized by a relatively wide continental shelf, and its hydrographic variability, typical of many western boundary shelves, is strongly influenced by wind forcing, tides and freshwater input, especially on the inner shelf (Lohrenz and Castro, 2006). The large latitudinal range and strong spatial heterogeneity in both tidal ranges and bathymetry provides for strong differences in the SST seasonal cycle, both in amplitude and phase (Townsend et al., 2006). In the Gulf of Maine, the amplitude of the SST seasonal cycle is largest over the deeper basins and western portion of the Gulf, and weakest over the strongly tidally-mixed regions of the eastern Gulf and southern Scotian Shelf (Mountain and Manning, 1994). Timing of the peak in seasonal stratification varies from late July over the MAB, to early August in the Gulf of Maine, and late August over the Scotian Shelf (Li et al., 2015). Analysis of the competing influence of salinity and temperature on stratification shows temperature dominates stratification in mid-summer, but early-season development of stratification is driven primarily by salinity buoyancy (Li et al., 2015) with a northward progression of the dates when this switch occurs. The northeastern shelf has one of the strongest latitudinal gradients in amplitude of SST seasonal cycles of any continental shelf (Townsend et al., 2006). These studies suggest a regionally varying potential impact of warming temperatures on SST phenology.

Here we have used 33 years of satellite SST data, from 1982 to 2014, to map overall SST trends over the North American continental shelf from Cape Hatteras to the Scotian Shelf to provide a spatial geography of trends. We quantified the extent to which the strengths of these trends are symmetric over the seasonal cycle and the spatial geography of this pattern. We then used a series of metrics of SST phenology to quantify and map 33-year trends in changes to the annual timing of aspects of SST seasonality. We were motivated to address a series of related questions. Are overall warming trends shared equally across the annual cycle, or do they occur primarily in a particular season? Do seasonal trend differences translate into SST phenology changes? If so, what are the nature and quantitative trends of these phenology changes? Over the oceanographically heterogeneous shelf, which regions are the most susceptible to SST phenology change and which appear more resilient?

Data and methods

Daily, optimally interpolated NOAA SST data (OISST, Version 2) (Reynolds et al., 2007; Bazon and Reynolds, 2017) from the period of January 1982 to December 2014 were acquired from the NOAA Earth System Research Laboratory (http://www.esrl.noaa.gov/psd/). These data are at 0.25 × 0.25 degree resolution. The global fields were subset to the study area (**Figure 1**) and the region seaward of the 1000-m bathymetric contour was masked to focus attention on the shelf. A 15-day running mean at each grid location was applied to reduce the influence of short time-scale events and focus attention on the underlying shape of the seasonal cycle. Averaging all days within a month formed monthly averages, from which monthly climatology fields were formed. Monthly anomaly time series were calculated by subtracting the climatologies from monthly SST fields to view SST trends over the 33-year study period. Trends in the monthly SST anomalies at each location were calculated as least squares fit slopes. The monthly SST anomaly time series exhibit temporal autocorrelation, meaning the monthly values are not necessarily independent. We therefore adjusted the degrees of freedom associated with the significance (probability that the slope = 0) of calculated slopes using the methodology of Emery and Thomson (2004). This approach is based on the integral time scale calculated from the autocorrelation at each location, producing effective degrees of freedom at each grid location.

SST phenology metrics were calculated from the smoothed daily time series in each year, creating a 33-year time series for each phenology metric at each study area grid location. A wide range of metrics of phenology calculated from satellite data time series have been utilized in the past (e.g. Platt et al., 2009; Vargas et al., 2009; Cole et al., 2012; Goubanova et al., 2013), although usually from ocean color data. We tested a number of different metrics of SST phenology and extracted them from each study year. The warmest day of the year was defined as the yearday of maximum SST in the annual cycle; the coldest day of the year, as the yearday of minimum SST in the annual cycle. Spring start day was defined as the first yearday after the day of winter seasonal minimum SST that surpassed a specific SST threshold for 8 sequential days. Thresholds of 8° and 12°C were used, as they tended to be expressed in most years over the entire latitudinal range of our study area. We defined metrics describing the warmest portion of the annual cycle, hereinafter referred to as summer. To account for latitudinal and local hydrographic control over phenology dates, local summer start day and local summer end day were defined using a location-specific SST threshold, chosen to be 0.5°C colder than the coldest maximum summer SST observed over the 33-year study period at that location. This definition ensured that every location has a summer, and summer has a local definition based on climatological variability. Summer start day was defined as the yearday that the location first exceeded the local temperature threshold; summer end was defined as the yearday the location fell below this threshold, after the summer maximum. Tests of the sensitivity of resulting patterns to the choice of 0.5°C using other temperature differences (0.75°C, 1.0°C) resulted in different absolute values, but did not change overall phenology patterns in time or space. The length of summer was defined as the number of days separating these two dates. Trends in the 33-year time series of these phenology metrics were calculated using the non-parametric Sen's slope to avoid issues associated with unknown underlying distributions and to reduce the impact of outliers at each end of the time series.

Four data sets that track processes previously found to influence regional temperature anomalies and/or hydrographic structure were acquired for comparison to the phenology metric time series to provide a preliminary view into possible drivers of observed phenology changes. The NAO index time series captures the dominant mode of large scale North Atlantic atmospheric variability and impacts SST through oceanic pathways along the North American continental shelf. We obtained time series of the winter (January–March) NAO index from NOAA National Weather Service Climate Prediction Center (www.cpc.ncep.noaa.gov). The Gulf Stream position was indexed from an analysis of the monthly location of the north wall using the 15° isotherm at 200 m (Joyce et al., 2000). We averaged these data to form quarterly values. The influence of local atmospheric forcing on SST phenology changes was estimated using pressure as a metric of interannual variability of regional-scale atmospheric processes. The 700 hPa pressure surface is in the low-to-mid troposphere and captures changes in the atmospheric structure that drives weather patterns and storm tracks in the lower atmosphere over the region. This height level is in the free troposphere just above the boundary layer and so avoids some of the biases in surface data to do with topography and small-scale local effects. It is a widely used reference height for tracking lower troposphere variability and has correlates to surface air temperatures, winds, weather and heating (e.g. Fettweis et al., 2013; Overland and Wang, 2015, Simpson and Voigt, 2015). We acquired the 0.3° spatial resolution 700 hPa geopotential height data of the North Atlantic Regional Reanalysis (NARR) from the NOAA Earth System Research Laboratory (www.esrl.noaa.gov) and formed time series of quarterly averaged data over the study period, spatially averaged over the shelf study area. Surface air temperatures are part of the coupled ocean-atmosphere system with feedbacks between each other on time scales longer than months (Barsugli and Battisti, 1998; Bhatt et al., 1998). Surface air temperatures have correlations to SST over the Gulf of St. Lawrence (Galbraith et al., 2012). We acquired the 0.3° spatial resolution surface air temperature data of the North Atlantic Regional Reanalysis (NARR) from the NOAA Earth System Research Laboratory (www.esrl.noaa.gov) and formed time series of quarterly averaged data over the study period, spatially averaged over the shelf study area. Climatologies of both the geopotential height and air temperature quarterly time series over the 33 years were calculated, and from these climatologies anomalies were formed. To provide maps that quantify the interaction of the phenology variability with these environmental indices, regressions were made against the phenology metrics defining summer start day, end day and duration on a site-specific basis. These regressions reflect interactions across multiple time scales including overall trends. The geopotential height and air temperature time series were normalized by their standard deviation prior to regression analysis.

Results

SST trends and their seasonal differences

The magnitude of the SST trends over the 33-year study period in the northeast North American continental shelf are mapped in **Figure 2**. These quantify, at a high enough spatial resolution to show regional shelf details, the overall trends shown by Pershing et al. (2015). A small region immediately north of Cape Hatteras in the southernmost portion of the study area shelf exhibits zero, or a negative trend (–0.1 to –0.3°C decade^{-1}). The remainder of the study area has positive trends, ranging from 0.2°C decade^{-1} on the inner shelf in the MAB, to 0.4°C decade^{-1} in the Gulf of Maine, and over 0.5°C decade^{-1} in the Bay of Fundy, on the Scotian Shelf and in the northeast portion of the study area. Trends are weakest over the southernmost inner-shelf portion of the study area, over Nantucket Shoals and over Georges Bank. All of these trends are statistically significant with the exception of a small region in the southern MAB.

These overall patterns, however, hide seasonal differences. **Figure 3** shows the SST trends over the 33-year time period separated by month. This depiction quantifies changes in the relative strength of trends over the annual cycle and documents strong regional differences over the study area within each month. The overall warming evident in **Figure 2** is not shared equally across months, meaning that not all portions of the annual cycle were warming at the same rate. In winter (January–March), positive SST trends are present and strongest over the Scotian Shelf, but relatively weak over the Gulf of Maine

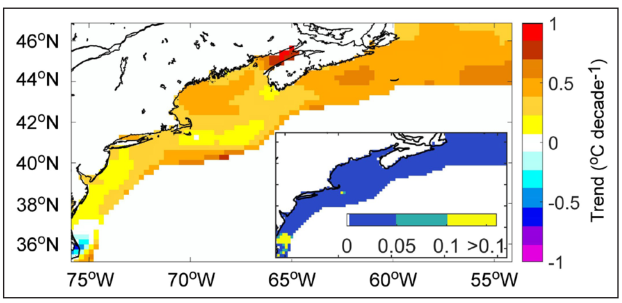

Figure 2: SST trends over the study period. The magnitude of 33-year (1982–2014) trends in monthly SST anomalies over the study area. The insert maps the p values indicative of the probability that the trend slope is equal to zero, taking into account the effective degrees of freedom at each location (mean of 122.2 over the study area). DOI: https://doi.org/10.1525/elementa.240.f2

and even negative in some months/locations in the Gulf of Maine and the MAB. In spring (April–May), the negative trends decrease in spatial extent and magnitude and are restricted to the outer shelf regions immediately north of Cape Hatteras and on the seaward side of Georges Bank. The warming trends become more spatially dominant and strengthen, especially over the Gulf of Maine and the shelf area south of Cape Cod. In summer (June–September), warming trends are evident over almost the entire study area, strongest in the Gulf of Maine, Scotian Shelf and far northeastern portion of the study area, and weaker in the MAB, especially close to shore. Values in the central Gulf of Maine exceed 0.8°C decade^{-1} in July–September. In fall (October–December), these trends remain but weaken in October, and in November–December they weaken further over the Gulf of Maine and switch to negative over southern portions of the MAB. These seasonal and spatial differences in the annual distribution of trends are summarized by spatially averaging over three broad regions of the shelf study area showing a) the decadally

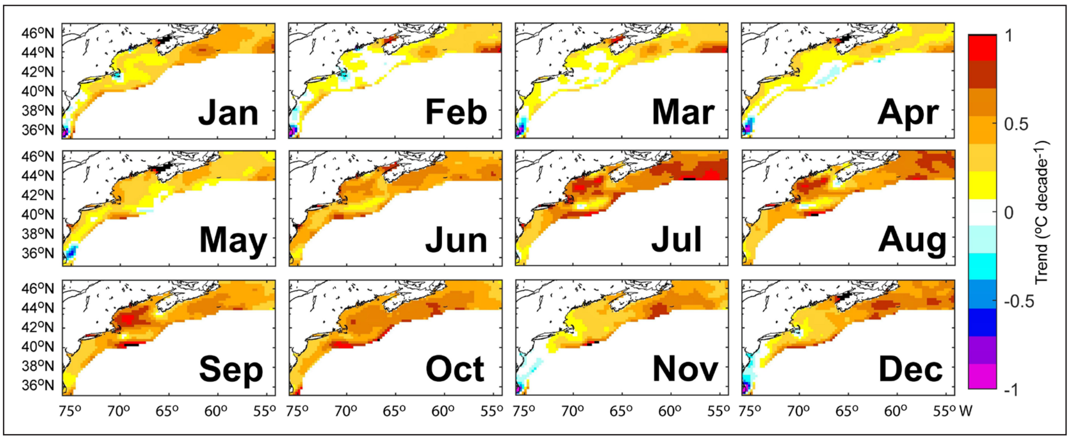

Figure 3: SST trends separated by month over the study period. The magnitude of 33-year monthly (1982–2014) trends in SST anomalies calculated separately within each month, showing spatial and seasonal differences in the trends. DOI: https://doi.org/10.1525/elementa.240.f3

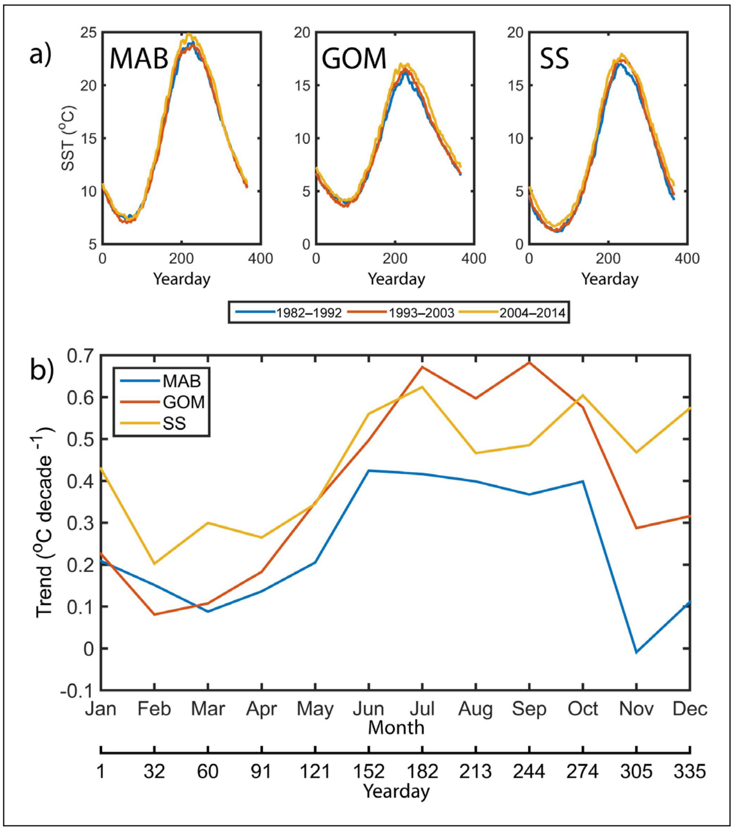

Figure 4: Regionally averaged seasonal cycles and monthly trends. a) Decadal-average changes in the seasonal cycle averaged spatially over three geographic regions of the shelf study area, the mid-Atlantic Bight (MAB), the Gulf of Maine (GOM), and the Scotian Shelf (SS) (note the change in temperature scale between the MAB and the northern regions). **b)** The seasonal dependence of 33-year SST trends (°C decade^{-1}) from Figure 3, averaged spatially over the same three geographic regions. DOI: https://doi.org/10.1525/elementa.240.f4

averaged changes in the shape of the annual cycle for the MAB, the Gulf of Maine and the Scotian Shelf and b) the seasonal dependence of trends for each region. In the MAB (**Figure 4a**), the decadal seasonal changes show maximum differences in summer and in the 2004–2014 period. In the Gulf of Maine, summer and fall changes become steadily warmer over the three decades. In the Gulf of Maine and Scotian Shelf, the 1982–1992 period appears most strongly different in summer and the winter months are obviously warmer in the last decade. The seasonal difference in monthly 33-year SST trends (**Figure 4b**) is most strongly expressed in the Gulf of Maine where summer trends (July–September) are approximately 6–7 times those of winter (February–March). Seasonality in trends is present but weaker in the MAB and has a different annual cycle over the Scotian Shelf where higher values are present June–December, and winter month trends remain more strongly positive than elsewhere in the study region.

Phenology changes

One possible ramification of seasonal differences in SST trends is shifts in SST phenology. We examined the yearday of maximum and minimum SST in the annual cycle over the study region. There was strong spatial heterogeneity in the climatological value of the yearday, superimposed on an expected strong latitudinal gradient. Examination of the 33-year time series of these phenology metrics, however, showed no obvious trends over the study period (not shown). Interannual variability in these dates was present, but no clear geographic pattern was evident in the magnitude or sign of the overall 33-year trend and less than 3% of the grid locations had significant ($p < 0.10$) slopes to their trend. These aspects of the annual cycle remain relatively stable behind the overall increasing SST.

The yearday on which locations exceed a specific spring temperature threshold will obviously have strong latitudinal and hydrographic influences. The climatological yeardays when the northeastern shelf first exceeds 8° and 12°C are shown in **Figure 5a** and **c**. Spatial patterns for each temperature are similar, with dates for each becoming progressively later in the year with latitude and, in the southern portion of the study area, cross-shelf distance from the shelf break towards shore. Latest dates are in the most strongly tidally mixed regions in the eastern Gulf of Maine and in the far northeast of the study area. Trends (**Figure 5b** and **d**) in these phenology metrics over the 33-year study period are mostly negative (thresholds are reached at progressively earlier yeardays), with strongest negative trends in the Gulf of Maine and Scotian Shelf, weakest and even slightly positive in the MAB. The trend is stronger (–0.5 days year^{-1} or larger) and statistically significant over a broader area for the 12°C threshold, consistent with the stronger trends evident in **Figure 3** as summer approaches.

We examined trends in summer start date, summer end date and summer length defined by locally specific SST metrics. There was strong spatial heterogeneity in both the maximum annual summer SST and its interannual variability over our study region during the period examined, necessitating a locally specific definition of summer start and end date. The SST value used to define the summer warm period is mapped in **Figure 6**, showing progressively warmer thresholds south of the Gulf of Maine, and coldest thresholds over the strongly tidally mixed eastern Gulf of Maine and southern Scotian Shelf and at the highest latitudes. At each location, trends in the yearday that this SST threshold was first crossed during each year are shown in **Figure 7a**, mapping trends in summer start date. Trends are negative everywhere, indicative of progressively earlier summer start dates,

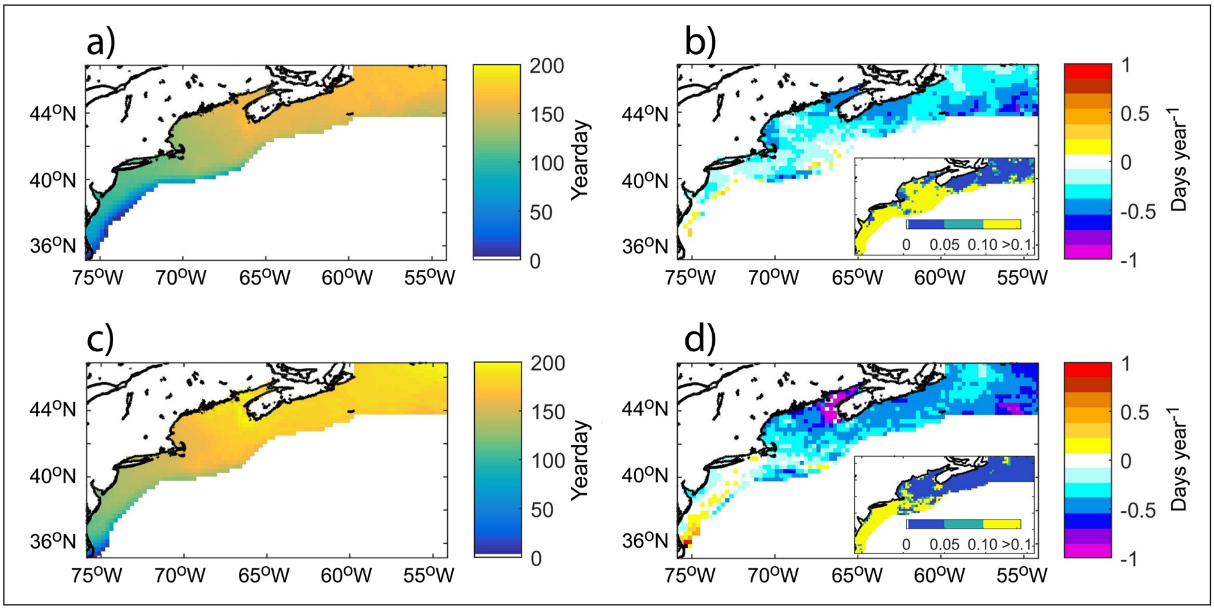

Figure 5: Spring SST phenology changes. SST phenology changes over the study area documenting the start of spring, showing **a)** the climatological yearday that SST rises above 8°C, **b)** the 33-year trend in these yeardays, **c)** the climatological yearday that SST rises above 12°C, and **d)** the 33-year trend in these yeardays. The inserts in b) and d) map the probability (p values) that slopes are equal to zero. DOI: https://doi.org/10.1525/elementa.240.f5

strongest over the Gulf of Maine and Scotian Shelf. In the northern portion of the Gulf of Maine they approach –1 day year^{-1}. These trends are relatively weak south of Long Island with the exception of the near coastal region south of New Jersey, and off the southern tip of Nova Scotia, and are weakest over Georges Bank and Nantucket Shoals. Trends in the yearday that this local SST threshold was crossed after summer are shown in **Figure 7b**, mapping trends in summer end date. Trends are positive everywhere, indicative of progressively later summer end dates. These trends are weakest (<0.5 days year^{-1}) south of Long Island and in the furthest northeastern region of the study area and are strongest over the Gulf of Maine where they exceed 1.0 days year^{-1} (they approach 1.5 days year^{-1} in places).

Together, the summer start date and summer end date define the duration of summer. Trends in summer duration over the study period are mapped in **Figure 7c**, quantifying the degree to which the trends in start and end date combine to drive changes in summer duration. The entire study region is positive, strongest over northern portions of the Gulf of Maine where rates exceed 2 days year^{-1} and weakest over Nantucket Shoals and in the MAB.

The difference in the strength of the trends for summer start and end dates quantifies whether shifts at the beginning or end of summer dominate the changes in summer duration. The difference in the absolute magnitude of the start and end date trends of **Figure 7a** and **b** is mapped in **Figure 7d**. It shows three distinct regions. South of Long Island over most of the MAB, summer duration shifts are dominated by changes in summer start date. Over the farthest northeastern portion of the study region, this pattern is also true. Over the entire Gulf of Maine, Georges Bank and most of the Scotian Shelf, however, trends in the summer end date dominate, most strongly along the eastern Maine coast.

Against a background of overall increasing SST over the study region, many metrics of phenology based on temperature thresholds will change (**Figure 5**), including the locally-defined summer start, end and duration dates of **Figure 7**. Such changes in SST phenology, while real and of potentially significant importance to the ecosystem, do not necessarily reflect a change in the actual structural shape of the SST seasonal cycle. To examine changes in phenology separately from those that result from overall increasing SST trends, we recalculated the same summer start, end and duration phenology metrics in each year at each location after first normalizing the yearly vector of daily values to the same annual mean value (the climatological annual mean at that location). This approach retains the shape of each annual cycle, but removes the 33-year increasing SST trend and any other

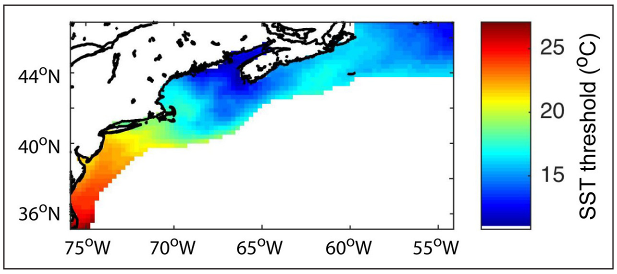

Figure 6: SST thresholds for definition of summer. Map of the SST thresholds used to locally define the start date and end date of summer. Start date is the first yearday that exceeds this SST. End date is the first day after summer that the SST drops below this threshold. DOI: https://doi.org/10.1525/elementa.240.f6

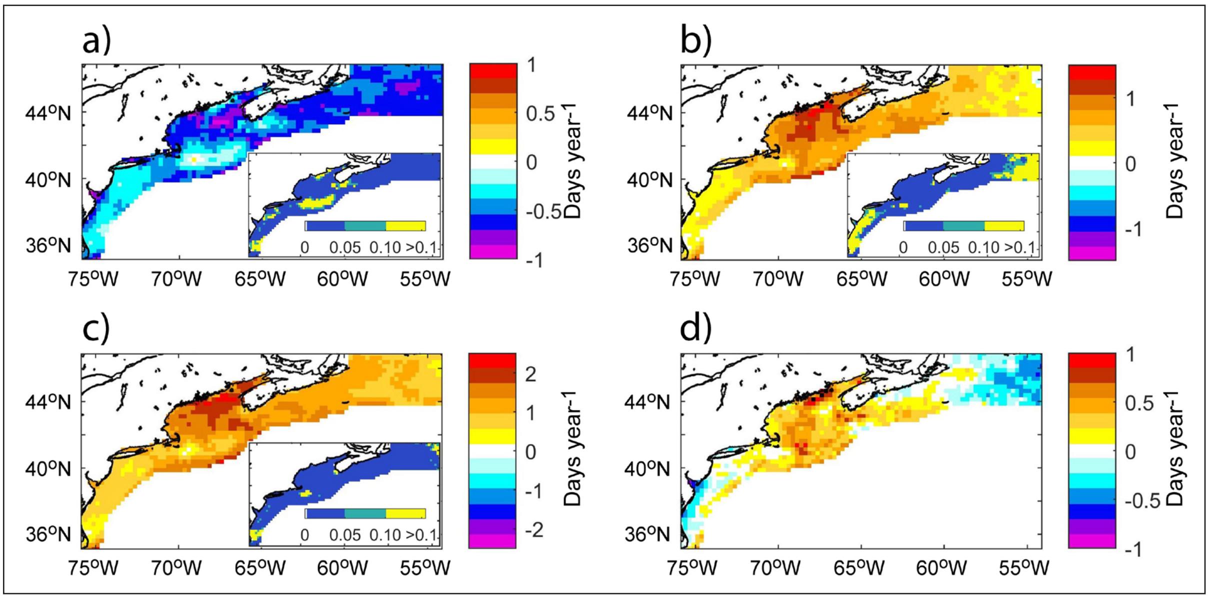

Figure 7: Summer SST phenology changes. SST phenology changes over the study area for the 33-year study period, showing **a)** trends in the summer start date, **b)** trends in the summer end date, **c)** the duration of summer, and **d)** the difference in the absolute magnitudes of the trends in summer start and end date (end yearday minus start yearday: positive (red) regions have stronger summer end date trends). Inserts in a), b), c) map the probability (p values) that slopes are equal to zero. DOI: https://doi.org/10.1525/elementa.240.f7

interannual variability in annual mean SST. The resulting SST thresholds that define summer for these normalized annual cycles (**Figure 8**) are similar to those of **Figure 6** with differences evident primarily in the northern portion of the MAB and the far northeastern portion of the study area. Trends in the resulting phenology metrics (**Figure 9a–d**) show that the same patterns observed in **Figure 7** are still present after removal of the background SST increase, although slopes are weaker. With the exception of the Bay of Fundy and a weak positive trend over Georges Bank, summer start day has a negative slope, towards earlier start dates, over the entire study area, most strongly in the Gulf of Maine and the Scotian Shelf. Similarly, summer end dates still have a positive slope over most of the study area, except the Bay of Fundy and far eastern portions of the study area, documenting a trend towards later end dates, strongest over the Gulf of Maine. These translate into increasing summer duration over most of the study area (**Figure 9c**), strongest over the Gulf of Maine and on the shelf immediately south of Long Island. The difference in absolute magnitude of these slopes shows that the change in end dates dominates over most of the study area, most strongly in the Gulf of Maine and Georges Bank, and also over the MAB. This pattern is weak or changes to a start date domination over the eastern Scotian Shelf and far eastern areas.

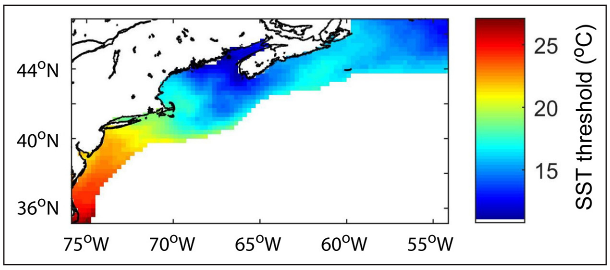

Figure 8: SST thresholds for definition of summer: no background trends or interannual variability. Map of the SST thresholds used to locally define the start date and end date of summer, after normalization of each year to the same annual mean to remove interannual variability and the overall increasing SST trend. DOI: https://doi.org/10.1525/elementa.240.f8

Environmental connections to SST phenology changes

We examined the relationship of the NAO to observed SST phenology changes by regressing the time series of winter NAO index values onto the three time series of metrics defining the summer warm period. Regressions were made with the annual phenology metrics lagged by 0–5 years. Regression coefficients at lags of 0 and 5 years were relatively weak, and those at 5 years are not presented. The dominant overall impact of the NAO on shelf SST phenology is positive for summer start date and negative for summer end day and summer duration; an increased NAO index is linked to delayed summer start, earlier summer end and shortened summer (**Figure 10**). The lag that resulted in maximum regression values in both magnitude and spatial extent varied by region. Over the MAB, maxima are present at 1 year lag for summer start date, but are stronger at 2 and 3 years lag for end date and over lags of 2–4 years for summer length. In the Gulf of Maine, strongest summer start regression values are at 3 years lag. Summer end values are strongest at 2–4 years lag and switch from strongest in the western Gulf at 2 years lag to stronger in the eastern Gulf at 3 and 4 years

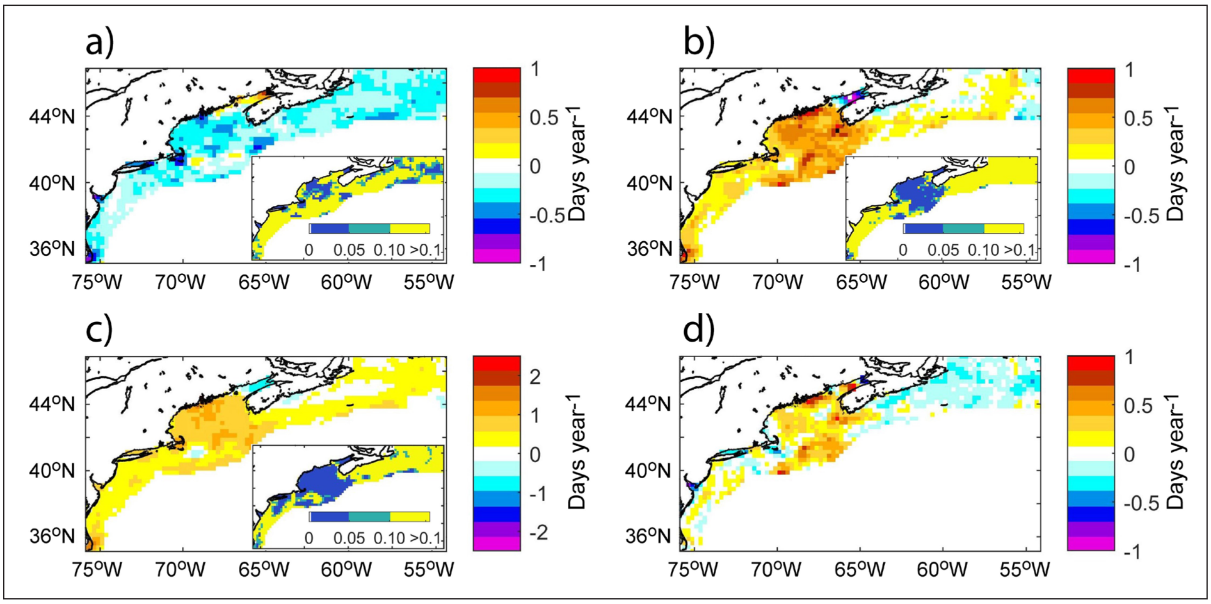

Figure 9: Summer SST phenology changes after removing background SST trends. SST phenology changes over the study area for the 33-year study period after normalization to remove interannual variability along with the multi-year increasing SST trend (Figure 2), showing **a)** trends in the summer start date, **b)** trends in the summer end date, **c)** the duration of summer, and **d)** the difference in the absolute magnitudes of the trends in summer start and end date, where positive (red) regions have stronger summer end date trends. Inserts in a), b), and c) map the probability (p values) that slopes are equal to zero. DOI: https://doi.org/10.1525/elementa.240.f9

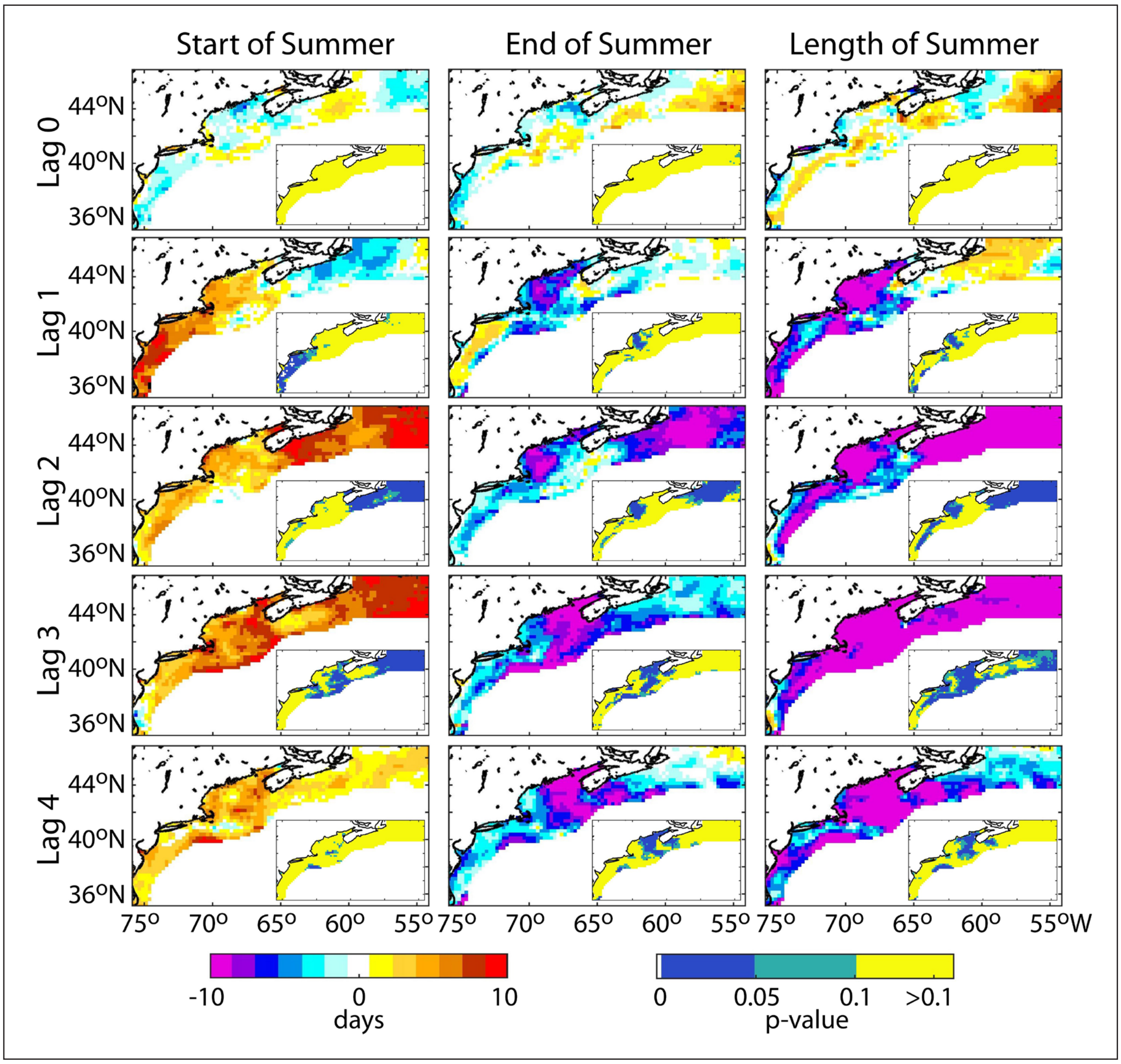

Figure 10: Regression of winter NAO onto summer phenology changes. Regression of the winter NAO index onto the three phenology metrics defining the summer warm period at each grid location in the study area for phenology lagging the NAO by 0 through 4 years. The units of the regression are in days. The inserts in each figure provide the spatial pattern of the associated p value of the coefficient. DOI: https://doi.org/10.1525/elementa.240.f10

lag. Strong summer length regression values in the Gulf of Maine are spread over 1–4 years lag, switching from the western Gulf at 1 and 2 years, to the whole Gulf at 3 years, and predominantly the eastern Gulf at 4 years lag. Over the Scotian Shelf and far northeastern portion of the study area, coefficients for all three phenology metrics are strongest at 2 and remain at 3 years lag.

We then regressed winter, spring and summer quarterly time series of the Gulf Stream Index (GSI) onto the three summer warm period phenology metrics. Spatial patterns of the resulting coefficients were similar for each quarter, but maxima (values and spatial extent) were evident for the summer (July–September) quarter (**Figure 11**) with no lag. The general relationship is of positive GSI values (more northerly position) associated with decreasing summer start date over the MAB, Georges Bank and the Gulf of Maine, and increasing summer end date and length over the Gulf of Maine, Georges Bank and western Scotian Shelf. The spatial pattern shows the relationship is stronger over most of the study region at the shelf edge, and weakens on the inner shelf, and is weakest over the eastern Scotian Shelf.

Quarterly values of regionally averaged 700 hPa height capture interannual variability in the broad-scale atmospheric structure that steers weather over the region. Fall (October–December) and winter (January–March) 700 hPa height regressions onto the following summer phenology metrics did not show strong relationships. Both spring (April–June) and summer (July–September) of the same year, however, showed similar and stronger regressions (**Figure 12**). In general, increased height (higher pressure over the region) in spring (April–June) and summer (July–September) is associated with decreasing (earlier) summer start dates, increasing (later) summer end dates, and increasing summer duration. The regression is strongest over the Gulf of Maine, Georges Bank and the Scotian Shelf, and strongest for summer end dates and summer duration.

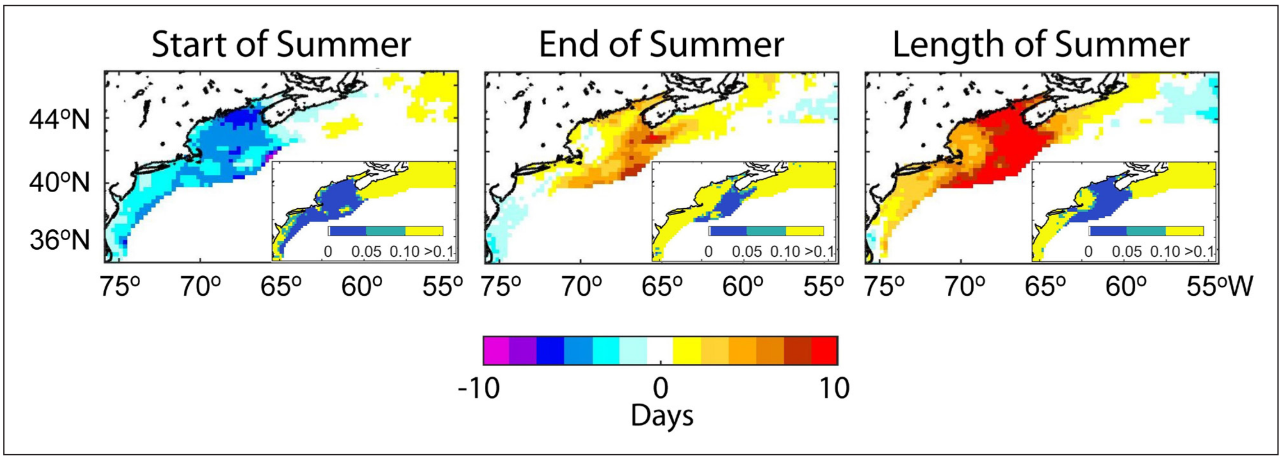

Figure 11: Regression of Gulf Stream Index onto summer phenology changes. Regression of the summer (July–September) Gulf Stream Index onto the three phenology metrics defining the summer warm period at each grid location in the study area. The units of the regression are in days. The inserts in each figure provide the spatial pattern of the associated p value of the coefficient. DOI: https://doi.org/10.1525/elementa.240.f11

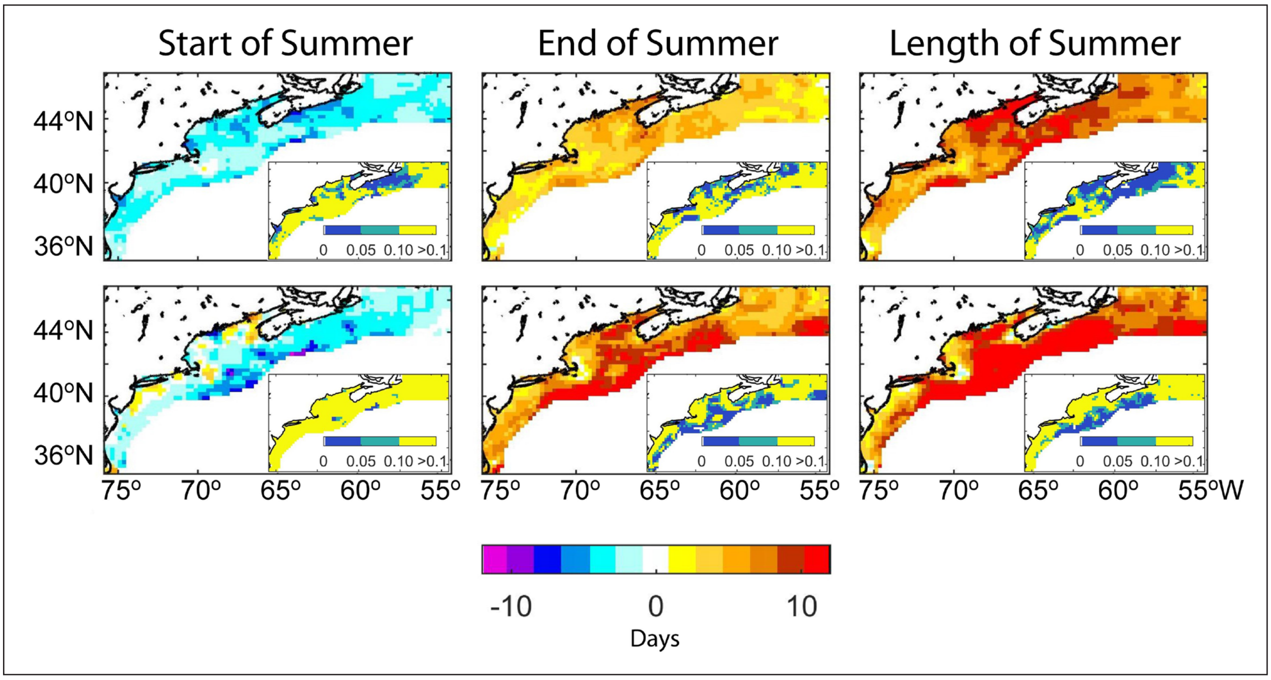

Figure 12: Regression of regional atmospheric pressure onto summer phenology changes. Regression of regionally-averaged, normalized, quarterly spring (April–June) (top row) and summer (July–September) (bottom row) 700 hPa height onto the three phenology metrics defining the summer warm period at each grid location in the study area. The units of the regression are in days. The inserts in each figure provide the spatial pattern of the associated p value of the coefficient. DOI: https://doi.org/10.1525/elementa.240.f12

Quarterly, regionally averaged surface air temperature anomalies over the study region all have positive trends, strongest in summer (not shown). Trends also present in the summer phenology metrics result in regression values that are strong. Spatial patterns in the regression patterns of air temperatures for winter (January–March), spring (April–June) and summer (July–September) onto summer phenology are similar, and we present those of spring and summer that are stronger (**Figure 13**). In general, warmer air temperatures are associated with decreasing (earlier) summer start dates, increasing (delayed) summer end dates and longer summer duration. This coupling is strongest for the summer quarter (July–September), strongest over the Gulf of Maine and weaker over the MAB and Scotian Shelf.

Discussion

While previous work (e.g. Friedland et al., 2013; Pershing et al., 2015; Larouche and Galbraith, 2016) provides a general understanding of the warming trends in the northeast shelf region, the SST trends evident here add spatial detail on the shelf not evident in earlier studies. Our results support previous conclusions derived from coarser resolution data, and over the Scotian Shelf the rates are the same as those calculated by Larouche and

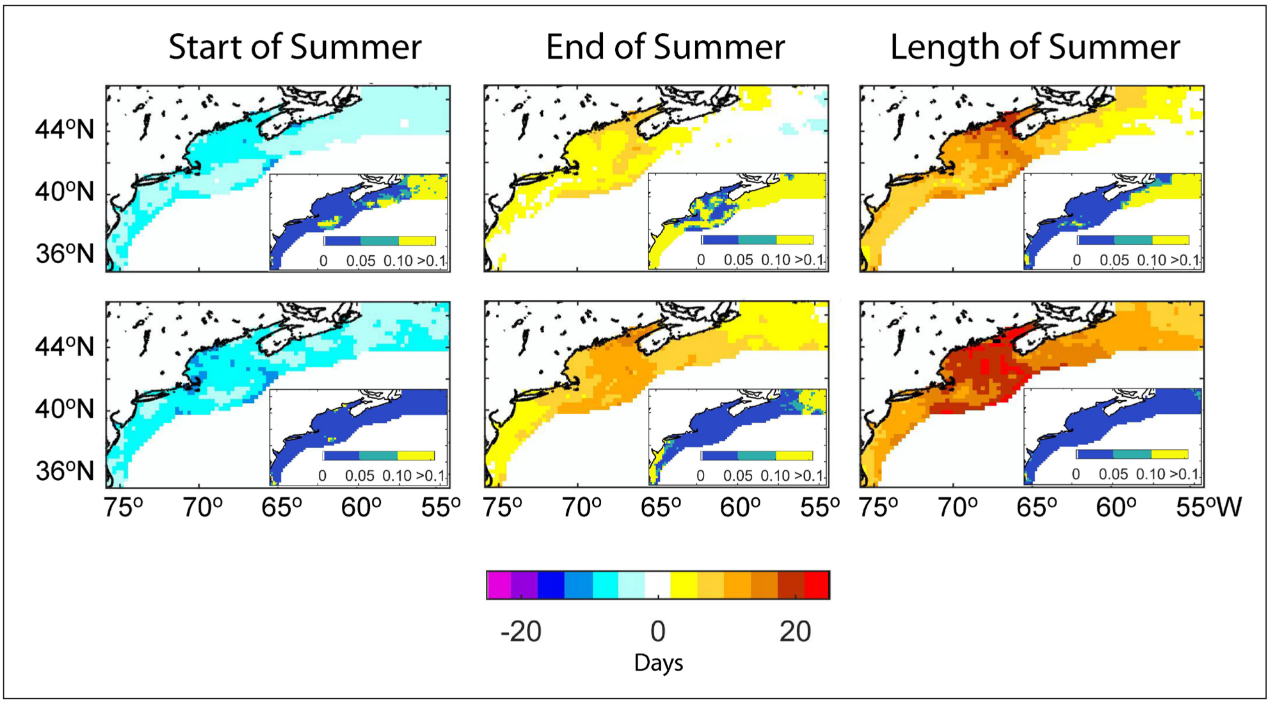

Figure 13: Regression of regional surface air temperatures onto summer phenology changes. Regression of regionally-averaged, normalized, quarterly spring (April–June) (top row) and summer (July–September) (bottom row) surface air temperature anomalies onto the three phenology metrics defining the summer warm period at each grid location in the study area. The units of the regression are in days. The inserts in each figure provide the spatial pattern of the associated p value of the coefficient. DOI: https://doi.org/10.1525/elementa.240.f13

Galbraith (2016) from a different SST data set. The data show slower warming rates in localized regions over the strongly tidally mixed shallow bathymetry of Georges Bank, Nantucket Shoals and the southwestern shore of Nova Scotia. Increased vertical mixing, however, cannot be the only mechanism suppressing warming rates, as the strongly mixed Eastern Maine Coastal Current and mouth of the Bay of Fundy (Pettigrew et al., 2005) exhibit strong positive trends that are only slightly less than those over the stratified deeper Gulf of Maine basins and the Scotian Shelf. Over much of the MAB, shelf SST trends have a cross-shelf gradient, strongest on the outer shelf in closest proximity to the Gulf Stream, weakest near shore where shallower depths likely enable more rapid water column cooling and episodic summer wind-driven upwelling events (e.g. Chant et al., 2004) may modulate warming trends. Separation on a monthly basis (**Figure 3**) highlights the stronger warming rates of summer months compared to winter. This analysis also adds spatial detail and finer scale temporal resolution to better understand the increasing winter-summer differences that have been attributed to warmer summers (Friedland and Hare, 2007). These data (summarized in **Figure 4**) show that most of the overall warming trend of **Figure 2** is contributed by summer-fall (June–October) months and that, except on the Scotian Shelf, winter months (February–April) have much slower warming, and some regions have even cooled. The positive trends in the Gulf of Maine and Scotian Shelf in fall–early winter (October–January) suggest that the strong seasonal cooling that is characteristic of this period has weakened. The extent to which this weakening is due to heat flux, water column mixed layer depth changes and/or advective forcing processes acting during fall or due to the increased water column heat left over from the strongly warming summer is best addressed with future model studies. Chen et al. (2015, 2014) suggest that, at least for the extreme warming event of 2012, changes in atmospherically-driven heat flux that began the previous fall and extended into winter and spring drove warm anomalies the following spring–summer. An important factor that could influence a seasonal bias in SST trends is mixed layer depth. In our study region, winter mixed layers are considerably deeper than those of summer. For the same positive anomaly in surface heat flux forcing, a shallower (deeper) mixed layer depth would distribute the heating on less (more) of the water column and result in stronger (weaker) SST trends in warmer (colder) months (Alexander et al., 2017). Similarly, stronger stratification during summer would require increased energy to break down in fall, delaying fall cooling. In our study region, these relationships would be applicable in space, where trends are usually weaker over more strongly tidally mixed regions than over stratified areas, and over the annual cycle, where winter mixing distributes surface heat flux over a deeper water column than that during summer stratification. This relationship is amplified in our region where summer surface air temperatures are increasing faster than those of winter.

The seasonally differing SST trends result in SST phenology shifts in some, but not all of the metrics we examined. Although characterized by interannual variability and strong warming trends, we did not observe significant phenology trends in the warmest and coldest day of the year. These aspects of the seasonal cycle are likely more strongly phase-controlled by the overall seasonal solar cycle than other metrics.

Other aspects of the SST seasonal cycle, however, exhibit significant phenology trends. The yearday on which the shelf crosses specific SST thresholds in the spring has become progressively earlier, most strongly so in the Gulf of Maine, Georges Bank and on the Scotian Shelf. In the Bay of Fundy and far eastern parts of the Gulf of Maine, the rate at which the yearday that 12°C is reached in spring (**Figure 5**) is advancing at ~1 day yr^{-1}, which is similar to the value of –1 week $decade^{-1}$ shown by Galbraith and Larouche (2013) for a regional mean that also includes part of the Scotian Shelf. Over the MAB, the trends are considerably weaker, and in southern-most regions even positive (delaying). Such trends may have important ecological implications, as key aspects of the behavior and/or seasonal distribution of many species are linked to specific temperature cues (e.g. Nye et al., 2009; Richards et al., 2012; Friedland et al., 2013). The trend towards earlier spring thresholds is in agreement with trends towards earlier spring thermal transition dates shown by Friedland et al. (2015) in data averaged over broad regions of the shelf. These authors also found that trends over the MAB were weaker than those farther north, as our results also indicate.

A specific SST threshold has a latitudinal propagation over our study area and so is a metric of different aspects of the annual cycle at different locations: relatively early in the season at southern latitudes and later at high latitudes. A local definition of summer based on climatological summer SST and variability at each location provides phenology metrics that have the same relative meaning in the annual cycle over the entire study area. Summer start and end day characterize the start, end and duration of the warmest period at each location in the same manner. Significant trends in each of these metrics are evident in the study area. We quantified and mapped a progressively earlier summer start day over the entire region except on top of Georges Bank, where strong tidal mixing and an increased interaction of the water column with atmospheric heat flux may dampen the trend. The data provide spatial detail within the Gulf of Maine that also has similarities to known hydrographic processes. The summer start trend is strongest over the deeper basins, and relatively weak over the strongly advective and tidally mixed Eastern Maine Coastal Current and southern tip of Nova Scotia (Pettigrew et al., 2005; Townsend et al., 2006). The progressively later summer end date is strongest in the Gulf of Maine, over Georges Bank and on the Scotian Shelf, but weaker over MAB, where it is weakest nearshore. Combined, these trends define a lengthening summer period over the entire study area, especially in the Gulf of Maine, even in the vertically well-mixed Eastern Maine Coastal Current region. The relative strength of these trends divides the northeast shelf into three regimes; the Gulf of Maine, Georges Bank and the southernmost Scotian Shelf where increases in summer length are dominated by changes in the summer end day, and the MAB and far eastern portion of the study area where changes in summer length are dominated by changes in the summer start day.

There is evidence that these phenology shifts in the summer warm period impact biological components of the ecosystem. Recent work by our group (Henderson et al., 2017) shows shifts in both distribution and biomass of many fish stocks associated with the duration of summer phenology changes calculated here. These authors used fall trawl survey data to show that ecologically and economically important species such as American lobster, Atlantic herring and Atlantic mackerel all have statistically significant shifts northward in their center of biomass associated with increasing summer duration. An even larger suite of species have statistically significant increases in fall stock biomass associated with increasing summer SST duration, including Atlantic herring, American shad, alewife, American lobster, summer flounder, Acadian redfish and spiny dogfish. Importantly, the increasing summer duration did not have a positive impact on all species. The lengthening summer warm period was associated with a decline in fall stock biomass in some more northerly-distributed species, including cod, cusk, and thorny skate (Henderson et al., 2017). Ecologically, differences in the spatial pattern of the phenology trends suggest that SST phenology changes may impact the same species in different ways in different parts of our study area. SST phenology shifts may also affect interactions between species that experience different phenology cues during different portions of the year. As an example, for seasonal migrants, temperature cues for migration and/or cues for their prey may reduce or enhance the temporal overlap between prey, predators, or competitors (e.g. Pershing et al., 2009; Mills et al., 2013; Runge et al., 2014).

Changes in SST phenology are occurring beyond changes that may be associated with overall increasing temperatures. After normalizing to remove interannual variability, the same temporal trends in summer phenology remained, but with weaker slopes. To the extent that the warm period is also associated with increased stratification, this change implies a longer stratified period and shifts in the timing of spring and fall phytoplankton blooms that result from the onset and breakdown of stratification (Song et al., 2010). Recent work (Li et al., 2015) shows that temperature dominates salinity in controlling stratification over the entire study area during summer and also in spring for the MAB. At the beginning and end of the warm period, however, they show that salinity increases in importance. Our results suggest that SST phenology changes have the potential to shift the timing of this transition and play an increasing role in shelf stratification over a longer period of the annual cycle. Beyond ocean ecology impacts, a warmer shelf in the later summer–fall also has ramifications for the strength of hurricanes as they track north into the region, as warmer SSTs will not reduce their energy as effectively as colder shelves of the past.

The results add phenology implications to previously published analyses of the interaction between SST and four indices of environmental conditions. The strongest direct ocean temperature impact of NAO variability is in the Labrador Sea, upstream from our study area, where changes in the wind field induce colder (warmer) temperatures during positive (negative) phases of the NAO (Greene et al., 2013). Through changes in relative water mass transport, positive (negative) NAO phases result in warmer and saltier (colder and fresher) slope waters off the northern portion of our study area (Petrie, 2007; Greene et al., 2013). Changes in slope water hydrographic characteristics appear along the Scotian Shelf and enter the Gulf of Maine with 1–2 years lag (Greene and Pershing, 2003; Petrie, 2007; Mountain, 2012). We found maximum interaction between the NAO and summer phenology metrics across 2 and 3 years of lag, extending to 4 years, encompassing the time frames of these studies and that of Xu et al. (2015), who found a maximum cross-correlation of Gulf of Maine SST anomalies with the NAO at 4 years lag for the period 1982–2010. These authors found no such correlation with NAO for SST anomalies in the MAB or over Georges Bank. One possible mechanism for both delays in the communication of slope and subsurface water with surface SST phenology and for the sign of the phenology response we see is if the interaction is imposed primarily through salinity changes that impact local stratification, and it takes winter convection to link subsurface water masses with surface waters. Winter mixing in the Gulf of Maine often extends to depths greater than 100 m (Mupparapu and Brown, 2002). In this manner, positive NAO phases could be associated with a more saline water column, weaker stratification and later summer starts, earlier ends and shorter durations spread over the 2–4 year time frame. There is a negative trend in the winter NAO over our study period.

Anomalous Gulf Stream proximity to the shelf in the MAB has been shown to influence shelf temperatures (Gawarkiewicz et al., 2012). Direct influence of the Gulf Stream on shelf temperatures north of Cape Cod is not likely, but Pershing et al. (2001) diagram how changes in Gulf Stream proximity to the shelf in this region influence the water masses present at the entrance to the Gulf of Maine and along the Scotian Shelf shelfbreak. Saba et al. (2015) show that CO_2-driven climate change over the North Atlantic results in weakened Atlantic meridional overturning circulation and a northerly shift in Gulf Stream position that causes increases in both temperature and salinity on the northwest Atlantic shelf. Changes in Gulf Stream position therefore have a mechanistic basis by which they might influence SST phenology throughout our study area. The influence of these changes appears strongest in the Gulf of Maine and along the outer regions of the southern Scotian Shelf and MAB, with positive Gulf Stream shifts (northward) associated with decreasing summer start days and increasing summer end days and summer length. Each of these trends is consistent with warmer conditions imposed on the shelf.

Oceanic anomalies are imposed on this shelf region from advective processes (e.g. Pershing et al. 2001; Shearman and Lentz, 2010; Mountain, 2012), but this is not the only mechanism. Local atmospheric conditions that control wind and heat flux can play a role in hydrographic, SST and ecological variability of the shelf (e.g. Pershing et al., 2012; Li et al., 2014; Chen et al., 2014). Our results suggest that atmospheric conditions over the region in spring and summer are also related to changes in SST phenology, especially on the Scotian Shelf and Gulf of Maine. Higher pressure is linked to earlier summer start, later summer end and longer summer durations. The mechanisms through which this forcing acts is beyond these data and our analysis. We note, however, that higher pressure is associated with reduced storminess and cloudiness, and thus with decreased wind mixing and increased solar heating and surface air temperatures. In this manner, weather, tracked by our index of atmospheric pressure (700 hPa height), is strongly related to surface air temperatures (the quarterly data are correlated at the 99% significance level, $r = 0.47$), and so atmospheric pressure and air temperature are not independent. Close coupling between the atmosphere-ocean system and feedbacks between the two mean that SST is also coupled to surface air temperatures on time scales longer than a few months (e.g. Bhatt et al., 1998). Both our summer SST phenology metrics and air temperatures have long-term trends over our study period, resulting in strong regression values consistent with the strong correlations between air temperature and SST shown by Galbraith et al. (2012). Other environmental indices that we have compared to shelf SST phenology are also not independent of each other. The NAO interacts with both the position of the Gulf Stream and atmospheric pressure over the study region (Joyce et al., 2000; Jones et al., 2003). These processes, however, act at differing time lags and strengths, and have differing spatial footprints.

Summary and conclusions

Quarter-degree spatial resolution SST data over the northeastern North American shelf have provided the regional geography of overall warming rates not evident in previous work. We have shown that these SST warming rates exhibit strong seasonal biases at many locations. In general, summer is warming faster than winter, and in some locations, winter months are cooling despite an overall warming trend. These seasonal biases result in changes in SST phenology. Summer start date is getting earlier and summer end date is getting later over the entire study region. This pattern is most strongly pronounced over the Gulf of Maine, and weaker over the southern portion of our study area. Together, these changes drive an increasing summer duration over the entire region by ~0.5 days year^{-1} in areas south of Long Island, and over 2 days year^{-1} in portions of the Gulf of Maine. Comparisons of the strength of start and end date changes show that changes in end date dominate over the Gulf of Maine, Georges Bank and most of the Scotian Shelf. Elsewhere, changes in summer start date dominate. The increasing duration of the summer warm period has implications for both lower trophic levels, as timing of vertical nutrient flux and seasonal blooms may be altered, and also directly on higher trophic levels as many species have behavioral and/or distributional patterns that are linked to temperature. A key contribution of the work reported here is to map these SST phenology trends over the shelf to show which regions appear relatively resilient to climate-forced SST phenology changes, and which are changing most rapidly. Such information is critical in developing management strategies that seek to incorporate climate trends.

Data Accessibility Statement

All data sets used in this research are from publicly available on-line resources.

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: ACT, AJP, JAN, KEM, MAA
- Contributed to data processing and presentation: ACT, AJP, JAN, KEM, MAA, RW
- Contributed to data analyses and interpretation: ACT, AJP, KDF, JAN, KEM, MAA, NRR, RW, MEH
- Drafted, edited and revised the manuscript: ACT, AJP, KDF, JAN, KEM, MAA, NRR, RW, MEH
- Approved submitted version for publication: ACT, AJP, KDF, JAN, KEM, MAA, NRR, RW, MEH

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