SUPPLEMENTARY MATERIALS FOR

Rapid Climate-Driven Circulation Changes Threaten Conservation of Endangered North Atlantic Right Whales

By Nicholas R. Record, Jeffrey A. Runge, Daniel E. Pendleton, William M. Balch, Kimberley T.A. Davies, Andrew J. Pershing, Catherine L. Johnson, Karen Stamieszkin, Rubao Ji, Zhixuan Feng, Scott D. Kraus, Robert D. Kenney, Christy A. Hudak, Charles A. Mayo, Changsheng Chen, Joseph E. Salisbury, and Cameron R.S. Thompson

Correspondence to: nrecord@bigelow.org

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Materials and Methods

DATA SOURCES

E. glacialis Sightings Per Unit Effort (SPUE)

Analyses of *E. glacialis* habitat-use patterns used data extracted from the North Atlantic Right Whale Consortium (NARWC) database (Kenney, 2001, 2015, 2018; NARWC 2017). We included survey effort and right whale sighting information from aerial right whale surveys by the NOAA National Marine Fisheries Service Northeast Regional Office and Northeast Fisheries Science Center (NEFSC; Cole et al. 2007), aerial surveys conducted by the Center for Coastal Studies (Brown et al., 2007), and aerial and vessel-based surveys by the New England Aquarium and other NARWC member organizations. First, line-transect aerial surveys were conducted to derive estimates of density and abundance of species within defined areas (which differed within and between programs). These surveys were conducted under rigorous criteria by highly trained observers from one of two aircraft, and were designed to represent statistically random samples of the area. Second, platforms-of-opportunity (POP) surveys were those where the observers collected complete records of aircraft or ship tracks and associated sighting conditions, but where the surveys were not sufficiently standardized to use for line-transect methods. Data from line-transect surveys conducted by the NEFSC are archived in the NARWC database in the POP format. We calculated a sightings per unit effort (SPUE) index to overcome the potential bias in raw sighting data. The units are numbers of whales sighted per unit length of survey track. Development of this method began during CETAP (Cetacean and Turtle Assessment Program, 1982), and it has been used in a variety of analyses (Kenney and Winn, 1986; Kenney, 1990; Winn et al., 1986; Hain et al.,1992; Shoop and Kenney, 1992; Kraus et al., 1993; Department of the Navy, 2005; Pittman et al., 2006; Campana et al., 2008; Vanderlaan et al., 2009; Kenney and Vigness-Raposa, 2010). All available aerial and shipboard survey data from 2004 to 2016 were extracted from the NARWC database and combined to quantify sampling effort and derive right whale SPUE values. Only trackline segments completed with at least one observer on watch, clear visibility of at least two nautical miles (3.7 km), sea state of Beaufort 4 or lower, and altitude of less than 366 m for aerial surveys were included as acceptable effort. The entire area was partitioned spatially into a grid of cells measuring five minutes of latitude (9.3 km) by five minutes of longitude (6.6–7.0 km) and temporally by year and half-month periods. All acceptable effort within each grid cell and time period was summed. Similarly, only right whales sighted during acceptable effort were included and summed within each cell and period. Grid cells in which there were less than 2.5 km of survey track completed were excluded from our analysis as inadequately sampled. The effort threshold value of 2.5 km was chosen after experimenting with several threshold values between 0 km and 6.6 km (the minimum east-west distance across a 5 × 5 minute cell). This threshold appeared to remove the most outliers without drastically reducing the number of records available for analysis. Finally, the number of animals sighted was divided by effort to generate the SPUE index, in units of animals sighted per 1,000 km of valid effort.

Atlantic Zone Monitoring Program (AZMP)

Fisheries and Oceans Canada's Atlantic Zone Monitoring Program (AZMP) collected zooplankton samples monthly at the Prince-5 time-series Station in the Bay of Fundy and semi-annually at stations along the Browns Bank section on the western Scotian Shelf. Zooplankton sampling and analysis were performed according to the standard AZMP (Mitchell et al., 2002; Johnson et al., 2018). In brief, zooplankton samples were collected using 0.75 m diameter ring nets equipped with 200 µm mesh nets and towed vertically from near bottom to the surface at approximately 1 m min^{-1}. Samples were preserved in 4% buffered formalin and later split, with one half used for estimation of abundance and composition. Subsamples were taken of this split such that at least 200 organisms were identified to the lowest taxonomic level and enumerated, and additional subsamples were taken until approximately 150–200 *C. finmarchicus* were identified and staged. Stations used in this study include the Browns Bank Line (Station 1, 65.4800°W, 43.2500°N, depth = 53 m; Station 2, 65.48°W, 43.00°N, 122 m; Station 3, 65.48°W, 42.76°N, 107 m; Station 4, 65.48°W, 42.45°N, 101 m; Station 5, 65.50°W, 42.13°N, 179 m; Station 6, 65.51°W, 42.00°N, 983 m; Station 7, 65.35°W, 41.8670°N, 1,904 m) and Prince 5 (66.85°W, 44.93°N, 100 m).

Wilkinson Basin Time Series (WBTS) Station

The WBTS Station is in the northwestern corner of Wilkinson Basin (69.86°W, 42.86°N, 256 m). The Station was sampled at monthly or longer intervals between January 2005 and July 2008, at monthly intervals between April 2012 and May 2013 and between March 2015 and October 2016, and at longer intervals during other periods. Salinity and temperature were measured with an SBE 19plus or 25plus CTD mounted on a rosette, and chlorophyll-*a* concentration was determined with an in situ fluorometer calibrated with discrete water samples. Prior to 2014, stimulated fluorescence was measured with a

Wetlabs inherent optical property (IOP) profiler equipped with a FLS fluorometer S/N 131. After 2014, fluorescence was measured with a Wetlabs Wetstar Chlorophyll Fluorometer S/N WSS-164. During each cruise, Niskin bottles were deployed at discrete depths to capture water samples from which chlorophyll-*a* concentration was determined using a fluorometric acidification method following EPA 445.0 and Ocean Color Protocols (Arar and Collins, 1997). After 2014, the nominal chlorophyll-*a* readings as measured were corrected with chlorophyll concentrations measured from bottle samples. The discrete sample data are served by the University of New Hampshire (http://www.opal.sr.unh.edu/data/boats/bottle/index.jsp). Measurement of copepod abundance followed the AZMP protocols (Mitchell et al., 2002).

Cape Cod Bay

The Center for Coastal Studies collected zooplankton samples at eight to nine fixed stations throughout Cape Cod Bay at least once a month (January–May) during the study period. At each station, surface samples were collected with a 30 cm diameter, 333 µm mesh conical net at a depth of approximately 0.5 m. Oblique samples were collected with a 60 cm diameter, 333 µm mesh conical net, with a maximum depth of 19 m. The 333 µm mesh size was determined to emulate the filtration capacity of the right whale's baleen (Mayo et al., 2001). Totals of 908 surface and 941 oblique samples were collected and preserved in 10% formaldehyde. Each sample was diluted and then subsampled to identify to species, genus, or taxon group and enumerated to obtain the average zooplankton densities per month. Zooplankton counts were normalized through the use of a standard haul factor.

ECOMON

NOAA's Northeast Fisheries Science Center Ecosystem Monitoring (ECOMON) program collects zooplankton measurements as part of an ongoing mission to monitor and assess the Northeast Continental Shelf ecosystem. Sampling is conducted at a seasonal time scale each year, using a 61 cm bongo net fitted with a 333 µm mesh net. Oblique tows were a minimum of 5 minutes in duration, and fished from the surface to within 5 m of the seabed or to a maximum depth of 200 m. A mechanical flowmeter was fitted in the mouth of each net to record the volume sampled. Samples were preserved in 5% formalin. Zooplankton counts were normalized through the use of a standard haul factor. Samples were reduced to approximately 500 organisms by subsampling into aliquots with a modified box splitter. Zooplankton were sorted, counted, and identified to the lowest possible taxon. The number for each taxon identified was multiplied by the number of aliquots to estimate total sample abundance and scaled by one of the standard haul factors. Data are served by NOAA (ftp://ftp.nefsc.noaa.gov/pub/hydro/zooplankton_data/). For the analysis in this study, data were binned into a 1-degree grid and converted to monthly time series.

Gulf of Maine North Atlantic Time Series (GNATS) Temperature Transects

The Gulf of Maine North Atlantic Time Series (GNATS) is performed along a transect that runs between Portland, Maine, USA, and Yarmouth, Nova Scotia, Canada, the widest part of the Gulf of Maine (300 km). It was initiated in 1998, running on a variety of ships of opportunity including ferries and other commercial and small research vessels. More details of the GNATS program can be found elsewhere (Balch et al., 2008, 2012, 2016). The frequency of transects was typically once every two to three weeks in the late spring to early autumn, and once every two to three months in the late autumn through early spring. Vertical temperature profiles were taken every ~35 km across the Gulf of Maine using expendable bathythermograph (XBT; Sippican) or Moving Vessel Profiler (MVP200; Brook Ocean Technologies) casts from the ships traveling at speeds of 8–38 knots. The effective profile depth was a minimum of 100 m (MVP200); for XBTs, the profiles reached the bottom. When traveling on slower ships, T10 XBTs were used for profiles, while from faster ships, T4 XBTs were used. The data from the top 1–2 m of each XBT cast were removed from each profile (5 m for the MVP200 profiles) as the respective probes were equilibrating to the ocean temperature within this depth range. Data are archived in the NASA SeaBASS repository (https://seabass.gsfc.nasa.gov/archive/BIGELOW/BALCH). For this study, data were binned into half-degree stretches along the transect and averaged into seasonal anomalies and 1 m depth bins.

Buoy and Climate Data

The Gulf of Maine Ocean Observing System (GoMOOS; now the Northeastern Regional Association of Coastal Ocean Observing Systems, NERACOOS) deployed a series of oceanographic buoys in the Gulf of Maine beginning in 2001. These buoys are equipped with a suite of sensors, including thermistors located at various depths in the water column. Data are recorded and transmitted hourly via cellular telephone and the GOES satellite system. Data are maintained and served through the NERACOOS website (http://neracoos.org/), available through multiple data interfaces. For this study, data were averaged into monthly time series at each thermistor depth. The Gulf Stream Index (GSI) was taken from a widely utilized GSI time series (Joyce et al., 2000; Nye et al., 2011; Pershing et al., 2015) that uses the dominant mode of variability (via empirical orthogonal function analysis) of variability of the 200 m temperature at the mean location of the 15°C isotherm.

ANALYSIS

The analysis aggregated data from oceanographic buoys and multiple zooplankton and whale surveys (Figure 1, data described above). We focused analysis primarily on the period of rapid warming (2004–present), except where specified, using two approaches. First, based on a regime shift reported to occur around 2010, we subdivided data into early (2004–2008) and late (2012–2016) periods and compared time series data between these two periods using a Mann-Whitney rank sum comparison test (Gibbons et al., 2011). We ran the test comparing data in the early period to the late period for each month within each time series (Figure S1). Second, focusing on areas where spatial and temporal overlap would suggest a possibility of a causal effect between variables, we examined correlations between interannual time series, from the data sets described above. Specifically, we computed Pearson linear correlation coefficients between the Gulf Stream Index and the seasonal temperatures along the GNATS transect (Figure 3), between deep water Jordan Basin temperatures and Jordan Basin *C. finmarchicus* abundance (Figure 4a–d), between Browns Bank Line *C. finmarchicus* abundance and two-month lagged *C. finmarchicus* abundance throughout the Gulf of Maine (Figures 4e and S3), and between Gulf of Maine *C. finmarchicus* abundance and *E. glacialis* SPUE (Figure 4f, Table S1). Significant correlations mainly aligned along an oceanographical transport pathway identified by the Lagrangian particle tracking described below, and these are the relationships that are described in the text. The two complementary approaches pulled out stepwise and more continuous shifts over the recent warming time period and highlighted probable oceanographic linkages. Specific details for processing of each data set, correlation analysis, and backward-in-time particle tracking simulations are described below.

Lagrangian Particle Tracking

Lagrangian particle tracking experiments were conducted in the month of August from 2004 to 2016 to track sources of deep diapausing *C. finmarchicus* individuals in the Grand Manan Basin (black line polygon in Figure S2). The goal was to outline the oceanographically coherent structure that supplies the Bay of Fundy feeding area in late summer. The hydrodynamic forcing was the third-generation Finite Volume Community Ocean Model – Gulf of Maine (FVCOM-GOM3) hindcast, which provides hourly output of ocean velocity fields (Ji et al., 2017). The Lagrangian tracking model solved the advection equation using a fourth-order Runge-Kutta method. The particles were uniformly distributed every 1 km and kept at the depth of 150 m. A batch of particles was released daily and backward-in-time tracked for 60 days (approximately one generation time). The end locations of particles in all years were aggregated to calculate probability density distribution of particles. The resulting feature outlines the source water (Figure S2) for the Bay of Fundy feeding area for *E. glacialis* in late summer.

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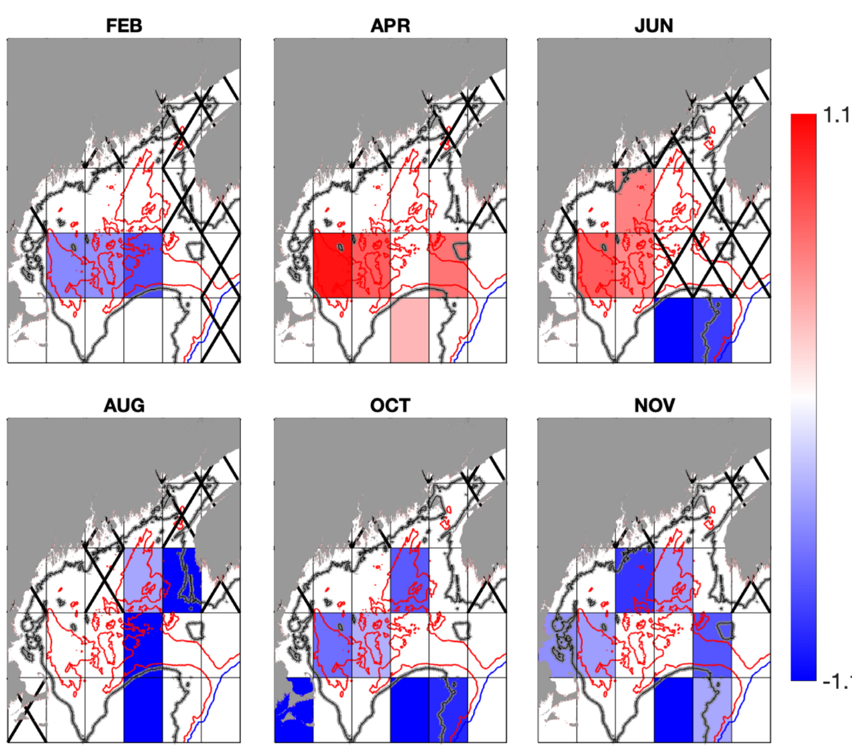

FIGURE S1. Spatial distribution of differences in late-stage *C. finmarchicus* (log abundance) from ECOMON survey data, between the early period (2004–2008) and the late period (2012–2016). Only significant differences are shown (Whitney-Mann rank sum, p <0.05). Xs indicate insufficient data.

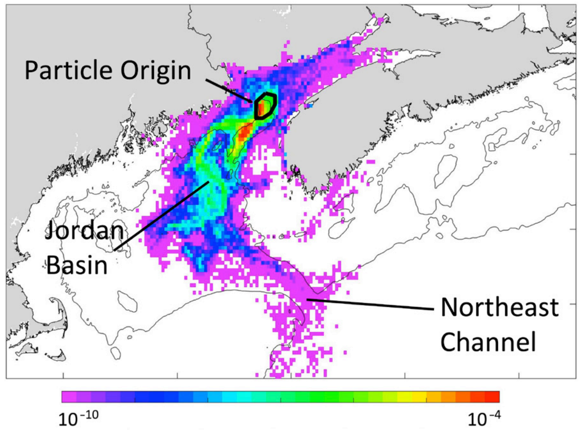

FIGURE S2. Oceanographic transport pathway for deep water leading into the Bay of Fundy feeding habitat. Backtracking particles from Grand Manan Basin in the Bay of Fundy feeding habitat in August for 60 days at 150 m depth, averaged over the years 2004–2016. Color scale shows probability density of 60-day backtracked particles at the end of the run. Details provided in the Supplement text.

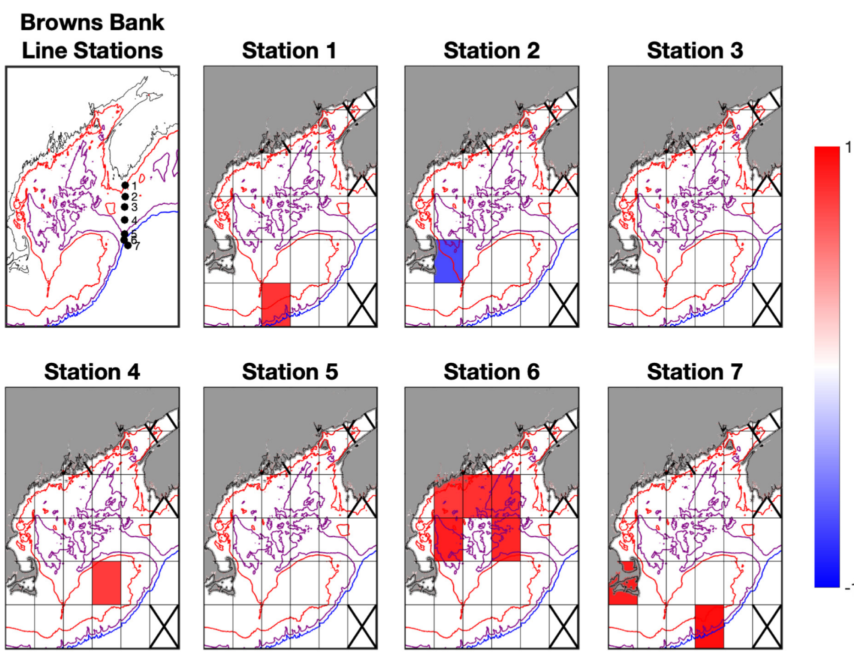

FIGURE S3. Browns Bank Line stations, and the correlations between April C1-C4 *C. finmarchicus* abundances and June *C. finmarchicus* abundances from the ECOMON survey at different locations. Color shows the strength and direction of the correlation. Only correlations with p <0.05 are shown. Xs indicate insufficient data.

TABLE S1. Correlation coefficients (r) between copepod abundances (CI–CIV is the sum of all early stages for all species combined) and *E. glacialis* SPUE for different months in Cape Cod Bay. None are significant at the $p < 0.05$ level.

Cape Cod Bay Correlation Coefficients

	C. finmarchicus	*Pseudocalanus*	*Centropages*	CI-CIV
Jan	−0.5216	−0.4851	0.4460	0.4191
Feb	−0.5474	0.2046	0.2325	0.2164
Mar	−0.1690	0.1858	0.3615	0.1337
Apr	0.0913	0.1349	−0.1397	0.1340
May	0.0866	0.2137	0.0813	0.0713
Spring	−0.0601	0.4778*	−0.0337	−0.0495
Winter	−0.2710	0.2074	0.5291**	0.5194**
All	−0.3006	0.1696	0.4309	0.1072

*p = 0.09; **p = 0.06