

Passive acoustics reveal low-latitude distribution of North Atlantic minke whales

Raick et al. 2026 *MEPS*

Supplementary material:

Note S1 Details on the repertoire of the North Atlantic common minke whale

The North Atlantic common minke whale subspecies has a vocal repertoire mainly consisting of low frequency (< 1 kHz) pulse trains. These pulse trains consist of a repetition of brief pulses (< 0.2 s), with varying interpulse interval (IPI, time in between the start of two consecutive pulses), for all durations ranging from 12 over 40 s (Mellinger et al., 2000; Winn and Perkins, 1976). The changes in IPI over the call duration allow the pulse trains to be categorized as slow-down, constant or speed up. Slow down pulse trains are characterized by a larger IPI towards the end of the call. On the contrary, speed up pulse trains are characterized by a shorter IPI toward the end. The IPI of constant pulse trains does not change throughout the call (Risch, 2022). While pulse trains represent the main calls produced by individuals in the Atlantic subspecies, these minke whales can also produce other sounds such as ratchet-like pulses centered around 850 Hz, grunts between 80 and 140 Hz (Thompson et al., 1979; Winn and Perkins, 1976), frequency downsweeps ranging from 200 to 80 Hz (Edds-Walton, 2000; Perrin et al., 2017) and higher frequency clicks at 5-6 kHz (Beamish and Mitchell, 1973; Risch et al., 2015; Winn and Perkins, 1976).

References

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Note S2 Details regarding recorder and hydrophones

For the U.S. Virgin Islands site, the recorders were deployed as part of a NOAA/NPS Ocean Noise Reference Station Network (Haver et al. 2018). The instruments used were NOAA's PMEL recorders, connected to an ITC-1032 hydrophone (International Transducer Corp.; Santa Barbara, CA, USA), with a sensitivity of -191.5 dB re $1 \text{ V}\mu\text{Pa-1}$ and a flat frequency response from 10 to 2000 Hz. The sampling frequency was 5 kHz, with a low-pass cutoff filter at 2 kHz and a resolution of 16 bits. The pre-amplifier gain varied between 41 and 56 dB for frequencies from 40 to 800 Hz. The peak-to-peak voltage (V_{pp}) was 2.5 V.

In Bermuda, SoundTrap ST300 STD and ST500 STD recorders (Ocean Instruments; Auckland, New Zealand) were used. While an end-to-end calibration of -172.7 dB was used for the ST300, the ST500 had a sensitivity of -1.8 dB in addition to the hydrophone sensitivity of -177 dB re $1 \text{ V}\mu\text{Pa-1}$. The V_{pp} values for the ST300 and ST500 were respectively 10 V and 2 V. ST300 STD's frequency response is flat within ± 3 dB from 12.8 Hz to 140,000 Hz (24-bit). ST500 has similar characteristics.

Deployments along Mexico's coast (Mujeres, Contoy and Nizuc) used Snap recorders (Loggerhead Instruments, St. Petersburg, FL, USA) connected to HTI-96-Min hydrophones (High Tech, Inc., Long Beach, Mississippi). Sensitivities were of -170 dB re $1 \text{ V}\mu\text{Pa-1}$ with a default gain of 2 dB. The sampling frequency was 44.1 kHz (16-bit). The system's frequency response is flat within ± 3 dB from 10 Hz to 20,900 Hz, and within ± 1 dB from 40 Hz to 18,000 Hz. In Cozumel, the deployment involved a AMAR G3 recorder (JASCO Applied Sciences; Silver Spring, MD, USA) with a GTI M36-V35 hydrophone (GeoSpectrum Technologies Inc.; Dartmouth, Nova Scotia, Canada). The sampling frequency was 32 kHz, with a sensitivity of -165 dB re $1 \text{ V}\mu\text{Pa-1}$ and a 24-bits resolution. The maximum voltage was 2.048 V. The system exhibits a flat frequency response from at least 100 Hz to 1000 Hz.

In Montserrat and Curacao, ST600 recorders (Ocean Instruments; Auckland, New Zealand) were used with sensitivities approaching -176 dB re $1 \text{ V}\mu\text{Pa-1}$. The sampling frequency used in the first location was 96 kHz, whereas in Curaçao it was 48 kHz. The V_{pp} value for the instruments was 2 V. The ST500 exhibits characteristics comparable to other ST instruments.

At the remaining sites, Marine Acoustic Recording Units, MARUs (Yang Center for Conservation Bioacoustics; Ithaca, NY, USA), were used. Those units are built with HTI-94-SSQ hydrophones (High Tech, Inc.; Gulfport, MS, USA), which possess a sensitivity of -198 dB re $1 \text{ V}\mu\text{Pa-1}$. MARUs are additionally equipped with a preamplifier (gain of 30 dB), a system amplifier (gain of 23.5 dB) and an analog-to-digital converter (sensitivity of 60 dB re 1 bitV-1). The overall MARU system sensitivity is -169 dB with a flat frequency response (± 2.0 dB) between 10 Hz and $0.4 * \text{ sampling frequency}$. The sampling frequency varied among deployments, from 2 to 64 kHz, and the resolution was 12 bits (stored as 16 bits, with the last four bits zero-padded). Finally, the V_{pp} was 4.096 V.

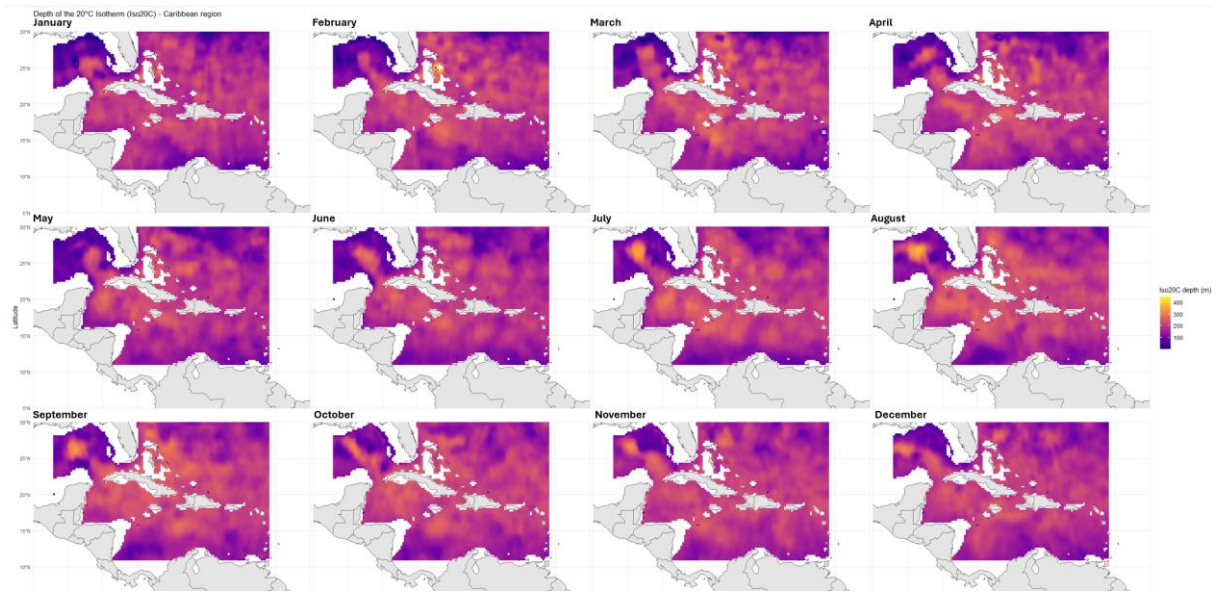


Fig. S1. 20°C-isobath depth (m) from January to December 2021. Data are from Ocean Heat Content Product Suite (North Atlantic), 0.25° NOAA NESDIS CoastWatch (Dataset ID: noaacwOHCna)

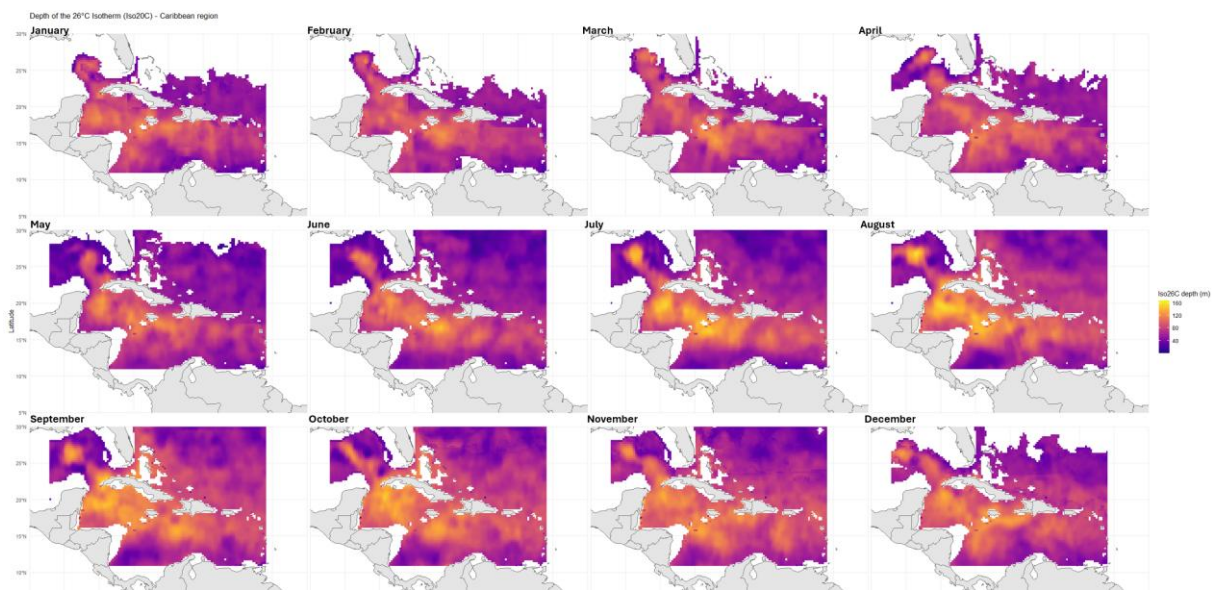


Fig. S2. 26°C-isobath depth (m) from January to December 2021. Data are from Ocean Heat Content Product Suite (North Atlantic), 0.25° NOAA NESDIS CoastWatch (Dataset ID: noaacwOHCna).

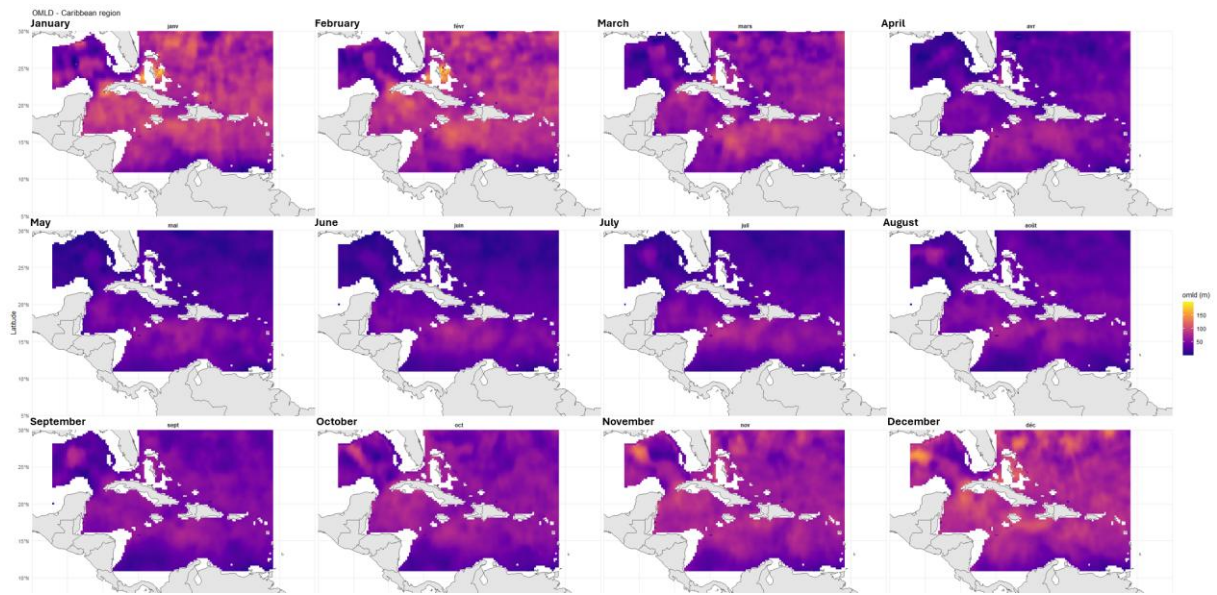


Fig. S3. Ocean mixed layer thickness (OMLD, in m) from January to December 2021. Data are from Ocean Heat Content Product Suite (North Atlantic), 0.25° NOAA NESDIS CoastWatch (Dataset ID: noaacwOHCna).

Table S1 Details of the passive acoustic monitoring (PAM) recorder deployment ID for each region. Lat = latitude (nearest 0.25°). Long = longitude (nearest 0.25°). Depth = water depth when provided; otherwise, it was estimated from the GPS coordinates. Number of instrument days = number of days the recorders were recording underwater. * Depth obtained from online sources (not available in the original metadata).

Region	Collection ID	ID	Year	Months	Lat (°N)	Long (°E)	Depth (m)	N of instruments days
Aruba	S138B_71426_NOAANE10_CHAMP_TC20161209		2016-2017	Dec-Jun	12.375	290.125	38	188
Belize	2020_NPT	Belize (Dog Flea)	2022-2023	Dec - May	17.625	272.375	33	139
Belize	2020_NPT	Belize (Maugrey Caye)	2022-2023	Dec - Apr	17.625	272.125	20-40*	150
Bermuda	2019c	Bermuda 2019	2019	Aug-Oct	32.125	294.875	18	30
Bermuda	2019SE	Bermuda 2019	2019	Aug-Oct	32.125	294.875	4	47
Bermuda	Retrieval2021	Bermuda 2020	2020	Aug	32.125	294.875	4	1
Bermuda	2022_ST500	Bermuda 2021	2021	May-Jun	32.125	294.875	31.3944	21
Bermuda	S1130_2019NW	Bermuda 2019	2019	Jul-Oct	32.125	294.875	25	31
Bonaire	S138B_71426_NOAANE10_CHAMP_TC20161212		2016-2017	Dec-May	12.375	291.625	35	144
Curaçao	Dec2023_200ft	Curaçao 200ft	2023	May-Dec	12.125	291.125	61	177
Curaçao	Jul2024_200ft	Curaçao 200ft	2024	Dec-May	12.125	291.125	61	165
Dominican Republic	S138B_71426_NOAANE10_CHAMP		2016-2017	Dec-Jun	20.625	290.125	30	179
Florida	S034B_2009_1_S01	Florida 1 2009	2009	Sep-Oct	30.125	279.875	364	24
Florida	S034B_2009_1_S02	Florida 2 2009	2009	Dec	30.125	279.875	364	33
Florida	S006B_69040_NOAA_2014_1_S04	Florida 1 2014	2014	Nov-May	30.125	278.875	16	176
Florida	S006B_69040_NOAA_2014_1_N04	Florida N4 2014	2014	Nov-May	30.625	278.875	20	171
Florida	S034B_2009_2_S01	Florida 1 2009	2009	Sep-Oct	30.125	279.875	393	21
Florida	S034B_2009_2_S02	Florida 2 2009	2009	Dec	30.125	279.875	393	22
Florida	S006B_69040_NOAA_2014_2_S04	Florida 4 2014	2014	Nov-May	30.375	278.875	19	176
Florida	S034B_2009_4_1_S04	Florida 4 2009	2009	Sep-Oct	30.375	279.875	168	21
Florida	S034B_2009_4_2_S04	Florida 4 2009	2009	Dec	30.375	279.875	183	22
Florida	S034B_2009_5_1_S05	Florida 5 2009	2009	Sep-Oct	30.125	279.875	201	21
Florida	S034B_2009_5_2_S05	Florida 5 2009	2009	Dec	30.125	279.875	183	22
Florida	S034B_2009_6_1_S06	Florida 5 2009	2009	Sep-Oct	30.125	279.875	192	21

Florida	S034B 2009 6 2 S06	Florida 6 2009	2009	Dec	30.125	279.875	183	22
Florida	S006B 69040 NOAA 2014 6 S06	Florida 6 2014	2014	Nov-May	30.125	278.875	16	176
Florida	S034B 2009 7 1 S07	Florida 7 2009	2009	Sep-Oct	30.125	279.625	44	21
Florida	S034B 2009 7 2 S07	Florida 7 2009	2009	Dec	30.125	279.625	44	22
Florida	S034B 2009 8 2 S08	Florida 8 2009	2009	Dec	30.125	279.625	46	33
Florida	S034B 2009 9 1 S09	Florida 9 2009	2009	Sep-Oct	30.375	279.625	44	21
Florida	S034B 2009 9 2 S09	Florida 9 2009	2009	Dec	30.375	279.625	44	22
Florida	S006B 69040 NOAA 04 South channel3	Florida 3 2014	2014	Nov-May	30.125	278.875	*	176
Florida	S006B 69040 NOAA 04 South channel4	Florida 4 2014	2014	Nov-May	30.125	278.875	*	115
Florida	S006B 69040 NOAA 04 South channel5	Florida 5 2014	2014	Nov-Jan	30.125	278.875	*	50
Florida	S034B 2009 01 S03 PU024	Florida 3 2009	2009	Sep-Oct	30.375	279.875	*	24
Florida	S034B 2009 01 S08 PU024	Florida 8 2009	2009	Sep-Oct	30.125	279.625	*	24
Georgia	S021B_79296_NOAAEC03_03_1	Georgia 1	2016-2017	Nov-May	31.125	278.875	15.8	200
Georgia	S021B_79296_NOAAEC03_03_2	Georgia 2	2016-2017	Nov-May	30.875	279.125	22.9	200
Georgia	S021B_79296_NOAAEC03_03_3	Georgia 3	2016-2017	Nov-May	30.875	279.375	40.3	200
Georgia	S021B_79296_NOAAEC03_03_4	Georgia 4	2016-2017	Nov-May	30.875	279.875	40.1	200
Georgia	S021B_79296_NOAAEC03_03_5	Georgia 5	2016-2017	Nov-May	30.875	280.125	243	200
Georgia	S021B_79296_NOAAEC03_03_6	Georgia 6	2016-2017	Nov-May	30.875	280.375	590	200
GoM	S111B 62378 GoMex01 S01 PU202	GoM 01S01	2010	Jul-Nov	27.625	268.375	971	126
GoM	S111B 62378 GoMex01 S02 PU191	GoM 01S02	2010	Jul-Nov	27.625	268.625	771	126
GoM	S111B 62378 GoMex01 S04 PU172	GoM 01S04	2010	Jul-Nov	27.875	269.625	826	128
GoM	S111B 62378 GoMex01 S05 PU226	GoM 01S05	2010	Jul-Nov	27.875	270.125	892	126
GoM	S111B 62378 GoMex01 S16 PU195	GoM 01S16	2010	Jul-Oct	27.875	274.125	1152	81
GoM	S111B 62378 GoMex01 S17 PU160	GoM 01S17	2010	Jul-Oct	28.375	273.125	1136	83
GoM	S111B 62378 GoMex01 S19 PU218	GoM 01S19	2010	Jul-Dec	26.125	275.125	1108	155
GoM	S111B 62378 GoMex01 S20 PU162	GoM 01S20	2010	Jul-Dec	25.375	275.375	1081	164
GoM	S111B 62378 GoMex01 S21 PU153	GoM 01S21	2010	Jul-Dec	24.875	275.625	1370	170
GoM	S111B 62378 GoMex02 S01 PU048	GoM 02S01	2010-2011	Nov-Apr	27.625	268.375	972	166
GoM	S111B 62378 GoMex02 S09 PU186	GoM 02S09	2010-2011	Oct-Mar	29.125	271.875	1119	166
GoM	S111B_62378_GoMex02_S10_PU024	GoM 02S10	2010-	Oct-Mar	29.125	272.375	1195	166

				2011				
GoM		GoM 02S11	2010-	Oct-Mar				171
	S111B 62378 GoMex02 S11 PU157		2011		29.125	272.875	803	
GoM		GoM 02S16	2010-	Oct-Mar				161
	S111B 62378 GoMex02 S16 PU144		2011		27.875	274.125	1175	
GoM		GoM 02S17	2010-	Oct-Apr				172
	S111B 62378 GoMex02 S17 PU038		2011		28.375	273.125	1165	
GoM		GoM 02S18	2010-	Oct-Mar				129
	S111B 62378 GoMex02 S18 PU062		2011		28.625	272.625	1309	
GoM	GoMex03 S01	GoM 03S01	2011	May-Oct	27.625	268.375	951	146
GoM	GoMex03 S02	GoM 03S02	2011	May-Oct	27.625	268.625	761	147
GoM	GoMex03 S03	GoM 03S03	2011	May-Sep	27.875	269.125	679	139
GoM	GoMex03 S04	GoM 03S04	2011	May-Oct	27.875	269.625	834	147
GoM	S150B 62378 GoMex03 S06 PU135	GoM 03S06	2011	May-Oct	28.375	270.625	982	146
GoM	S150B 62378 GoMex03 S07 PU130	GoM 03S07	2011	May-Oct	28.625	271.125	873	147
GoM	S150B 62378 GoMex03 S08 PU219	GoM 03S08	2011	May-Oct	28.875	271.375	1038	147
GoM	S150B 62378 GoMex03 S09 PU156	GoM 03S09	2011	May-Oct	29.125	271.875	1083	147
GoM	S150B 62378 GoMex03 S10 PU217	GoM 03S10	2011	May-Oct	29.125	272.375	1158	147
GoM	S150B 62378 GoMex03 S11 PU148	GoM 03S11	2011	May-Oct	29.125	272.875	790	147
GoM	S150B 62378 GoMex03S12 PU054	GoM 03S12	2011	May-Sep	29.625	273.125	249	127
GoM	S150B 62378 GoMex03S13 PU092	GoM 03S13	2011	May-Sep	29.375	273.625	290	117
GoM	S150B 62378 GoMex03S14 PU220	GoM 03S14	2011	May-Sep	28.625	274.125	253	128
GoM	S150B 62378 GoMex03S15 PU016	GoM 03S15	2011	May-Sep	28.375	274.375	230	125
GoM	S150B 62378 GoMex03 S17 PU221	GoM 03S17	2011	May-Oct	28.375	273.125	1136	147
GoM	GoMex03 020K S19	GoM 03S19	2011	Jul-Dec	26.125	275.125	1096	146
GoM	GoMex03 020K S20	GoM 03S20	2011	Jul-Dec	25.375	275.375	1055	146
GoM	S150B 62378 GoMex03 S21 PU169	GoM 03S21	2011	Jul-Dec	24.875	275.625	1375	146
GoM	S150B 62378 GoMex03 S22 PU201	GoM 03S22	2011	Jul-Dec	24.375	276.375	775	146
Guadeloupe	S138B_71426_NOAANE10_CHAMP_TC20161214_E_PU207	Guadeloupe E	2016-	Dec-Jun	16.125	298.875	29.5	169
			2017					
Guadeloupe	S138B_71426_NOAANE10_CHAMP_TC20161214_W_PU169	Guadeloupe W	2016-	Dec-Jun	16.125	298.125	28	180
			2017					
Martinique			2016-	Dec-Jun				165
	S138B 71426 NOAANE10 CHAMP FLAC TC20161219		2017		14.875	299.125	59	
Montserrat			2017-	Sep-Jan				108
	Montserat 8604		2018		16.875	297.875	10	
Plant Bank			2021-	Dec-Jun				178
	S1105BMU01_S01_RH410		2022		31.875	294.875	1006	

Plant Bank	S1105BMU02 S01 RH427 D1		2022	Jun-Sep	31.875	294.875	951	91
Puerto Rico	S137B 2001NOAANMFS S1036S1036 PR01 PR1	Puerto Rico 1	2001	Feb	18.125	292.625	4	7
Puerto Rico	S137B 2001NOAANMFS S1036S1036 PR01 PR2	Puerto Rico 2	2001	Feb-Mar	18.375	292.375	307.155	13
Quintana Roo	PADI2022PADI 2022 Mujeres	Mujeres	2022	Jun-Jul				16
Quintana Roo	S120B S1088 Cozumel AMAR394 2 32000 M36-V35-100	Cozumel	2017	Jul-Sep	21.625	273.375	13	
Quintana Roo	PADI2022PADI 2022 Contoy	Contoy	2022	Jun-Jul	20.375	273.125	11	51
Quintana Roo	PADI2022PADI 2022 Nizuc	Nizuc	2022	Jun-Jul	21.375	273.375	4	16
Saba Bank	S124B 65601 NOAANE04		2011-2012	Oct-Apr	21.125	273.375	5	16
Silver Bank	S120B S1034 NOAASB01 20050122 PU022	Silver Bank 22	2005	Jan-Feb	17.625	296.875	30	183
Silver Bank	S120B S1034 NOAASB01 20050122 PU082	Silver Banl 82	2005	Jan-Feb	20.625	290.125	38*	20
Virgin I.	nrs 12 2016-2017		2016-2017	Nov-May	20.625	290.375	37*	23
Virgin I.	nrs 12 2017-2018		2017-2018	May-...	17.875	295.375	39.6	169
Virgin I.	nrs 12 2018-2019		2018-2019	...	17.875	295.375	39.6	384
Virgin I.	nrs 12 2019 2020		2019-2020	...	17.875	295.375	39.6	368
Virgin I.	nrs 12 2020-2022		2020-2021	...	17.875	295.375	39.6	561
Virgin I.	nrs_12_2020-2022		2021-2022	...-May	17.875	295.375	39.6	362
					17.875	295.375	39.6	154

Table S2 Summary of Fitted Generalized Additive (Mixed) Models. Models 1 and 2 are equivalent but model 1 includes the GoM while model 2 excludes it. Models 3 and 4 are equivalent but model 3 includes the GoM while Model 4 excludes it.

Model	Formula	R-squared (Adj.)	Deviance Explained	REML
1	s(long, lat, k = 14)	0.263	35.7%	2489.1
2	s(long, lat, k = 13)	0.206	22.4%	2415.9
3	te(doy, lat, bs = c("cc", "tp") + k = c(10, 15)) + s(depth, k = 10)	0.672	67.3%	1358.3
4	te(doy, lat, bs = c("cc", "tp") + k = c(10, 15)) + s(depth, k = 10)	0.635	60.9%	1317.8
5	s(doy, bs = "cc")	0.611	58.0%	471.57