Supporting Information for

**Cold-water corals in the Subpolar North Atlantic Ocean exposed to aragonite undersaturation if the 2 ºC global warming target is not met**

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**Introduction**

This supplementary file contains two figures and four data tables. Figure S1 compiles the vertical sections of the average in situ temperature, salinity, total alkalinity, total dissolved inorganic carbon (DIC), natural DIC, and anthropogenic CO2. Figure S2 represents the long-term temporal trends of the drivers of the changes in the aragonite saturation state (Ωaragonite) per water-mass layer. Table S1 contains the list of hydrographic cruises used in this study. Table S2 contains the long-term trends of Ωaragonite and the decomposition into their main physical and chemical drivers. Table S3 contains the rates of change in Ωaragonite represented in Figure 5. Table S4 contains the trends of the natural logarithm of Ωaragonite versus the natural logarithm of the atmospheric mole fraction of CO2 (xCO2), i.e., ln(Ωaragonite) vs ln(xCO2); the estimated Ωaragonite for xCO2 of 280 ppmv (preindustrial), and of 558 ppmv (2 ºC warming); and the estimated xCO2 values necessary to reach aragonite undersaturation (Ωaragonite < 1).



Figure S1. Average (a) in situ temperature (in oC), (b) salinity, (c) total alkalinity (TA, in µmol kg-1),   
(d) total dissolved inorganic carbon (DIC, in µmol kg-1), (e) natural DIC (Cnat, in µmol kg-1), and   
(f) anthropogenic CO2 (Cant, in µmol kg-1) along the section (inset) for 1991–2018. Black lines depict the limits of basins and layers (Table 1). White dots represent the sampling grid. Produced with Ocean Data View (Schlitzer, 2020).

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Figure S2. Temporal evolution between 1991 and 2018 of average (a, b) in situ temperature (Tis, in oC), (c, d) salinity (S), (e, f) salinity-normalized total alkalinity (sTA, in µmol kg-1), (g, h) salinity-normalized total dissolved inorganic carbon (sDIC, in µmol kg-1), (i, j) salinity-normalized anthropogenic CO2 (sCant, in µmol kg-1), and (k, l) salinity-normalized natural DIC (sCnat, in µmol kg-1) in the water-mass layers (Table 1) of the Irminger (first column) and Iceland (second column) Basins. The error bars are two times the standard error of the mean (i.e., 95% confidence interval; ; where , where   
σ is the standard deviation of the samples within each layer, and N is the number of samples within each layer). Trends (lines) ± standard error, and their corresponding coefficients of determination (R2) are also given for statistically significant trends. \* denotes that the trend is statistically significant at the 90% level (p-value < 0.1), \*\* at the 95% level (p-value < 0.05) and \*\*\* at the 99% level (p-value < 0.01).

**Table S1.** List of hydrographic cruises used in this study.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Expocode** | **Year (Month)** | **#St a** | **Measurements b** | **QCed in GLODAPv2** | |
| 64TR19910408 | 1991 (Apr-May) | 11 | DIC | Yes | |
| 06MT19910902 | 1991 (Sept) | 15 | DIC | Yes | |
| 06MT19941115 | 1994 (Nov-Dec) | 28 | DIC | Yes | |
| 06MT19970815 | 1997 (Aug-Sept) | 32 | DIC | Yes | |
| 35TH20020611 | 2002 (Jun-Jul) | 38 | TA and pH | Yes | |
| 35TH20040604 | 2004 (Jun-Jul) | 56 | TA and pH | Yes | |
| 06MM20060523 | 2006 (May-Jun) | 44 | TA and pH | Yes | |
| 35TH20080610 | 2008 (Jun-Jul) | 45 | TA and pH | Yes | |
| 35TH20100608 | 2010 (Jun) | 46 | TA and pH | Yes | |
| 29AH20120623 | 2012 (Jun-Jul) | 44 | TA and pH | Yes | |
| 35PK20140515 | 2014 (Jun-Jul) | 31 | TA and pH | Yes | |
| 29AH20160617 | 2016 (Jun-Jul) | 49 | TA and pH | Yes | |
| 35TH20180613 | 2018 (Jun-Jul) | 23 | TA and pH | No | |
| a Number of stations selected for the study.  b Performed measurements of the CO2 system (DIC: total dissolved inorganic carbon; and TA: total alkalinity). | | | | |

Table S2. Observed changes in the aragonite saturation state (Ω) in the water-mass layers (Table 1) of the Irminger and Iceland Basins (and their coefficients of determination (R2)) and the decomposition into their main physical and chemical drivers (± standard error) for 1991–2018, following Eq. (5): in situ temperature (T), salinity (S), salinity-normalized total alkalinity (sTA), salinity-normalized total dissolved inorganic carbon (sDIC), salinity-normalized anthropogenic CO2 (sCant), and salinity-normalized natural DIC (sCnat). compiles the sum of the contributions of the drivers. Values in parenthesis are the percentages of explained by each driver. Note that sDIC = sCant + sCnat and, therefore, ∆ΩsDIC = ∆ΩsCant + ∆ΩsCnat (Section 2.2). Trends in yr-1.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Layer |  |  |  |  |  |  |  |  | |
| *Irminger Basin* | | | | | | | | |
| SPMW | -0.0052 ± 0.0007 (R2 = 0.86)\*\* | -0.0041 ± 0.0007  (79%)\*\* | -0.04 ± 0.08  (1%) | 0.420 ± 0.092  (-8%) \* | -0.03 ± 0.03  (1%) | -0.0044 ± 0.0007  (85%) \* | -0.0041 ± 0.0004  (79%) \* | -0.0002 ± 0.0006  (4%) | |
| uLSW | -0.0036 ± 0.0004 (R2 = 0.88)\*\* | -0.0039 ± 0.0006  (108%)\*\* | 0.04 ± 0.05  (-1%) | -0.011 ± 0.012  (0%) | 0.20 ± 0.23  (-6%) | -0.0041 ± 0.0006  (114%) \* | -0.0051 ± 0.0008  (142%) \* | 0.0014 ± 0.0008  (-39%) | |
| cLSW | -0.0023 ± 0.0002 (R2 = 0.93)\*\* | -0.0025 ± 0.0006  (109%)\*\* | 0.18 ± 0.03  (-8%) \* | 0.577 ± 0.007  (-25%) \* | 0.58 ± 0.33  (-25%) | -0.0039 ± 0.0005  (170%) \* | -0.0016 ± 0.0006  (70%) \* | -0.0022 ± 0.0005  (96%) \* | |
| ISOW | -0.0020 ± 0.0002 (R2 = 0.91)\*\* | -0.0023 ± 0.0005  (115%)\*\* | 0.05 ± 0.03  (-3%) | 0.043 ± 0.007  (-2%) \* | 0.54 ± 0.29  (-27%) | -0.0029 ± 0.0004  (145%) \* | -0.0021 ± 0.0003  (105%) \* | -0.0008 ± 0.0003  (40%) \* | |
| DSOW | -0.0021 ± 0.0003 (R2 = 0.85)\*\* | -0.0021 ± 0.0005  (100%)\*\* | 0.12 ± 0.07  (-6%) | 0.157 ± 0.006  (-7%) \* | 1.02 ± 0.25  (-49%) \* | -0.0034 ± 0.0004  (162%) \* | -0.0027 ± 0.0004  (129%) \* | -0.0006 ± 0.0002  (29%) \* | |
| *Iceland Basin* | | | | | | | | | |
| SPMW | -0.0049 ± 0.0015 (R2 = 0.60)\*\* | -0.0039 ± 0.0012  (80%)\*\* | -0.19 ± 0.15  (4%) | 1.073 ± 0.084  (-22%) \* | -0.17 ± 0.15  (3%) | -0.0046 ± 0.0012  (94%) \* | -0.0031 ± 0.0004  (63%) \* | -0.0011 ± 0.0009  (22%) | |
| uLSW | -0.0025 ± 0.0002 (R2 = 0.91)\*\* | -0.0027 ± 0.0004  (108%)\*\* | -0.02 ± 0.01  (1%) | -0.005 ± 0.006  (0%) | 0.05 ± 0.26  (-2%) | -0.0027 ± 0.0003  (108%) \* | -0.0040 ± 0.0004  (160%) \* | 0.0013 ± 0.0003  (-52%) \* | |
| cLSW | -0.0017 ± 0.0002 (R2 = 0.88)\*\* | -0.0024 ± 0.0006  (141%)\*\* | 0.05 ± 0.02  (3%) \* | 0.050 ± 0.006  (-3%) \* | 0.40 ± 0.40  (-24%) | -0.0029 ± 0.0004  (170%) \* | -0.0021 ± 0.0003  (124%) \* | -0.0008 ± 0.0004  (47%) | |
| ISOW | -0.0014 ± 0.0002 (R2 = 0.85)\*\* | -0.0016 ± 0.0006  (114%)\*\* | 0.01 ± 0.01  (1%) | 0.002 ± 0.003  (0%) | 0.47 ± 0.34  (-34%) | -0.0020 ± 0.0004  (143%) \* | -0.0015 ± 0.0002  (107%) \* | -0.0006 ± 0.0003  (43%) | |
| \* denotes that the trend is statistically significant at 95% level, and \*\* denotes that the trend is statistically significant at 99% level. | | | | | | | | | |

Table S3. Rates of change (± standard error of the estimate) in aragonite saturation state (∆Ωaragonite; in year-1) represented in Figure 5.

|  |  |  |  |
| --- | --- | --- | --- |
| Location | Time period | ∆Ωaragonite | Reference |
| *Surface and mode waters* | | | |
| Iceland Sea  (~67–70ºN ~10–15ºW) | 1981–2019 | -0.0112 ± 0.0022 (0–200 m depth)  -0.0064 ± 0.0007 (200–500 m depth) | Fransner et al. (2020) |
| Iceland Sea time-series (68°N 12.66°W) | 1985–2008 | -0.0072 ± 0.0007 | Olafsson et al. (2009) |
| Norwegian Basin  (~64–67ºN ~5 ºW–2ºE) | 1981–2019 | -0.0128 ± 0.0043 (0–200 m depth)  -0.0079 ± 0.0032 (200–500 m depth) | Fransner et al. (2020) |
| Irminger Sea time-series (64.3°N 28°W) | 1983–2014 | -0.0080 ± 0.0040 | Bates et al. (2014) |
| North-East Atlantic  (40–45ºN 9–36ºW) | 1997–2018 | -0.0080 ± 0.0017 | Fontela et al. (2020) |
| BATS (32°N 64°W) | 1983–2020 | -0.009 ± 0.001 | Bates and Johnson (2020) |
| ESTOC  (29.04ºN 15.50ºW) | 1995–2014 | -0.0115 ± 0.0023 | Bates et al. (2014) |
| HOT  (22.45ºN 158ºW) | 1988–2014 | -0.0084 ± 0.0011 | Bates et al. (2014) |
| CARIACO  (10.5°N 64.67°W) | 1995–2014 | -0.0066 ± 0.0028 | Bates et al. (2014) |
| Subtropical South Pacific (~17–25ºS ~80–168ºW) | 1994–2009 | -0.025 | Murata et al. (2015) |
| Munida Time-Series (45.7°S 171.5°E) | 1998–2014 | -0.0085 ± 0.0026 | Bates et al. (2014) |
| *Upper intermediate waters* | | | |
| Iceland Sea  (~67–70ºN ~10–15ºW) | 1981–2019 | -0.0045 ± 0.0007 | Fransner et al. (2020) |
| Norwegian Basin  (~64–67ºN ~5 ºW–2ºE) | 1981–2019 | -0.0052 ± 0.0017 | Fransner et al. (2020) |
| Entire North Atlantic Ocean | 1989–2010 | -0.0013 ± 0.0003 | Jiang et al. (2015) |
| North-East Atlantic  (40–45ºN 9–36ºW) | 1997–2018 | -0.0052 ± 0.0006 | Fontela et al. (2020) |
| *Lower intermediate waters* | | | |
| Iceland Sea  (~67–70ºN ~10–15ºW) | 1981–2019 | -0.0026 ± 0.0005 | Fransner et al. (2020) |
| Iceland Sea time-series (68°N 12.66°W) | 1985–2008 | -0.0009 ± 0.0002 | Olafsson et al. (2009) |
| Norwegian Basin  (~64–67ºN ~5 ºW–2ºE) | 1981–2019 | -0.0045 ± 0.0017 | Fransner et al. (2020) |
| North-East Atlantic  (40–45ºN 9–36ºW) | 1997–2018 | -0.0024 ± 0.0003 | Fontela et al. (2020) |

Table S4. Long-term trends (1991–2018) of the natural logarithm of aragonite saturation state (Ωaragonite) versus the natural logarithm of the atmospheric mole fraction of CO2 (xCO2; in ppmv) in the water-mass layers (Table 1) of the Irminger and Iceland Basins. stands for the estimated preindustrial Ωaragonite, i.e., at xCO2 of 280 ppmv. compiles the estimated Ωaragonite by the time xCO2 reaches 558 ppmv (level of the 2 ºC warming for the SSP5 Baseline Marker). compiles the estimated xCO2 values necessary to reach aragonite undersaturation, i.e., Ωaragonite equal to 1. The trends were calculated taking into account the variability within each layer through a weighted linear regression. The ± represent the standard error of the estimate.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Layer** |  | **R2** |  |  |  | |
| *Irminger Basin* | | | | | |
| SPMW | -0.608 ± 0.063 | 0.90\* | 2.00 ± 0.07 | 1.32 ± 0.06 | 876 ± 83 | |
| uLSW | -0.486 ± 0.053 | 0.89\* | 1.62 ± 0.05 | 1.16 ± 0.04 | 757 ± 50 | |
| cLSW | -0.361 ± 0.029 | 0.94\* | 1.37 ± 0.02 | 1.07 ± 0.02 | 669 ± 20 | |
| ISOW | -0.355 ± 0.042 | 0.88\* | 1.20 ± 0.03 | 0.94 ± 0.03 | 463 ± 7 | |
| DSOW | -0.426 ± 0.055 | 0.86\* | 1.05 ± 0.03 | 0.78 ± 0.03 | 315 ± 6 | |
| *Iceland Basin* | | | | | |
| SPMW | -0.615 ± 0.165 | 0.58\* | 1.94 ± 0.19 | 1.27 ± 0.15 | 819 ± 193 | |
| uLSW | -0.366 ± 0.031 | 0.93\* | 1.47 ± 0.03 | 1.14 ± 0.02 | 808 ± 34 | |
| cLSW | -0.287 ± 0.033 | 0.89\* | 1.26 ± 0.02 | 1.03 ± 0.02 | 628 ± 19 | |
| ISOW | -0.269 ± 0.033 | 0.87\* | 1.06 ± 0.02 | 0.88 ± 0.02 | 350 ± 2 | |
| \* Statistically significant at the 99% level (p-value < 0.01). | | | | | |