SUPPLEMENTARY INFORMATION

Oysters as sentinels of climate variability and climate change in coastal ecosystems

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Figure S1 - **Wintertime (DJFM) north Atlantic weather regimes.** Centroids of the four weather regimes obtained from daily anomalous sea level pressure (SLP) from the National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis over 1958-2014 based on k-means clustering. Contour interval is every 1 hPa. The box shows the region of interest of our study.
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Figure S2 - Relationship between observed mean annual oyster mortality rate, winter NAO+ occurrences and winter-SST anomalies. The mean annual oyster mortality rate averaged over the six stations is given by the size of the bubble (see legend in upper-left corner) and the colour code corresponds to a tercile ranking: green, yellow and red for lower, middle and upper tercile, respectively. The crosses stand for the tercile average. The horizontal lines materialize the 10th, 33rd, 66th and 90th percentile level of the SST anomaly distribution. The blue line corresponds to the NAO+ vs. winter-SST linear regression. Numbers in the bubbles correspond to the years.

This figure illustrates the co-occurrence of high annual mortality rate of adult oyster, with warmer SST and higher cumulated NAO+ occurrences during the preceding winter. Most of the years (6 out of 8) showing a high mortality rate (> 66th percentile) are located in the upper-right corner of the graph; this partly justifies the choice of the winter SST anomaly field as ‘analog’ to evaluate the evolution of the mortality risk in the future using climate projections, as presented in Fig. 5. 2009 appears clearly as an exception and an outlier. This event is not related to climate factors as extensively described in literature (see e.g. Pernet et al. 2016); it corresponds to the aftermath of the European-wide contamination of oyster juveniles by OsHV1, which hit many countries (from Italy to Ireland, see Alfaro et al. 2018 for a review). This all together further encouraged us to adopt a “risk factor” approach based on temperature threshold for future mortality assessment rather than classical mean relationship based on multiple regression type of models.

Pernet F, Lupo C, Bacher C and Whittington R J 2016 Infectious diseases in oyster aquaculture require a new integrated approach Philos Trans R Soc Lond B Biol Sci 371

Alfaro A C, Nguyen T V and Merien F 2018 The complex interactions of Ostreid herpesvirus 1, Vibrio bacteria, environment and host factors in mass mortality outbreaks of Crassostrea gigas Reviews in Aquaculture.
Table S1 - **List of the rivers located in each of the six embayments studied here.** The daily river discharge was extracted for each of these 12 rivers and cumulated when several rivers were located in the same embayment. River discharge partly controls the variability of organic and inorganic matter concentration, nutrients input and salinity in coastal waters.

| Embayment                        | River name                  |
|----------------------------------|-----------------------------|
| Arcachon Bay (A)                 | Leyre                       |
| Breton Sounds (Br)               | Sèvre, Lay                  |
| Bourgneuf Bay (B)                | Falleron, Loire             |
| Vilaine Bay (Vi)                 | Vilaine                     |
| Mont Saint-Michel Bay (M)        | Couesnon, See, Selune       |
| Veys Bay (V)                     | Aure, Douve, Vire           |
Table S2 – Cross-correlation Pearson coefficient between annual oyster mortality rate at the six studied locations. Significant correlations based on r-statistics are given in bold face (* P < 0.1, ** P < 0.05, *** P < 0.01). Locations from south to north: Arcachon (A), Breton sounds (Br), Bourgneuf (B), Vilaine (Vi), Mont Saint-Michel (M) and Veys (V).

|     | A    | Br   | B    | Vi   | M    |
|-----|------|------|------|------|------|
| Br  |      | 0.52* |      |      |      |
| B   | 0.73*** |      | 0.53** |      |      |
| Vi  | 0.81*** | 0.31  |      | 0.63*** |      |
| M   | 0.65*** | 0.25  | 0.40* |      | 0.69*** |
| V   | 0.31  | 0.25  | 0.28  | 0.20  | 0.42* |
Table S3 - Correlations between the interannual oyster mortality rate and the wintertime DJFM occurrences of the four weather regimes, and the traditional wintertime NAO index (rightmost column, see Methods). Correlation coefficients are computed for each of the six locations either taken separately or combined (“All”). Significant correlations are given in bold face (* P < 0.05, ** P < 0.01, *** P < 0.001).

| Location                  | NAO+  | NAO-  | AR    | BL    | Index |
|---------------------------|-------|-------|-------|-------|-------|
| Arcachon Bay (A)          | 0.64* | -0.43*| 0.09  | -0.40 | 0.51* |
| Breton sounds (Br)        | 0.55* | -0.31 | -0.07 | -0.30 | 0.35  |
| Bourgneuf Bay (B)         | 0.66**| -0.43*| -0.08 | -0.26 | 0.42* |
| Vilaine Bay (Vl)          | 0.56**| -0.40 | 0.08  | -0.29 | 0.42* |
| Mont Saint-Michel Bay (M) | 0.56**| -0.35 | 0.25  | -0.53*| 0.34  |
| Veys Bay (V)              | 0.51* | -0.19 | -0.13 | -0.37 | 0.28  |
| All                       | 0.77**| -0.46*| 0.02  | -0.48*| 0.50* |

These results show the overwhelming predominance of significant positive correlation with the wintertime NAO+ occurrences for each of the six locations. The latter is further enhanced when all the stations are combined. Weak anti-correlation found with NAO- illustrates the relevance and added value of the weather regime paradigm adopted here in our study. It allows capturing the spatial asymmetry of the NAO characterized by an intrinsic eastward shift of the Azores and Icelandic pressure centres of action towards Europe in positive phase (Cassou et al. 2004). This explains the greater potential influence of NAO+ circulations versus NAO- ones along the European Coast. Such a conclusion is further reinforced by the weaker positive correlation found with the traditional NAO Index, which is computed from fixed locations and thus assumes symmetry, by construction (Hurrell et al., 2001). No significant correlation is found with AR (Atlantic Ridge) and only weak anti-correlation with BL (Scandinavian BLocking) regimes for the Mont Saint Michel station and when all locations are combined.

Cassou, C. L. Terray, J.W. Hurrell and C. Deser, 2004: North Atlantic winter climate regimes: spatial asymmetry, stationarity with time and oceanic forcing. J. Climate, 17, 1055-1068.

Hurrell J.W. Kushnir Y. Visbeck M. 2001: The North Atlantic Oscillation. Science, 291, 603–605.
Table S4 - Seasonal correlations between coastal ecosystems bioclimatic variables and wintertime NAO+ occurrences (DJFM). Significant correlations are given in bold face (* P < 0.05, ** P < 0.01, *** P < 0.001).

| Variable                  | Winter (JFM) | Spring (AMJ) | Summer (JAS) | Fall (OND) |
|---------------------------|--------------|--------------|--------------|------------|
| Sea surface temperature   | 0.61***      | 0.16         | -0.04        | 0.18*      |
| River flow                | 0.31***      | 0.41***      | 0.48***      | 0.29***    |
| Salinity                  | -0.22*       | -0.19*       | -0.30***     | -0.25**    |
| Chlorophyll-a concentration | 0.23*        | 0.18         | 0.36***      | 0.21*      |
| Oyster mortality          | 0.17         | 0.50***      | 0.34***      | 0.21*      |

This table illustrates, at seasonal scale, the temporal lagged relationship between the climate forcing (here NAO+ regime occurrence) and the coastal ecosystem response. The winter atmospheric circulation has a long-lasting imprint on the river flow and salinity, with significant correlation all year long. The sea surface temperature mainly reacts concomitantly with the winter forcing but the correlation is lost in subsequent spring and summer when the ocean mixed layer is very shallow and is mostly responsive to local and concurrent forcings. This is consistent with earlier studies on observed SST along the North Western coast of Europe (van Aken et al., 2008). Regain of correlation in fall is likely explained by so-called re-emerging mechanism as the seasonal mixed layer is deepening and re-entains back to the surface the previous winter anomalies stored in the subsurface (Cassou et al., 2007). Correlation with phytoplankton is maximum during summer months. Note finally that most of the oyster mortality response occurs during spring- and summer-time.

Cassou C., C. Deser and M. A. Alexander, 2007: Investigating the impact of reemerging sea surface temperature anomalies on the winter atmospheric circulation over the North Atlantic. *J. Climate*, 20, 3510-3526.

van Aken, H. M. Variability of the water temperature in the western Wadden Sea on tidal to centennial time scales, 2008:. *J. Sea Res.* 60, 227–234.
Table S5 - Correlations between JFM SST anomalies and the wintertime DJFM occurrence of the four weather regimes, and the traditional wintertime NAO index (rightmost column). Pearson’s r coefficients are given. Correlations are computed for each of the six locations either taken separately or combined (“All”). Significant correlations are given in bold face (* P < 0.05, ** P < 0.01, *** P < 0.001).

| Location                  | NAO+   | NAO-   | AR     | BL     | Index |
|---------------------------|--------|--------|--------|--------|-------|
| Arcachon Bay (A)          | 0.44*  | -0.23  | -0.01  | -0.30  | 0.30  |
| Breton sounds (Br)        | 0.68** | -0.37  | -0.08  | -0.39  | 0.50* |
| Bourgneuf Bay (B)         | 0.70***| -0.50* | 0.04   | -0.34  | 0.69***|
| Vilaine Bay (Vi)          | 0.56** | -0.42  | 0.05   | -0.24  | 0.61**|
| Mont Saint-Michel Bay (M) | 0.77** | -0.54  | -0.10  | -0.26  | 0.61* |
| Veys Bay (V)              | 0.77** | -0.66* | -0.14  | -0.02  | 0.77**|
| All                       | 0.72** | -0.47* | -0.03  | -0.34  | 0.63**|

Results are very similar to the ones with interannual adult oyster mortality rate (Table S1). This further supports, in addition to Fig. S2, the choice of the winter SST as ‘analog’ to study the evolution of the mortality risk in the future based on projections as presented in Fig. 5. Note that the positive correlation with the traditional NAO index is reinforced, except in Arcachon Bay, which is the southernmost location studied here. This lower correlation in the south, which is also found with NAO+, is in accordance with the spatial distribution of the NAO+ basin-scale influence zone illustrated in Fig. 4.
Table S6 - Climate models from the CMIP5 archive used in the estimation of the risk factor over historical and future period. Name, ocean model spatial resolution, member number per model is provided. For each model, the variance and 90th percentile (P90) are computed from anomalies with respect to the 1986-2015-reference period. To do so, RCP2.6 and RCP8.5 are concatenated to historical runs ending in 2005 in CMIP5. Observational counterpart is given at the end of the table. We account for biases in the full distribution of the modelled SST because we use anomalies (correction of the mean bias) and percentile (correction of the variance bias) computed from the raw model output distribution to compute the risk factor.

| id | Climate model | Institute | Ocean model | Resolution | Member | HIST+RCP2.6 | HIST+RCP8.5 | HIST+RCP2.6 | HIST+RCP8.5 |
|----|---------------|-----------|-------------|------------|---------|-------------|-------------|-------------|-------------|
| 1  | ACCESS1-0     | CSIRO-BOM | NOAA/GFDL  | 1° x 1°    | r01     | 0.17        | 0.08        | 0.48        | 0.08        |
| 2  | ACCESS1-1     | CSIRO-BOM | NOAA/GFDL  | 1° x 1°    | r01     | 0.28        | 0.08        | 0.6         | 0.2         |
| 3  | bcc-csm1-1    | BCC-CMA   | MOM4_L40   | 1° x 1° - 0.3° | r01 | 0.19       | 0.17        | 0.47        | 0.44        |
| 4  | bcc-csm1-1-m  | BCC       | MOM4_L40v2 | 1° x 1° - 0.3° | r01 | 0.38       | 0.39        | 0.69        | 0.7         |
| 5  | BNU-Esm1     | CSIRO     | CSIRO      | 1° x 0.7°  | r01     | 0.17        | 0.09        | 0.55        | 0.49        |
| 6  | CanESM2      | CCSma     | CanOM4 - CMOC1.2 | 1.4° x 1.4° | r01 | 0.13       | 0.13        | 0.43        | 0.39        |
| 7  | CCSM4        | NCAR      | POP2       | 1° x 1°    | r01     | 0.10        | 0.18        | 0.43        | 0.53        |
| 8  | CESM1-BGC     | NSF-DOE   | POP2       | 1° x 1°    | r01     | 0.11        | 0.11        | 0.37        | 0.34        |
| 9  | CESM1-CAM5    | NCAR      | POP2       | 1° x 1°    | r01     | 0.11        | 0.11        | 0.37        | 0.34        |
| 10 | CESM1-WACCM   | NSF-DOE   | POP2       | 1° x 1°    | r01     | 0.11        | 0.11        | 0.37        | 0.34        |
| 11 | CMCC-CESSM1   | CMCC      | OPA2       | 1° x 1°    | r01     | 0.22        | 0.22        | 0.58        | 0.59        |
| 12 | CMCC-CMS     | CMCC      | OPA2       | 1° x 1°    | r01     | 0.21        | 0.21        | 0.58        | 0.59        |
| 13 | CMCC-CMS     | CMCC      | OPA2       | 1° x 1°    | r01     | 0.21        | 0.21        | 0.58        | 0.59        |
| 14 | CNRM-CM5     | CNRM      | NEMO       | 1° x 1°    | r01     | 0.21        | 0.21        | 0.58        | 0.59        |
| 15 | CSIRO-Ma3-6-0 | CSIRO      | GFDL MOM2.2 | 1.9° x 0.9° | r01 | 0.15        | 0.15        | 0.55        | 0.54        |
| 16 | GFDL-CM3     | NOAA GFDL | MOM4       | 0.3° x 1°  | r01     | 0.21        | 0.21        | 0.67        | 0.67        |
| 17 | GFDL-ESM2G   | GFDL      | MOM4       | 0.3° x 1°  | r01     | 0.13        | 0.13        | 0.38        | 0.38        |
| 18 | GFDL-ESM2M   | GFDL      | MOM4       | 0.3° x 1°  | r01     | 0.09        | 0.09        | 0.29        | 0.29        |
| 19 | GISS-E2-H    | NASA-GISS | NASA-GISS  | 0.28 x 0.28 | r01 | 0.28        | 0.28        | 0.52        | 0.7         |
| 20 | GISS-E2-H-CC | NASA-GISS | NASA-GISS  | 0.28 x 0.28 | r01 | 0.25        | 0.25        | 0.72        | 0.72        |
| 21 | GISS-E2-R    | NASA-GISS | NASA-GISS  | 0.28 x 0.28 | r01 | 0.26        | 0.26        | 0.72        | 0.72        |
| 22 | GISS-E2-R-CC | NASA-GISS | NASA-GISS  | 0.28 x 0.28 | r01 | 0.26        | 0.26        | 0.72        | 0.72        |
| 23 | HadGEM2-CC   | MOHC      | HadGEM2   | 1° x 0.3   | r01     | 0.16        | 0.16        | 0.41        | 0.41        |
| 24 | HadGEM2-ES   | MOHC      | HadGEM2   | 1° x 0.3   | r01     | 0.22        | 0.22        | 0.41        | 0.41        |
| 25 | INMCM4      | INM      | INMCM4    | 0.5° x 1°  | r01     | 0.29        | 0.29        | 0.74        | 0.74        |
| 26 | IPSL-CM5A-LR | IPSL     | ORCA2     | IPSL       | r01     | 0.13        | 0.13        | 0.41        | 0.41        |
| 27 | IPSL-CM5A-MR | IPSL     | ORCA2     | IPSL       | r01     | 0.29        | 0.29        | 0.77        | 0.77        |
| 28 | IPSL-CM5B-LR | IPSL     | ORCA2     | IPSL       | r01     | 0.13        | 0.13        | 0.44        | 0.44        |
| 29 | MIROC-ESM   | MIROC    | COCCO3.4  | 0.6° x 1.7° x 1.4° | r01 | 0.27       | 0.27        | 0.54        | 0.54        |
| 30 | MIROC-ESM- CHEM | MIROC | COCCO3.4  | 0.6° x 1.7° x 1.4° | r01 | 0.23       | 0.23        | 0.56        | 0.56        |
| 31 | MIROC5      | MIROC    | COCCO3.4  | 0.6° x 1.7° x 1.4° | r01 | 0.19       | 0.19        | 0.46        | 0.46        |
| 32 | MPI-ESM-LR  | MPI-M    | MPIOM     | 1° x 1.    | r01     | 0.11        | 0.11        | 0.44        | 0.44        |
| 33 | MPI-ESM-MR  | MPI-M    | MPIOM     | 1° x 1.    | r01     | 0.09        | 0.09        | 0.36        | 0.36        |
| 36 | NorESM1-ME  | NCC      | NCC       | 1° x 1°    | r01     | 0.12       | 0.12        | 0.43        | 0.43        |

Mean ± SD: 0.19 ± 0.08, 0.19 ± 0.08, 0.51 ± 0.14, 0.51 ± 0.13
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Figure S3 – Observed and simulated evolution of yearly salinity anomaly along the French Atlantic coast over 1993-2100. Historical + projected yearly salinity anomalies from CMIP5 climate models a, averages over a broad Biscay Bay + English Channel domain following RCP8.5 and RCP2.6 scenarios as in Fig. 5a. b, in each coastal grid points over the selected domain for all the models in RCP8.5 and c, RCP2.6 projections.

This figure allows us to explore the risk of exceptional mortality associated with sea surface salinity (SSS) anomalies based on the observational relationship given in Fig. 2. When averaged over the same regional domain as the SST in Fig.5 (and shown in Fig. 3), models project a gradual decrease of SSS, which is amplified in RCP8.5 versus RCP2.6 (Fig. S3a). However, when compared to observations over the historical period, there is an obvious mismatch in variance between in-situ records and model behaviours, thus limiting our ability to use regional-scale SSS to study local-scale processes, as opposed to SST (see validation in Fig.5a).

Instead of averaging over a broad domain, we selected the coastal points and reported the projected change in Fig.S3bc for RCP8.5 and RCP2.6, respectively. Interestingly, the variance is recovered and models outputs and in-situ measurements match relatively well over the common period. We could thus assess quantitatively the mortality risk through this new prism but the confidence in CMIP-class type of models to correctly account for local processes is very low, because of resolution issues and associated modelled physical (e.g. very crude treatment or river runoff, etc.) and biological processes; regional Earth System-class type of models (ESM) would be necessary.

That said, if we qualitatively believe the CMIP5 modelled signals, projection lean towards enhanced mortality risk due to overall reduced salinity in both scenarios. Note also that interannual SSS variance exhibits a major shift from 2040 onwards in RCP8.5 in most of the models (Fig. S3b) making it difficult to use past knowledge to anticipate the future. This clearly reinforces the relevance to limit the global temperature rise to +2°C to avoid climate surprises with potential very high impacts on biology. The origin of such a tipping behaviour, which is not present in RCP2.6, needs further investigation.