Causes and projections of abrupt climate-driven ecosystem shifts in the North Atlantic

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Supplementary figures

Figure S1. Relationship between mean annual SST and the mean annual concentration in oxygen for the whole ocean. Data are from the World Ocean Atlas (see Materials and methods).

Figure S2. Observed mean annual wind intensity and direction in the North Atlantic Ocean in the 1960-70s (**A**), 1980s (**B**), 1990s (**C**) and the period 2000-2005 (**D**). The difference (Dif.) in wind intensity between the 1980s and the period 1960-1979 is indicated (**E**). A positive value means an increase in wind intensity. The 1960s and 1970s were combined as no substantial change was detected during this period.

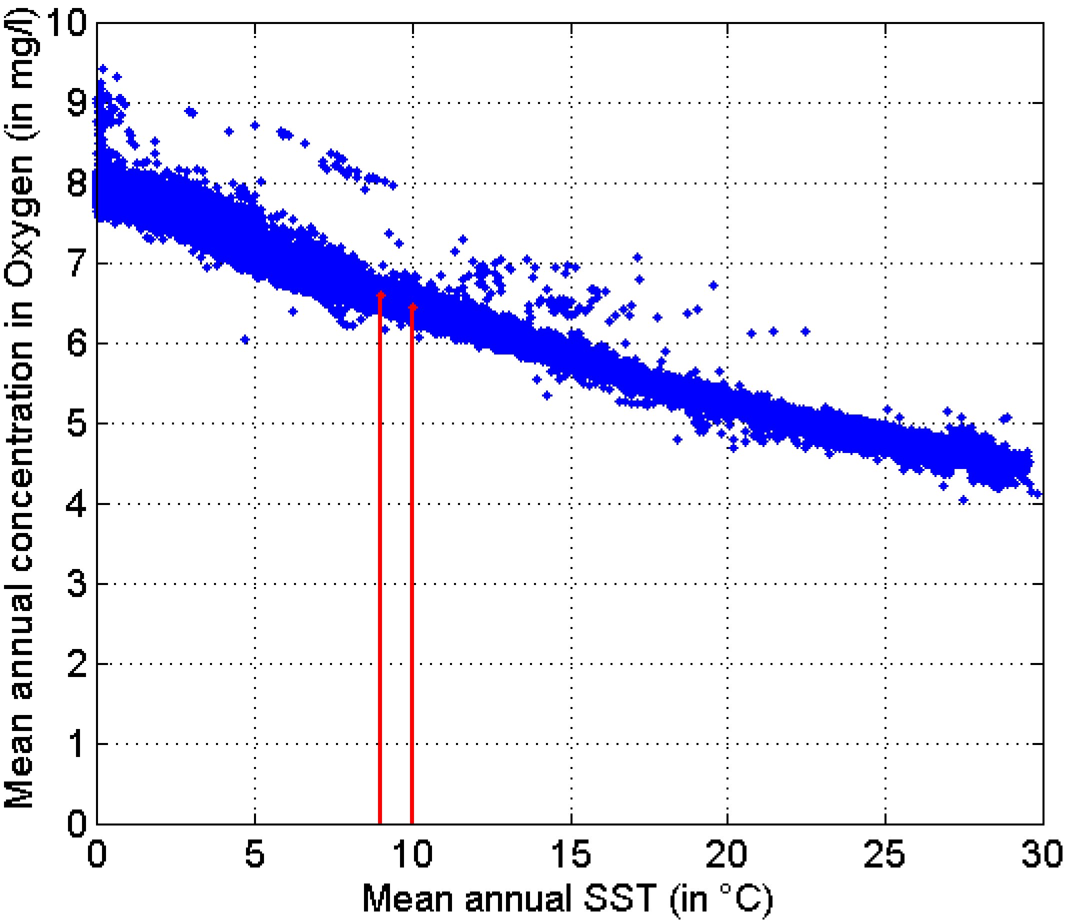
Wind data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.cdc.noaa.gov). We used NCEP Reanalysis monthly mean surface u-wind and v-wind for the period 1960-2005 with a spatial resolution of 2.5 degree latitude x 2.5 degree longitude. The NCEP/NCAR Reanalysis 1 project uses a forecast system to run data assimilation using past data from 1948 to the present (Kalnay *et al.* 1996).

Figure S3. Long-term biological changes in the North Sea (1958-2005). **A.** Index of plankton community structure (first principal component representing 18.95% of the total variance, significant percentage well above the equiprobability = 1/ 115 species = 0.87%) from a PCA performed on 115 plankton species. This index showed that the plankton ecosystem experienced an abrupt shift in its biological composition starting in the 1980s. The shift was clearly detected although not involving all species. These changes involved diatoms (e.g. *Biddulphia alternans*), dinoflagellates (e.g. *Scrippsiella* spp.), both holo- (copepods, *Calanus helgolandicus*) and meroplankton (increase in decapod larvae), the latter possibly indicating a link with changes reported in the benthos in different parts of the North Sea (Kirby *et al.* 2007). **B.** CPR Phytoplankton Colour Index. Changes in the indices of plankton community structure and in the phytoplankton colour were more observed at the end of the 1980s when the critical thermal boundary started to shift. **C.** Mean size of female calanoid copepods. **D.** Diversity of calanoid copepods measured as the Gini coefficient. **E.** Cod recruitment (1963-2005) at age 1. The different biological indicators show variations in the exact timing of the changes, a feature often suggested (Beaugrand 2004b). Changes in the mean size and diversity of calanoids appeared at the beginning of the 1980s, thereby a few years prior to the shift in the critical thermal boundary (shift detected in 1988). The strengthening of the wind from the beginning of the 1980s (Supplementary Fig. 1) involved probably a northward advection of warm-water species along the European shelf-edge and into the northern part of the North Sea, explaining the early increase in calanoids reported in this region (Beaugrand *et al.* 2002).

Figure S4. Observed mean annual sea surface temperature in the North Sea for the period 1980-1989. The location of the critical thermal boundary (9-10°C) is indicated by '+'. This shows that the northward movement of the critical thermal boundary initiated in 1988.

Figure S5. Differences in sea surface temperature and wind intensity between the 1980s and the period 1960-1979 (A, D), the 1990s and the period 1960-1979 (B, E) and the period 2000-2005 and the period 1960-1979 (C, F). Gray lines denote the isobath 200 m. Black lines indicate a change of -1, 0 and +1 in sea surface temperature (in °C) or wind intensity (in $m.s^{-1}$). The 1960s and 1970s were combined as no substantial change was detected during this period. Gray lines denote the isobath 200 m.

Figure S6. Relationships between annual observed (COADS) and modelled (ECHAM 4) SST for the period 1990-2005 in the North Atlantic (40-80°N, 80°W-30°E). The relationship between annual SST from observed data (ICOADS) and modelled data (ECHAM 4) is high and the coefficient of correlation is $r = 0.95$ ($p<0.0001$; $n = 1809$).



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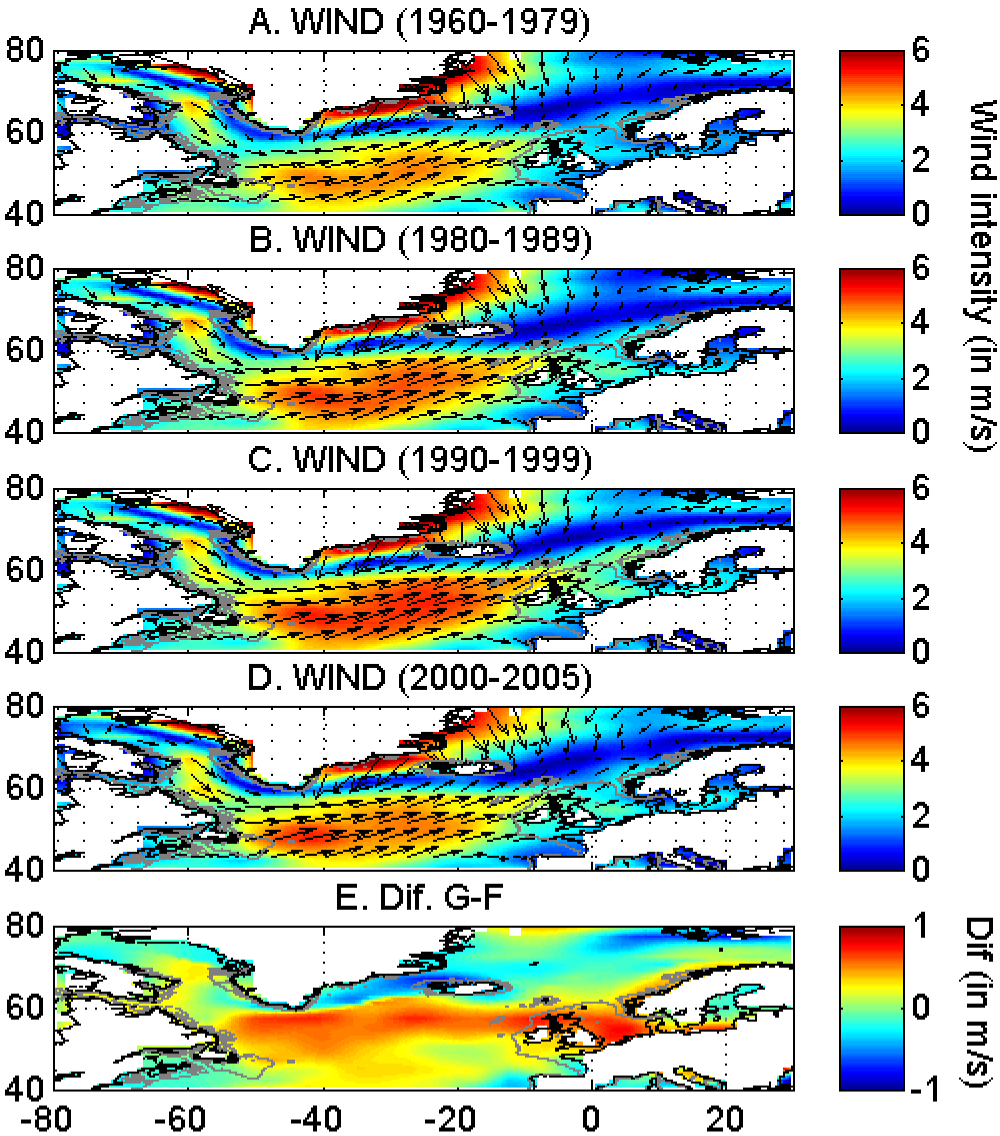

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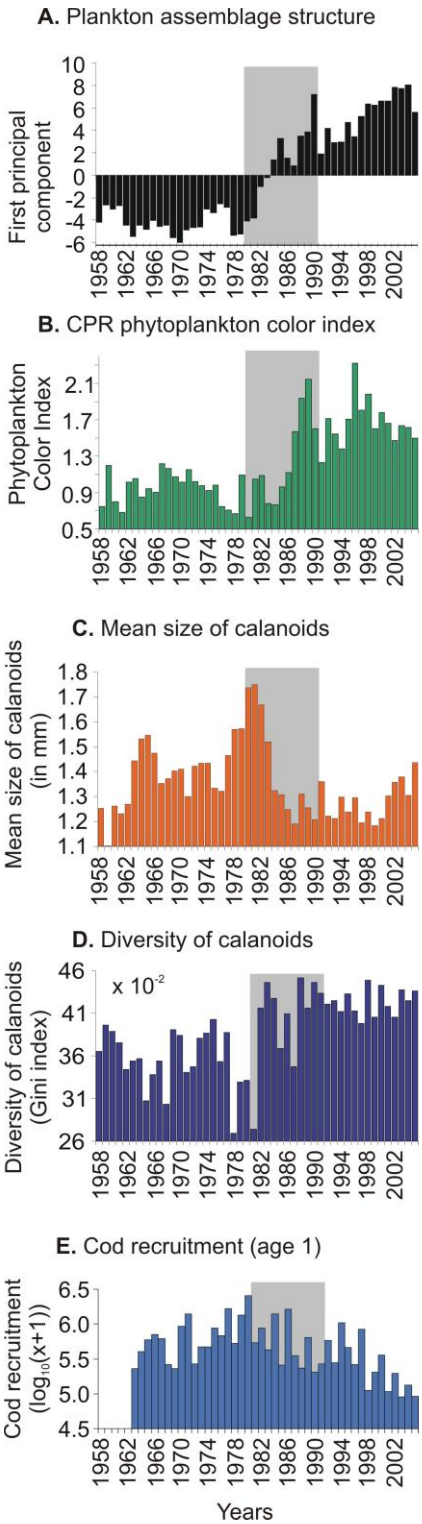

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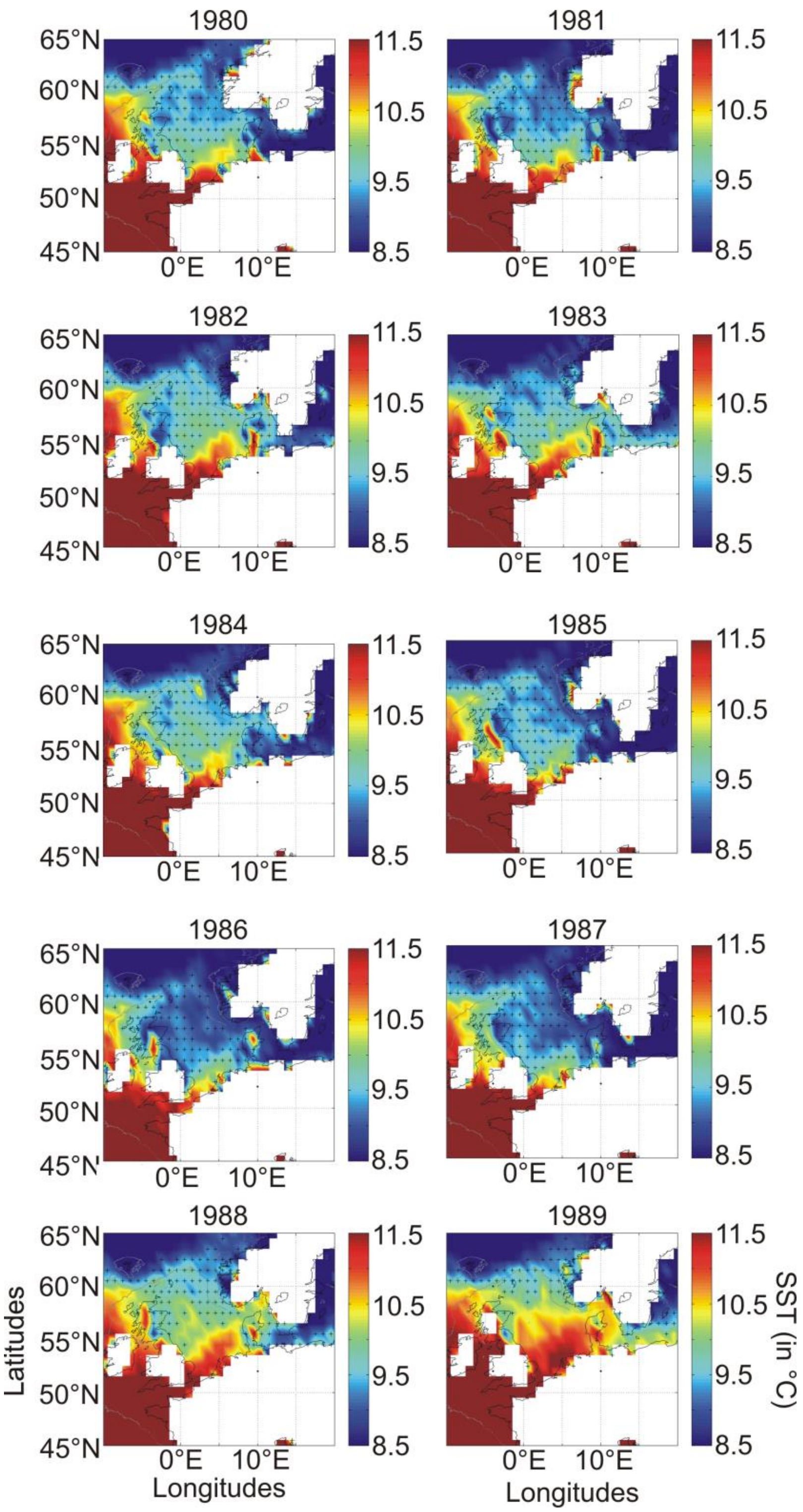

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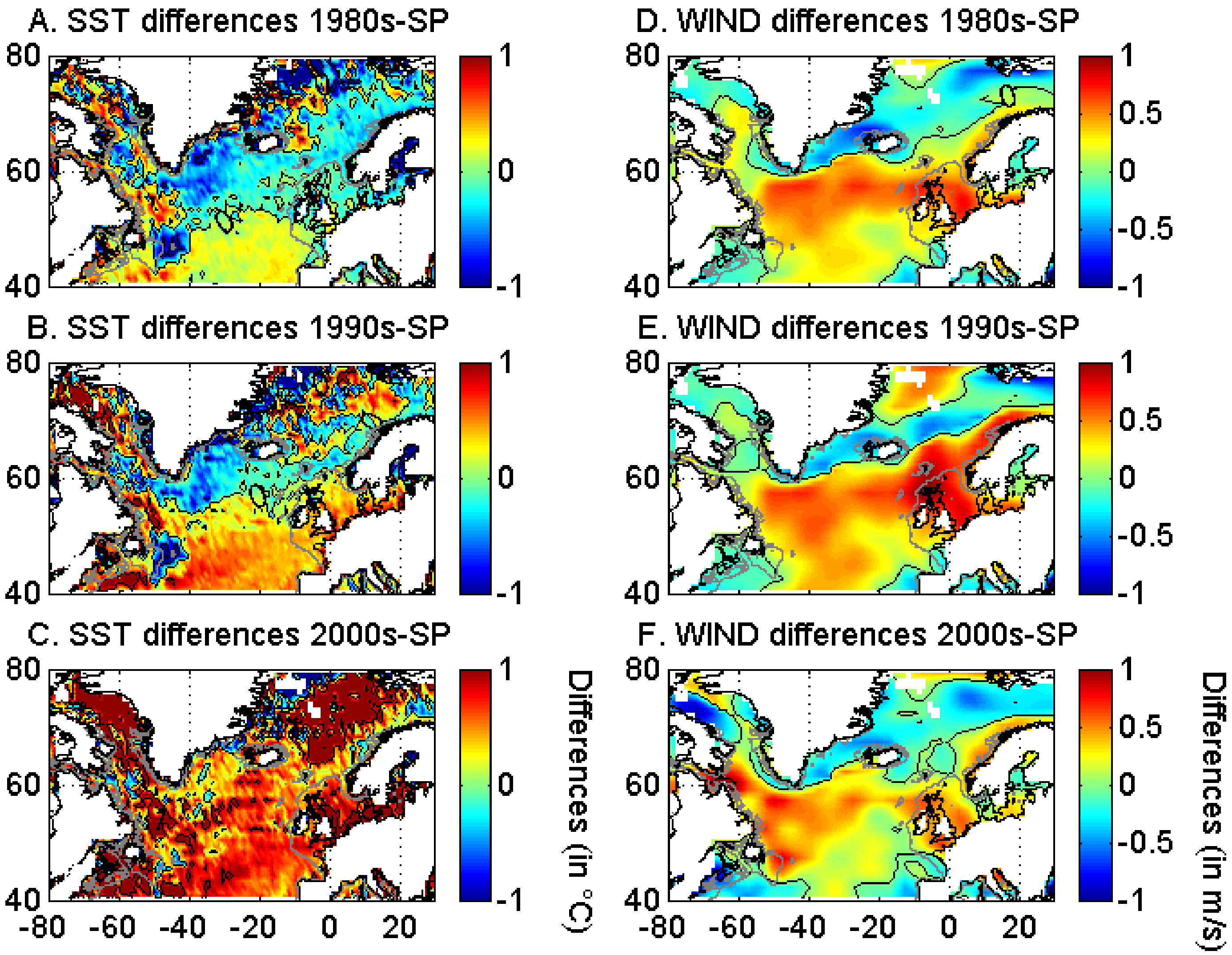

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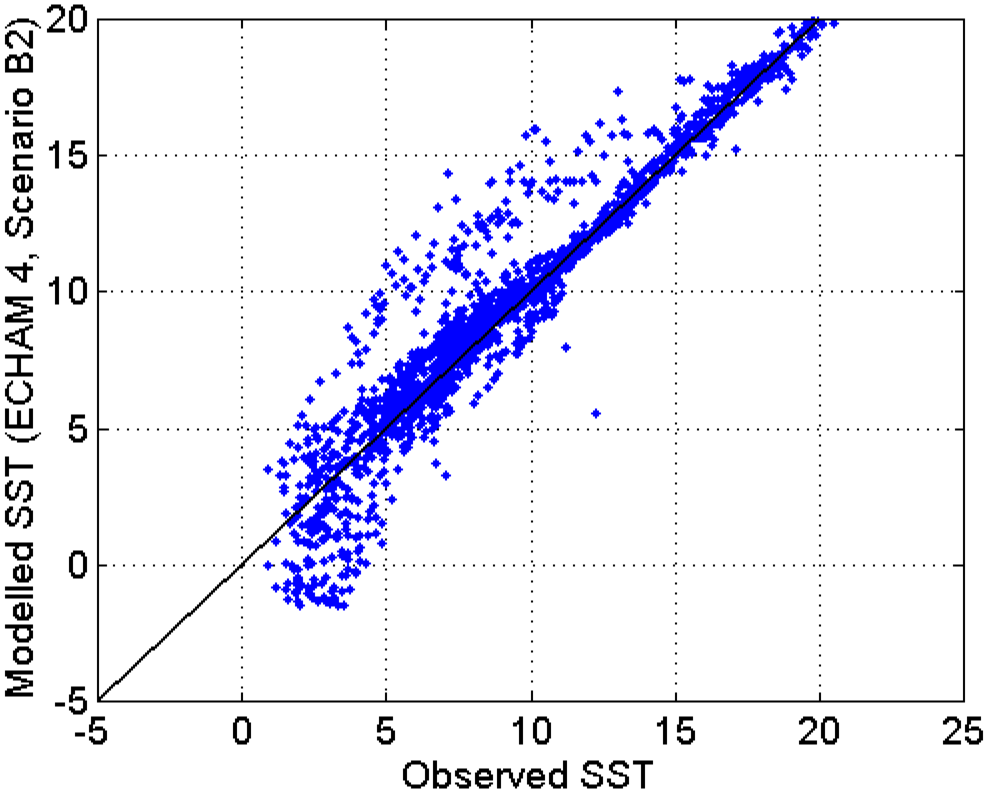

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