Supporting Information for

Slower long-term coastal warming drives dampened trends in coastal marine heatwave exposure

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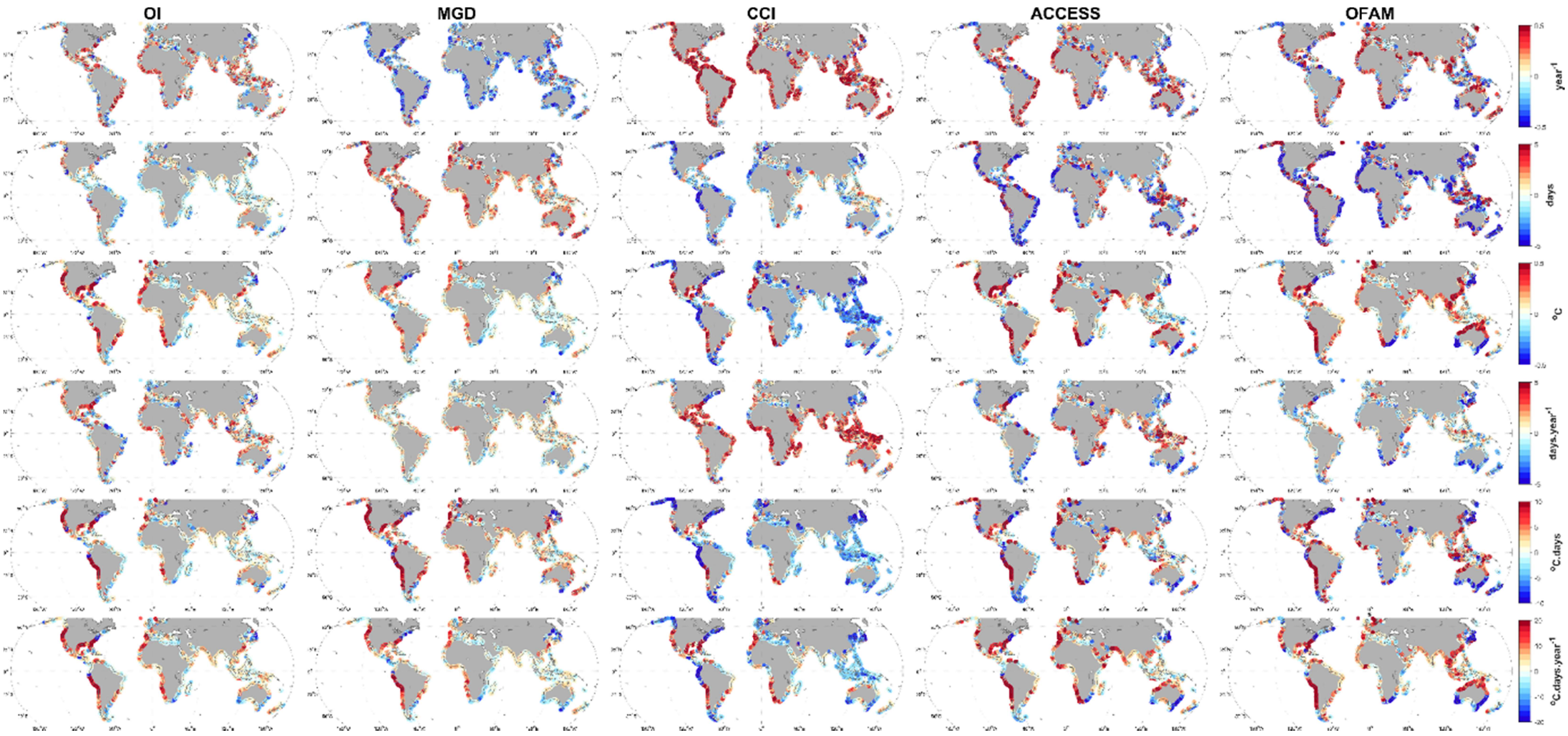

Figure S1: Average MHW metric differences between onshore and offshore pixels. Annual frequency, duration, mean intensity, annual MHW days, cumulative intensity and yearly cumulative intensity (top to bottom row, respectively) average difference during 1982-2014 for all STT products and models. Positive indicates onshore pixel has higher MHW metric value than offshore.

Text S1: Case study - Gulf Stream Region

A heat budget analysis was also performed for the Gulf Stream region, where OFAM3 and ACCESS-OM2 both reproduced the lower onshore trends. Results support the complexity of coastal processes controlling long-term changes of upper ocean temperature. However, the amplitude of heat budget terms is much higher than the change in temperature, lowering our confidence in the results.

The yearly averaged heat budget highlighted the importance of mixing processes in the GS region (Figure S2). While both advection and net air-sea heat flux acted to remove heat onshore, ocean mixing was the dominant term of the mean heat budget and had a positive contribution (Figure 1S2a). Advection was solely driven by its horizontal component, as vertical advection was negligeable (Figure S2b). The role of ocean mixing was reversed at offshore pixels, cooling surface waters (Figure S2d), but was smaller than the dominant advection term. Horizontal and vertical advection were equally important in driving total advection, both positively contributing to offshore variations of temperature (Figure S2e).

Contrary to the Chilean region, the most recent period in the Gulf Stream region was not characterised by any significant temperature trend (Figure S3a). Instead, a significant offshore warming of 0.25°C per decade was observed during 1982-2004. This contrasted with the absence of significant long-term temperature change at onshore pixels during the 1982-2004 period, resulting in the negative onshore-offshore temperature trend difference. Therefore, the temperature trend difference between onshore and offshore pixels is solely explained by the drivers of the offshore temperature trend during 1982-2004.

The P_t-P_{ref} heat budget revealed that the offshore 1982-2004 warming was mostly driven by an increase of advective warming by more than 1°C per year (Figure S3e). Ocean mixing and air-sea heat flux cooling both increased to counterbalance the advective warming but their combined amplitude remained smaller than advection. Results from the heat budget analysis, and in particular the contribution of advection and other non-advective processes, had a large variance within the GS region, translating to a poor confidence of the mean value of heat budget terms (Figure S3). This variance can be attributed to the position of offshore pixels included in the GS box. The core of the Gulf Stream is located approximately 150km away from the coastline, corresponding to the distance chosen for offshore pixel (Figure S4). Offshore pixels were therefore located on both sides of the Gulf Stream core (Figure S4). Advective and mixing processes in WBC systems can vary significantly across the direction of the current. In addition, strong mesoscale enhances variability on a similar horizontal scale than OFAM3 resolution (i.e., pixel scale). As advective inputs of heat tend to be balanced by cooling from mixing (Figure S3d), the addition of both terms represents the contribution of oceanic internal processes to temperature changes. As the advection term was larger than the mixing term in driving the GS offshore pixels temperature trend (Figure S3e), the contribution of oceanic processes all together remained positive (Figure S5b). Importantly, the error associated with this term was significantly reduced, indicating that the contribution of oceanic processes dominated air-sea heat fluxes consistently within the GS region (Figure S5b).

The increased advective warming was driven by an increase in vertical heat advection which dominated a decrease of horizontal heat advection (Figure S3e). However, the mean horizontal velocity field difference between P_t and P_{ref} revealed that the current velocity was faster during 1982-2004 than 2005-2014 (Figure S6). Assuming negligible changes in horizontal temperature gradients, this result is inconsistent with a horizontal advective cooling. The study of trends in the GS strength is an on-going topic of research as the GS influence on weather and climate of the northern hemisphere is critical. Further studies are needed to quantify recent changes in the GS strength west of 70W and assess the performance of OFAM3 in this region, and better understand how ocean processes influence offshore decadal changes of temperature.

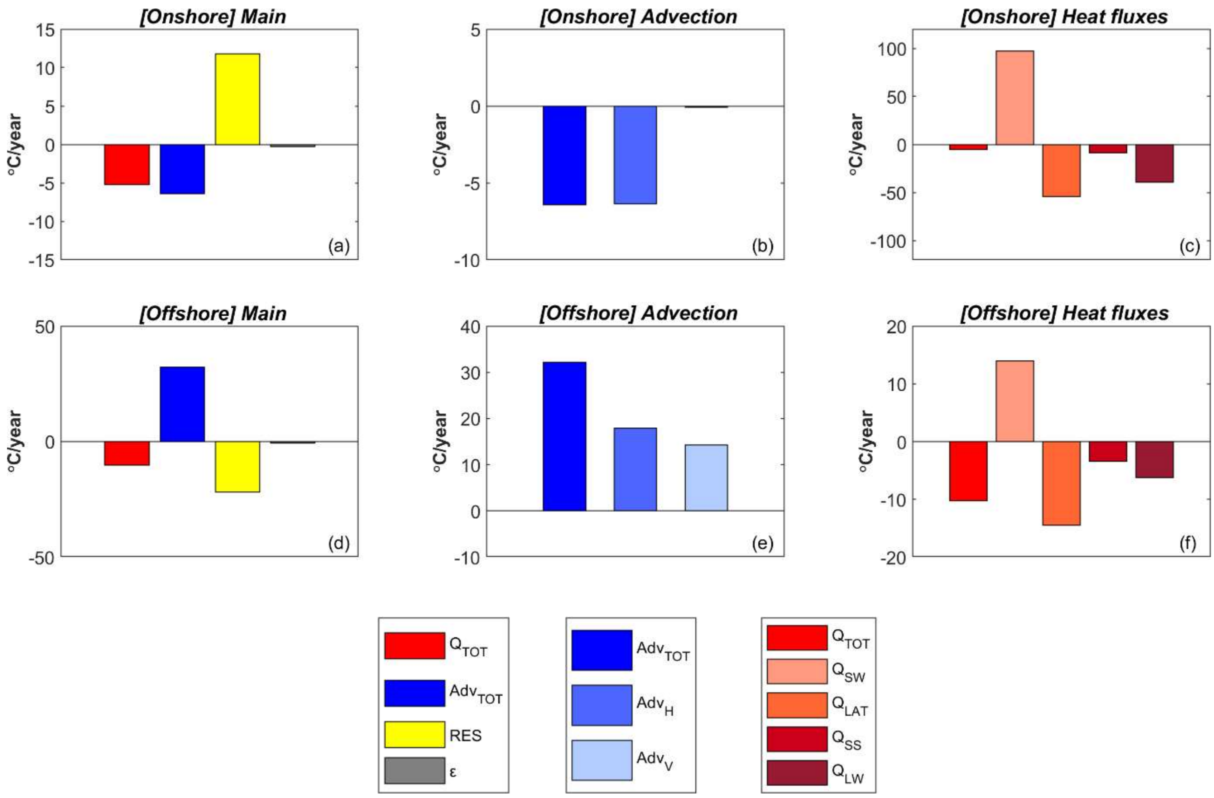

Figure S2: Mean 0-110m heat budget at the GS region. Average yearly heat budget terms (°C.year^{-1}) for the period 1982-2014 at (a) onshore and (d) offshore pixel. Q_{TOT} (red) is the net air-sea heat flux term, Adv_{TOT} (blue) is the total advection term, RES (yellow) is the non-advective ocean processes term and Ɛ (grey) is the residual term. (b,e) decomposition of the advection term into its horizontal (Adv_H) and vertical (Adv_V) components. (c,f) decomposition of the net air-sea heat flux term into turbulent (sensible and latent heat fluxes, denoted Q_{SS} and Q_{LAT}, respectively) and radiative heat fluxes (downward shortwave and longwave radiation, denoted Q_{SW} and Q_{LW}, respectively). Note the difference in y-axis scale between onshore and offshore pixels.

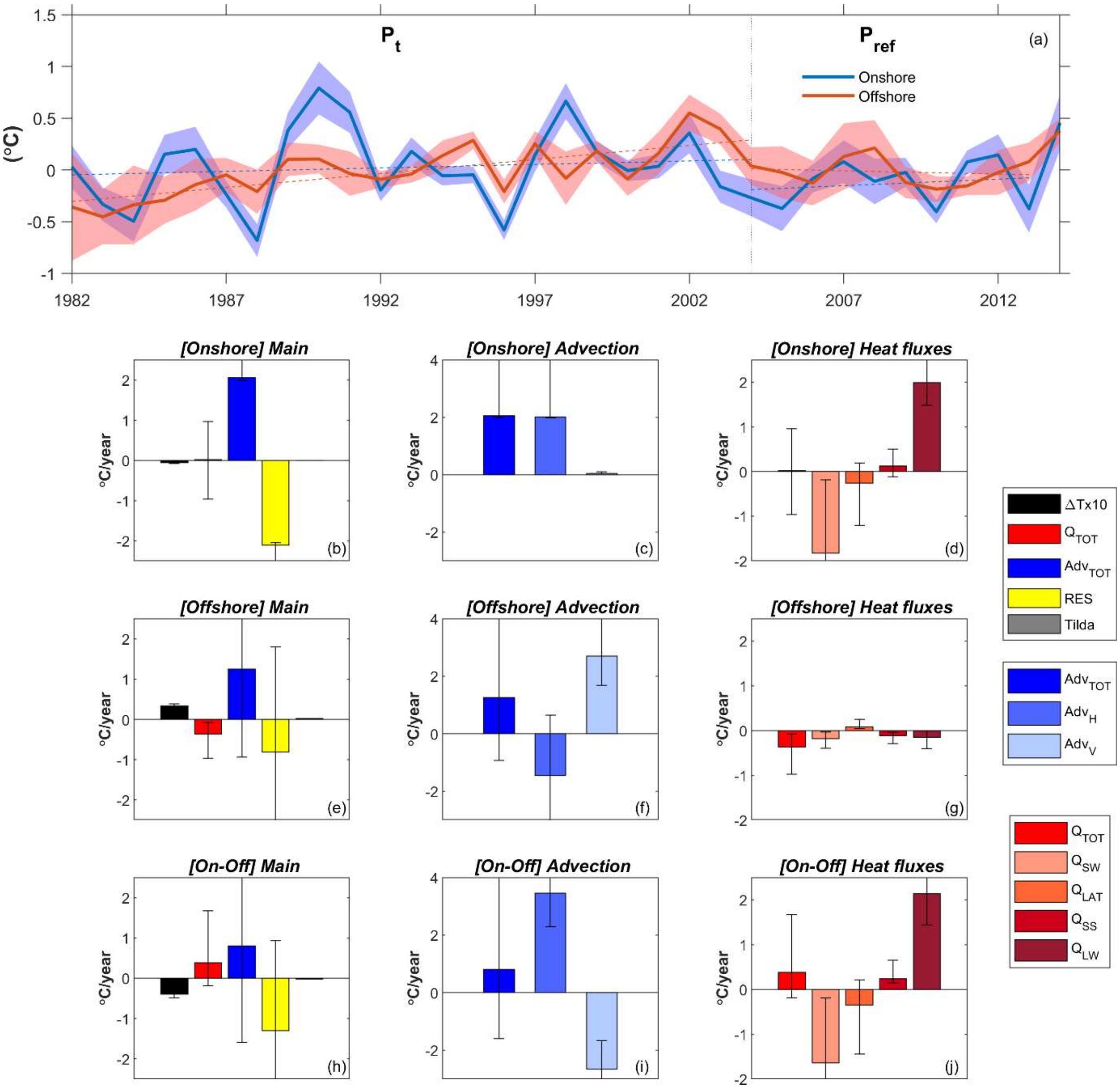

Figure S3: Heat budget analysis of temperature long-term trends in the Gulf Stream region. (a) Timeseries of yearly mean 0-110m depth averaged temperature anomalies of the Gulf Stream region. The thick lines depict the onshore (blue) and offshore (red) pixel's average for the region, and its standard error (shaded). P_{ref} define a period where there is no long-term change in temperature. P_t define a period of significant long-term change in temperature. Linear trends of individual periods are shown by the dashed line. The $P_t - P_{ref}$ difference of mean annual heat budget terms are plotted for (b) onshore, (e) offshore and (h) onshore-offshore pixels' average. ΔT (black) represents the mean annual temperature change difference between P_t and P_{ref} due to the linear trend. The contribution from (red) net air-sea heat flux, (blue) advection, and (yellow) remaining ocean processes to the linear trend difference (see [11]) are indicated by the remaining bars. The grey bar (Tilda) indicates the mean annual temperature change that is not captured by the linear trend. The relative contribution of (c,f,i) horizontal and vertical advection to total advection and (d,g,j) turbulent (sensible and latent heat fluxes, denoted Q_{SS} and Q_{LAT}, respectively) and radiative heat fluxes (downward shortwave and longwave radiation, denoted Q_{SW} and Q_{LW}, respectively) to the total heat flux are also plotted. The 1st and 3rd quartile of budget terms from individual pixels included in the region are indicated by the error bars for each budget term. Note that the mean annual temperature change difference between P_t and P_{ref} due to the linear trend, ΔT, was multiplied by a factor of 10 for better visualisation. We also note that P_{ref} was selected as the most recent 10 years (2004-2014) as there were no significant linear temperature trends for neither onshore nor offshore pixel averages

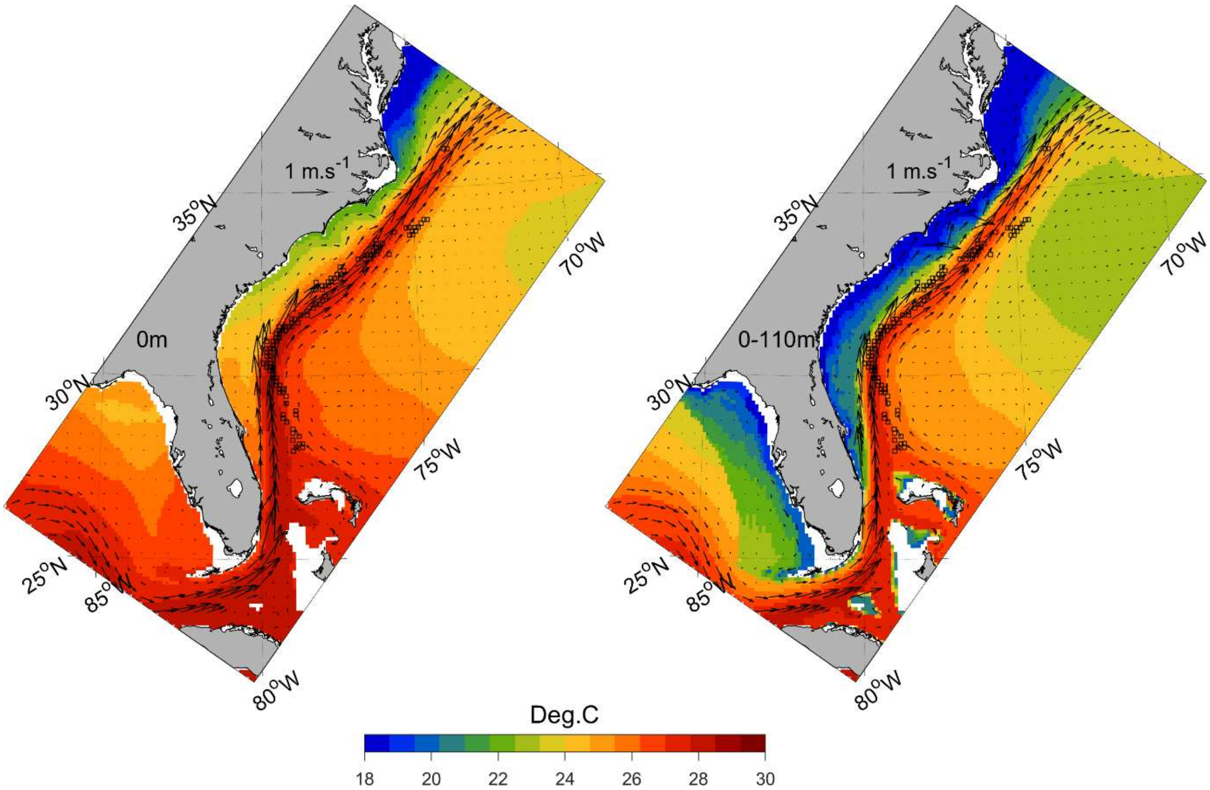

Figure S4: OFAM3 mean surface (left) and 0-110m depth-averaged (right) temperature during 1982-2014. Black arrows denote the corresponding mean horizontal velocity vectors during 1982-2014. The location of the offshore pixels comprised in the GS region are marked by the black squares.

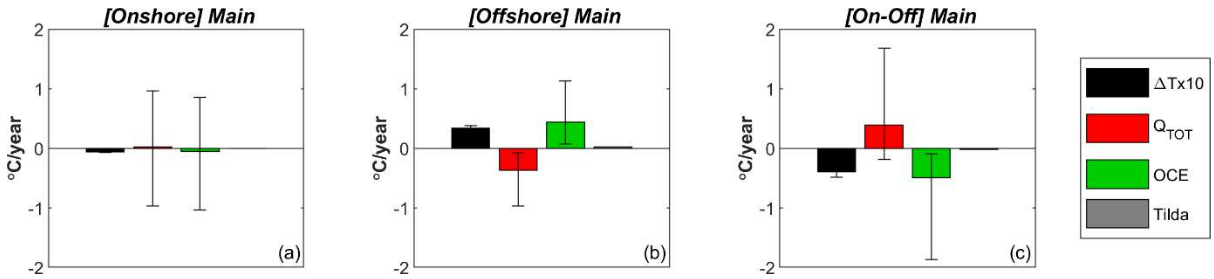

Figure S5: Mean 0-110m heat budget at the GS region. Average yearly heat budget terms (°C.year^{-1}) for the period 1982-2014 at (a) onshore, (b) offshore pixel and (c) the onshore-offshore difference. ΔT (black) represents the mean annual temperature change difference between P_t and P_{ref} due to the linear trend. Q_{TOT} (red) is the net air-sea heat flux term, OCE (green) is the sum of the total advection term and non-advective ocean processes and Tilda indicates the mean annual temperature change that is not captured by the linear trend. The 1st and 3rd quartile of budget terms from individual pixels included in the region are indicated by the error bars for each budget term. Note that the mean annual temperature change difference between P_t and P_{ref} due to the linear trend, ΔT, was multiplied by a factor of 10 for better visualisation.

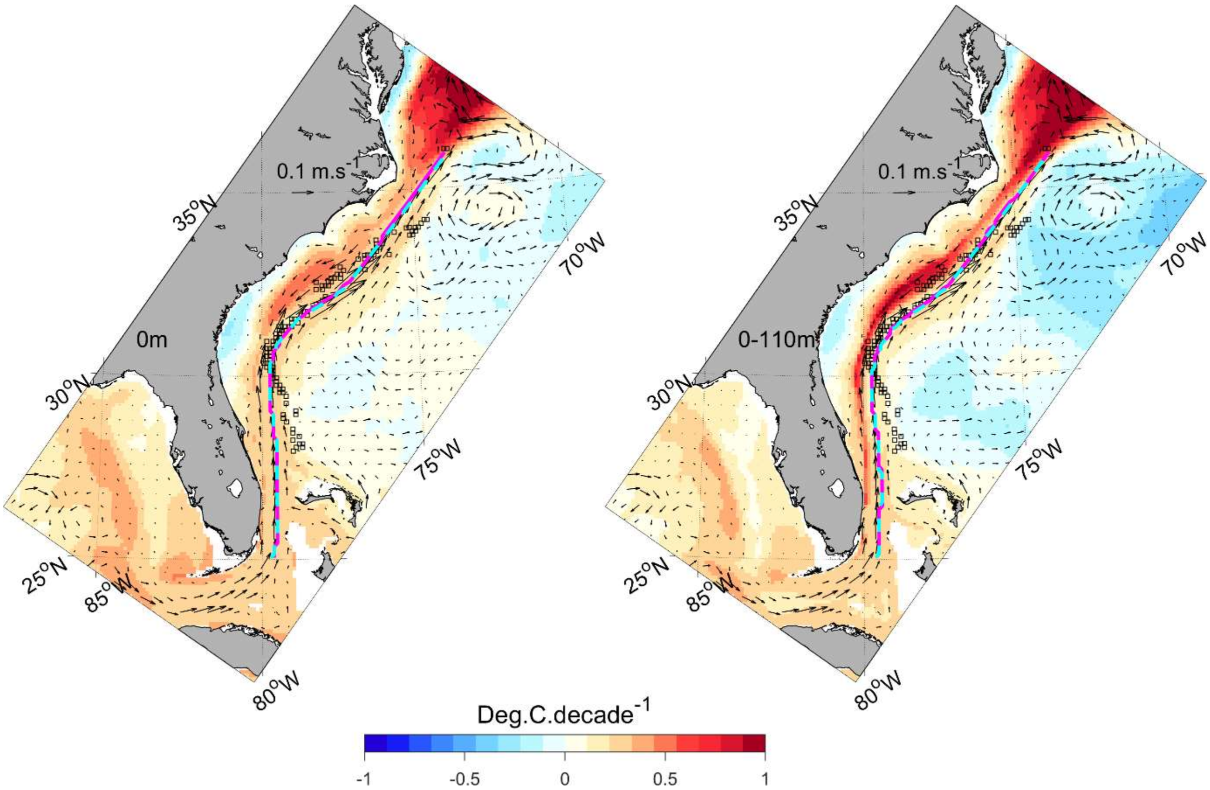

Figure S6: OFAM3 mean surface (left) and 0-110m depth-averaged (right) temperature difference between 1994-2004 and 1982-1992, representing the mean change of temperature during the period of significant offshore temperature change P_t. Black vectors represent the corresponding horizontal current anomalies between during P_t relative to P_{ref} (2005-2014). The mean position of the Gulf Stream during P_{ref} (magenta) and P_t (dashed cyan) is shown between 25°N-36°N. The location of the offshore pixels comprised in the GS region are marked by the black squares.

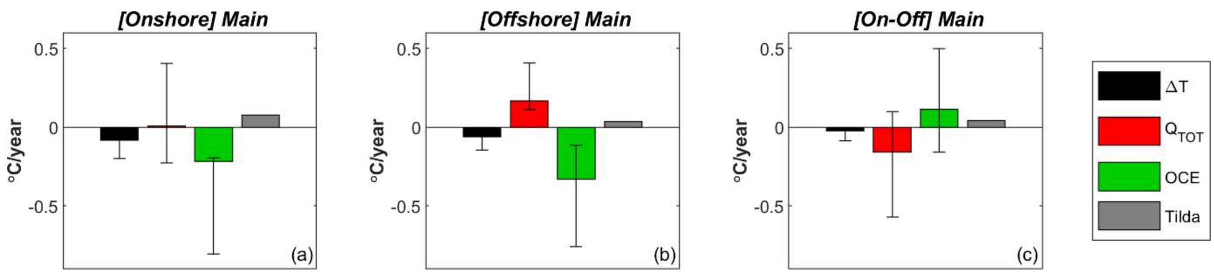

Figure S7: Mean 0-110m heat budget at the CHIL region. Average yearly heat budget terms (°C.year⁻¹) for the period 1982-2014 at (a) onshore, (b) offshore pixel and (c) the onshore-offshore difference. ΔT (black) represents the mean annual temperature change difference between P_t and P_{ref} due to the linear trend. Q_{TOT} (red) is the net air-sea heat flux term, OCE (green) is the sum of the total advection term and non-advective ocean processes and Tilda indicates the mean annual temperature change that is not captured by the linear trend. The 1st and 3rd quartile of budget terms from individual pixels included in the region are indicated by the error bars for each budget term.

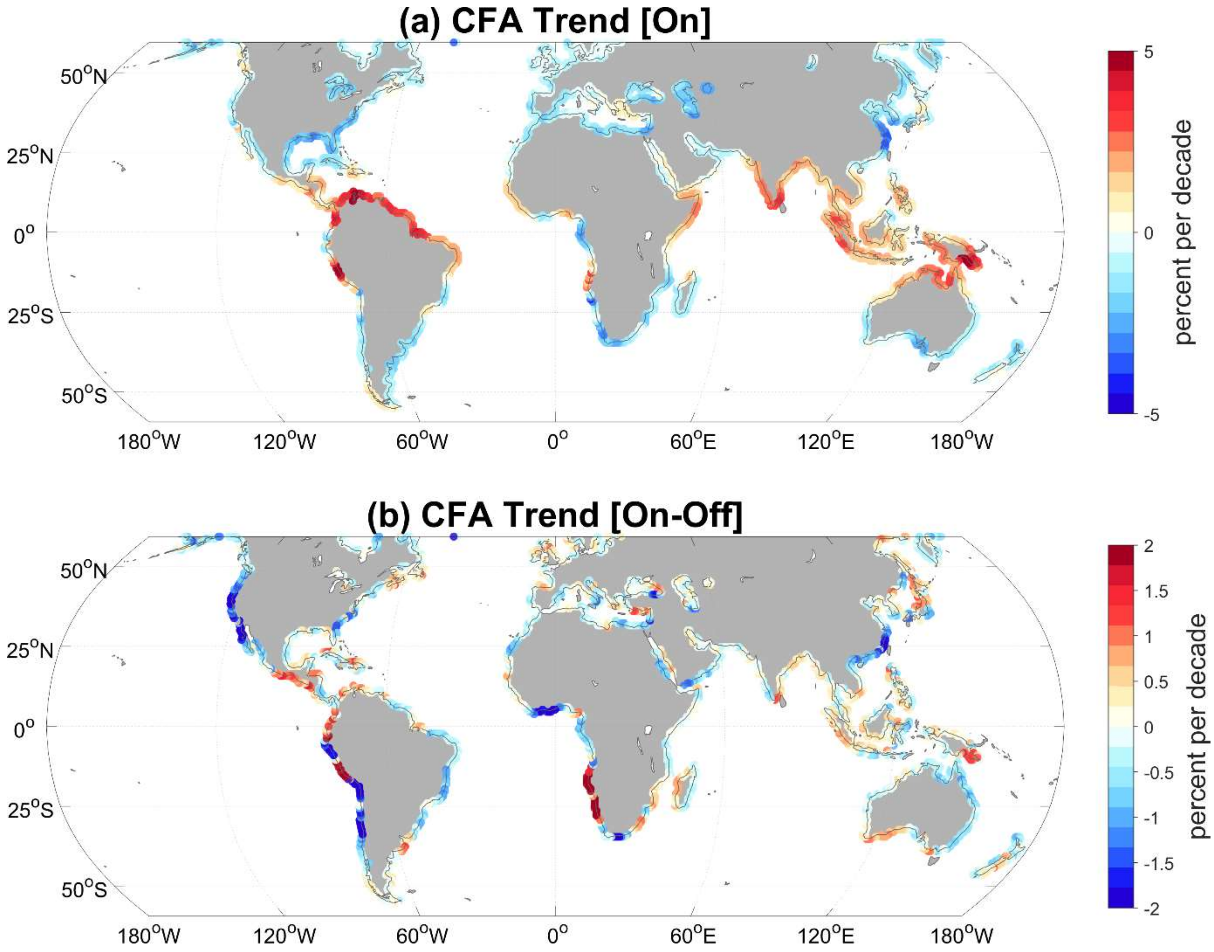

Figure S8: (a) ERA-Interim annual Cloud Fraction Area (CFA) long-term trends at onshore pixels for the 1982-2014 period. (b) Annual CFA long-term trend differences between onshore and offshore pixels. Offshore pixels were chosen as the closest pixel that was at least 150km away from the corresponding onshore pixel, while not being closer to any other onshore pixel.