Geophysical Research Letters

RESEARCH LETTER
10.1029/2025GL118383

Key Points:

- The "warming hole" or "cold blob" in the northern Atlantic represents a full-depth heat content decline
- The region of declining heat content does not correspond to an area of increasing surface heat loss
- Multidecadal heat content variations in this region correlate strongly with horizontal heat transport variations

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:
S. Rahmstorf,
rahmstorf@pik-potsdam.de

Citation:
Rahmstorf, S., Jendrkowiak, J., Gou, R., Cheng, L., Ruiz-Angulo, A., & Björnsson, H. (2026). Multidecadal Atlantic "warming hole" heat content variations are caused by ocean heat transport, not by surface fluxes. *Geophysical Research Letters*, *53*, e2025GL118383. https://doi.org/10.1029/2025GL118383

Received 25 JUL 2025
Accepted 1 MAY 2026

Author Contributions:
Conceptualization: Stefan Rahmstorf, Angel Ruiz-Angulo, Halldór Björnsson
Data curation: Lijing Cheng
Formal analysis: Ruijian Gou, Angel Ruiz-Angulo, Halldór Björnsson
Investigation: Jan Jendrkowiak
Methodology: Stefan Rahmstorf
Software: Jan Jendrkowiak
Validation: Stefan Rahmstorf, Jan Jendrkowiak
Visualization: Jan Jendrkowiak, Ruijian Gou, Lijing Cheng, Angel Ruiz-Angulo, Halldór Björnsson
Writing – original draft: Stefan Rahmstorf
Writing – review & editing: Angel Ruiz-Angulo, Halldór Björnsson

Multidecadal Atlantic "Warming Hole" Heat Content Variations Are Caused by Ocean Heat Transport, Not by Surface Fluxes

Stefan Rahmstorf[1], Jan Jendrkowiak[1], Ruijian Gou[1], Lijing Cheng[2], Angel Ruiz-Angulo[3], and Halldór Björnsson[4]

[1]Potsdam Institute for Climate Impact Research, Potsdam, Germany, [2]Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences, Beijing, China, [3]Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland, [4]Icelandic Met Office, Reykjavík, Iceland

Abstract The northern Atlantic south of Greenland and Iceland is the only part of the world which has cooled significantly since the 19th Century both in the atmosphere and ocean. The oceanic cooling is widely assumed to be a result of reduced ocean heat transport into this region. However, some studies have suggested it could be due to increased net heat loss at the sea surface. Here we use observation-based reanalysis data of ocean heat content and surface flux changes in this region to show that the observed cooling trend cannot be explained by surface heat flux changes, and that multidecadal heat content variations are generally larger and more tightly correlated with ocean heat transport than with surface heat flux variability.

Plain Language Summary A region of the northern Atlantic–sometimes called the "cold blob"–has cooled since the 19th Century while the rest of the world has warmed. It is particularly the ocean which has cooled there. Scientists have been discussing whether this is because ocean currents bring less heat into this region, or because more heat is being lost through the sea surface there. An analysis of temperature data sets based on measurements show it is the former–changing ocean heat transport–which dominates heat content changes in the "cold blob." This is of concern because a further weakening of Atlantic heat transport in future climate change could lead to serious impacts on climate and weather conditions in Europe and other parts of the world.

1. Introduction

One of the most remarkable features of climate change since the 19th Century is this: while otherwise surface temperature of the entire planet has been warming, a region in the subpolar North Atlantic has not only defied this warming trend but has significantly cooled. This region (shown in Figure 1) is located to the south of Greenland and Iceland and to the west of the British Isles, and it has been dubbed the Atlantic "warming hole" or "cold blob." This pattern is also seen in surface air temperature trends, see for example figure TS.3 of the IPCC 6th Assessment report (IPCC, 2021).

(Dima & Lohmann, 2010) analyzed patterns of SST variability since 1870 using the empirical orthogonal function method and found that the northern Atlantic cooling is part of a pattern anticorrelated with the South Atlantic. They concluded that this pattern is linked to Atlantic meridional overturning circulation (AMOC) variations, and that the AMOC has been weakening since the 1930s. That is plausible, since the "cold blob" region is where the AMOC delivers its heat and passes it to the atmosphere, and much of this heat is drawn from the South Atlantic and transported northward across the equator (Trenberth & Fasullo, 2017). In fact, that is the main reason why the Northern Hemisphere is 1°–2°C warmer than the Southern Hemisphere (Feulner et al., 2013).

Subsequently, (Drijfhout et al., 2012) analyzed temperature trend patterns in observations and historic-forcing simulations of CMIP5 climate models. Using bivariate regression, they demonstrate that the warming hole is associated with the AMOC. This result was supported by (Caesar et al., 2018), who find a strong correlation of AMOC weakening with the cold blob temperature in future global warming simulations of CMIP5 models. Several further studies have likewise concluded that the "cold blob" is of anthropogenic origin (Chemke et al., 2020) and due to AMOC slowdown (Lee et al., 2026; K. Y. Li and Liu, 2025).

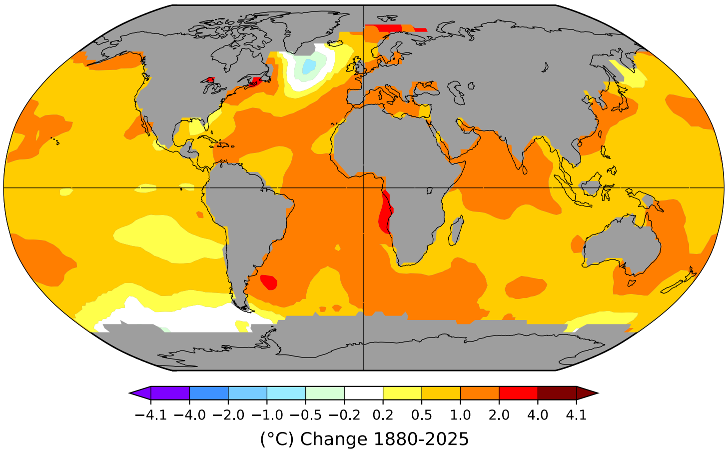

Figure 1. Sea-surface temperature linear trend (°C) from 1880 to 2025, NASA GISTEMP data (Lenssen et al., 2024). Gray areas indicate missing data. Interactive map generated at https://data.giss.nasa.gov/gistemp/maps/ on 14.1.2026.

Other studies have used observed sea surface salinity changes (Zhu & Liu, 2020) or various types of paleoclimatic proxy data (Caesar et al., 2021; Rahmstorf et al., 2015) to conclude that the AMOC has slowed down since preindustrial time, or further indications of a weakening over more recent decades (Biló et al., 2024; Michel et al., 2025; Pontes & Menviel, 2024; Ren, Li, et al., 2025, Ren, Xie, et al., 2025; Zhu et al., 2023). A further weakening of the AMOC could have major repercussions for future climate for millennia, given that the AMOC is known to have a tipping point beyond which it is likely to shut down, as reviewed in (Rahmstorf, 2024).

Note that the linkage of the "cold blob" to the AMOC refers to the longer-term, multi-decadal evolution. This connection is stronger in the winter half of the year (Caesar et al., 2018) and is expected to involve a time lag of a few years (Caesar et al., 2022). Shorter-term SST variability is likely dominated by weather and thus surface forcing (Fox et al., 2022). That is expected particularly in summer when a shallow and warm surface mixed layer develops, which is more susceptible to surface forcing than to horizontal ocean heat transport. A striking example of this was the summer 2023 with record-breaking sea-surface temperatures in the North Atlantic including in the "cold blob" region, as an exceptionally shallow surface mixed layer–in some areas only 10 m deep–heated up in the summer sun (England et al., 2025). The "cold blob" subsequently reappeared after deep winter mixing.

Nevertheless, it has been proposed based on modeling that at least a part of the long-term cooling trend in the subpolar Atlantic could be due to surface forcing (Fan et al., 2023; He et al., 2022; L. Li et al., 2021). However, climate models disagree on the cause of the "cold blob" (Fan et al., 2024), so that an analysis of observational data is needed. Here, we present such a data analysis to examine the causes of the "cold blob" further.

2. Results

The normalized SST trends in the Atlantic since 1993 from the Copernicus satellite data are shown in Figure 2. The cold blob is clearly visible also for this time period where high resolution satellite data are available. In addition, we see a strip of strong warming along the American coast north of Cape Hatteras, a feature known to be an "AMOC fingerprint" dynamically linked to an AMOC weakening via a northward shift of the Gulf Stream (Zhang, 2008). Such a shift is also suggested by the below-average warming to the south of the strong warming strip, with some blue patches.

Another important diagnostic is the heat content change in the water column (Cheng et al., 2022). While the global ocean has generally accumulated heat at a rate of the order of 1 W/m^2 during this period, the cold blob region has lost heat (Figure 3). It is thus clear that the cold blob is not merely a surface layer phenomenon. The heat content trend during 1955–2024 over this region is $-4.9 \pm 2.8 \times 10^{11}$ W, or on average -0.15 ± 0.09 W/m^2.

To analyze the role of surface fluxes we use the ERA5 reanalysis data, which combine data and model physics by way of data assimilation as used in weather forecasting. They thus provide the most comprehensive available data set following actual weather systems with hourly output and 31 km horizontal resolution (Hersbach et al., 2020).

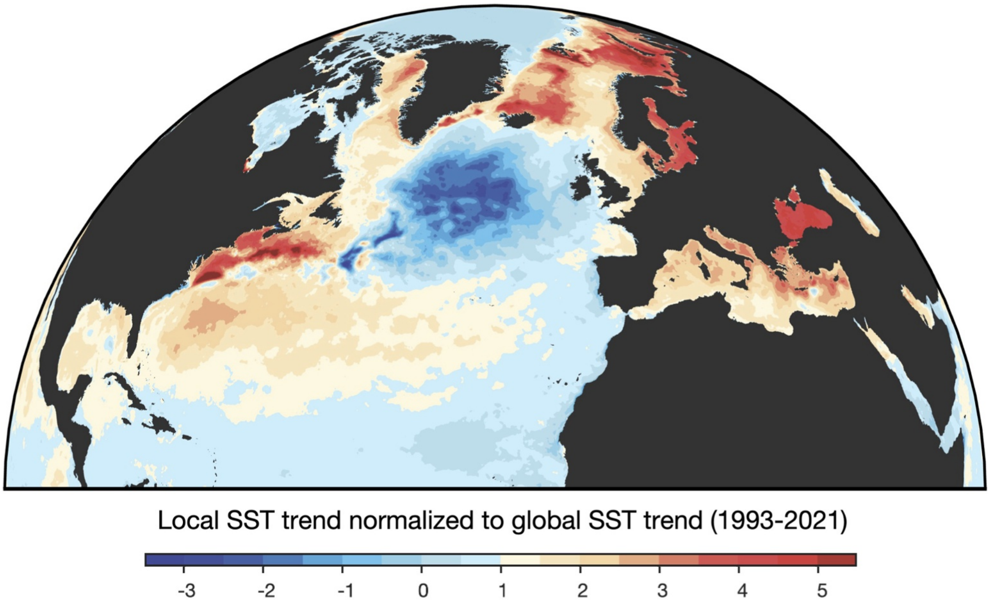

Figure 2. Local sea surface temperature trend divided by the global SST trend for 1993–2021. This normalization is useful for comparing different time intervals and for removing the average global warming trend. Data source: (Copernicus Climate Change Service, 2023).

With surface heat flux we mean the net flux from all contributions: shortwave and longwave radiative fluxes, sensible and latent heat fluxes (positive is downward into the ocean).

Figure 4 maps the trends in SST and in surface heat flux through the ocean surface since 1955 (the period covered by quality reanalysis data) and 1993 (the satellite data period).

The ERA5 SST trend shows similar features as the satellite SST trend (Figure 2), including the cold blob and the warm strip along the American coast north of Cape Hatteras, here shown without normalization; hence the orange background shows the general global warming trend.

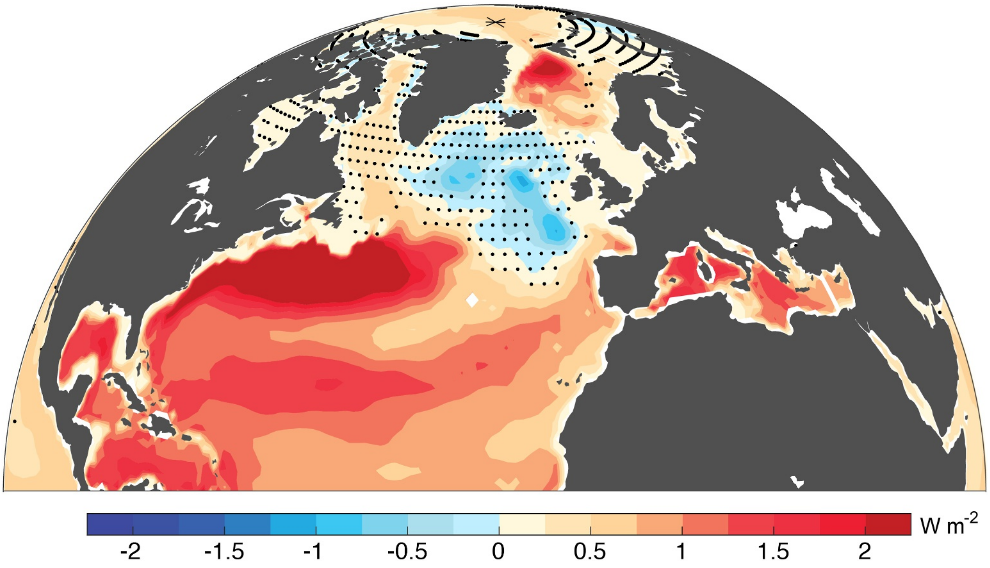

Figure 3. Trend of ocean heat content in W/m^2 in the full-depth water column for 1955–2024, the interval over which these data are considered sufficiently reliable (Cheng et al., 2024). Non-significant trends (90% level) are indicated by stippling. Note that even no trend in the “cold blob” region would be highly relevant when almost the whole globe is warming.

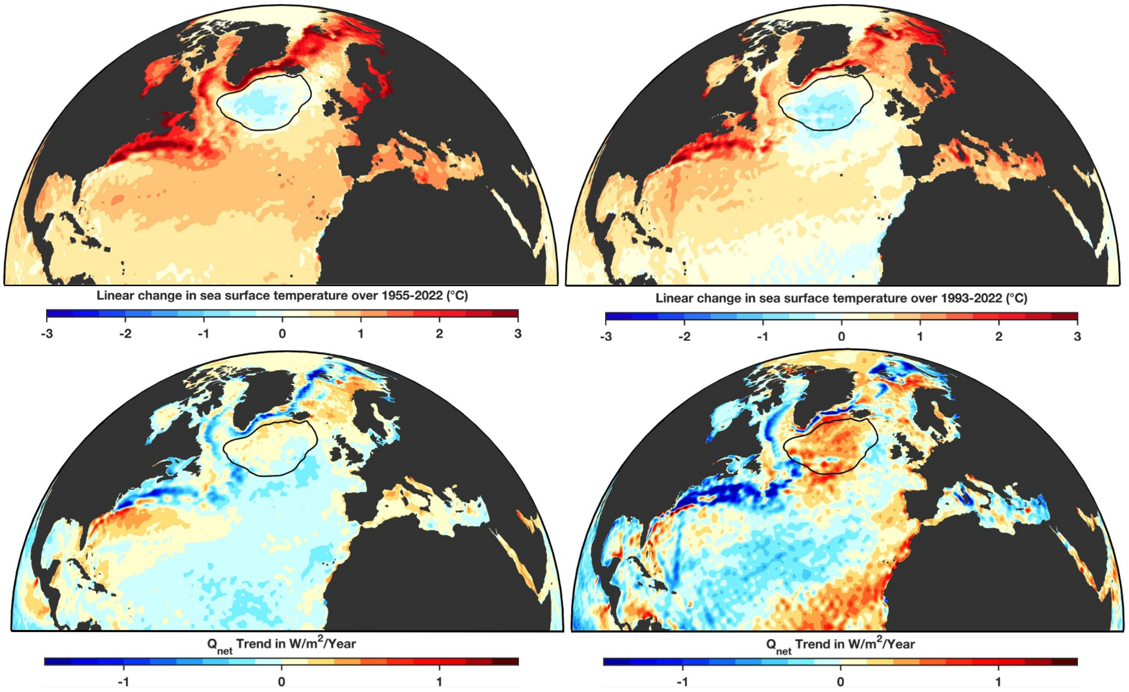

Figure 4. Trend in sea surface temperature over 1955–2022 and 1993–2022 (top panels), and trend in surface ocean heat flux over the same periods (bottom), all from ERA5 reanalysis (Hersbach et al., 2020). The contour shows the "cold blob region" as used in the subsequent figures; its exact location depends somewhat on time period but does not affect the results. The contour encircles the region without significant SST warming during 1955–2022 (90% level). While the key feature here is lack of warming, the center of the "cold blob" has cooled significantly.

To explain a cooling trend in the cold blob region by surface heat loss while the AMOC is steady, this heat loss would need to increase to outcompete the AMOC's heat supply. The opposite is seen in the ERA5 data: surface heat loss has in fact decreased (since 1993 significantly, since 1955 slightly) over the cold blob. The latter is to be expected when the AMOC supplies less heat to the region and thus less is released to the atmosphere.

It must be mentioned that reanalysis data for surface fluxes have substantial uncertainties, since unlike SST these fluxes are not measured but modeled using bulk formulas based on atmospheric parameters like differences between air and skin temperature, air and surface humidity, and wind speeds. We have therefore repeated the analysis with the US NCEP/NCAR reanalysis (Kalnay et al., 1996) as well as the Japanese JRA-3Q reanalysis (Kosaka et al., 2024) products, both available from 1955. The flux time series over the "cold blob" for all three reanalysis products are shown in Figure S1. They deviate mainly after 2015; the ERA5 reanalysis used here is very close to the average of all three.

The same argument as for the "cold blob"–with reversed sign–applies to the warm part of the AMOC fingerprint along the American coast. Such a warming could in principle result from decreasing heat loss at the surface–but the data show the opposite trend, namely increasing heat loss. This is to be expected if the Gulf Stream has shifted north and brings more heat to this area.

ARGO data show that the Gulf Stream has in fact shifted north since 2001 (Todd & Ren, 2023). That time interval largely overlaps with the period of direct AMOC observations starting in 2004, in which the AMOC has decreased (McCarthy et al., 2025). That is consistent with the mentioned dynamic link between a weakening AMOC and a northward shift of the Gulf Stream (Zhang, 2008).

The availability of full-depth ocean reanalysis data further allows us to perform a heat-budget analysis for the "cold blob" region. For this purpose, we focus on the 'cold blob' region shown in Figure 4, where the water column has been losing heat since 1955. Consider the heat budget of the ocean volume under this area:

$$dHC/dt = \mathrm{OHT} + \mathrm{SHF},$$

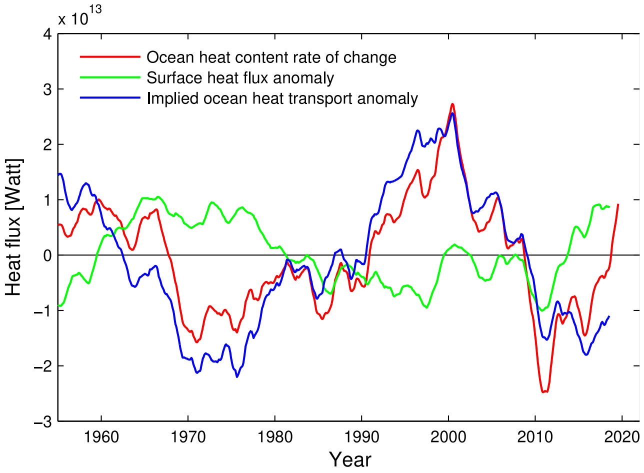

Figure 5. Heat content change, surface heat flux anomaly and implied heat transport anomaly (all given in Watt). The data are 10-year running averages over monthly data to highlight the decadal and longer time scale. To obtain absolute heat loss and transport subtract 1.21×10^{14} W, which is the average heat loss over the full data period. Data sources: heat content IAPv4 (Cheng et al., 2024), surface heat loss ERA5 (Hersbach et al., 2020).

where HC = heat content, OHT = ocean heat transport into the region and SHF = heat gain from the ocean surface. From the heat content and surface flux data, we can thus calculate ocean heat transport as a residual as

$$\mathrm{OHT} = d\mathrm{HC}/dt - \mathrm{SHF}.$$

Figure 5 shows the multidecadal time evolution of these three metrics.

The time-averaged surface heat loss from this area and the corresponding heat transport into the area are around 0.121 Petawatt (in equilibrium, with $d\mathrm{HC}/dt = 0$, these two would balance). The multidecadal variability in OHC cannot be explained by surface heat flux variability and this implies that OHT changes are the main driver of the multidecadal OHC variability. The multidecadal changes of heat content are coherent and largest over the top ~1,000 m of the water column, which coincides with the thickness of the northward flowing AMOC layer. The anomalies appear to penetrate down from there over a 10-year time scale; below 2,500 m depth we see very little change (Figure 6).

The heat content changes are generally larger and more tightly correlated with ocean heat transport than the surface heat loss variations. This is physically expected, since any transport changes affect heat content directly, while they affect surface heat loss only indirectly with delay after the sea surface has warmed. It is also clear that phases of heat content increase (e.g., the one peaking in year 2000) coincide with phases of anomalously large surface heat loss, so that the surface heat flux does not drive heat content change, but rather responds to surface warming. This is a robust result across different reanalysis products despite the substantial uncertainty in reconstructed surface fluxes. The qualitative time evolution of ocean heat transport and heat content change corresponds to the 30-year AMOC reconstruction by (Worthington et al., 2021) based on hydrographic data: low in the 1980s, rising to a peak around 2000, declining until 2010 and then recovering. A similar evolution is found in long-term paleoclimate reconstructions based on sediment data (Caesar et al., 2022).

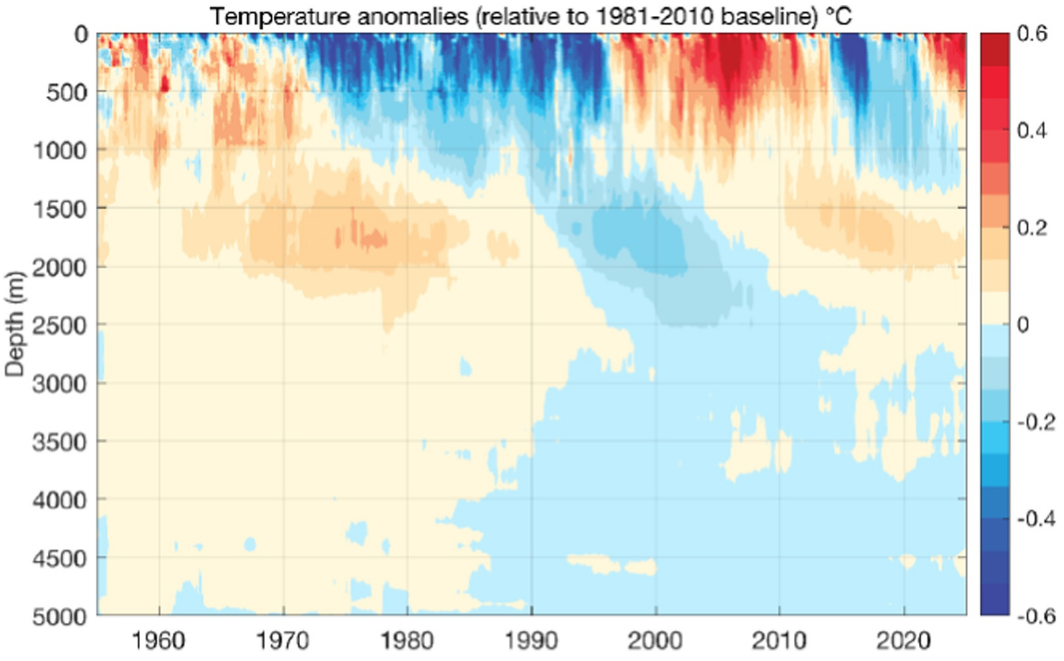

Figure 6. Temperature anomalies in the cold blob region of Figure 4 as function of depth and time. Data source: (Cheng et al., 2024).

For the period since 1955, neither of these three curves show a statistically significant trend given the large multidecadal variability. The exact numbers should in any case be treated with caution given their uncertainty, and such a trend calculation would be the trend of the trend for ocean heat content, that is the second derivative, and thus not very robust. The lack of statistical significance over this time period is consistent with the "AMOC index" of (Caesar et al., 2018): this also does not show a statistically significant downward trend from 1955 onwards; the statistical significance of that index essentially derives from it starting in 1870 and the reconstructed AMOC being stronger in the first half of the data series than in the second. In the presence of multidecadal variations, long data series are needed to establish significant trends, and hence a limitation of our study is the lack of below-surface data going back further in time.

3. Conclusions

The subpolar Atlantic is the only region of the world ocean which has been cooling significantly (Cheng et al., 2024; IPCC, 2021). Our analysis of this "cold blob" and of ERA5 reanalysis data strongly suggest that this is not just a surface phenomenon but a deep-reaching loss of ocean heat content, and that it cannot be explained by increasing surface heat loss but requires declining or weakened lateral heat transport. Surface heat loss appears to respond as a negative feedback to heat content changes: periods of increasing heat content coincide with periods of large surface heat loss. Thus from observational data, we reach the same conclusion as (K. Y. Li and Liu, 2025) did based on the analysis of model results.

Of course, we cannot rule out some contribution to surface heat loss for example from increasing cold winds linked to the positive phase of the North Atlantic Oscillation (Fan et al., 2023). However, to evaluate such a contribution, it is critical to include the effect of changing heat content and lateral heat transport, as these terms show even larger multidecadal variations than the surface flux. Also, the variations in North Atlantic Oscillation may be a delayed response to AMOC variations (Haarsma & Drijfhout, 2025).

Our analysis supports the interpretation of the observed "cold blob" as a sign of a weakening AMOC, which is a major component of the lateral heat transport into that subpolar gyre region. A contribution from increasing lateral heat transport out of the subpolar gyre toward the Nordic Seas has also been suggested (Keil, 2020), and both may well be dynamically linked (Roewer et al., 2026).

There is substantial evidence for a weakening AMOC independent of the "cold blob." On long time scales this includes paleoclimatic proxy data suggesting the AMOC is at its weakest in a millennium (Caesar et al., 2021, 2022). Also, salinity in the "cold blob" region is at its lowest in 120 years of data, consistent with reduced AMOC salt transport from the subtropical net-evaporation region (Holliday et al., 2020).

On shorter time scales this includes a robust observed weakening of the Gulf Stream over the past 4 decades (Piecuch & Beal, 2023), consistent in magnitude with the 15% AMOC weakening inferred from the subpolar SST data (Caesar et al., 2018), and an ocean density reduction in the subpolar gyre since 1950 which "is suggestive of a long-term AMOC weakening of 2.2 Sv or 13%" (Chafik et al., 2022).

Global warming scenarios of the current climate model generation CMIP6 tend to show an AMOC weakening starting only late in the 20th Century (McCarthy & Caesar, 2023), later than the "cold blob" history suggests. This could be related to radiative forcing issues (aerosol forcing, (Robson et al., 2022)), a generally too stable AMOC in models (in the monostable rather than bistable regime (Arumí-Planas et al., 2024)), or the neglect of increasing Greenland meltwater influx (Pontes & Menviel, 2024).

Given the well-established existence of a tipping point of the AMOC, as well as recent studies finding a range of different "early warning signals" of the ocean circulation approaching such a tipping point (Boers, 2021; Ditlevsen & Ditlevsen, 2023; Michel et al., 2022; van Westen et al., 2024), the strong evidence for a weakening AMOC is a serious concern for society and policy. While large uncertainty remains over how close the Earth is to this tipping point, standard CMIP6 simulations of future global warming scenarios suggest it is crossed in a substantial subset of these model simulations around the middle of this century (Drijfhout et al., 2025; van Westen et al., 2025). From a risk management perspective (Rahmstorf & Zickfeld, 2005), this risk requires urgent attention by policy makers.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All data used are publicly available. These are:

NASA GISTEMP global temperature data, https://data.giss.nasa.gov/gistemp/maps/.

Copernicus satellite data (Copernicus Climate Change Service, 2023).

ERA5 reanalysis data (Hersbach et al., 2020).

IAPv4 ocean temperature and ocean heat content gridded data set (Cheng et al., 2024).

Acknowledgments

The authors benefited from stimulating discussions with H. Van den Budenmeyer and helpful reviewer comments. Open Access funding enabled and organized by Projekt DEAL.

References

Arumí-Planas, C., Dong, S., Perez, R., Harrison, M. J., Farneti, R., & Hernández-Guerra, A. (2024). A multi-data set analysis of the freshwater transport by the Atlantic meridional overturning circulation at nominally 34.5°S. *Journal of Geophysical Research: Oceans*, *129*(6), e2023JC020558. https://doi.org/10.1029/2023jc020558

Biló, T. C., Perez, R. C., Dong, S., Johns, W., & Kanzow, T. (2024). Weakening of the Atlantic meridional overturning circulation abyssal limb in the North Atlantic. *Nature Geoscience*, *17*(5), 419–425. https://doi.org/10.1038/s41561-024-01422-4

Boers, N. (2021). Observation-based early-warning signals for a collapse of the Atlantic meridional overturning circulation. *Nature Climate Change*, *11*(8), 680–688. https://doi.org/10.1038/s41558-021-01097-4

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., & Rahmstorf, S. (2022). Reply to: Atlantic circulation change still uncertain. *Nature Geoscience*, *15*(3), 168–170. https://doi.org/10.1038/s41561-022-00897-3

Caesar, L., McCarthy, G. D., Thornalley, D. J. R., Cahill, N., & Rahmstorf, S. (2021). Current Atlantic meridional overturning circulation weakest in last millennium. *Nature Geoscience*, *14*(3), 118–120. https://doi.org/10.1038/s41561-021-00699-z

Caesar, L., Rahmstorf, S., Robinson, A., Feulner, G., & Saba, V. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature*, *556*(7700), 191–196. https://doi.org/10.1038/s41586-018-0006-5

Chafik, L., Holliday, N. P., Bacon, S., & Rossby, T. (2022). Irminger sea is the center of action for subpolar AMOC variability. *Geophysical Research Letters*, *49*(17), e2022GL099133. https://doi.org/10.1029/2022gl099133

Chemke, R., Zanna, L., & Polvani, L. M. (2020). Identifying a human signal in the north Atlantic warming hole. *Nature Communications*, *11*(1), 1540. https://doi.org/10.1038/s41467-020-15285-x

Cheng, L., Foster, G., Hausfather, Z., Trenberth, K. E., & Abraham, J. (2022). Improved quantification of the rate of ocean warming. *Journal of Climate*, *35*(14), 4827–4840. https://doi.org/10.1175/jcli-d-21-0895.1

Cheng, L., Pan, Y., Tan, Z., Zheng, H., Zhu, Y., Wei, W., et al. (2024). IAPv4 ocean temperature and ocean heat content gridded dataset. *Earth System Science Data*, *16*(8), 3517–3546. https://doi.org/10.5194/essd-16-3517-2024

Copernicus Climate Change Service. (2023). Climate indicators: Sea surface temperature 2023. Retrieved from https://climate.copernicus.eu/climate-indicators/sea-surface-temperature

Dima, M., & Lohmann, G. (2010). Evidence for two distinct modes of large-scale ocean circulation changes over the last century. *Journal of Climate*, *23*(1), 5–16. https://doi.org/10.1175/2009jcli2867.1

Ditlevsen, P., & Ditlevsen, S. (2023). Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. *Nature*, *14*(1), 4254. https://doi.org/10.1038/s41467-023-39810-w

Drijfhout, S., Angevaare, J. R., Mecking, J., van Westen, R. M., & Rahmstorf, S. (2025). Shutdown of northern Atlantic overturning after 2100 following deep mixing collapse in CMIP6 projections. *Environmental Research Letters*, *20*(9), 094062. https://doi.org/10.1088/1748-9326/adfa3b

Drijfhout, S., van Oldenborgh, G. J., & Cimatoribus, A. (2012). Is a decline of AMOC causing the warming hole above the north Atlantic in observed and modeled warming patterns? *Journal of Climate*, *25*(24), 8373–8379. https://doi.org/10.1175/jcli-d-12-00490.1

England, M. H., Li, Z., Huguenin, M. F., Kiss, A. E., Sen Gupta, A., Holmes, R. M., & Rahmstorf, S. (2025). Drivers of the extreme north Atlantic marine heatwave during 2023. *Nature*, *642*(8068), 636–643. https://doi.org/10.1038/s41586-025-08903-5

Fan, Y., Chan, D., Zhang, P., & Li, L. (2024). Disagreement on the north Atlantic cold blob formation mechanisms among climate models. *Journal of Climate*, *37*(16), 4061–4078. https://doi.org/10.1175/jcli-d-23-0654.1

Fan, Y., Liu, W., Zhang, P., Chen, R., & Li, L. (2023). North Atlantic oscillation contributes to the subpolar north Atlantic cooling in the past century. *Climate Dynamics*, *61*(11–12), 5199–5215. https://doi.org/10.1007/s00382-023-06847-y

Feulner, G., Rahmstorf, S., Levermann, A., & Volkwardt, S. (2013). On the origin of the surface air temperature difference between the hemispheres in Earth's present-day climate. *Journal of Climate*, *26*(18), 7136–7150. https://doi.org/10.1175/JCLI-D-12-00636.1

Fox, A. D., Handmann, P., Schmidt, C., Fraser, N., Rühs, S., Sanchez-Franks, A., et al. (2022). Exceptional freshening and cooling in the eastern subpolar north Atlantic caused by reduced labrador sea surface heat loss. *Ocean Science*, *18*(5), 1507–1533. https://doi.org/10.5194/os-18-1507-2022

Haarsma, R., & Drijfhout, S. (2025). Evidence for Atlantic Ocean forcing the atmosphere and the negative role of model bias. *Communications Earth & Environment*, *6*(1), 125. https://doi.org/10.1038/s43247-025-02123-5

He, C., Clement, A. C., Cane, M. A., Murphy, L. N., Klavans, J. M., & Fenske, T. M. (2022). A north Atlantic warming hole without ocean circulation. *Geophysical Research Letters*, *49*(19), e2022GL100420. https://doi.org/10.1029/2022gl100420

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Holliday, N. P., Bersch, M., Berx, B., Chafik, L., Cunningham, S., Florindo-Lopez, C., et al. (2020). Ocean circulation causes the largest freshening event for 120 years in eastern subpolar north Atlantic. *Nature Communications*, *11*(1), 585. https://doi.org/10.1038/s41467-020-14474-y

IPCC. (2021). Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, *77*(3), 437–470. https://doi.org/10.1175/1520-0477(1996)077<0437:tnyrp>2.0.co;2

Keil, P., Mauritsen, T., Jungclaus, J., Hedemann, C., Olonscheck, D., & Ghosh, R. (2020). Multiple drivers of the north Atlantic warming hole. *Nature Climate Change*, *10*(7), 667–671. https://doi.org/10.1038/s41558-020-0819-8

Kosaka, Y., Kobayashi, S., Harada, Y., Kobayashi, C., Naoe, H., Yoshimoto, K., et al. (2024). The JRA-3Q reanalysis. *Journal of the Meteorological Society of Japan. Series II*, *102*(1), 49–109. https://doi.org/10.2151/jmsj.2024-004

Lee, S. K., Kim, D., Lopez, H., & Gomez, F. A. (2026). Future shoaling of the AMOC and its impact on Oceanic heat transport to the subpolar north Atlantic. *Geophysical Research Letters*, *53*(2), e2025GL119487. https://doi.org/10.1029/2025gl119487

Lenssen, N., Schmidt, G. A., Hendrickson, M., Jacobs, P., Menne, M. J., & Ruedy, R. (2024). A NASA GISTEMPv4 observational uncertainty ensemble. *Journal of Geophysical Research: Atmospheres*, *129*(17), e2023JD040179. https://doi.org/10.1029/2023jd040179

Li, K.-Y., & Liu, W. (2025). Weakened Atlantic meridional overturning circulation causes the historical north Atlantic warming hole. *Communications Earth & Environment*, *6*(1), 416. https://doi.org/10.1038/s43247-025-02403-0

Li, L., Lozier, M. S., & Li, F. (2021). Century-long cooling trend in subpolar north Atlantic forced by atmosphere: An alternative explanation. *Climate Dynamics*, *58*(9–10), 2249–2267. https://doi.org/10.1007/s00382-021-06003-4

McCarthy, G. D., & Caesar, L. (2023). Can we trust projections of AMOC weakening based on climate models that cannot reproduce the past? *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, *381*(2262), 20220193. https://doi.org/10.1098/rsta.2022.0193

McCarthy, G. D., Hug, G., Smeed, D., Morris, K. J., & Moat, B. (2025). Signal and noise in the Atlantic meridional overturning circulation at 26°N. *Geophysical Research Letters*, *52*(7), e2025GL115055. https://doi.org/10.1029/2025gl115055

Michel, S. L. L., Dijkstra, H. A., Guardamagna, F., Jacques-Dumas, V., van Westen, R. M., & von der Heydt, A. S. (2025). Deep learning based reconstructions of the Atlantic meridional overturning circulation confirm twenty-first century decline. *Environmental Research Letters*, *20*(6), 064036. https://doi.org/10.1088/1748-9326/add7f0

Michel, S. L. L., Swingedouw, D., Ortega, P., Gastineau, G., Mignot, J., McCarthy, G., & Khodri, M. (2022). Early warning signal for a tipping point suggested by a millennial Atlantic multidecadal variability reconstruction. *Nature Communications*, *13*(1), 5176. https://doi.org/10.1038/s41467-022-32704-3

Piecuch, C. G., & Beal, L. M. (2023). Robust weakening of the gulf stream during the past four decades observed in the Florida straits. *Geophysical Research Letters*, *50*(18), e2023GL105170. https://doi.org/10.1029/2023gl105170

Pontes, G. M., & Menviel, L. (2024). Weakening of the Atlantic meridional overturning circulation driven by subarctic freshening since the mid-twentieth century. *Nature Geoscience*, *17*(12), 1291–1298. https://doi.org/10.1038/s41561-024-01568-1

Rahmstorf, S. (2024). Is the Atlantic overturning circulation approaching a tipping point? *Oceanography*. https://doi.org/10.5670/oceanog.2024.501

Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., & Schaffernicht, E. J. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, *5*(5), 475–480. https://doi.org/10.1038/nclimate2554

Rahmstorf, S., & Zickfeld, K. (2005). Thermohaline circulation changes: A question of risk assessment - An editorial review essay. *Climatic Change*, *68*(1–2), 241–247. https://doi.org/10.1007/s10584-005-4038-0

Ren, Q., Li, Y., Hu, S., Xie, S. P., Lyu, Y., & Wang, F. (2025). Heat storage pattern linked to the Atlantic meridional overturning circulation slowdown. *Geophysical Research Letters*, *52*(13), e2025GL116801. https://doi.org/10.1029/2025gl116801

Ren, Q., Xie, S.-P., Peng, Q., Li, Y., & Wang, F. (2025). Equatorial Atlantic mid-depth warming indicates Atlantic meridional overturning circulation slowdown. *Communications Earth & Environment*, *6*(1), 819. https://doi.org/10.1038/s43247-025-02793-1

Robson, J., Menary, M. B., Sutton, R. T., Mecking, J., Gregory, J. M., Jones, C., et al. (2022). The role of anthropogenic aerosol forcing in the 1850–1985 strengthening of the AMOC in CMIP6 historical simulations. *Journal of Climate*, *35*(20), 3243–3263. https://doi.org/10.1175/jcli-d-22-0124.1

Roewer, S., Fiedler, L., Årthun, M., Huiskamp, W., & Rahmstorf, S. (2026). Nordic overturning increases as AMOC weakens in response to global warming. https://doi.org/10.5194/egusphere-2025-6172

Todd, R. E., & Ren, A. S. (2023). Warming and lateral shift of the gulf stream from in situ observations since 2001. *Nature Climate Change*, *13*(12), 1348–1352. https://doi.org/10.1038/s41558-023-01835-w

Trenberth, K. E., & Fasullo, J. T. (2017). Atlantic meridional heat transports computed from balancing earth's energy locally. *Geophysical Research Letters*, *44*(4), 1919–1927. https://doi.org/10.1002/2016gl072475

van Westen, R. M., Kliphuis, M. A., & Dijkstra, H. A. (2024). Physics-based early warning signal shows that AMOC is on tipping course. *Science Advances*, *10*(6), eadk1189. https://doi.org/10.1126/sciadv.adk1189

van Westen, R. M., Vanderborght, E., Kliphuis, M., & Dijkstra, H. A. (2025). Physics-based indicators for the onset of an AMOC collapse under climate change. *Journal of Geophysical Research: Oceans*, *130*(8), e2025JC022651. https://doi.org/10.1029/2025jc022651

Worthington, E. L., Moat, B. I., Smeed, D. A., Mecking, J. V., Marsh, R., & McCarthy, G. D. (2021). A 30-year reconstruction of the Atlantic meridional overturning circulation shows no decline. *Ocean Science*, *17*(1), 285–299. https://doi.org/10.5194/os-17-285-2021

Zhang, R. (2008). Coherent surface-subsurface fingerprint of the Atlantic meridional overturning circulation. *Geophysical Research Letters*, *35*(20), L20705. https://doi.org/10.1029/2008GL035463

Zhu, C., & Liu, Z. (2020). Weakening Atlantic overturning circulation causes south Atlantic salinity pile-up. *Nature Climate Change*, *10*(11), 998–1003. https://doi.org/10.1038/s41558-020-0897-7

Zhu, C., Liu, Z., Zhang, S., & Wu, L. (2023). Likely accelerated weakening of Atlantic overturning circulation emerges in optimal salinity fingerprint. *Nature Communications*, *14*(1), 1245. https://doi.org/10.1038/s41467-023-36288-4